Microwave Photonics Signal Processing by Exploiting Stimulated Brillouin Scattering in Optical Fiber for Future Radar and Wireless Systems

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Microwave Photonics Signal Processing by Exploiting Stimulated Brillouin Scattering in Optical Fiber for Future Radar and Wireless Systems

By

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“**If I have seen further than others, it is by standing on the shoulders of giants**”

Issacs Newton

This PhD studentship was funded in part by Leonardo, Luton, UK

Declaration

I, Mohamed Alom declare that this thesis has been conducted by me as the result of my own original research. Some of my research work has been submitted for patent GB2567646 which was filed by Leonardo MW LTD on 18th October 2017 and granted on 22 May 2020. This work is strictly **confidential** and should not be shared with anyone without prior consent of the PhD Supervisor (Dr. Shyqyri Haxha). The author rights for the Patent have been equally distributed among me, Dr. Shyqyri Haxha (PhD supervisor), and Dr. Ian Flint (Leonardo Employee).

I confirm that this thesis has not been submitted before for any degree of examination in any University.

Name of candidate: Mohamed Alom

Signature

Date: 27/09/20

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Abstract

In this thesis, Stimulated Brillouin Scattering (SBS) in optical fiber is exploited as a very powerful optical signal processor to synthesize, distortion removing and amplification of ultra-high frequency high bandwidth Radio Frequency (RF) signal in optical domain. Future radar and wireless communication systems are facing significant increase in bandwidth as well as RF signal, they operate, shifting from microwave to millimetre waves (>30 GHz). The high bandwidth demands have raised significant challenges to synthesize and process high bandwidth and ultra- high frequency RF signal using conventional electronics systems with limited bandwidth.

Optical domain offers 100 GHz of bandwidth with hundreds of THz of optical frequencies and intrinsic immune to electromagnetic noise and interference. As a result, processing ultra-high frequency and high bandwidth RF signals in optical domain is the demand for future radar and wireless communication systems. Microwave Photonics (MWP) emerged as a solution to the problems faced by conventional electronics systems to process high bandwidth RF signal. MWP being such an advantageous also possesses some limitation such as the requirement of MWP signal processor which is pure optical. Unlike electronic domain, optical domain has no memory and no commercially available microprocessors. Hence, processing high bandwidth RF signal requires an optical signal processor.

Interestingly, optical fiber can be used as very powerful microwave photonics signal processor. Stimulated Brillouin Scattering (SBS), which is an intrinsic third order nonlinear phenomenon in an optical fiber can be exploited as a very powerful optical signal processor to process ultra-high frequency RF signal in optical domain. SBS has been thought to be problematic in

telecommunication as it limits maximum optical transmitting power. However, SBS can be utilized as a very powerful optical domain signal processor to perform high bandwidth RF signal processing tasks which are not possible to perform in pure electronic domain. As a result, optical fiber performs as a RF photonics link but simultaneously process high bandwidth RF signal in real time on the fly while RF signal propagates through the fiber.

In this thesis, chapter 2 provides in depth theoretical, simulation, experimental and application of SBS in MWP. Three novel microwave photonic signal processing methods are proposed using SBS as an optical signal processor and presented in chapter 4, 5 and 6. In chapter 4, high frequency RF signal at 10.8 GHz is synthesized by beating SBS stokes with optical carrier to realize all optical microwave photonic mixer. In chapter 5, a novel distortion removal method from an optical signal using SBS is proposed where SBS is exploited as high Q optical notch filter to selectively remove distortion from MWP signal. A patent (**GB2567646**) has been granted based on this work. In chapter 6, a novel Brillouin selective sideband amplifier is proposed using SBS to selectively amplify modulated sideband of an MWP signal to achieve better SNR. Finally, chapter 7, concludes the thesis with future works.

Patent Grant Certificate

GB2567646 – Apparatus and Method for Reducing Distortions of an Optical Signal (filling date: 18 Oct 2017, publication date: 24April 2019, granted 22nd May 2020)

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Certificate of Grant of Patent

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This is to Certify that, in accordance with the Patents Act 1977,

a Patent has been granted to the proprietor for an invention entitled **"Apparatus and method for reducing distortion of an optical signal"** disclosed in an application filed **18.10.2017**

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1. M. Alom, S. Haxha and A. Aggoun, "Photonic Mixer Incorporating All-Optical Microwave Frequency Generator Based on Stimulated Brillouin Scattering Using Single Laser Source," in *IEEE Access*, vol. 8, pp. 37045-37051, 2020.

2. F. Paloi, S. Haxha, T. N. Mirza and M. S. Alom, "Microwave Photonic Down Conversion with Improved Conversion Efficiency and SFDR," in IEEE Access, vol. 6, pp. 8089-8097, 2018.

3. Brillouin selective sideband amplification for future electronic warfare and wireless communication systems. (Currently is being prepared for publication).

List of Acronyms

ADC	Analogue to Digital Converter
AM	Amplitude Modulation
ASE	Amplified Spontaneous Emission
BOSA	Brillouin Optical Spectrum Analyser
BSSA	Brillouin Selective Sideband Amplification
BW	Bandwidth
CW	Continuous Wave
DARPA	Defence Advanced Research Projects Agency
DFB	Distributed Feedback
DPMZM	Dual Parallel Mach Zehnder Modulator
DSP	Digital Signal Processing
EDFA	Erbium Doped Fiber Amplifier (EDFA)
EM	Electromagnetic
EMI	Electromagnetic interference

EOM	Electro-Optic Modulator
EW	Electronic Warfare
FB	Fabry Perot
FBG	Fiber Bragg Gratings
FSR	Free Spectral Range
GaAs	Gallium arsenide
GPS	Global Positioning System
HNLF	Highly Nonlinear Fiber
IBW	Instantaneous Bandwidth
IF	Intermediated Frequency
IFM	Instantaneous Frequency Measurement
IoT	Internet of Things
MWP	Microwave Photonics
MZM	Mach Zehnder Modulator
OF	Optical Fiber
OSA	Optical Spectrum Analyser
PD	Photo Diode
PhASER	Photonic Analogue Signal Processing Engines with Reconfigurability
PM	Phase Modulation
PMF	Polarization Maintaining Fiber

PoIM	Polarization Modulator
RADAR	RAdio Detection And Ranging
RF	Radio Frequency
RIN	Relative Intensity Noise
RoF	Radio over Fiber
SBS	Stimulated Brillouin Scattering
SC-SSB	Suppress Carrier Single Sideband
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SRS	Stimulated Raman Scattering
SSB	Single Side Band
SWaP	Size, Weight and Power Consumption

Contents

Declaration iii

Acknowledgement iv

Abstract v

Patent and publications vii

List of acronyms ix

1 Introduction to Microwave Photonics 18

1.1 RF and Microwave Frequency 18

1.2 Microwave Systems & Bandwidth Limitation 19

1.3 Microwave Photonics 23

1.3.1 Microwave Photonics Components 25

1.3.2 Microwave Photonics Signal Processing 28

1.4 Motivation 33

1.5 Research Question 34

1.6 Research Methodology 35

1.7 Major Contribution and Thesis Organisation 36

2 Background Theory 37

3 Stimulated Brillouin Scattering (SBS) in Optical Fiber & Applications 41

3.1 Overview of Nonlinearities in Optical Fiber 41

3.1.1 Raman Scattering 42

3.1.2 Cross Phase Modulation (XPM) 43

3.1.3 Four wave -Photon mixing 43

3.1.4 Brillouin Scattering 44

3.2 Stimulated Brillouin Scattering (SBS) in Optical Fiber 46

3.2.1 Theoretical analysis of SBS in optical fiber 48

3.2.2 Maxwell equation for EM wave in free space 50

3.2.3 Wave equation and nonlinear polarization 52

3.2.4 SBS equation....53
3.2.5 Brillouin Frequency Shift....54
3.2.6 SBS threshold....55
3.2.7 SBS amplified spontaneous noise (ASE)....56
3.2.8 Linewidth of SBS Stokes....57
3.3 Simulation of SBS in Optical Fiber....58
3.3.1 Simulation....58
3.4 Experimental Work – observation of SBS in fiber....65
3.4.1 Experimental setup....65
3.5 Discussions....68
3.6 Application of SBS in Microwave Photonics....69
3.7 Summary....75
4 Proposed Photonic Mixer Incorporating All-Optical Microwave Frequency Generator based on Stimulated Brillouin Scattering using Single Laser Source....76
4.1 Introduction....76
4.2 Theory and Operation Principal....79
4.3 Experimental Results and Discussion....83
4.4 Summary....90
5 Proposed Apparatus and Method for Reducing Distortions of an Optical Signal (Patent: GB2567646)....92
5.1 Introduction....92
5.2 Principle Method....95
5.3 Simulation and Analysis....99
5.3.1 Simulation Setup....105
5.3.2 Result and Discussions....108
5.4 Experimental work....112
5.5 Summary....118
6 Proposed Brillouin Selective Sideband Amplification....119
6.1 Introduction....119
6.2 Principal method....120
6.3 Simulation....122
6.3.1 Simulation results....124
6.4 Experimental work....128
6.4.1 Summary....131
7 Conclusion and Future Work....132

7.1 Conclusions 132
7.2 Future work 133
8 References 135

List of figures

Figure 1.1 The electromagnetic spectrum is comprised of Radio and Optical Spectrum [5]..18
Figure 1.2 The assigned RF spectrum band for different communication services [7] [17]. ..19
Figure 1.3 SFDR and receiver sensitivity as a function of bandwidth for a typical RF receiver, assuming SNR requirement of 5 dB, noise figure of 5 dB, and SFDR of 110 dB in a 1 HZ band [17]. 21
Figure 1.4 Basic structure of an MWP system consists of a light source, an optical modulator and a photodetector. 25
Figure 1.5 Voltage power characteristic of an MZM which is voltage driven not current driven like direct modulation [13] 26
Figure 1.6 Typical power-current characteristic for a photodiode [13] 27
Figure 1.7 (a) Microwave terrestrial link (b) Microwave photonic terrestrial link 29
Figure 1.8 Microwave phonics signal processing structure 30
Figure 1.9 Optical fiber as very powerful optical signal processor 31
Figure 2.1 Frequency response for different filter types. WS: wave shaper, FBG: Fabry-perot, SBS: stimulated Brillouin scattering [42] 38
Figure 3.2 Spectrum of scattered light resulting from three well known scattering process in optical fiber [53] 44
Figure 2.3 Stimulated Brillouin scattering in optical fiber 46
Figure 2.4 Stimulated Brillouin Scattering in optical fiber....47
Figure 2.5 The Gaussian curve fitting result of the optically generated microwave signal.....57
Figure 2.6 Simulation configuration for SBS Stokes and anti-Stokes....58
Figure 2.7 Simulation results on software OSA showing SBS Stokes with 5 dBm power 59
Figure 2.8 Simulation setup for evaluating SBS Stokes effect on modulated signal 60
Figure 2.9 Optically modulated RF signal of 11 GHz; the sidebands signals power -12.81 dBm at null biasing point; optical carrier signal frequency 193.423 THz at -15.62 dBm.......60
Figure 2.10 The effect of Stokes and anti-Stokes on modulated signal; MZM is biased at null operating point 61
Figure 2.11 Overlapping of modulated signal with stokes effected modulated signal; SBS Stokes and anti-Stokes effect is clearly observed; the MZM is at null biasing point....62
Figure 2.12 Modulated sideband signal at the output of MZM at quadrature 63
Figure 2.13 At quadrature no SBS effect on signal 64
Figure 2.14 Overlapping of signal at quadrature no SBS effect is observed....64
Figure 2.15 Experimental setup to observe SBS Stokes anti-Stokes effect on optically modulated signal; CW: continuous laser; CIR: Circulator; SMF: Single Mode Fiber; MZM: Mach Zehnder Modulator; OSA: Optica Spectrum Analyser....65
Figure 2.16 Measured power of Thorlabs laser 1550s at 253 mA with frequency 193.423 THz of 16.79 dBm. 66
Figure 2.17 Brillouin Stokes and anti-Stoke measured at -26 dBm and -37 dBm....66
Figure 2.18 Stokes and anti-stokes generation using EM650-193.400 laser 67
Figure 2.19 Application of SBS in microwave photonic for EW [89] [90]....70

Figure 2.20 Application of SBS in fiber as notch filter 71
Figure 2.21 Brillouin gain and loss resonance and the related optical phase shifts due to strong dispersion papering around the resonance [113]. 73
Figure 3.1 Fiber original length and calculated effective length 80
Figure 3.2 The schematic diagram of the proposed structure. CW: continuous wave laser; CIR: optical circulator; PD: photo detector; SMF: Single Mode fiber; DPMZM: Dual Parallel Mach Zehnder Modulator. 82
Figure 3.3 Experimental setup of the proposed structure. 84
Figure 3.4 Optical spectrum measured at CIR port 3 shows Brillouin Stokes frequency shift (V_{BS}) at 193.411 THz and CW laser frequency at 193.421 THz imitating SC-SSB signal..... 85
Figure 3.5 RF spectrum- phase noise of the 10.87 GHz generated microwave signal -109.20 dBc/Hz at 15 MHz offset. 86
Figure 3.6 The Gaussian curve fitting result of the optically generated microwave signal.... 87
Figure 3.7 Measured conversion efficiency of the proposed DPMZM structure as a function of RF frequencies. 88
Figure 3.8 SFDR of the proposed photonic mixer. 89
Figure 4.1 Proposed patent structure 95
Figure 4.2 Simulation configuration of the patent 99
Figure 4.3 Optical supress carrier lower single side band signal 100
Figure 4.4 SBS Stokes are generated by two modulated sideband of the MZM-3 101
Figure 4.5 The output of the MZM-2 before SBS suppression (A), and, after SBS suppression (B) 101
Figure 4.6 Merging image A and B from Figure 4.5 102
Figure 4.7 RF spectrum analyser shows the PD output without SBS (A) and with SBS effect (B) 103
Figure 4.8 Overlapping of PD output with and without Brillouin effect 104
Figure 4.9 Simulation setup of the patent as auto tuned BSSA 105
Figure 4.10 Optical spectrum analyser showing the output at distorted MZM 106
Figure 4.11 Amplified LO and RF signal by SBS Stokes at the input of the photo detector 107
Figure 4.12 RF analyser showing the demodulated signal the photo detector output to the patent 108
Figure 4.13 Simulation of E Chan et.al. photonic down converter 108
Figure 4.14 Dynamic range of E Chan et.al. photonic downconverter using EDFA[122]... 109
Figure 4.15 Dynamic range of the Patent 110
Figure 4.16 Comparison of E Chan downconverter with patent down converters shows noise floor was not amplified by the proposed patent structure. Hence SFDR improvement by 15 dB. 111
Figure 4.17 Noise floor improved by 15 dB compare to using EDFA 111
Figure 4.18 Experimental setup for patent 112
Figure 4.19 RF spectrum analyser shows SBS Stokes shift at 10.86 GHz 113
Figure 4.20 RF analyser shows SBS stokes linewidth of 12 MHz 114
Figure 4.21 Optical spectrum analyser show the SC-SSB signal 115
Figure 4.22 Optical spectrum analyser shows EW signal with distortion (A); EW signal without distortion suppressed by the proposed method 117

Figure 5.1 Schematic diagram of BSSA; LO: Local Oscillator; SC-SSB: Supress Carrier Single Sideband; EDFA: Erbium Doped Fiber Amplifier; CIR: Circulator; SMF: Single Mode Fiber..120
Figure 5.2 BSSA simulation 122
Figure 5.3 SC-SSB signal at DPMZM -1 output 124
Figure 5.4 Simulated output signal at MZM output 125
Figure 5.5 Simulated optical spectrum analyser shows EW signal form DPMZM-2 output falls on SBS Stokes generated by MZM signal 126
Figure 5.6 Simulated RF spectrum analyser shows of 15 dB noise floor improvement compared to conventional optical amplifier 127
Figure 5.7 Experimental setup for BSSA 128
Figure 5.8 Optical spectrum analyser shows DPMZM-2 signal is selectively amplified by the two SBS Stokes frequency generated by the MZM...130
Figure 5.9 RF analyser shows 15 dB dynamic improvement by the proposed method........130

Chapter 1

1 Introduction to Microwave Photonics

1.1 RF and Microwave Frequency

The existence of Electromagnetic (EM) wave was theoretically predicted by Maxwell in 1864 [1][2] [3]. After the prediction of Maxwell, it took about a century to figure out how to generate and detect EM waves to an extent that has revolutionized our technological civilization. EM wave is fascinating, it can propagate through space without any medium at the speed of light. The spectrum of EM waves has frequencies up to 10^{24} Hz. Radio waves, Infrared light, ultraviolet light, X-rays, and gamma rays are also example of EM waves; like radio waves they were unknown at the time of Maxwell's equations were discovered [4]. EM waves are assigned a name and spectrum based on their frequency and applications as shown in Figure 1.1 [5].

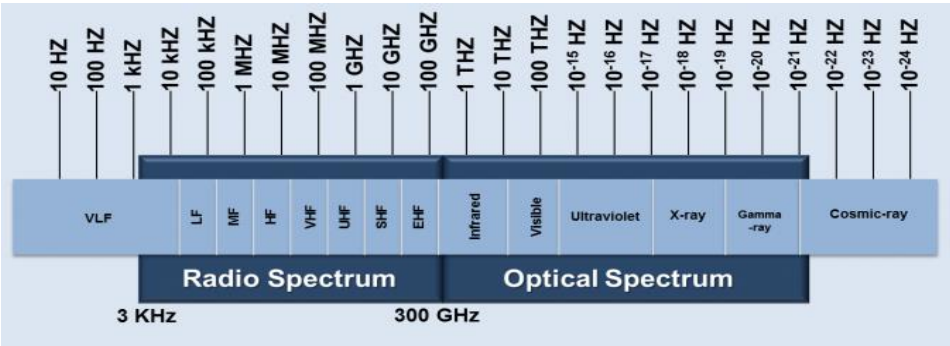

Figure 1.1 The electromagnetic spectrum is comprised of Radio and Optical Spectrum [5]

The portion of EM wave named radio wave due to its usage in radio (wireless, satellite and RADAR) communications and its spectrum ranges from (3 KHz – 300 GHz) called Radio Frequency (RF) spectrum as shown in Figure 1.2. The term microwave frequencies also fall within the radio waves spectrum, frequencies range between 30 MHz and 300 GHz [6], so radio waves with these frequencies are called microwaves. The assigned RF bands (including UWB frequency) for different communication and sensing are shown in Figure 1.2.

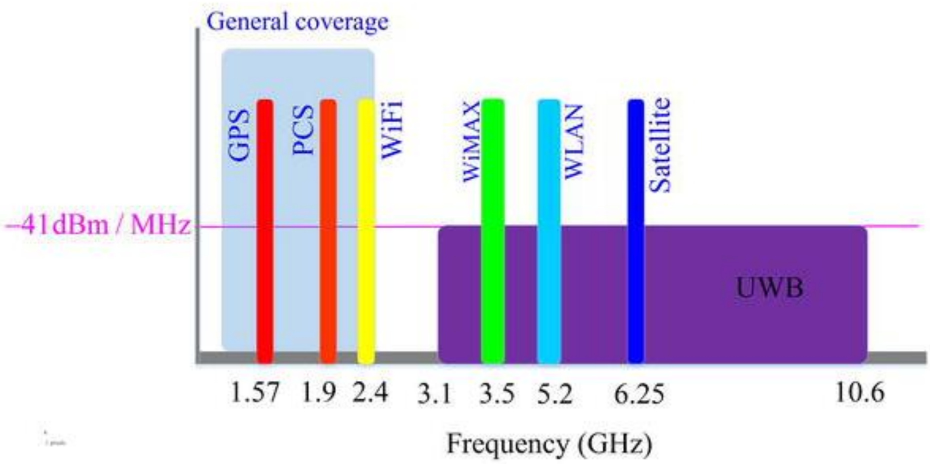

Figure 1.2 The assigned RF spectrum band for different communication services [7] [17].

1.2 Microwave Systems & Bandwidth Limitation

Early generation of wireless systems have operated at a few GHz of RF signal [8]. The demands on great capacity and large instantaneous bandwidth have driven RF and microwave systems to operate at higher carrier frequency with wider signal bandwidth. We have witnessed phenomenal growth in wireless communications in order to support increasingly mobile and internet data. Recently, (RAdio Detection And Ranging) RADAR is extending up to 40 GHz for lowering the probability of being intercepted [9]. As a result, this is pushing the boundaries of current electronic-based technologies.

Radio Frequency (RF) and microwave frequency systems are facing significant increase in bandwidth as well as the radio RF frequency they operate, shifting from microwave to millimetre waves (>30 GHz) for certain applications [10]. Despite microwave spectrum has been assigned huge frequency range of 30 MHz – 300 GHz, electronic based conventional microwave systems are limited to operate on few GHz bandwidth. This is because at very high frequencies, conventional electronics signal processing circuitry performs poorly. Transistors amplification is saturated, capacitor and inductor start to interfere with high frequency RF signal. Furthermore, conventional electronic circuit-based systems operate on very limited instantaneous bandwidth. This raised significant challenges to process and transferring future high bandwidth and ultra-high frequency RF signal using conventional electronic circuitry based systems and coaxial cable as transmission medium [11]. At the heart of all wireless and radar systems are numerous electronics devices which perform various microwave signal processing tasks which are mainly done digitally and requires the input analogue signal converted into digital form. The analogue to digital conversion is performed by electronic analogue-to-digital converter (ADC). The ADC is limited by sampling rate and resolution and unable to handle microwave frequency beyond a few GHz [12] . Such a wide band microwave signals are currently used in numerous application, such as radar, and become increasingly important in 5G network and beyond [13] [14]. Microwave receiver systems can be divided into two categories: wide band and narrow band. Wide-band receivers cover approximately 1 GHz instantaneous bandwidth are usually used to intercept radar pulses and often referred to as electronic warfare (EW) receivers. Narrow-band receivers covers up to 50 – 100 MHz instantaneous bandwidth (IBW). IBW is the bandwidth which a device can continuously acquire to extract messages from a received signal [15]. Typical (EW) microwave receiver requires wide IBW of operation (at least 0.5 GHz to 18 GHz, and recently extending to 40 GHz), high resolution, and near real time response. A microwave receiver, however, usually operates in a very narrow frequency band from 50MHz to 1 GHz [9]. This is due to current state-of-the-art microwave receivers' dynamic range and sensitivity dependency on IBW as shown in Figure 1.3. The dynamic range is the measurement of a receiver's ability to process a range of input powers from the antenna. If the signal is too weak, it cannot be picked up from the noise, whereas too large power signal saturate the receiver causing spur and harmonics [16].

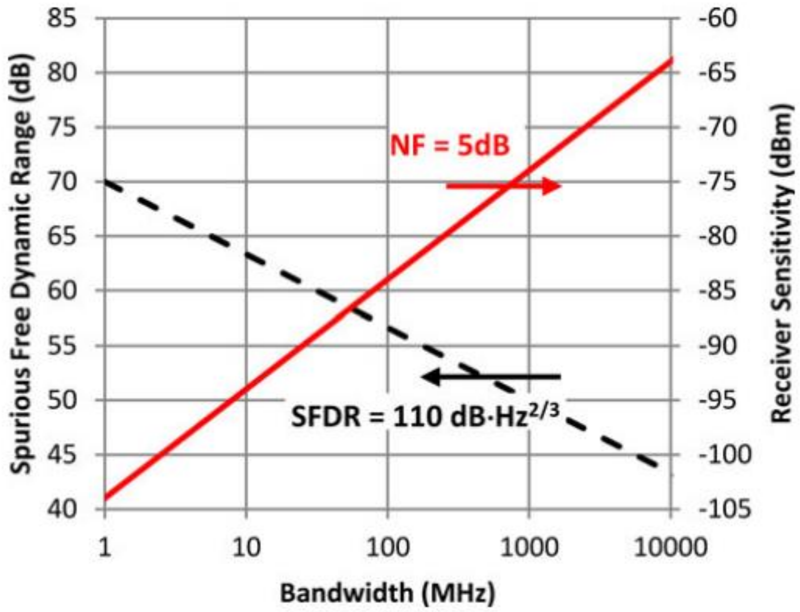

Figure 1.3 SFDR and receiver sensitivity as a function of bandwidth for a typical RF receiver, assuming SNR requirement of 5 dB, noise figure of 5 dB, and SFDR of 110 dB in a 1 HZ band [17].

The black dashes line in Figure 1.3, shows the relationship between bandwidth and Spurious Free Dynamic Rang (SFDR) for a receiver with normalised SFDR = 110 dB. Hz $^{2/3}$. As it is shown in Figure 1.3, that the bandwidth and the noise figure influence the receiver's sensitivity as well as SFDR [17]. Among many figures of merit, one of these very important figures of merit is IBW. Achieving wide IBW is complex tasks using current state-of -the-art electronic microwave receivers as increasing IBW limits the dynamic range of the microwave systems as shown in Figure 1.3.

The black dashes line in Figure 1.3 also shows that at 110 dB. Hz $^{2/3}$ is representative of the SFDR of the state-of-the-art electronic receiver. The solid red line in the Figure 1.3, denotes the sensitivity as a function of bandwidth for a typical X-band receiver with a noise figure of 5 dB. According to Figure 1.3, to achieve the desired dynamic range of greater than 60 dB and sensitivity of -90 dBm requires a receiver IBW must be around 10-100 MHz [17]. This is problematic for EW receiver which required wide instantaneous bandwidth typically (2-20) GHz. Wireless communication microwave receivers usually receive one signal at a time and are designed for known signal. The EW receiver is interested in searching for unknown signals in wide frequency range (2-20 GHz), currently shifting to >30 GHz. This is difficult goal to accomplish because the EW receiver must be able to detect a weak signal in the presence of a strong signal which requires high instantaneous dynamic range. This is not possible to achieve by single electronic circuitry-based microwave receiver as the increasing instantaneous bandwidth gradually decreased the SFDR of the microwave receiver [15].

The ideal EW receiver is a wide band software defined receiver which replaces all the hardware functionality with advanced digital signal processing (DSP). The problem is that digital electronics does not evolved quickly and analogue to digital converter's sampling rate is limited to 2 GHz [18]. The current practical solution for EW receivers is still realized through a channelized implementation [9]. In the channelized receiver, the RF spectrum is detected by several heterodyne receivers simultaneously, down converted to fixed Intermediated Frequency (IF). Then, a set of ADCs simultaneously acquire all the spectrum portions providing a complete picture of the electromagnetic environment.

Although, this approach reaches high performance, it is characterized by Size, Weight and Power Consumption (SWaP) and require huge effort in the design of the filters banks [9].

A potential solution to solve the limitation of ADC is processing microwave signal directly in analogue domain where ADC is not required [19]. However, analogue electronic domain can only able process limited bandwidth and has frequency dependent loss and tunability is normally restricted to a few GHz [20] In the last decade, photonic signal processing (technologies) have been demonstrating attractive features for microwave photonic signal processing. Defence Advanced Research Projects Agency (DARPA) has made significant investments toward advancing the field of microwave phonics signal processing projects [17]. The exponentially growing bandwidth demand of modern radar and wireless communication has forced to explore both RF and microwave spectrum shifting to their full potential. This is only possible by realizing ultra-wideband RF [21] and microwave systems, and Microwave Photonics (MWP) signal processing provide a possible solution [13].

1.3 Microwave Photonics

MWP enables the transmission and processing of RF signals with unprecedented features as compared to other approaches based on traditional microwave technologies [22]. The use of optical devices and techniques to generate, manipulate, transport and measure ultra-wide-bandwidth RF frequency signals, widely known as MWP [23]. Optical fibers show many advantages in comparison with other propagation media, their capacity is very high, they show low transmission losses; and standard component like transmitters receivers, filters and amplifier are available at low cost commercially available off-the-shelf (COTS) [24]. The attractiveness of the optical fiber communication is the ability of silica optical fibers to carry large amounts of information over long repeaterless distance. To utilize the huge bandwidth of the optical fiber, numerous channels at different wavelengths can be multiplexed on the same fiber. High frequency analogue RF photonic links are desirable in military and wireless communications to reduce size, weight and power of RF system by offering the replacement of lossy, bulky coaxial RF cabling for lightweight, low loss and broadband optical fiber, particularly in applications of avionic and Radar system and electronic warfare (EW) [25].

Whatever form future generations of communications networks take, the physical layer will continue be dominated by photonics technology (for wired) and microwave technology (for wireless). The 'interface' between microwave and photonics technologies will therefore also be major importance and this 'interface' has created a new interdisciplinary field known as microwave photonics (MWP) [8]. MWP encodes RF signal into optical signal. One of the main applications of MWP technologies is the transport and distribution of radio or wireless signals over optical fiber [26]. To accommodate ultra-broad bandwidth links demand for future wireless and RADAR sensing, it is necessary to use waveguide with high bandwidth, low loss, light weight and immune to electromagnetic noise interference. To increase systems margins, higher transmitter power or lower waveguide losses are required. MWP links has fulfilled these demands.

1.3.1 Microwave Photonics Components

Whether performing some signal processing function or simply transferring information on RoF link requires some basic MWP components as shown in Figure 1.4. These are a laser, an optical modulator, optical components and a photodetector.

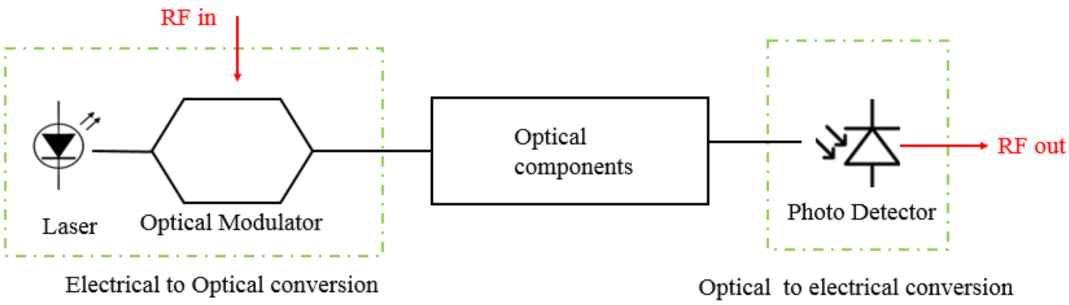

Figure 1.4 Basic structure of an MWP system consists of a light source, an optical modulator and a photodetector.

As MWP process and transfer RF signal in optical domain, first task in any MWP signal processing is to convert RF signal to optical signal. This is performed through modulation of a laser signal using an optical modulator called Mach Zehnder Modulator (MZM) as shown in Figure 1.4. The MZM is driven by an RF signal to modulate the laser light. It is desirable in MWP to have a laser with high output power and low noise which is generated due to emissions of spontaneous and stimulated photons in time. The requirement of high output power with low noise is benchmarked by laser Relative Intensity Noise (RIN). The light form laser diodes has some random amplitude flection which is measured in terms of noise power in 1 Hz bandwidth compared with the average laser power level expressed as RIN [27] . Lower RIN value of minimum -155 dB/Hz is desired in MWP. Laser diode such as Distributed Feedback

(DFB) semiconductor laser can fulfil this demand [28]. DFB lasers have low threshold and high electrical to optical conversion efficiencies at relatively low current levels [29].

Modulation of laser output is performed using an external MZM optical modulator as shown in Figure 1.4. In external modulation, a Continuous Wave (CW) laser is modulated by an Electro-Optic Modulator (EOM). Using external modulation has added benefits such as modulation bandwidth becomes independent of the laser which solves the limitation of the directly modulated systems. As a result, ultra-high frequency millimetre wave RF signal can be processed with modulation bandwidth beyond 145 GHz [30]. The transfer function characteristic of an MZM is shown in Figure 1.5.

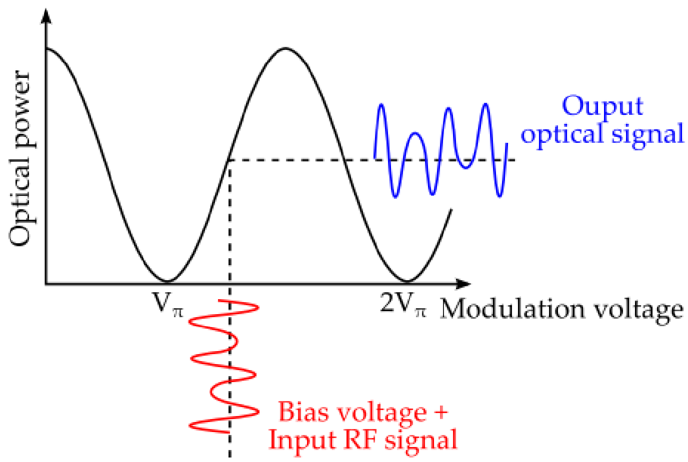

Figure 1.5 Voltage power characteristic of an MZM which is voltage driven not current driven like direct modulation [13]

The V_Π in Figure 1.5 is an MZM parameter called switching DC voltage which control the nonlinear distortion of the MZM output. To minimize nonlinear distortions of the MWP signal at the output of the MZM, the V_Π is biased between halfway between minimum and maximum transmission point known as quadrature. In MWP systems, V_Π with low DC voltage across a wide bandwidth is desirable. Achieving low V_Π voltage requires trade-off between electrode length and bandwidth. Lower V_{Π} voltage is achieved by increasing the electrode length but longer electrode length will decrease the bandwidth of the MZM [31] .

After processing the optical signal is converted back to electrical domain. This is done by using a photodetector. The power current characteristic of the photo detector is shown in Figure 1.6. The output electrical power of the photo detector is directly proportional to the input optical power.

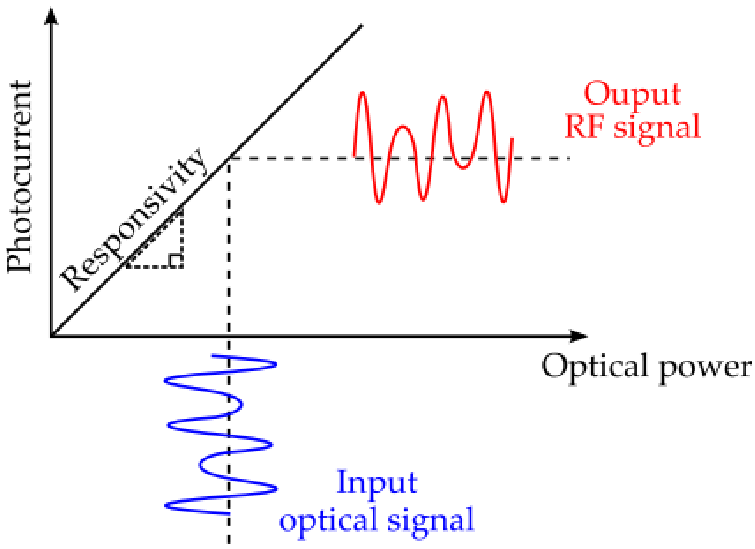

Figure 1.6 Typical power-current characteristic for a photodiode [13]

P-I-N photodiode is used by present MWP systems. In P-I-N photodiode structure a semiconductor layer is sandwiched between P and N layers. Photodetector with high output power (responsivity) and bandwidth is desired in MWP systems. However, in practice this is not achievable due to the saturation of the photodetector power at certain optical power (around 10 dBm). However, P-I-N photodetector with 172 GHz bandwidth and high 76 GHz bandwidth efficiency product with 20 dBm input optical power has been reported in ref [32].

1.3.2 Microwave Photonics Signal Processing

Microwave photonics signal processing is a photonic subsystem design with the aim of carrying equivalent tasks to those of an ordinary electronics microwave system performs but at very high ultra-frequency with extremely wide bandwidth by bringing supplementary advantages inherent to photonics such as low loss, high bandwidth, immunity to electromagnetic interference. Furthermore, photonics approach provides features which are very difficult or even impossible to achieve with conventional electronic circuitry-based microwave systems such as fast tunability and reconfigurability frequency mixing and amplification at greater than 30GHz [22]. Furthermore, current state-of-the-art electronics components are limited to operate on only (10-1000) MHz Instantaneous Bandwidth (IBW). This is huge bottleneck problem for future RADAR and wireless communication systems as they demand for processing high frequency and wide Instantaneous bandwidth (IBW) RF signal on the fly in real time. Optical domain offers 100 GHz IBW. There are mainly two tasks performed by MWP signal processing. These are transferring radio signal over optical fiber called Radio over Fiber (RoF) and performing high bandwidth microwave signal processing task such as modulation and demodulation, filtering, spectrum analysis, amplification and synthesize of high bandwidth RF signal in optical domain.

The invention of laser in 1960 [33] and low loss optical fiber for transporting light [34] opened door to use optical fiber to transfer ultra-wide bandwidth Radio Frequency (RF) signal using RF photonic links due to compelling advantages of the optical fibers. The exceptional qualities of optical fiber as a transmission medium which are behind the success of optical communications in general, and which provide one of the primary motivations for microwave photonics research. The exceptional qualities of the optical fiber are extremely high bandwidth more than 100 GHz, high security, low cost, low weight (typically 1.7 kg/km for fiber as opposed to 567 kg/km for coaxial cable) and intrinsic immune to electromagnetic noise and interference. MWP has two broad applications. These are MWP link also called Radio over Fiber (RoF) and MWP signal processing. MWP link was seen by some visionaries as a possible alternative to long distance terrestrial microwave wireless communications link in the 1960 [8]. Towards the end of that decade it was not clear which one of these two technologies would prevail for terrestrial telecommunications. There were trials of a long distance 'millimetric waveguide' system by UK post office which was eventually abandoned in favour of optical fiber [8][35] as shown in Figure 1.7.

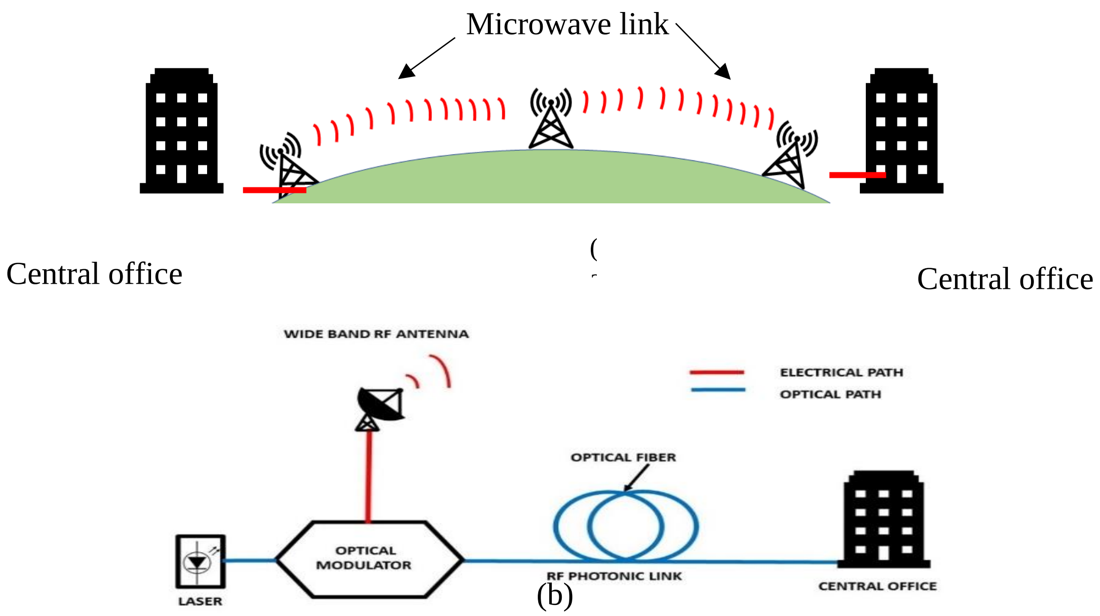

Figure 1.7 (a) Microwave terrestrial link (b) Microwave photonic terrestrial link

On the other hand, MWP signal processing offers a new, powerful paradigm for processing ultra-high frequency and high bandwidth RF signals in optical domain [36]. MWP signal processing brings together the world of Radio Frequency (RF) engineering and optoelectronics. MWP signal processing transforms ultra-high frequency and high bandwidth RF signal processing tasks into optical domain; so that the ultra-high frequency and high bandwidth RF signal can be processed and generated in optical domain without having bottleneck problems on the fly in real time. MWP enables the transmission and processing of high bandwidth RF signals with unprecedented features as compared to other approaches based on traditional microwave technologies [22]. MWP transforms ultra-high frequency and high bandwidth RF signal processing tasks into optical domain; so that the ultra-high frequency and high bandwidth RF signal can be processed and transferred in optical domain without having bottleneck problems on the fly in real time as shown in Figure 1.8.

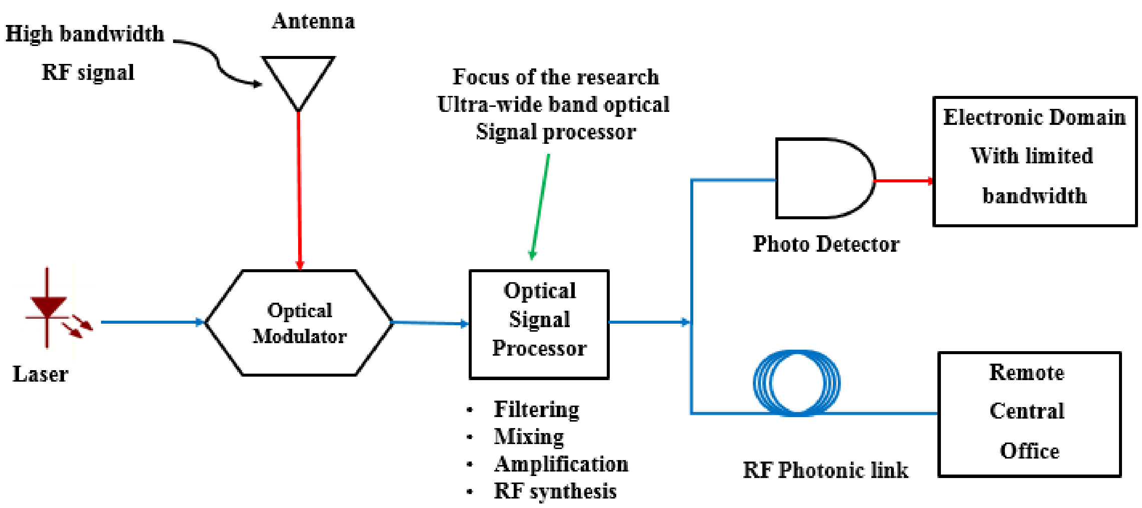

Figure 1.8 Microwave phonics signal processing structure

By saying all the advantages of the MWP, there are some limitation in MWP such as in MWP there is no standard signal processor like microprocessor used in digital electronics. Hence, to process the high bandwidth microwave signal in optical domain requires pure optical signal processor and controlling optical signal processing comes with some challenges. The benefits of the microwave photonic signal processing are tremendous. However, unlike electronic domain, optical domain is pure analogue. Optical domain has no switches, no memory and no digital signal processors. Hence, processing microwave signal in optical domain requires optical analogue signal processing engine [37]. Over the last two decades DARPA has invested in the Photonic Analogue Signal Processing Engines with Reconfigurability (PhASER) program considered RF signal processing in optical domain, using reconfigurable optical filters and delay lines to improve the SFDR of an RF photonic link [17] using different optical components and methods.

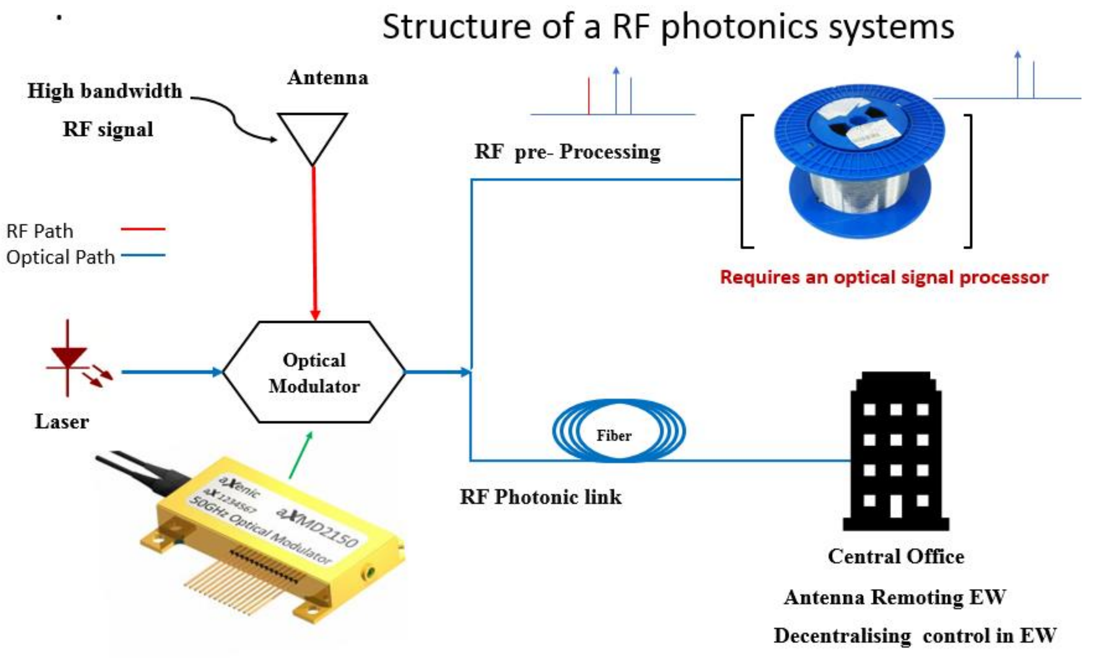

Figure 1.9 Optical fiber as very powerful optical signal processor

Present microwave photonic systems are combination of electrical and optical systems. As a result, electronic domain bottleneck problem not fully circumvented. To utilize the tremendous bandwidth of the optical domain, it is desired to generate, process and transfer microwave signal using all optical domain systems structure. Extensive research must be conducted to develop controllable analogue optical signal processor to perform ultra-high frequency RF signal processing tasks such as generation, mixing, filtering and amplification of the ultra- high frequency high bandwidth RF signal all in optical domain. Interestingly, optical fiber itself be exploited a very strong optical signal processor as shown in Figure 1.9 .

Stimulated Brillouin Scattering (SBS), which is an intrinsic third order nonlinear phenomenon in an optical fiber, can be exploited as very powerful microwave photonics signal processor to process ultra-high frequency RF signal in optical domain. Due to being nonlinear phenomenon, SBS in optical fiber which thought to be problematic in telecommunication as it limits maximum optical transmitting power. However, SBS can be utilized as very powerful optical domain analogue photonic signal processor to realize all optical domain microwave photonics signal processing and generation. There are many types of scattering occurs when light is propagated through an optical fiber. These scattering mainly occurred due to the interaction of optical properties of the matter (in this case optical fiber) with light. For example, well know Rayleigh scattering occurs due to the scattering of light of the molecules of optical fiber [38]. Brillouin scattering occurs when light is scattered by the acoustic wave inside and fiber. Acoustic wave is also called material deformation wave, which is generated by randomly (spontaneous) due to temperature or strain on the fiber. This has normally no effect on the light carrying signal propagating through the fiber. However, when high power laser light is propagated through the optical fiber, this spontaneous acoustic wave inside the fiber becomes stimulated due to electrostriction effect on the dielectric. Electrostriction effect is a property of all dielectric material which displace ion in the crystal lattice material when exposed to an electric field. As a result, dynamic Bragg grating is generated in the fiber, which reflect most of the incident light backward and limits maximum transmitted power through the optical fiber. This phenomenon is called stimulated Brillouin scattering (SBS).

This is problematic in telecommunication as it limits maximum transmitted power. However, interestingly, SBS found to be useful to process RF signal in optical domain. In other words, SBS can be exploited as a very powerful microwave photonic signal processor. This research exploits the nonlinear characteristic of the SBS in optical fiber as a very powerful optical signal processor to process high bandwidth and ultra-high frequency RF signal in optical domain for future radar and wireless communication systems. This research mainly focused on generation, filtering and amplification of high frequency & high bandwidth RF signal in optical domain using SBS. Detailed background theory and application of SBS are discussed in chapter 2.

1.4 Motivation

Future radar and wireless communication systems are facing significant increase in bandwidth as well RF signal, they operate, shifting from microwave to millimetre waves (>30 GHz). This raised significant challenges to process and transferring this high bandwidth and ultra-high frequency RF signal using pure electronic domain. Optical domain is a green field comes with 100 GHz of bandwidth with hundreds of THz of optical frequencies and intrinsic immune to electromagnetic noise and interference. As a result, processing ultra-high frequency and high bandwidth RF signals in optical domain is the demand for future radar and wireless communication systems. Hence, the motivation of this research is to process ultra-high frequency & high bandwidth RF signal in optical domain by exploit Stimulated Brillouin scattering (SBS) in optical fiber to be used as optical signal processor to process microwave signal in optical domain. The research is focused on generation, filtering and amplification of ultra-high frequency and wide bandwidth microwave signal in optical domain using SBS as a photonic analogue signal processor.

1.5 Research Question

The benefits of the microwave photonic signal processing are tremendous. However, unlike electronic domain, optical domain is pure analogue. Optical domain has no switches, no memory and no digital signal processors. Hence, processing microwave signal in optical domain requires optical analogue signal processing engine [37]. Over the last two decades DARPA has invested in the Photonic Analogue Signal Processing Engines with Reconfigurability (PhASER) program considered RF signal processing in optical domain, using reconfigurable optical filters and delay lines to improve the SFDR of an RF photonic link [17] using different optical components and methods. Interestingly, optical fiber itself be exploited a very strong optical signal processor. Stimulated Brillouin Scattering (SBS) inside an optical fiber is intrinsic third order nonlinear phenomenon which can be exploited as very powerful optical signal processor.

This research aims to answer above research questions/objectives. It proposes Stimulated Brillouin scattering (SBS) in optical fiber as an optical signal processor to synthesis and process (filtering and amplification) of ultra-high frequency & high bandwidth RF signal in optical domain for future photonic based high bandwidth wireless and RADAR signals in all optical domain.

1.6 Research Methodology

In this thesis, state-of-the-art microwave photonic simulation software called “VPI photonics” is used for the simulation works. The VPI photonics software sets the industry standard for end-to -end photonic analysis and optimization of components and systems. Experimental works are conducted in photonic lab using commercially available MWP components and devices. Distributed Feedback Laser (DFB) is used to generate light to be modulated by RF signal. Optical modulator called Dual Parallel Mach Zehnder Modulator (DPMZM) is used to convert RF signal into optical signal. DPMZM uses electro optic effects where RF signal’s electric field changes the refractive index of the optical path inside the DPMZM. As a result, light is modulated by the RF signal. Single Mode Fiber (SMF) is used as a very powerful MWP signal processor. SBS is generated inside the SMF fiber by injecting high power light from DFB laser. The Stoke and anti-Stoke effects of the SBS inside the SMF are exploited as a very powerful MWP signal processor. After processing the high bandwidth RF signal in optical domain, a Photo Diode (PD) is used to covert optically processed RF signal back into electrical domain. To observe and monitoring experimental works, optical signal Optical Spectrum Analyser (OSA) is used, and to observe and monitor electrical signal RF spectrum analyser is used. SBS Stoke (gain effect) method is used to synthesis and amplification of high bandwidth RF signal in optical domain. SBS anti-Stoke (notch effect) method is used as a very powerful MWP notch filter to suppress unwanted harmonics and distortion from RF modulated signal in optical domain.

1.7 Major Contribution and Thesis Organisation

The objective of this research is to investigate Brillouin scattering in particularly, Stimulated Brillouin Scattering (SBS) in optical fiber to use it as an optical signal processor to process high frequency and high bandwidth microwave signal in optical domain in real time on the fly. In this research, SBS is exploited as powerful optical signal processing engine to generate, filtering and amplify ultra-high bandwidth microwave signal in optical domain. This research is organised as follows: in **chapter 2,** detailed background of the thesis is conducted. In **Chapter 3,** then simulations of SBS in optical fiber is performed using industry standard simulation software called "VPI-photonics". The simulation results are validated by experimental work in microwave photonic lab comprises with state-of-the-art microwave photonics components. Furthermore, detailed literature review of the SBS applications in MWP signal processing is conducted. Three novel methods based on SBS are proposed. In **chapter 4**, an SBS method is proposed to synthesis ultra-high frequency microwave signal at 10.86 GHz by exploiting SBS stokes to realize all optical microwave photonic mixer. **In chapter 5**, A novel method of removing distortion of optical signal using SBS has been proposed where an apparatus and distortion removal method for reducing distortion of an optical signal is proposed. A patent (**GB2567646**) has been granted based on this work. In **chapter 6**, SBS is exploited as very high Q high bandwidth MWP selective side band amplifier to selectively amplify optical signal which has greatly improved signal to noise ratio compared to conventional optical amplifier. Finally, in **chapter 7** concludes with final conclusion and future works.

Chapter 2

2 Background Theory

In optical communication, SBS thought to be problematic as it limits maximum transmitted signal [39]. However, the use of SBS in MWP signal processing is attractive approach [40]. SBS can be used to obtain high Q-factor (narrow resonance bandwidth) MWP notch filters by exploiting its narrow band nature [40]. MWP filters are photonic subsystems design with the aim of carrying equivalent tasks to those of an ordinary microwave filter withing a RF system, bringing supplementary advantages inherent to photonics such as low loss, high bandwidth, wide tunability and reconfigurability [41]. The bandwidth demand of RF technologies is significantly increasing. High bandwidth demand yield for advanced all optical signal processing scheme previously it was not possible to process by electronics based systems [39]. SBS has great potential to address these challenges and offer solution for wireless and radar communication systems. Notch filters are used to suppress interferences in wireless and radar communications. MWP notch filters using SBS have unmatched performance in electronics, such as ultrawide tunability and immunity to electromagnetic noise and interference [41].

The main goal of a filter is to improve Signal-Noise-Ratio (SNR) of the intelligence signal either by rejecting unwanted signal or by allowing the desired signal. While commercially available photonic filters offer single band-reject or band-pass resonances with wide tunability, but their Q-factor is broad in the order of tens of GHz. Q factor is also known as quality factor which indicates how sharp or broad the resonance bandwidth of a filter [42]. This is much larger for most of the applications [41]. Photonic filter based on Fiber Bragg Gratings (FBG) achieve bandwidth of 5 GHz with a tuning range over 10nm or 1.27 THz. Recently, manufacturers have introduced FBG with ultranarrow bandwidth of 100 MHz, but the tuning range is limited to 20 GHz [43]. Another special type of grating-based filter is a wave shaper, which utilized spatial light modulators, can operate over a large frequency range and can be programmed individually with a resonance bandwidth of 10 GHz [43]. The Gaussian filter characteristic make them suitable as pre filtering. Furthermore, Fabry-Perot (FP) filter is another type of photonic filter which utilizes the interference of light bouncing withing a cavity. Due to the cavity, a FP filter has a periodic structure which impose Free Spectral Range (FSR) as a very important performance matric for the FP filter [43]. The FSR is the frequency space between consecutive transmission peaks in the transmission spectrum of the FP filter. The FSR is inversely proportional to the distance between reflective surfaces in the interferometer of the FB filter [44]. Commercially available FB filter has < 3 GHz resonance bandwidth at 1550nm with an FSR of 51 GHz. Unfortunately, the bandwidth varies independent of the wavelength. Hence custom devices are necessary to cover a large frequency range and fabrication for narrow bandwidth is technically challenging [43].

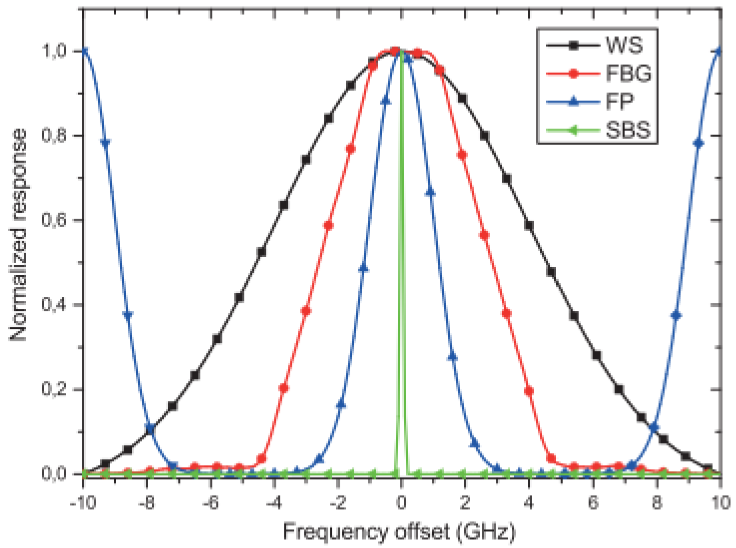

Figure 2.1 Frequency response for different filter types. WS: wave shaper, FP: Fabry-Perot, FBG: Fiber Bragg Grating, SBS: stimulated Brillouin scattering [42]

The visualisation of the bandwidth for different types of photonic filter realisation can be seen in Figure 2.1. Recently, a different approach for filtering in optical domain exploiting the nonlinear effect of SBS in optical fiber. SBS is a third order nonlinear process in optical fiber which results in a back-scattered Stokes wave with very narrow bandwidth gain resonance in the rage of 10 MHz with a frequency down shift of 10 GHz. Similarly, SBS also results, forward scattered anti-Stokes wave with very narrow bandwidth absorption resonance in the range of 10 MHz with a frequency up shift of 10 GHz [45]. The Stokes behaves like very narrow bandwidth (high Q) optical bandpass filter and anti-Stokes behave like very narrow bandwidth (high Q) notch filter. Although detrimental for optical communication as it limits maximum transmission power. The unique characteristics of the SBS which is very narrow band (10 MHZ) gain and absorption profile enabled over very narrowband filtering over wide frequency range which is independent of laser frequency [43].

There are many techniques of microwave photonic notch filtering bases on SBS has been proposed in literatures. The enabling technology for this breakthrough is the recently-reported ultra-wideband microwave photonic notch filter with very narrow isolation bandwidth (~ 10 MHz) and > 60 dB stopband rejection based on SBS has been reported [46] using sideband amplitude and phase controls using an electro-optic modulator and an optical filter. However, using an additional optical filter in this method [46] imposes system complexity. Tuneable dual-passband microwave photonic filter based on SBS has been reported in [47]. In this method, carrier suppressed modulated signal is implemented using both SBS gain and loss effects in the dual-passband filtering response. However, this method is dependent on a RF source and limited by the vector network analyser. Another method of using SBS to measure instantaneous multiple microwave frequencies is realized using a narrow-band tuneable notch filter [48]. This novel technique [48] combines the frequency agility of a scanning receiver and high accuracy of amplitude comparison function technique to simultaneously measure multiple frequencies in multiple GHz ranges. However, this method [48] is also limited by RF source frequency range. Tuneable and reconfigurable multi-tap microwave photonic filter based on dynamic SBS grating polarization maintaining fiber has been reported in [49]. In this method, SBS based tuneable periodic filter is proposed by reconfiguring the position and the number of dynamic gratings along the fiber respectively. However, reconfiguring the position of the dynamic grating is very complex task and which in turn makes the system structure very complex and costly. Another reconfigurable microwave photonic band stop filter based on SBS has been reported in [50], using SBS's anti-stokes loss resonance controlling by a programable electronic arbitrary waveform generator. But this approach in [50], greatly limit to realise all optical microwave photonic structure because of the requirement of electronic arbitrary waveform generator. This research proposes a novel method to reduce distortion from an optical signal on the fly in real time using SBS notch resonance effect. To the best of my knowledge, this method has not been proposed before in the literatures. A UK patent has been granted based on this work discussed in chapter 5.

Generation of high frequency RF signal optically using SBS is very attractive to realise all optical microwave photonic signal processing. In depth background theory and a proposed novel method has been discussed in chapter 4. This work has been published in IEEE. Another novel method of selectively side band amplification has been proposed based SBS gain resonance. In depth background theory and proposed novel method has been discussed in chapter 6.

SBS has a great potential to be used as a unified microwave photonic signal processing processor. It is the perfect candidate for future high frequency and high bandwidth RF signal processing in optical domain on the fly in real time. Harnessing SBS for microwave photonic signal processing is the demand for future wireless and radar systems.

Chapter 3

3 Stimulated Brillouin Scattering (SBS) in Optical Fiber & Applications

This chapter explores the background of Stimulated Brillouin scattering (SBS) and other nonlinearities in optical fiber. The theoretical and experimental overview of the SBS and its application in microwave photonic signal processing has been conducted. Then simulation of SBS in optical fiber and validated by experimental work in the state-of-the-art photonics lab. SBS is one of the most dominant nonlinear effects in standard single mode fibers and its unique spectral characteristics, especially the narrow bandwidth, enable many different applications. Most of the applications would benefit from a narrower bandwidth [43].

3.1 Overview of Nonlinearities in Optical Fiber

Optical fibers show many advantages in comparison with other propagation media-their capacity is very high, they show low transmission losses; and standard component like transmitters receivers, filters and amplifier are available at low cost [24]. The attractiveness of the optical fiber communication is the ability of silica optical fibers to carry large amounts of information over long repeaterless distance. To utilize the huge bandwidth of the optical fiber, numerous channels at different wavelengths can be multiplexed on the same fiber. To increase systems margins, higher transmitter power or lower fiber losses are required.

All these attempts to fully utilize the capabilities of the silica fibers will ultimately be limited by nonlinear interactions between the information-bearing light waves and the transmission medium. These optical nonlinearities can lead to interference, distortion and attenuation of optical signals causes optical system degradations [51]. There exists a rich collection of nonlinear optical effects in fused silica fibers, each of which manifest itself in a unique way [51]. These nonlinear optical effects are: Stimulated Raman Scattering (SRS), cross phase modulation, four-photon mixing and Stimulated Brillouin Scattering (SBS). Although nonlinearities in optical fiber are problematic in telecommunication but they can be exploited as a very powerful microwave photonics signal processor.

3.1.1 Raman Scattering

Stimulated Raman Scattering (SRS) in fiber is an interaction between light and vibrations of silica molecules, causes frequency conversion of light and results in excess attenuation of short-wavelength channels in wavelength-multiplexed systems [51]. SRS is a four-photon process which leads to the transfer of energy from a pump wave to lower frequency (Stokes) wave and higher frequency (anti-Stokes) wave through the intermediary of an optical phonon in the transmission medium [52] [53]. SRS is an important nonlinear process than can turn optical fibers into broadband Raman amplifiers and tuneable Raman laser. It can also severely limit the performance of multichannel light wave systems by transferring energy from one channel to another [54].

3.1.2 Cross Phase Modulation (XPM)

Cross phase modulation is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the Kerr effect. When the optical power from a wavelength impacts the refractive index, the impact of the new refractive index on another wavelength is known as XPM [55] [56] . Cross-phase modulation is an interaction, via the nonlinear refractive index, between the intensity of one light wave and the optical phase of other light waves [51].

3.1.3 Four wave -Photon mixing

Four-wave photon mixing is analogous to third-order intermodulation distortion in electrical systems, whereby two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths [51] [57] . it can occur if at least two different frequency components propagates together in a nonlinear medium such as an optical fiber [58]. The application of four-wave photon mixing in phase conjugation, supercontinuum generation, paramedic amplification, and micro resonator-based frequency comb. It is also good candidate for quantum optical regime for generating single photon and entangled photons [59].

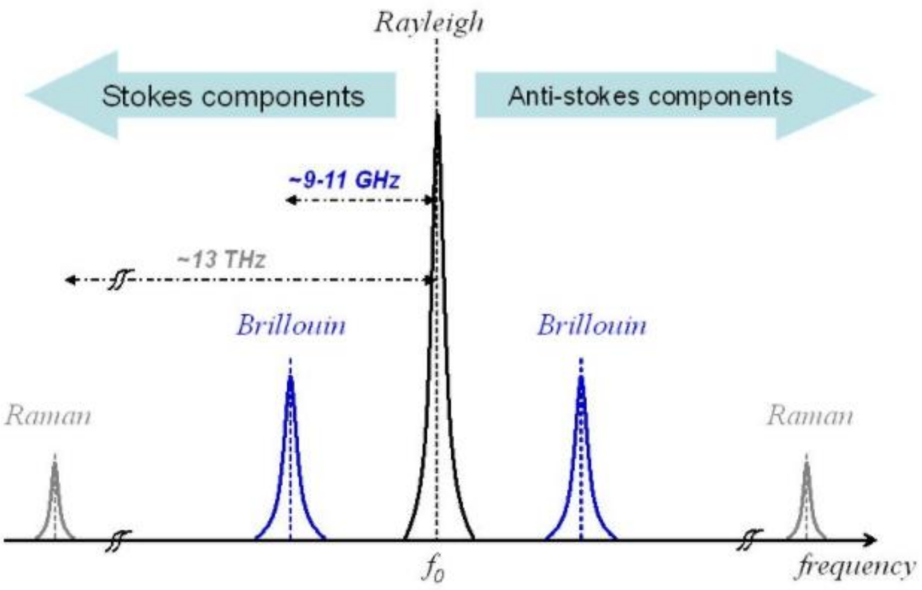

Figure 3.1 Spectrum of scattered light resulting from three well known scattering process in optical fiber [60]

3.1.4 Brillouin Scattering

Brillouin scattering is a spontaneous light scattering process from acoustic waves in materials, was discovered in 1922 by Louis Brillouin [61] [62]. The process is said to be spontaneous as the light scattering is happened by thermal fluctuation in media and the incident light is weak that it presence does not change the dielectric property of the material [62]. The scattered light wave that shifted to lower frequency from incident light frequency is called Stokes wave and the scattered light wave which shifted to higher frequency is called anti-Stokes waves as shown in Figure 3.1.

Stimulated Brillouin Scattering (SBS), an interaction between light and sound wave in the fiber, causes frequency conversion and reversal of the propagation direction of light [51]. Light is an electromagnetic wave, when light or other frequency of the electromagnetic spectrum, travels through matter various scattering processes can occur. The matter may be in the form of solid, liquid or gas, but in each case, light is scattered by fluctuation or excitations of the optical properties of the medium. The scattering process removes incident photons of light and produces scatter photons that are generally shifted in direction and frequency from the original light. There are two types of light scattering in optical fiber: spontaneous and stimulated scattering. In spontaneous scattering, the optical material constituting the optical fiber such as refractive index does not change due to the presence of the incident light wave (electromagnetic field). This type of scatterings is called elastic scattering. However, in the case of when a high power of incident light wave is lunched in the fiber, the spontaneous light scattering can become quite intense which causes changes the optical property of the material called inelastic scattering. Well-known example of elastic scattering is Rayleigh scattering, and inelastic scattering are Brillouin scattering and Raman scattering [63].

At its most fundamental level, scattering can be described by a quantum mechanical approach, although in practice the origin of some form of scattering can be described by classical mechanism (e.g. Brillouin scattering where phonon energy is less than K_BT, where K_B is Boltzmann's constant and T is temperature). Scattering occurs due to the interaction of the (classical) light wave with the excitation (oscillations) in the medium. In quantum theory, light can be considered as ***photons*** (quanta of the electromagnetic field) and the medium excitation as ***phonons*** (quanta of medium excitation) [63]. For very low light levels (low photon density) it is necessary to describe the process using photons and phonons. In practice, the light intensity very high (e.g. laser light) and the medium may have strong excitation. In this high quantum limit, it is appropriate to use semi-classical wave theory to describe the interaction. Brillouin scattered light originates from light interaction with propagating acoustic wave (or acoustic phonons). Incident photons are annihilated, which together with the creation or annihilation of the phonon gives rise to scattered photons (radiation) at the so-called Stokes or anti-Stokes frequencies, respectively. The Stokes components downshifted in frequency and the anti-Stokes upshifted [63] as shown in Figure 3.1.

3.2 Stimulated Brillouin Scattering (SBS) in Optical Fiber

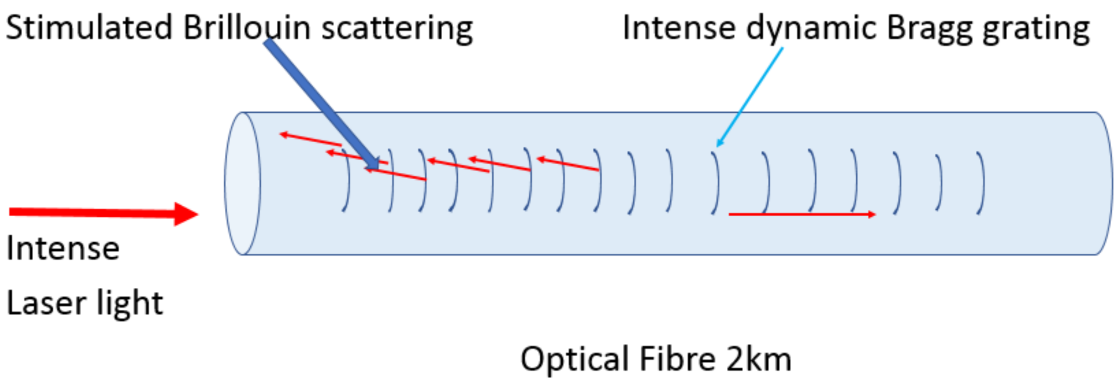

Figure 3.2 Stimulated Brillouin scattering in optical fiber

When intense beam of light such as laser light propagates through an optical fiber as shown in Figure 3.2, the intense electric filed of the laser beam induces acoustic vibration (rather than the acoustic vibration caused by the temperature) via electrostriction (also called radiation pressure). At this point, the spontaneous Brillouin scattering becomes stimulated Brillouin scattering. The power needed to generate stimulated Brillouin scattering (SBS) in bulk (non-guiding) material is of the order of 10^5 W. This power can be reduced by increasing the interaction length and by decreasing the cross-sectional are of the light beam. These requirements are satisfied by wave guides, among which optical fiber is the most attractive [63][64]. Brillouin scattering in optical fiber was first observed in 1964 by Chiao [3]. Brillouin scattering is the interaction of light with sound waves in matter. Sound waves in glass cause a variation in the refractive index corresponding to the density variations of the wave. Light can be diffracted by these indexes grating if the Bragg condition is met. Whereas, SBS was observed first time, in single mode fiber by Ippen and Stolen in 1972 [65]. There have been many investigations of this topic. The issues associated with SBS in optical fibers are of significant interest in optical communications. However, there are possible applications of SBS in fibers [66]. SBS is a nonlinear process that can occur in optical fibers at input power levels much lower than required for Stimulated Raman Scattering (SRS).

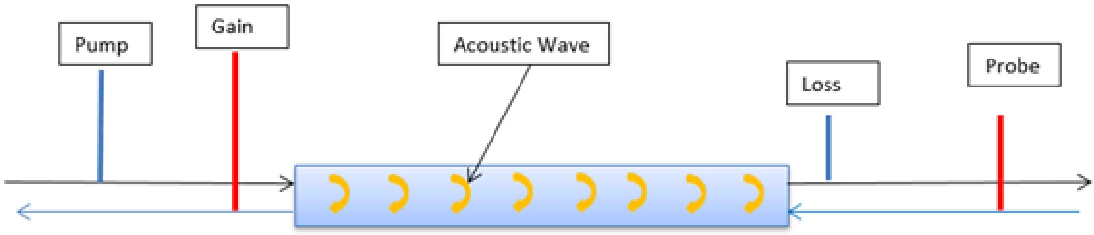

Figure 3.3 Stimulated Brillouin Scattering in optical fiber

SBS occurs when an optical signal interacts with acoustical phonons rather than the propagating material molecules. During this process, an incident optical signal reflects backward from the grating formed by acoustic vibration and downshift in frequency. The acoustic vibrations originate from the thermal effect if the power of the incident optical signal is low. If the power of the incident light is increases, it increases the material density through the electro strictive effect. The change in density enhances acoustic vibrations and forces Brillouin scattering to become stimulated [67] . The specular success of fiber optics communication originates from the development of low- loss single mode optical fiber together with high power laser. Since the breakthrough of silica optical fibers, there has been a continuing interest in the development of long-distance optical communication systems. In order to take fully advantage of the available bandwidth of the optical fibers, several channels can be multiplexed on the same fiber, by using narrow linewidth lasers. Furthermore, the power of optical transmitters is continuously increased to extend the repeater spacing [11]. However, using the narrow linewidth lasers and increasing the power of the optical transmitters stimulate the nonlinearities of the silica fiber which put ultimate limit in the capabilities of the optical fiber such as maximum optical transmission power limit [51]. When laser light is strong the Stokes wave experience gain, and this gain can be by a factor of $e^{30} \sim 10^{13}$. Hence, most of the can be converted into scattered power under appropriated condition. The optical fiber is perfect candidate to meet this condition. The incident and scattering wave travelling in the optical fiber causes periodic modulation of refractive index which scatters the laser light through Bragg diffraction. The scattered Stokes wave is down shifted in frequency due to the Doppler effect of the grating moving at the acoustic velocity. This phenomenon is called stimulated Brillouin scattering (SBS) in optical fiber. SBS creates dynamic Bragg grating inside the fiber, which in turn creates a notch filter and a sharp amplifier effect inside the fiber. As a result, when optically modulated microwave signal is propagated through the same fiber and if any frequency components matches with Brillouin Stokes, it is amplified while if matches with Brillouin anti-Stokes, it is filtered out or suppressed.

3.2.1 Theoretical analysis of SBS in optical fiber

To obtain detailed behaviour of the SBS process it is necessary to consider the propagation of light through a material using Maxwell equation and incorporate the material response to the light interaction [63]. Electric force and magnetic force at a point in empty space seem somewhat abstract: unless an electric charge or electric current are located at such a point. And yet Maxwell ultimately held that space without matter was not quite empty [67]. SBS originates from light interaction with propagating acoustic waves. The light wave can be described by Maxwell equations, acoustic waves raise from electro-strictive effect and can be described through Naiver-Stokes equation [68] good ref for SBS equation. The interaction of the light field with the scattering medium is described by Maxwell's equations [69]. Maxwell equation for electromagnetism where electric charge or current is present in space.

Maxwell's equation is based on three well know equations. These are Gauss law, Faraday's law and Amperes law.

Gauss's law

$$\vec{\nabla} \cdot \vec{D} = \frac{\boldsymbol{\rho}}{\in \mathbf{0}} \qquad \textbf{(1)}$$

Here, $\vec{\nabla}\cdot$ is divergence, $\vec{D}$ is electric flux, $\boldsymbol{\rho}$ is electric charge **and** $\in \mathbf{0}$ is the permittivity of free space.

Gauss law relates electric charge to the electric filed. It is the first law of the Maxwell's equation. It states that the net flux of an electric field is equal to the charge divided by the permittivity [70]. It is one of the four equation of Maxwell's law.

Gauss's law for magnetism

$$\vec{\nabla} \cdot \vec{B} = \mathbf{0} \qquad \textbf{(2)}$$

Here, $\vec{\nabla}$ is divergence, B is magnetic flux density

Gauss's law for magnetism states that the net magnetic flux of any close surface is zero. It is the second Maxwell's equation. There is no magnetic monopole, so divergence of magnetic flux density B is zero [71]

Faraday's Law

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt} \quad \textbf{(3)}$$

Here $\vec{\nabla} \times \vec{E}$ is curl of vector, E is electric filed, and B magnetic field and t is time.

Faraday's law is the third Maxwell's law which states that a magnetic field changing in time give rise to an electric field E [72].

Ampere's Law

$$\vec{\nabla} \times \vec{B} = \mu_0 J + \mu_0 \epsilon_0 \frac{d\vec{E}}{dt} \quad \textbf{(4)}$$

Here, $\vec{\nabla} \times \vec{B}$ is vector curl, μ_0 is the permeability, J is the current flow, E is electric field and t is time.

Ampere's Law state that a flowing electric current J gives rises to a magnetic field that circles around the current. Also, a time changing electric flux density gives rises to a magnetic field that circles the electric field [73].

3.2.2 Maxwell equation for EM wave in free space

In space where there is no charge or current, Maxwell equations becomes electromagnetic wave equation in free space there is no charge or current present in space. Hence, Maxwell equation (1) in derivative form for a free space where no electric charge or current flow exist. No electric charge in free space for EM wave, hence it equals zero as shown in equation (5).

$$\vec{\nabla}.\ \vec{D} = 0 \quad (5)$$

Magnetic field has no monopole, hence zero

$$\vec{\nabla}.\ \vec{B} = 0 \quad (6)$$

Changing magnetic field in time generates electric field

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt} \quad (7)$$

Changing electric field in time generates changing magnetic field. There is no current flow in space, hence $\mu_0 J$ is omitted from equation (4) as shown in equation (8).

$$\vec{\nabla} \times \vec{B} = \mu_0 \epsilon_0 \frac{d\vec{E}}{dt} \quad (8)$$

Now taking curl of equation (7),

$$\nabla.(\vec{\nabla} \times \overrightarrow{E}) = -\frac{d\,\overrightarrow{(\nabla \times B)}}{dt}$$

Now using equation (8),

$$\nabla.(\nabla.\mathrm{E}) - \nabla^2 E = -\mu_0 \epsilon_0 \frac{d^2\vec{E}}{dt^2}$$

$$\nabla.(\nabla.\mathrm{B}) - \nabla^2 B = -\mu_0 \epsilon_0 \frac{d^2\vec{B}}{dt^2}$$

Since, $\nabla . \mathrm{E} = 0$ and $\nabla . \mathrm{B} = 0$

$$\nabla^2 E = \mu_0 \epsilon_0 \frac{d^2 \vec{E}}{dt^2}$$

So, the Maxwell equation for electromagnetic wave becomes:

$$\nabla^2 \boldsymbol{E} \frac{\mathbf{1}}{\boldsymbol{\mu_0 \epsilon_0}} = \frac{\boldsymbol{d^2 \vec{E}}}{\boldsymbol{dt^2}} \qquad \textbf{(9)}$$

$$\nabla^2 \boldsymbol{B} \frac{\mathbf{1}}{\boldsymbol{\mu_0 \epsilon_0}} = \frac{\boldsymbol{d^2 \vec{B}}}{\boldsymbol{dt^2}} \qquad \textbf{(10)}$$

Maxwell equation (9) and (10) proves that empty space supports electromagnetic wave travelling at

$$\boldsymbol{v} = \frac{\mathbf{1}}{\sqrt{(\boldsymbol{\mu_0 \epsilon_0})}} = \mathbf{3} \times \mathbf{10^8}\ \mathrm{m/s} \qquad \textbf{(11)}$$

3.2.3 Wave equation and nonlinear polarization

The interaction of the light field with the scattering medium is described by Maxwell's equations in equation (7) and (8) as follows:

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \epsilon_0 \frac{d\vec{E}}{dt}$$

$$\nabla^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{dt^2}$$

$$\nabla^2 \vec{E} = \frac{1}{c^2} \cdot \frac{\partial^2 E}{dt^2} \qquad \text{where, } \frac{1}{c^2} = \mu_0 \epsilon_0$$

$$\frac{\partial^2 E}{dZ^2} - \frac{1}{c^2} \cdot \frac{\partial^2 E}{dt^2} = 0 \tag{12}$$

3.2.4 SBS equation

The three-wave interaction process of the SBS involves two light waves and an acoustic wave which are coupled through the process of electrostriction. The light wave obeys Maxwell equations subject to nonlinear polarization [74].

$$\nabla^2 E - \frac{n^2}{c^2} \frac{\partial^2 E}{dt^2} - \frac{\alpha n}{c} \frac{\partial E}{dt} = \mu_0 \frac{\partial^2 P^{(nl)}}{dt^2} \tag{13}$$

where E is the total electric field of light wave, $P^{(nl)}$ is the nonlinear polarization, α is the linear power absorption coefficient, *n* is the linear refractive index of the medium and c and μ0 are light speed and free space permeability.

The acoustic wave equation is derived from linearized Navier-Stokes equations [75][76][77] , given as

$$[\frac{\partial^2}{\partial t^2} + \boldsymbol{\Gamma_B} - \boldsymbol{\vartheta}^2\boldsymbol{\nabla}^2]\,\boldsymbol{\rho} = \frac{1}{2}\,\boldsymbol{\varepsilon_0\gamma_e\nabla^2}\,(\boldsymbol{E.E})] \qquad \textbf{(14)}$$

Where (E.E) stand for time average taken over an oscillation period of the light wave, $\boldsymbol{\Gamma}_B$ is the acoustic damping coefficient related to acoustic Brillouin line width $\Delta\vartheta_B$ by $\Gamma_B = 2\Pi\Delta\vartheta_B$, v is the acoustic velocity and $\boldsymbol{\gamma}_e$ is the electro strictive constant [74].

3.2.5 Brillouin Frequency Shift

In Single Mode Fiber (SMF) fiber, which have well defined axis of propagation, the only possible diffraction from these moving grating corresponds to reflection in the backward direction. Since the grating is formed by a wave moving at the speed of sound, the reflected wave experiences a Doppler shift, also called Brillouin shift (ϑ_B) given by [78]. Sound waves in glass cause a variation in the refractive index corresponding to the density variations of the wave. Light can be diffracted by these index gratins if the Bragg condition is met. In SMF fiber, which have well defined axis of propagation, the only possible diffraction from these moving grating corresponds to reflection in the backward direction. Since the grating is formed by a wave moving at the speed of sound, the reflected wave experiences a Doppler shift given by [78].

$$\vartheta_B = \frac{2nV_s}{\lambda} \quad (15)$$

Where n is the refractive index, V_S is the speed of sound in the glass, and λ is the wavelength of light.

3.2.6 SBS threshold

SBS threshold is the pump power at which spontaneous Brillouin scattering becomes stimulated Brillouin scattering.

$$g_B\, K\, (P_{th}\, / A_{eff})\, L_{eff} \cong 21 \quad (16)$$

where g_B is the Brillouin gain coefficient of the material, P_{th} is power corresponding to the Brillouin threshold, A_{eff} is the effective cross-sectional of fiber, L_{eff} is the effective length and K is a constant that depends on the polarization property of the fiber, which is 1 if the polarization is maintained and 0.5 otherwise. Typical silica based SMF-28 fiber has Brillouin gain coefficient $g_B\ is\ (4.40 \times 10^{-11})\frac{m}{W}$. Modeling the effective length L_{eff} is complicated. However, a simple model that assumes the signal power is constant over a certain effective length has proved to be useful in understanding the effects of the fiber nonlinearities.

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \quad (17)$$

where α is fiber attenuation per km, L is the original fiber length. Typically, α = 0.22 dB/km for SMF-28 fiber. The calculations of effective length as a function of fiber length in km. For 2km length of optical fiber, the calculated L_{eff} is 1.61 km. It is worth stating that after 20 km, the effective length of a fiber is around 4.85 km, and it is constant regardless of the fiber length. In our study, the effective cross section of the SMF fiber is 86.5 μm^2.

The SBS threshold P_{th} power is calculated based on the original fiber length of 2 km, using equation (16):

$$\boldsymbol{P_{th} = \frac{21 \times A_{eff}}{K \times P_{th} \times L_{eff}}} \quad \textbf{(18)}$$

$$\boldsymbol{P_{th} = \frac{21 \times 86.5\mu m^2}{0.5 \times (4.40 \times 10^{-11})\frac{m}{W} \times 1610m}} \quad \textbf{(19)}$$

$$\boldsymbol{P_{th} = \frac{21 \times 86.5\mu}{0.5 \times (4.40 \times 10^{-11}) \times 1610} W} \quad \textbf{(20)}$$

$$\boldsymbol{P_{th} = \frac{21 \times (86.5 \times 10^{-12})}{0.5 \times (4.40 \times 10^{-11}) \times 1610} W} \quad \textbf{(21)}$$

$$\boldsymbol{P_{th} = 51.29\, mW} \quad \textbf{(22)}$$

3.2.7 SBS amplified spontaneous noise (ASE)

The power transfer from the pump to the Stokes wave due to Brillouin scattering can be exploited for the amplification of signals, but the very high amplified spontaneous emission noise (ASE) is a disadvantage, which can be ~20 dB higher than that of an ideal amplifier. This limit the applicability of SBS for signal boosting in light-wave systems. However, under particular circumstances the ASE noise can be reduced significantly such as setting up the Brillouin amplification in the saturated regime ASE can be reduced significantly [79].

3.2.8 Linewidth of SBS Stokes

The linewidth of the Brillouin gain (Stokes) is related to the acoustic phonon's lifetime characterized by the time constant T_B and can be approximated by a Lorentzian and Gaussian profile as shown in [67].

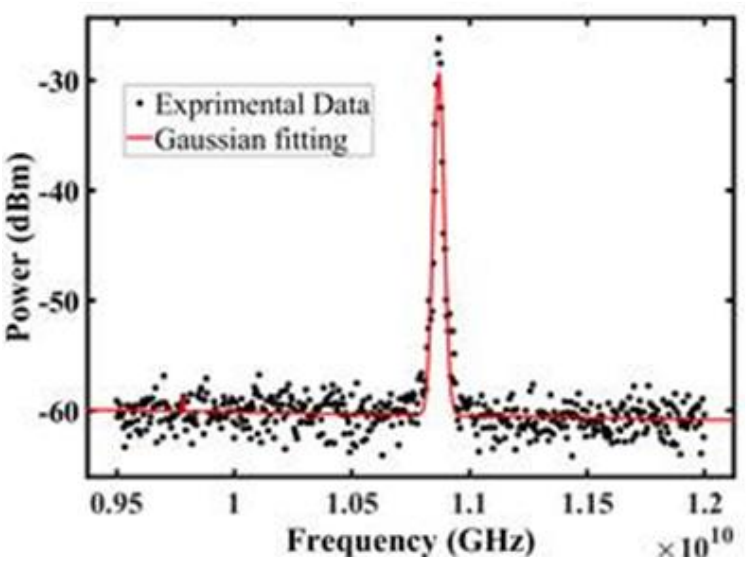

Figure 3.4 The Gaussian curve fitting result of the optically generated microwave signal

In fused silica based optical fiber the phonon lifetime is ~ 10^{-9} s. Brillouin linewidth $\nabla\vartheta$ is given [64]:

$$\nabla\vartheta = \frac{\Gamma^B}{2\pi} \tag{23}$$

Where Γ^B is the inverse of the acoustic (Phonon) lifetime, given by Γ^B is given by [64]:

$$\Gamma^B = \frac{1}{\tau_B} = (\kappa^2 B/\rho_0)\eta_{eff} \tag{24}$$

where $k_B = \omega_B/v$ is the acoustic wave vector, ρ_0 is the material density, and η_{eff} is the material viscosity.

3.3 Simulation of SBS in Optical Fiber

In this section, simulation of Stimulated Brillouin Scattering (SBS) in Single Mode Fiber (SMF) is conducted using state- of -the -art VPI photonic software.

3.3.1 Simulation

VPI-Photonic software is used to simulated SBS is simulated using 2km SMF fiber. The simulation configuration is shown in Figure 3.5. The lase frequency is 193.423 THz at 13.94 dBm power. The optical circulator (CIR) is non-ideal. The SMF fiber length is 2km with Brillouin gain coefficient is 4.6×10^{-11}.

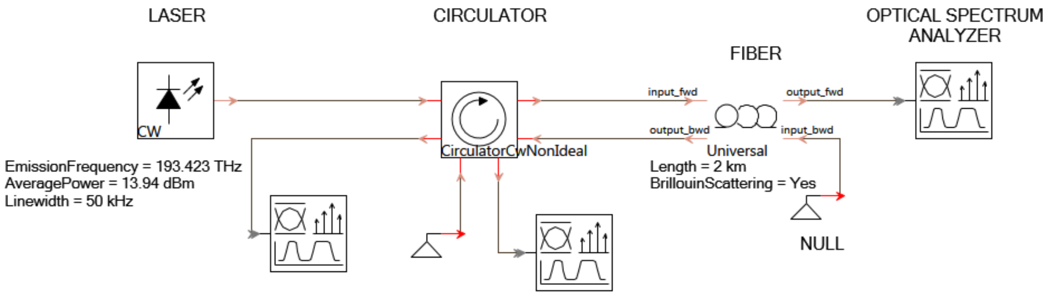

Figure 3.5 Simulation configuration for SBS Stokes and anti-Stokes

Simulation results are shown in Figure 3.6, the SBS Stokes shift is 11 GHz at 5 dBm power. the laser power is depleted from 13.94 dBm to -16.21 dBm. This is due to most of the laser power has back scattered into Stokes. There should be Brillouin anti-Stokes frequency shift is present in the simulation result.

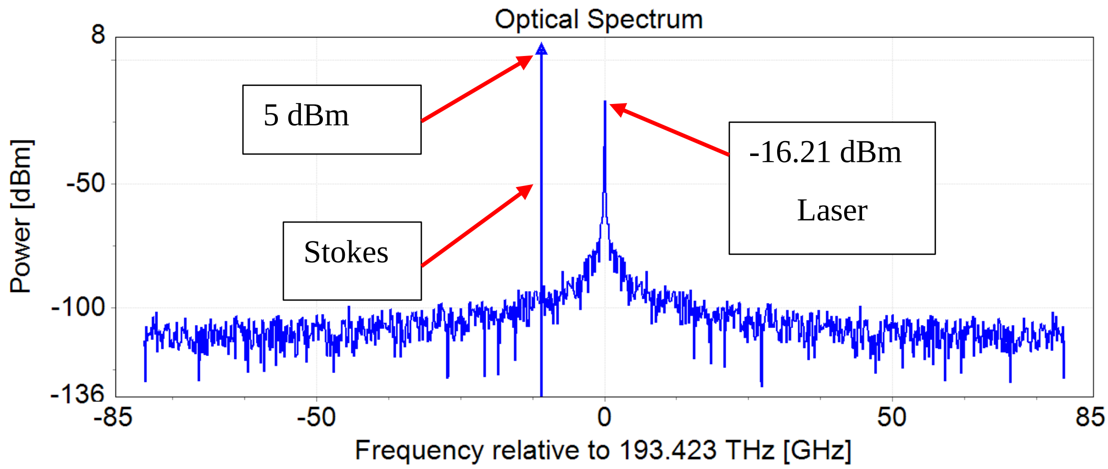

Figure 3.6 Simulation results on software OSA showing SBS Stokes with 5 dBm power

The effect of Stokes and anti-Stokes is simulated using continuous wave laser frequency 193.423 THz at 20mW optical power. The linewidth of the laser is 50 KHz. A 50/50 optical coupler is used to split the laser light, where half of the signal from one end is propagated to 2km SMF fiber and another half of the laser light is from other end of the coupler is propagated to a Mach Zehnder Modulator (MZM). The MZM is driven by 11 GHz RF signal at null biasing point of 10V DC. The insertion loss of the modulator is 6 dB, the extinction ratio of the MZM is 19 dB. The Brillouin shift of the 2km SMF fiber is set to 11 GHz in the simulation. As a result, the RF frequency has been chosen at 11 GHz, so that, lower side band of the modulated signal is fallen into Stokes shift frequency of the SBS and upper sideband of the modulated signal is fallen onto anti-Stokes shift frequency of the SBS. As a result, the lower side band will be amplified due to the amplification effect of the Stokes and upper side band of the modulated signal will be suppressed due to suppression effect of the SBS anti-Stokes suppression effect. The effects of Brillouin Stokes are observed on Optical Spectrum Analyser (OSA). The simulation setup is shown in Figure 3.7.

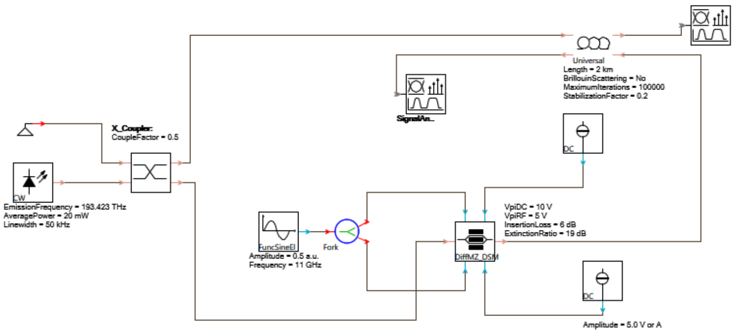

Figure 3.7 Simulation setup for evaluating SBS Stokes effect on modulated signal

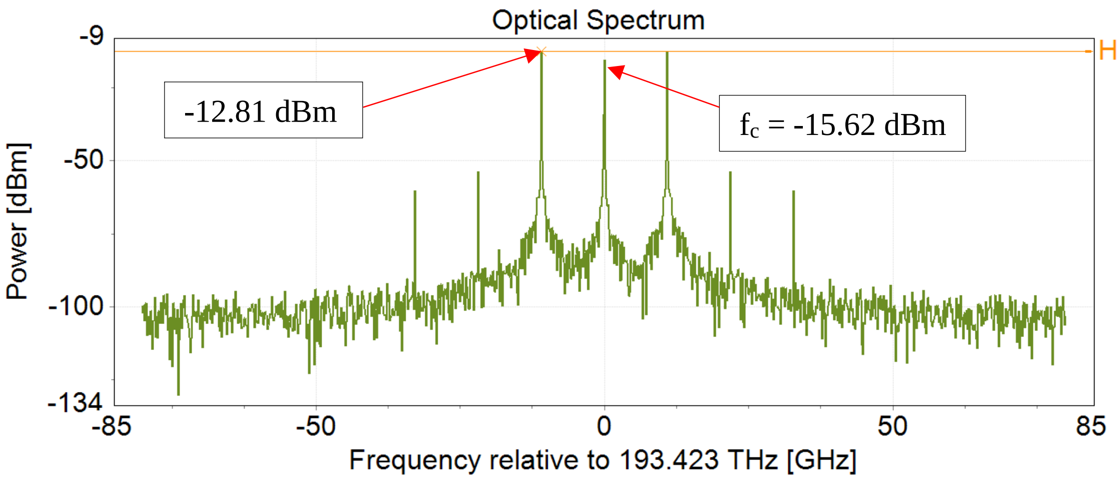

Figure 3.8 Optically modulated RF signal of 11 GHz; the sidebands signals power -12.81 dBm at null biasing point; optical carrier signal frequency 193.423 THz at -15.62 dBm

In Figure 3.8, laser light is modulated by 11 GHz microwave signal. The single MZM was used as optical modulator and set at null also called biasing point. In Figure 3.8, the upper and lower side band of the optically modulated signal is -12.81 dBm. When the optically modulated signal as shown in Figure 3.8, is propagated through the 2 km SMF fiber, the lower side band is amplified by SBS Stokes and upper sideband is suppressed by SBS anti-Stokes as shown

Figure 3.9. By comparing Figure 3.8 and Figure 3.9, it is evident that the lower side band is amplified by {8.0 – (-12.81) dBm} = **20.81** dBm. That is more > 20 dB amplification by SBS

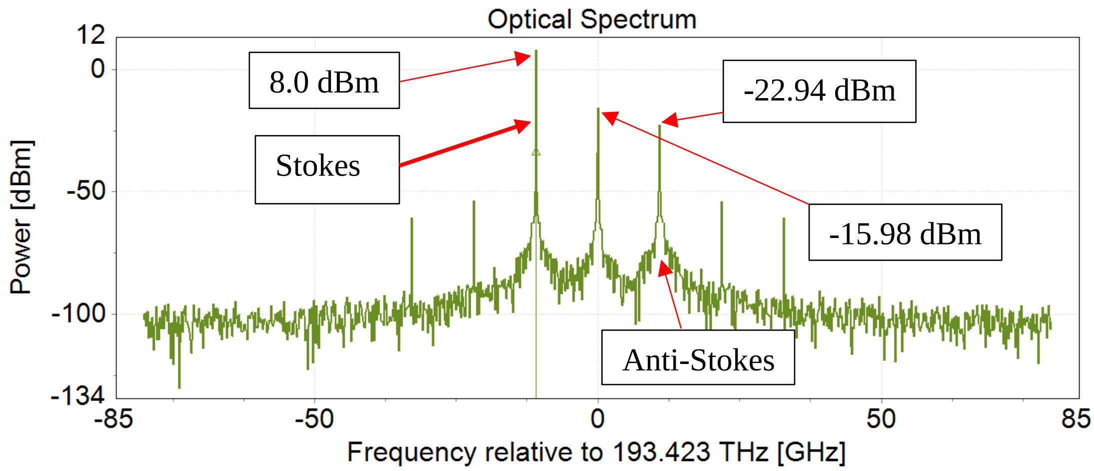

Figure 3.9 The effect of Stokes and anti-Stokes on modulated signal; MZM is biased at null operating point

Stokes. On the other hand, the upper modulated side band as shown in Figure 3.9 was suppressed by {-12.81 – (- 22.94)} dBm = **10.13** dBm. In Figure 3.10, the modulated optical side band signal form Figure 3.8 and processed version of the same sided bands from Figure 3.9 is overlapped for comparison.

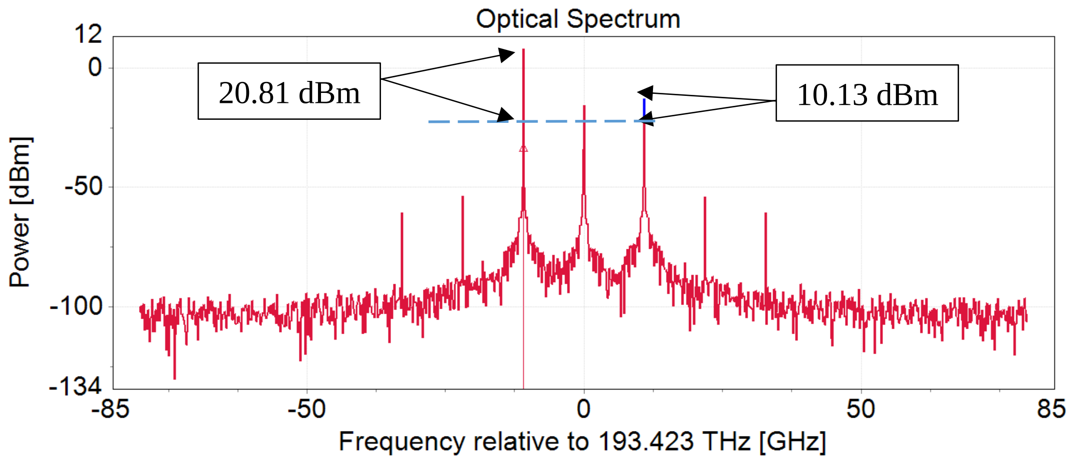

Figure 3.10 Overlapping of modulated signal with stokes effected modulated signal; SBS Stokes and anti-Stokes effect is clearly observed; the MZM is at null biasing point

It is evident from Figure 3.10, that lower side band of the modulated signal is amplified > 20 dB by SBS stokes, whereas, the upper sideband of the modulated signal is suppressed >10 dB by the anti-Stokes of the SBS. Next, the biasing point of MZM is changed to quadrature to observe the SBS stokes effect on the modulated signal. Figure 3.11, shows the output signal of the MZM at quadrature biasing point. The optical amplitude of the upper and lower side bands is -15.46 dBm and the optical carrier fc is -0.16 dBm.

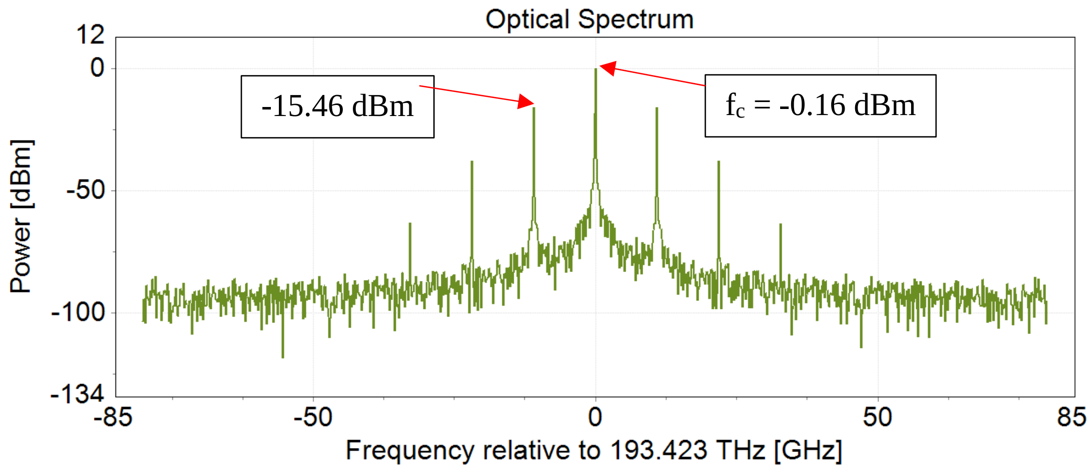

Figure 3.11 Modulated sideband signal at the output of MZM at quadrature

To observe the effect of SBS stokes (Stokes and anti-Stokes), the optical signal in Figure 3.11 is sent through the 2km SMF fiber. The output optical signal at the output end of the SMF fiber is observed on OSA as shown in Figure 3.12. It is evident from Figure 3.12, that, there is no SBS Stokes and anti-Stokes effect on the modulated sidebands. To further analysis the effect of the SBS Stokes on the quadrature modulated signal, Figure 3.11 and Figure 3.12 are superimposed as shown in Figure 3.13.

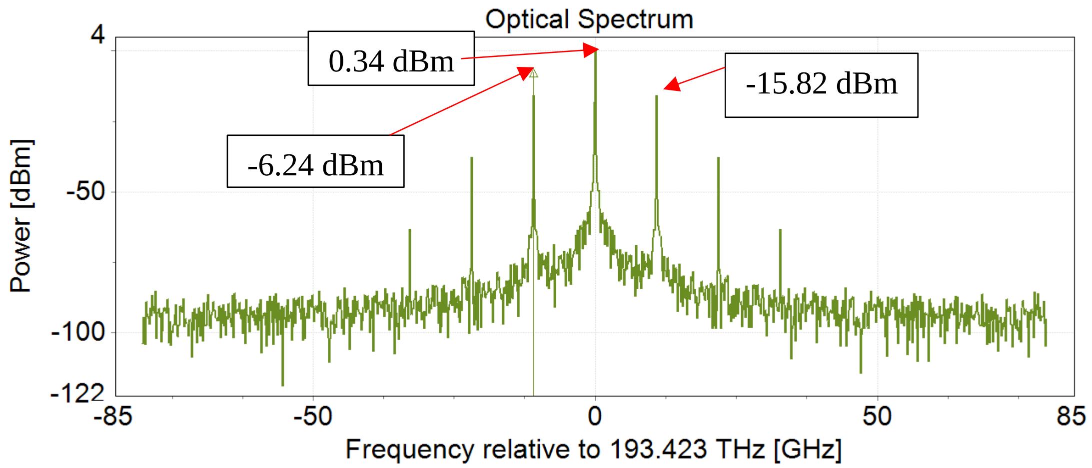

Figure 3.12 At quadrature no SBS effect on signal

It is again clear from Figure 3.13, that no SBS Stokes effect on the modulated sidebands. The blue line in Figure 3.13 represents SBS Stokes and it did not amplify the lower sidebands.

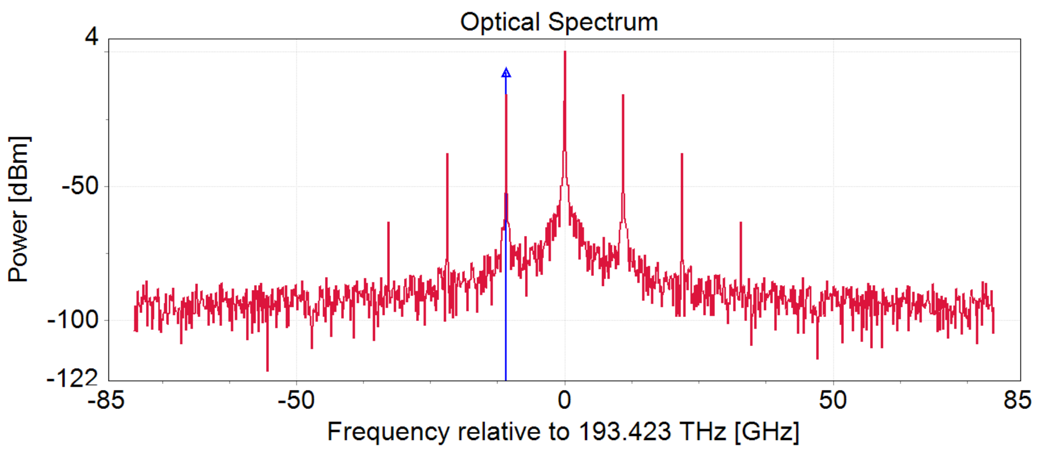

Figure 3.13 Overlapping of signal at quadrature no SBS effect is observed

3.4 Experimental Work – observation of SBS in fiber

In this section experimental work has been performed based on the simulation work presented in the previous section to observe SBS phenomenon in optical fiber to evaluate characteristic and all parameters of the SBS.

3.4.1 Experimental setup

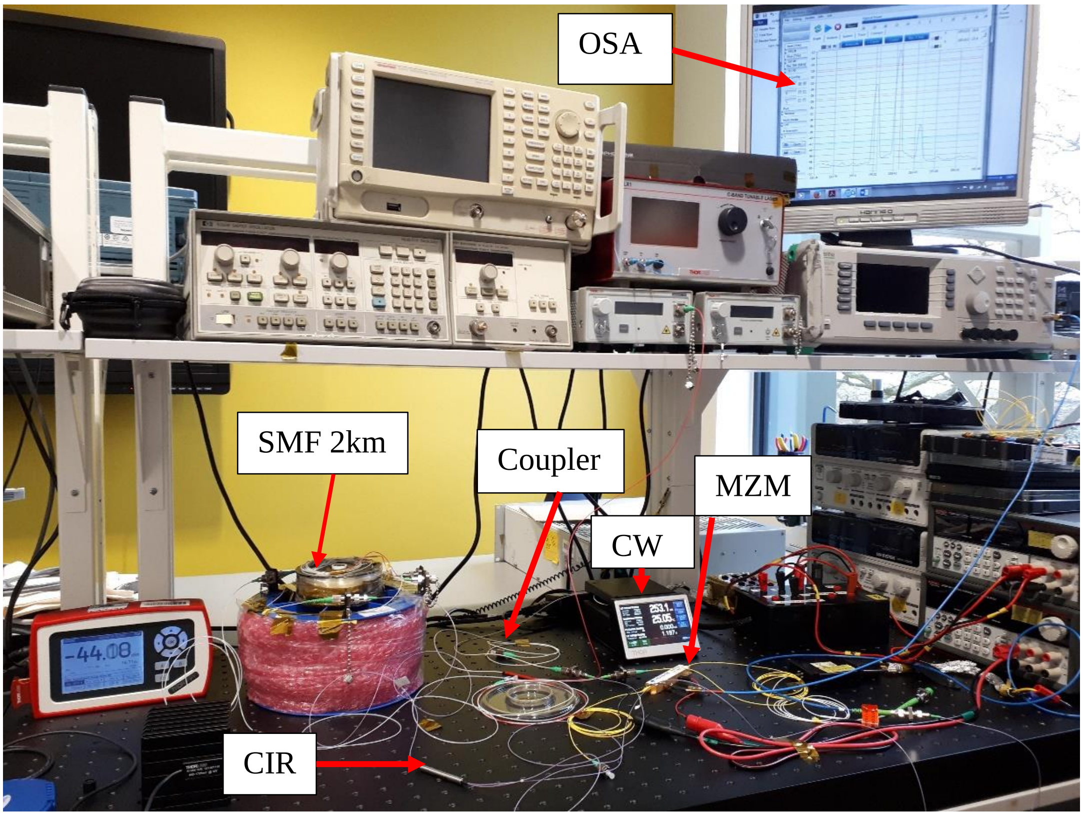

Figure 3.14 Experimental setup to observe SBS Stokes anti-Stokes effect on optically modulated signal; CW: continuous laser; CIR: Circulator; SMF: Single Mode Fiber; MZM: Mach Zehnder Modulator; OSA: Optica Spectrum Analyser.

The experimental setup was performed according to the schematic in Figure 3.5. light form laser (Thorlabs 1550s) at frequency 193.423 THz is propagates through an optical circulator (CIR) port-1 to port-2. The laser power is measured to be 16.79 dBm as shown in Figure 3.15. Light form CIR port-2 is then propagated into 2km SMF fiber. As a result, Brillouin Stokes

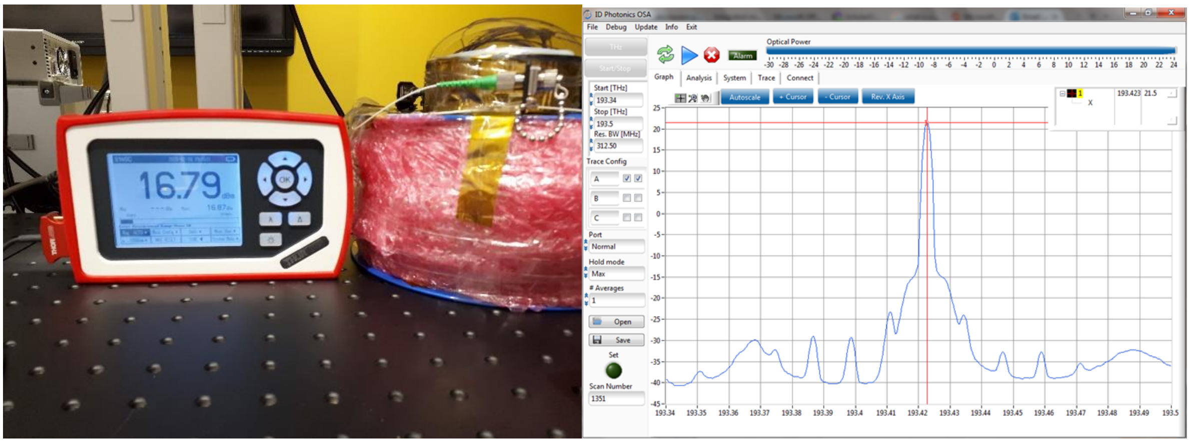

Figure 3.15 Measured power of Thorlabs laser 1550s at 253 mA with frequency 193.423 THz of 16.79 dBm.

and anti-Stokes frequency shift is generated, and counter propagated towards CIR port 3. Port-3 of the circulator is connected to optical spectrum analyser (OSA). The Stokes power is measured -26 dBm while anti-Stoke power is measured -37 dBm as shown in

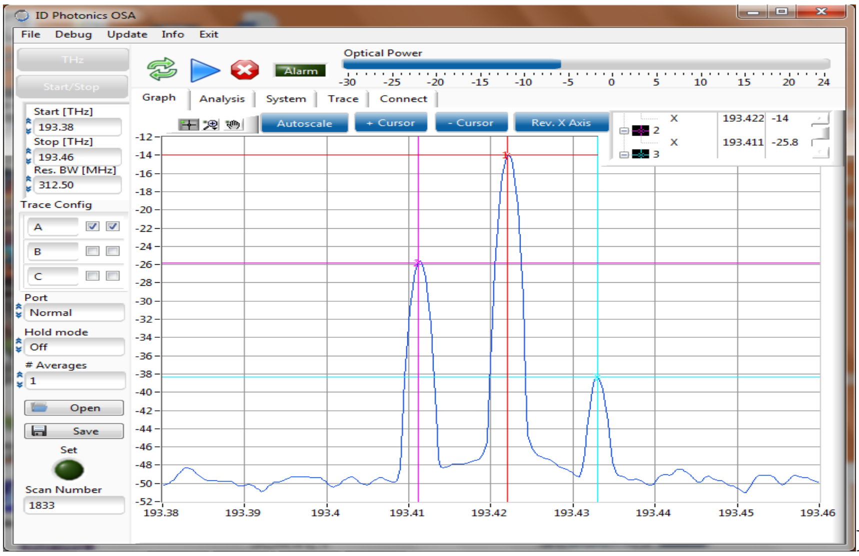

Figure 3.16 .

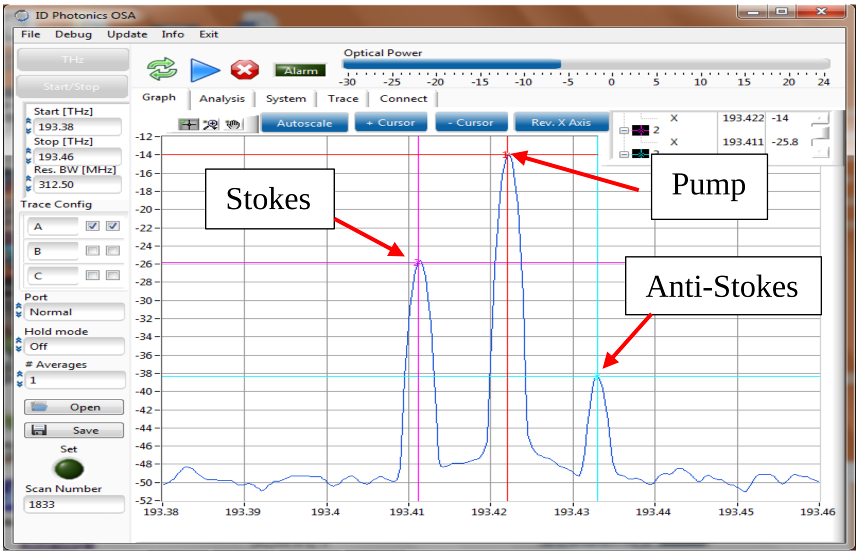

Figure 3.16 Brillouin Stokes and anti-Stoke measured at -26 dBm and -37 dBm

There is some leakage laser power also observed on CIR port 3, this is due to the power leakage of the CIR. The isolation of the CIR between port-1 to port-2 is 26 dBm. It is worth to state that, at lower SBS threshold power Brillouin Stokes and anti-Stokes is propagated counter propagate to the pump. This is well confirming the theory of the SBS. However, according to the theory, when SBS power is reached at high threshold power, according to the theory, there should not be very low power of anti-stokes counter propagates towards the laser working as Brillouin pump. This will be experimentally verified. The experimental setup was same as previous, just the laser was replaced with high power laser (EM650-193.400).

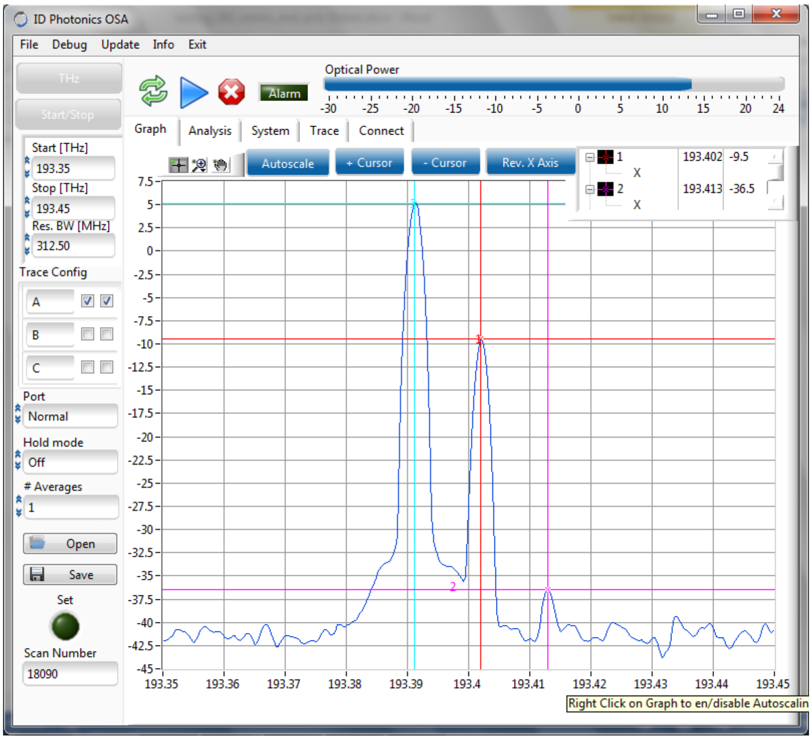

Figure 3.17 Stokes and anti-stokes generation using EM650-193.400 laser

The experimental setup was performed according to the schematic shown in Figure 3.7. To experimentally verify the characteristic at SBS at high threshold power, high power laser (EM650-193.400) with 20 dBm power is used. The laser frequency is 193.400 THz. The line width of the laser is 50 KHz. The experimental setup was same as previous, just the laser was replaced with high power laser (EM650-193.400).

The result is observed OSA connected at CIR port-3 as shown in Figure 3.17. According to Figure 3.7, SBS Stokes power is 5 dBm, which is very high comparing to at low SBS threshold power as shown in, and the SBS anti-Stokes power is very weak around -37 dBm. This corresponds well to the SBS theory. In other word, at high SBS threshold power Brillouin anti-Stokes frequency power is very low and Brillouin Stokes signal power is dominant.

3.5 Discussions

Above experimental results have confirmed the theory of SBS. It is found that at lower laser power Brillouin Stokes and anti-Stokes are present. However, at high laser power when SBS threshold is reached according to the SBS theory most of the light is backscatter toward the Brillouin pump. This make SBS anti-Stokes to suppressed. The observation from simulation and experimental results well confirms this phenomenon. Furthermore, the SBS Stokes and anti-Stokes has no effect on the optically modulated signal when MZM is biased at quadrature biasing point. However, when MZM was set to null biasing point, the Stokes of the SBS was amplifying of the lower sidebands of the modulated signal while anti-Stokes was suppressing the upper sideband of the modulated signal. This is due to the different phase shift between the modulated side bands and the SBS Stokes and anti-Stokes frequency shift. Hence, at null biasing point, the phase of the modulated sidebands and the out of phase. As a result, the upper sideband of the modulated signal is suppressed. This simulation and experimental work of the SBS greatly helps to understand Brillouin scattering and SBS in optical fiber. This work would be very valuable resource to understand SBS theoretically and experimentally in depth.

3.6 Application of SBS in Microwave Photonics

SBS is one of the most dominant nonlinear effects in standard single mode fibers and its unique spectral characteristics, especially the narrow bandwidth, enable many different applications. Most of the applications would benefit from a narrower bandwidth [43]. Although SBS is problematic in optical communications, because it limits maximum optical power transmission through the optical fiber [65], and high power laser[80] but it can be good microwave photonic signal processor. The last few years have major progress in harnessing on-chip photo-phonon interaction enabling the realization of microwave devices with unprecedented performance which are difficult to realize in all optical structures or electronically [81]. Since the observation of SBS many properties of the SBS has been exploited for application [82]. These are phase conjugation, optical limiting, pulse compression, beam combination, etc. These led to remarkable improvement in lase source and industrial laser application [83][84]. In microwave photonics tuneable delay, band-pass and band-reject filter and comb sources all of which are realizable using SBS, are critical for microwave photonics enabling microwave signal processing. SBS is emerging as a potential platform form for MWP [85]. Microwave photonic filter using SBS is attractive approach for implementation high Q filters because of inherent narrowband nature of the SBS [86] [87] [87] [88]. Unlike the conventional FIR-types MWP filters, MWP filter based on SBS has great flexibility and high Q and low threshold power required in optical fiber [87] [89] [90]. Microwave frequency measurement using SBS has also been attracted microwave photonic research community [91][92][93]. The key novelty of using SBS technique was using amplitude comparison function leading to an adjustable measurement range and resolution [91]. In [92], birefringence effect in the highly nonlinear fiber (HNLF) is exploited to microwave photonic frequency measurements. Brillouin Optical Spectrum Analyser (BOSA) has great attraction in research community and commercially available [94]. SBS is also used to generate high frequency RF signal in All optical domain [95] where SBS Stokes frequency is beat with optical carrier frequency to generate high frequency RF signal in optical domain to realize all optical microwave photonic mixer. SBS can be a unified microwave photonic signal processor in EW and wireless communication systems as shown in Figure 3.18.

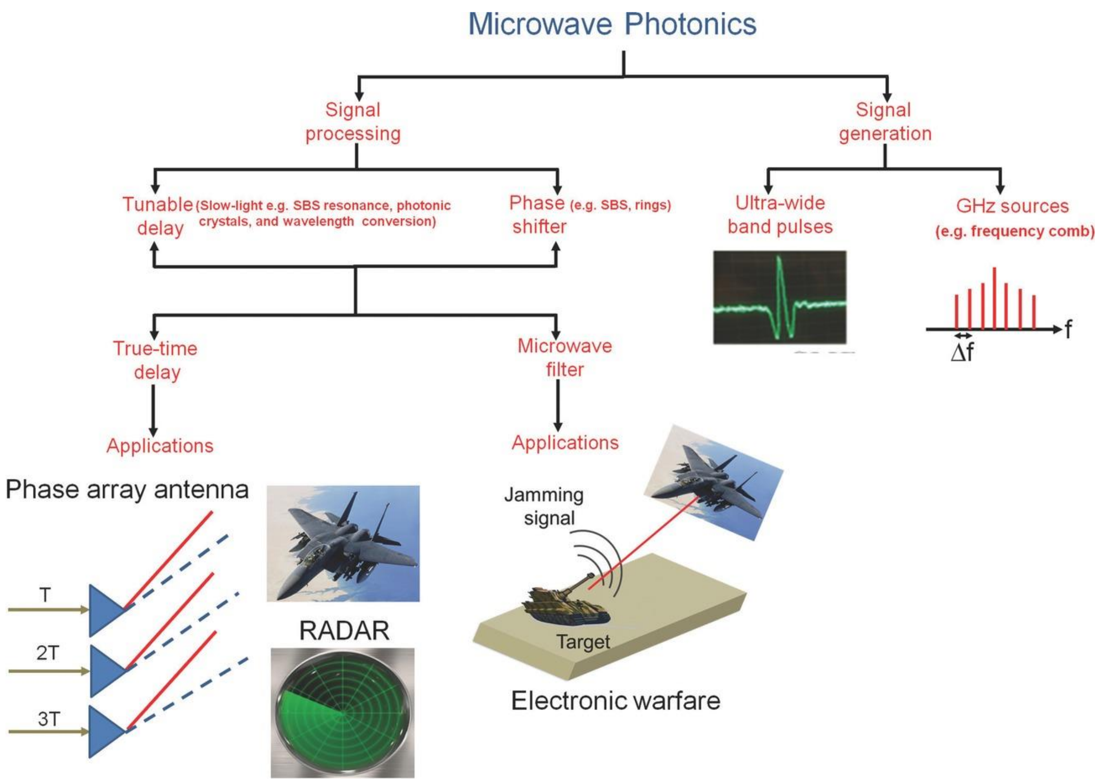

Figure 3.18 Application of SBS in microwave photonic for EW [96] [97]

In EW, SBS can be used as a signal generator or as a signal processor. In signal generation SBS can be used to generate ultra-wideband pulses which is essential in radar [98]. GHz frequency comb [99][100] is very important in microwave signal processing and SBS is capable to generate frequency comb with GHz range to realize microwave phonic mixing. In signal processing, SBS can be used as tuneable delay line [101] [102], and as a phase shifter [103] [104]. Combination of tuneable delay and phase shifter together becomes very powerful EW photonics signal processor. These can be used build photonic phased array radar [105][81] [106] and very powerful microwave photonic notch filter in EW for thread detection and jamming signal [107][108] [109] as shown in Figure 3.19. High frequency microwave frequency measurement has attracted much attention in the modern radar and EW application due to inherent advantages of photonics, such as large bandwidth , low loss, immunity or electromagnetic interference and light weight [110]. Recently Brillouin Optical Spectrum Analyser (BOSA) has achieved femtometre resolution [111] with large instantaneous bandwidth

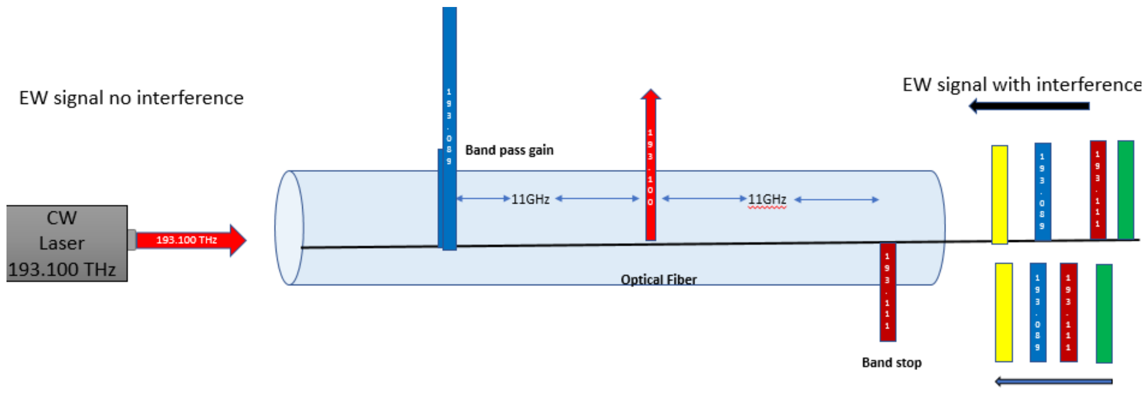

Figure 3.19 Application of SBS in fiber as notch filter

This has revolutionized Optical Spectrum Analyser (OSA) technology and based on SBS technology, BOSA is already commercially available [112]. BOSA uses purely SBS as very powerful optical filter (10 MHz) for high resolution spectrum analysis in optical domain with full spurious free dynamic range of > 80 dB. BOSA is capable to frequency analysis up to 400GHz. There is potential of SBS to achieve greater than 400GHz in future. This is revolutionary in spectrum analysis and without SBS it would not be reality.

Brillouin scattering is also used for fiber optic sensing for temperature and strain. The scattering of light wave by the acoustic phonon of a medium is the essence of Brillouin scattering. When this process occurs in an optical fiber, the backscattered light undergoes a frequency shift known as the Brillouin shift. Since the frequency shift and the backscattered power of the Brillouin scattering are sensitive to the temperature and strain, it becomes a very useful method for fiber optic sensing[113]. SBS method using optical fiber to sense temperature is very useful method in industrial temperature sensing. In this method, Brillouin slow light technique is used. The approach relies on temperature dependence of the Brillouin shift in a fiber. Hence, the time delay of the input probe pulse. By measuring the delay, temperature sensing can be realized [114] [115]. Brillouin Scattering Distributed Optic Fiber Sensor (BOTDA) is another method to sense temperature and strain simultaneously [116]. Optical fiber has advanced rapidly in current technologies and enable many useful applications. Optica fiber experiences geometrical and optical (refractive index, mode conversion) changes when subjected to perturbation which becomes the essence of distributed fiber optic sensing [113] . In particular temperature and strain can be sensed by optical fiber over long distances [117][118].

The active control of the speed of light signal in an optical fiber is attracting for developing fast access memories and optically controlled delay lines. Brillouin scattering is the right candidate for time delay or pulse delay of optical signal. Delaying signal is also requirement in implementing optical filter and phased array antenna. The delay is implemented by controlling the speed of the light in the fiber by exploiting gain and loss mechanism of the SBS in the fiber [119]. The development of dynamic photonic delay lines is very essential for digital and analogue signal processing in communication and EW systems [120]. In particular optical delay line has drawn great attention of the microwave photonic research community recently. The use of optical delay line in microwave photonics are phase array antenna, microwave photonic filter and arbitrary waveform generator due to their inherent advancement such as huge bandwidth of the optical domain, whole microwave frequency occupies only fraction portion of the optical domain, low loss and high delay time-signal product [120]. To implement delay in optical fiber, a control of group velocity of light signals, namely slow and fast light is completely depending on strong dispersion in the optical materials such as fiber. This can be readily induced by one or multiple complex optical resonances. The process of SBS in optical fiber is the most widely used mechanism to generate spectral resonances [120][121]. SBS can be viewed as a narrow band amplification process where a continuous wave pump produces a narrowband (30 – 50 MHz) gain. SBS is usually described as nonlinear interaction between two counter-propagating optical wave a strong pump wave and a weak probe wave mediated through an acoustic wave. For spectral spacing between two waves fraction of pump light is scattered off into the probe, which create a narrowband gain resonance resulting in exponential growth of the probe [120]

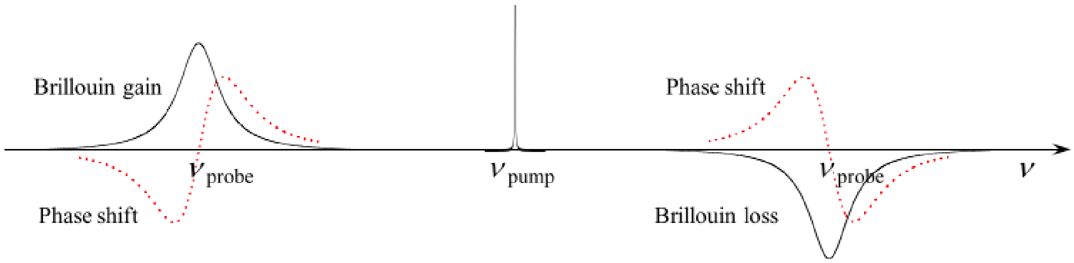

Figure 3.20 Brillouin gain and loss resonance and the related optical phase shifts due to strong dispersion papering around the resonance [120].

On the other hand, the energy transfer from the pump to the probe can cause to the generation of a loss resonance as shown in Figure 3.20. By simply swapping the spectral position of the pump and probe, the pump will lead to a spectral absorption cantered at the probe frequency [120]. The growing demand for higher data rates in wireless communication systems yield for new frequency band in mm wave range and photonic technique using SBS has greatly been research recently [96]. In this method, nonlinear side bands are generated by an optical phase modulator and then desired sideband is selectively amplified by SBS gain resonance. Using this method generated mm wave is very stable as phase of two independently amplified side bands of the modulated sidebands remain same, the SBS narrowband amplification has no effect on the phase [122]. Brillouin scattering also has great use in distributed smart civil structures. By using Brillouin loss, the sensor is able of detect strain on any region on a sensing fiber, even those that are kilometres in length [123]. The most common fiber optics sensors are fiber brag gratings and Fabry -Perot interferometer. Distributed fiber optic sensor differs form a point sensor in that it uses the fiber itself as the sensing medium. Once the fiber is attached to a structure, the strain measurements can be taken at any and every point along the fiber, which can be tens of kilometres in length [123]. Several types of scattering can occur as light is propagated through an optical fiber. Scattering is always present when light propagates through a non-homogeneous medium and fraction of that light is reflected due to different optical medium interaction with light. Each of scattering process occur due to different optical medium interaction with light, for example Rayleigh scattering is caused by small variation in the refractive index of the glass that are frozen into the fiber during fabrication process. Brillouin scattering on the other hand on which optical strain sensor is based, occurs when light is scattered by acoustic wave known as phonon. Phonon travel approximately 6000 m/s through the fiber towards the same direction as the light in the fiber. As a result, some of the light is Doppler shifted and shifted down in frequency from the original laser light frequency. This frequency difference between the incident laser light and the scattered light is called Brillouin shift [123]. This Brillouin shift is exploited in fiber sensor, it is the basis for optical sensor using Brillouin scattering. The Brillouin shift in a fiber is dependent on index of refraction and acoustic velocity. These parameters in turn changes based on environmental condition fiber is installed. Specially, environmental temperature or strain change will cause the Brillouin shift change. This allow either temperature or strain to be calculated by detecting Brillouin shift of an optical fiber [123].

3.7 Summary

In depth theorical work Brillouin scattering has been conducted. Moreover, extensive simulation work has been performed to evaluate the characteristic of the Brillouin scattering and stimulated Brillouin scattering. Finally, the simulation works has been experimentally verified in the state-of -the are microwave photonic lab. This work has greatly helped to understand Brillouin and stimulated Brillouin scattering and necessary for any one prior to exploit Brillouin scattering for microwave photonic signal processing. By conducting this theoretical, simulation and experimental work in this chapter, it is found that, Brillouin scattering can be exploited as a unified universal microwave photonic signal processor. Hence, the applications of Brillouin scattering in microwave photonics and other filed are countless. The beauty of the Brillouin scattering is that its nonlinear phenomenon lend itself to behaves as very narrow band optical filter and same time also very narrow band optical notch filter. Narrow band amplifiers and filters are very important essential components in wireless and radar communications. Secondly, among all Brillouin medium, the geometric shape of the optical fiber make it right candidate to be not only used as a microwave photonic link, but, also as a very powerful Brillouin medium. Optical fiber is also commercially available and comparatively cheaper in price.

Chapter 4

4 Proposed Photonic Mixer Incorporating All-Optical Microwave Frequency Generator based on Stimulated Brillouin Scattering using Single Laser Source

In this chapter the theoretical and experimental implementation of a photonic mixer for Radio-Over-Fiber (RoF) transmission systems, which incorporates an all-optical 10.87 GHz microwave frequency signal generator based on beating laser frequency with its first order Stimulated Brillouin Scattering (SBS) frequency shift. A 13GHz Radio Frequency (RF) is down converted to 2.13 GHz Intermediate Frequency (IF) signal. The proposed system configuration represents a cost-effective photonic mixer that can be deployed for up and down conversion around 11 GHz in RoF transmission systems. The optically generated microwave signal of 10.87 GHz has a phase noise of -109 dBc/Hz at 15- MHz offset. The proposed photonic mixer exhibits a Spurious-Free Dynamic Range (SFDR) of 93dB.Hz $^{2/3}$. This RoF transmission system configuration deploys dual parallel Gallium Arsenide (GaAs) Mach Zehnder Modulator as a photonic mixer, and a single laser source as a Brillouin pump and as an optical carrier at the same time. To the best of my knowledge, this type of photonic mixers has not been reported in the literature.

4.1 Introduction

Microwave photonics brings together the world of Radio Frequency (RF) engineering and optoelectronics [26] [124][125]. The limitation of microwave signal processing such as lack of configurability, limited bandwidth, high energy consumption, prone to electromagnetic noise and interferences can be circumvented through microwave photonics, which refers to the processing of RF signals in the optical domain [125][126].

Microwave signal processing in radar and wireless communication systems involve frequency mixing, where incoming high frequency RF signal, from an antenna, is mixed with Local

Oscillator (LO) signal by an RF mixer and then down converted to a lower Intermediate Frequency (IF) signal. The down-converted IF can be processed further by deploying low-speed electronic circuitry to recover the baseband signal. In this regard, photonic mixers have potentially game changing features when compared to electronic mixers. Photonic mixers offer extensive operational bandwidth, near infinite isolation between the RF and the LO ports, and Electromagnetic Interference (EMI) Immunity, which are unique fundamental features of photonics technology [127].

Currently, most common photonic mixer structures are based on two Lithium Niobate (LiNbO3) Electro-optic intensity modulators connected in series[127], and LiNbO3 integrated Dual Parallel Mach Zehnder Modulator (DPMZM) with integrated optical phase shifter [128][129]. However, in our proposed RoF system, we have used Gallium Arsenide (GaAs) integrated DPMZM as a photonic mixer which has an excellent capability in managing RF signals in space, aerospace and satellite-to-ground downlink communication systems. The proposed photonic mixer deploys Stimulated Brillouin Scattering (SBS) frequency shift. It is known that SBS causes system degradations in fiber-optic networks [129][130].

However, SBS can also have major beneficial characteristics for microwave photonic signal processing such as frequency selective amplification, specific loss spectrum (suppression) and Brillouin Stokes frequency shift. Among these major beneficiaries is the Brillouin Selective Side Band Amplification (BSSA). The BSSA has been used to achieve a gain in microwave photonic mixing [131][132]. It has also been used to achieve Single Sideband modulation (SSB) of 11-GHz RoF system [133]. Brillouin carrier suppression technique is also used to achieve high conversion efficiency in microwave photonic mixer [134].

Furthermore, BSSA has been exploited in opto-electronic oscillator (OEO) as a very high Q narrow-band optical filter to selectively amplify oscillation mode [135][136][137][138]. In this study, we have used SBS for microwave frequency generation.

Microwave frequency generation occurs by heterodyning the input laser and its second order Brillouin Stokes signal through the circulation/isolation of its first order Stokes signal in optical fiber has been reported in [139]. Brillouin scattering Stoke frequency shift in Single Mode Fiber (SMF) is reported in [140], where two-frequency Brillouin fiber laser is used as an optical microwave generator. However, none of the above stated literature evaluated the performance of all-optical microwave signal generation for microwave photonic mixing.

Furthermore, in ref. [139] and [140], they require two independent lasers to generate RF signal optically and provide an optical carrier to microwave photonic mixer, which is more expensive and adds the complexity to the RoF transmission systems.

In this study, a novel photonic mixer structure configuration using Gallium arsenide (GaAs) DPMZM incorporating 11-GHz all-optical microwave signal generator by heterodyning input laser and its first order Brillouin Stokes has been proposed . A single laser source is used as a Brillouin pump and provide the optical carrier for the DPMZM. The GaAs structures are traditionally the material of choice for designing photonic devices that operate at millimeter-wave frequencies, due to the availability of low-loss, semiconductor integration conveniences, and high resistivity substrate. Furthermore, characteristics of environmental stability, including a reasonable degree of radiation hardness make GaAs material structures ideal for systems which must survive and operate in harsh environment such as space and defence sectors [141].

4.2 Theory and Operation Principal

Light scattering in optical fiber is omnipresent regardless of the amount of optical power present in the fiber. There are two types of light scattering in optical fiber: spontaneous and stimulated scattering. In spontaneous scattering, the optical material constituting the optical fiber such as refractive index does not change due to the presence of the incident light wave (electromagnetic field). However, in the case of when a high power of incident light wave in lunched in the fiber, the spontaneous light scattering can become quite intense which causes changes the optical property of the material; this regime is known as SBS [65]. In other words, the SBS is an interaction between an intense optical field, a pump wave, and an induced electro strictive acoustic wave in the fiber. Due to the relative velocity interactions between the pump (incident light wave) and the acoustic wave, the backscattered wave is shifted in frequency [142]. The backscattered Brillouin frequency shift V_{BS} is defined as [142]:

$$v_{BS} = \frac{2nV_a}{\lambda} \tag{25}$$

where V_a is the acoustic velocity within the fiber, n is the refractive index of the fiber, and λ is the operating wavelength of the incident light wave. In the case of silica based optical fibers such as SMF-28, the Brillouin frequency shift is governed by the value of the acoustic velocity in silica v_a = 5587 m/s and refractive index n = 1.46. In silica based optical fibers, the Brillouin frequency shift is equal to the acoustic frequency which is around (9-11) GHz. The SBS threshold power is defined as [142]:

$$g_B\, K\, (P_{th}\, / A_{eff})\, L_{eff}\ \cong 21 \quad (26)$$

where g_B is the Brillouin gain coefficient of the material, P_{th} is power corresponding to the Brillouin threshold, A_{eff} is the effective cross-sectional of fiber, L_{eff} is the effective length and K is a constant that depends on the polarization property of the fiber, which is 1 if the polarization is maintained and 0.5 otherwise. Typical silica based SMF-28 fiber has Brillouin gain coefficient $g_B\ is\ \ (4.40 \times 10^{-11})\frac{m}{W}$. Modeling the effective length L_{eff} is complicated. However, a simple model that assumes the signal power is constant over a certain effective length has proved to be useful in understanding the effects of the fiber nonlinearities

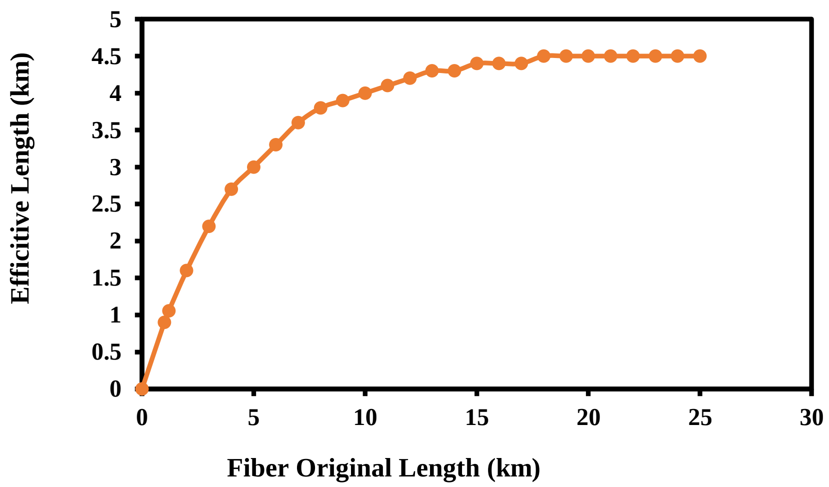

Figure 4.1 Fiber original length and calculated effective length

The effective length L_{eff} is defined [139]:

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \quad (27)$$

where α is fiber attenuation per km, L is the original fiber length. Typically, α = 0.22 dB/km for SMF-28 fiber. In Fig. 1, we illustrate calculations of effective length as a function of fiber length in km. For 2km length of optical fiber, the calculated L_{eff} is 1.61 km. It is worth stating that after 20 km, the effective length of a fiber is around 4.85 km, and it is constant regardless of the fiber length, as shown in Figure 3.1. In our study, the effective cross section of the SMF fiber is 86.5 µm^2. The SBS threshold P_{th} power is calculated based on the original fiber length of 2 km, using equation (20) .

$$g_B\, K\, (P_{th} / A_{eff})\, L_{eff} \cong 21 \quad (28)$$

$$P_{th} = \frac{21 \times A_{eff}}{K \times P_{th} \times L_{eff}}$$

$$P_{th} = \frac{21 \times 86.5\mu m^2}{0.5 \times (4.40 \times 10^{-11}) \frac{m}{W} \times 1610m}$$

$$P_{th} = \frac{21 \times 86.5\mu}{0.5 \times (4.40 \times 10^{-11}) \times 1610} W$$

$$P_{th} = \frac{21 \times (86.5 \times 10^{-12})}{0.5 \times (4.40 \times 10^{-11}) \times 1610} W$$

$$P_{th} = 51.29\, mW \quad (29)$$

According to the above calculation results, the SBS threshold power P_{th} for 2 km optical fiber is 51.29 mW.

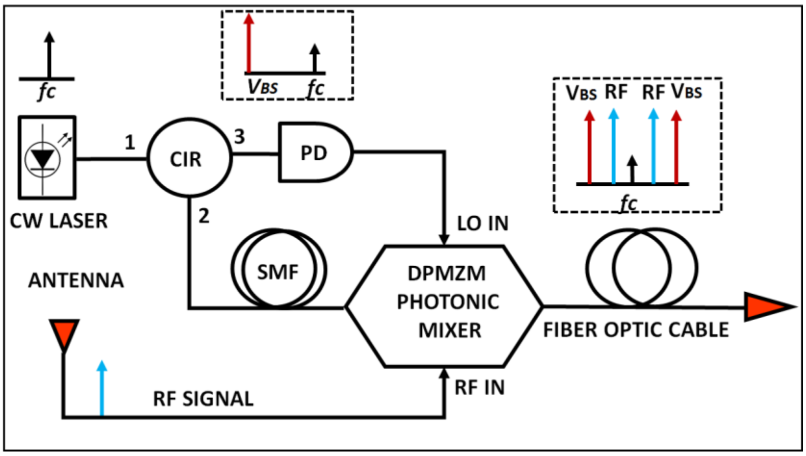

Figure 4.2 The schematic diagram of the proposed structure. CW: continuous wave laser; CIR: optical circulator; PD: photo detector; SMF: Single Mode fiber; DPMZM: Dual Parallel Mach Zehnder Modulator.

The schematic diagram of the proposed photonic mixer configuration is shown in Figure 4.2. The laser source provides a continuous wave light into the DPMZM via the Optical Circulator (CIR) port 2 over a reel of the SMF. An ideal CIR should stop (completely isolate) optical signal propagating between port 1 and port 3, allowing the optical signal to propagate only between ports 1 and Port 2, and port 2 and port 3. However, in the practical implementation of such CIRs, there is always some optical signal leakage between port 1 and port 3. This allows some of the CW laser optical carrier signal f_C to propagate towards the port 3 of the CIR. In this case, most of the laser light from port 2 is propagating through the SMF-28 reel. In our proposed schematics, the SMF-28 reel is used as a Brillouin gain medium where the counter-propagating Brillouin stokes gain is generated at the frequency V_{BS}, and it counter propagates towards port 2, and then to port 3.

At port 3, some of the CW laser signal leakage $f_{C,}$ from port 1 is already propagated. Hence, both signals ($f_{C,}$ from port 1, and Brillouin Stokes shift frequency $V_{BS,}$ from port 2) are mixed at port 3 and beat together at the Photo Detector (PD) to generate high frequency microwave signal. The generated microwave signal is amplified by built-in Electric Amplifier (EA) inside the PD and fed into the DPMZM's Local Oscillator (LO) port. Light propagating from the other end of the SMF-28 reel is propagating via the Polarization Controller (PC) into the DPMZM. The PC is deployed to maintain the light polarization. As shown in Figure 4.2, the upper arm of the DPMZM is modulated by the optically generated RF signal. The lower arm of the DPMZM is modulated by the RF signal from antenna [128]. Finally, both optical sideband V_{BS} and applied RF are mixed optically at the DPMZM, then transmitted at the remote destination thought the optical fiber. At the receiver the RF signals are then processed further by deploying low speed and low power electronic systems.

4.3 Experimental Results and Discussion

The experimental structure of the proposed photonic mixer configuration, illustrated in Figure 4.2, is developed and implemented in Microwave Photonics and Sensors lab, shown in Figure 4.3. This experimental set up shows the arrangement connections of photonic components and measurement equipment, including both microwave and optical spectrum analyser. As an optical source, we used a laser operating at 1549.948 nm (193.421THz), with a narrow linewidth of 50 kHz (Thorlabs-SFL 1550 S) and optical power of 18 dBm, connected to the CIR (Thorlabs CIR1550SM) in port 1. The insertion loss of the CIR is 1 dB, whereas the isolation between port 1 and port 3 is 25 dB. Port-2 of the CIR is connected at the one end of the 2 km SMF-28 fiber reel to generate the SBS.

Most of the CW laser light (18 dBm) from the port 2 is propagating through 2 km SMF. As explained in Figure 4.2, the SMF-28 reel works as Brillouin gain medium, consequently, Brillouin Stokes frequency (V_{BS}) is generated and counter propagates towards the CIR port 2. The counter-propagating Brillouin frequency (V_{BS}) from port 2 and some light leakage from the CW laser signal f_C at 1549.948 nm (192.421 THz) from port 1, are mixed at port 3, which operates like a Carrier Suppressed Single Side Band (CS-SSB) signal.

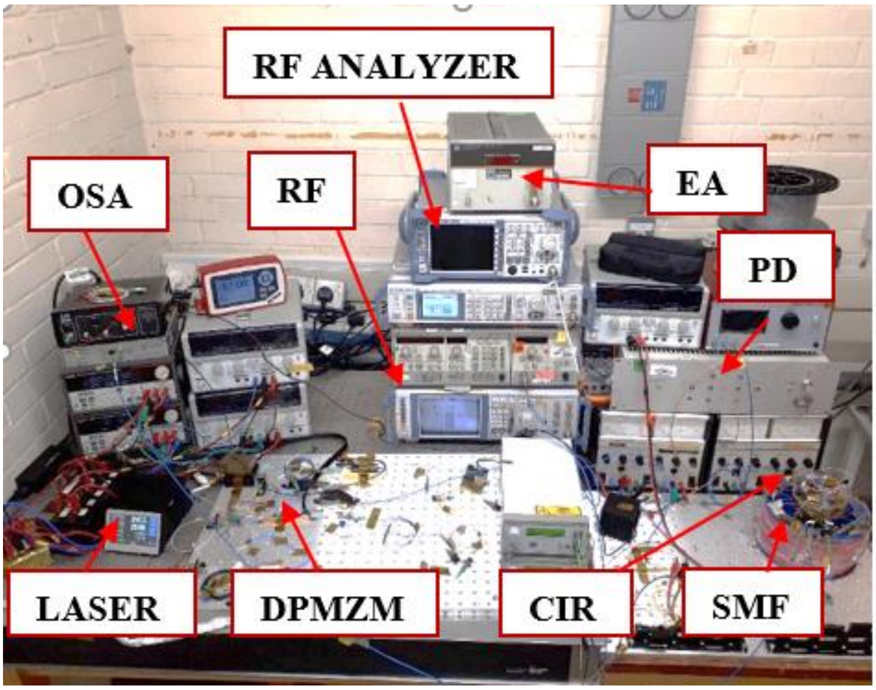

Figure 4.3 Experimental setup of the proposed structure.

Variation of the optical frequency (THz) as a function of the measured power in dBm is illustrated in Figure 4.4. This figure displays the optical spectrum measured at port 3,showing Brillouin Stokes frequency shift (VB_S) at 193.411 THz and the CW laser frequency at 193.421 THz, which is replicating the SC-SSB signal. Our experiment shows that the Brillouin Stokes frequency shift is observed at 1550.028 nm (193.411THz) with 5 dBm optical power. The linewidth of the SBS Stokes frequency is measured to be 10 MHz. It is worth stating that, the minimum achievable Brillouin first order stokes frequency linewidth is limited to 10MHz due to acoustic phonon lifetime in the silica based optical fiber. In Figure 4.4, both Stokes and the signal appear to be broader due to the resolution constraints of the Optical Spectrum Analyser (OSA) used to measure the optical carrier. The resolution of our OSA is limited to 10 GHz. Moreover, the linewidth of Brillouin stokes frequency shift is measured by heterodyning laser signal frequency with stokes frequency signal at the photodetector. Our heterodyning measurement results show the linewidth of the Brillouin Strokes is 10 MHz, as shown in Figure 3.5.

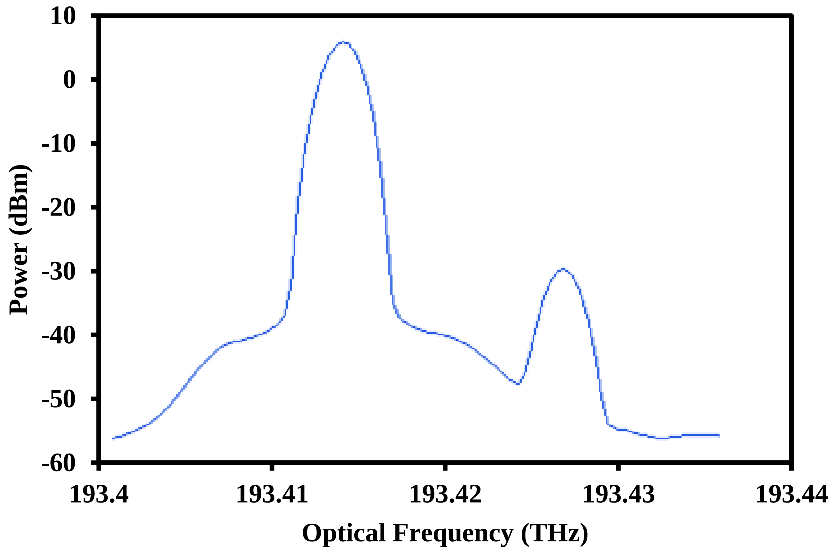

Figure 4.4 Optical spectrum measured at CIR port 3 shows Brillouin Stokes frequency shift (V_{BS}) at 193.411 THz and CW laser frequency at 193.421 THz imitating SC-SSB signal.

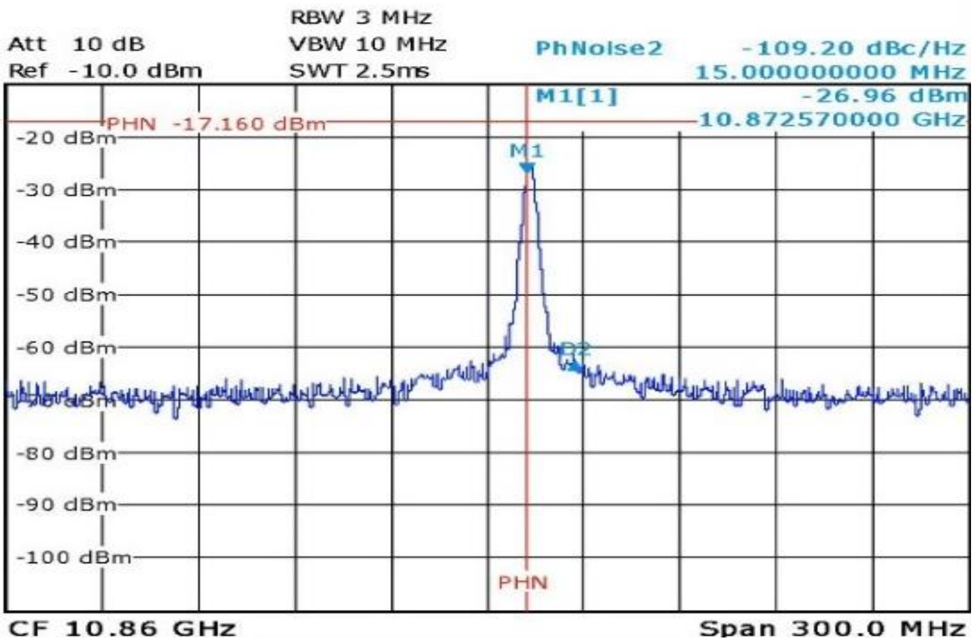

Figure 4.5 RF spectrum- phase noise of the 10.87 GHz generated microwave signal -109.20 dBc/Hz at 15 MHz offset.

The CS-SSB signal from port 3 is sent to the PD (DSC-40s). The 3-dB bandwidth of the PD1 is 18 GHz with a responsivity of 0.80 A/W. The CS-SSB beats at the PD and generates 10.87 GHz microwave signal which is then fed into DPMZM LO port. The phase noise of the optically generated 10.87 GHz microwave signal is measured to be -109 dBc/Hz at 15 MHz offset using Rode and Schwarz-FSL RF spectrum analyser, as shown in Figure 3.5. The line shape of the generated heterodyning microwave signal is observed on the electronic spectrum analyser is well matched with the Gaussian fitting curve shown in Figure 3.6.

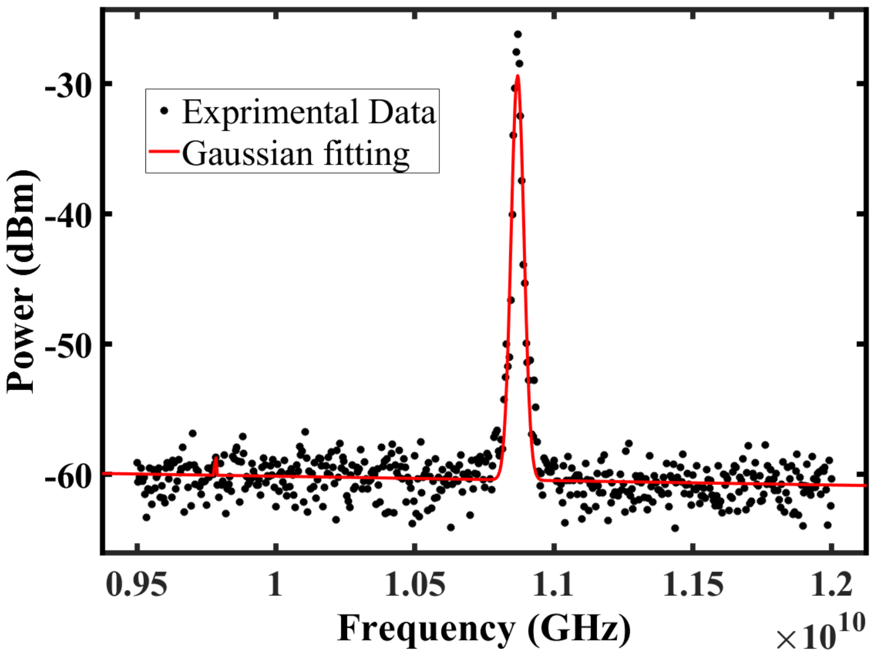

Figure 4.6 The Gaussian curve fitting result of the optically generated microwave signal

The linewidth of the optically generated microwave signal is ~ 10 MHz. This was measured by the heterodyne beating of the laser frequency with its first order (SBS) frequency shift on the PD, as shown in Figure 3.5. The generated 10.87 GHz microwave signal is amplified by 30 dB power amplifier built in the PD and then injected into the upper arm of the integrated DPMZM's LO port. A 13 GHz microwave signal is applied into the RF port of the DPMZM as an incoming RF signal. In this experiment, Gallium arsenide (GaAs) based Axenic -aXsd-2050) DPMZM are deployed due to their advantages in terms of harsh environment applications for radar and satellite communication systems. The 3-dB bandwidth of the DPMZM is 50 GHz with the insertion loss of 10 dB. The half-wave voltage $V\pi$ for the child-1 and child-2 modulators are around 10 V-DC, and for the parent modulator $V\pi$ is 12 V-DC.

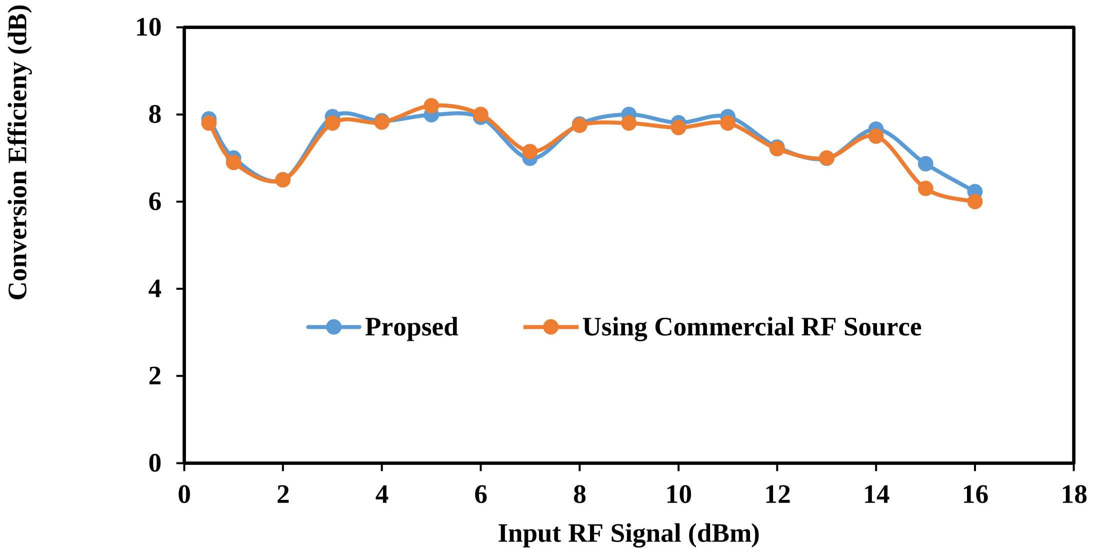

Figure 4.7 Measured conversion efficiency of the proposed DPMZM structure as a function of RF frequencies.

In such RoF transmission systems, it is necessary to suppress the carrier. Within this experiment, in order to minimize the carrier, we optimized the bias voltages of the DPMZM. Our measurements show that the optimized DPMZM bias voltages to minimize the carrier are at; V_{b1}= 6.50 V, V_{b2} = 11.85 V and V_{b3} = 1.85 V. These bias voltage values are proven to achieve a large carrier suppression of 45 dB, resulting in a down-converted IF signal of 2.13 GHz. The down-converted IF signal is measured at the remote destination.

Conversion efficiency as a function of input RF signal frequency of the proposed photonic mixer is shown in Figure 3.7, It can be seen from the figure that the photonic mixer response between 2-16 GHz is almost flat around 1.5 dB variation. This conversion efficiency of the generated optical microwave signal is benchmarked with the commercial RF Source (Rode& Schwarz-SFL-100A), shown in Figure 3.7.

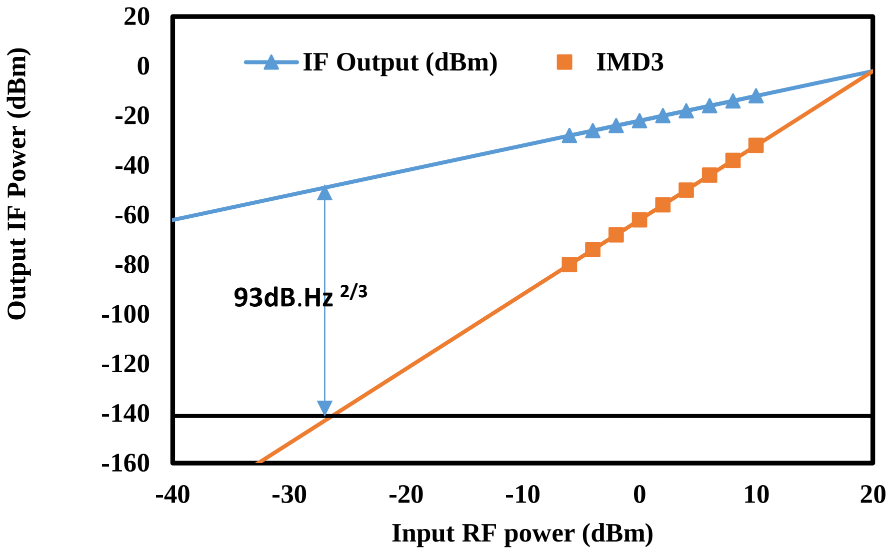

Figure 4.8 SFDR of the proposed photonic mixer.

As illustrated in the Figure 3.7, the generated RF source using in the proposed structure is very precise. This demonstrates the accuracy of our proposed DPMZM photonic mixer, where the conversion efficiency of the optically generated microwave signal and commercially available RF source are similar.

In addition to this, we have also investigated the dynamic range performance of the proposed RoF photonic mixer. The Spurious Free Dynamic Range (SFDR) measurement is carried out with two RF signal tones; 13.00 GHz (RF_1) and 13.01 GHz (RF_2), and they are fed to DPMZM RF electrodes. Our measurement shows that noise floor is -143.5 dBm/Hz. It is worth stating that during the SFDR measurements, third-order Intermodulation Distortion (IMD3) components at 2.12 GHz (IMD_3-Lower) and 2.15 GHz (IMD_3-Upper) are measured and calculated using the following equations 21 and 22:

$$\mathbf{IMD_3\ (Lower)} = \{(\mathbf{2RF_1} - \mathbf{RF_2}) - \mathbf{V_{BS}}\} \qquad \mathbf{(30)}$$

$$\mathbf{IMD_3\,(Upper)} = \{(\mathbf{2RF_2} - \mathbf{RF_1}) - \mathbf{V_{BS}}\} \quad \mathbf{(31)}$$

Where RF_1 is the first RF tone 13 GHz, and RF_2 is second RF tone 13.01 GHz, V_{BS} is the optically generated RF signal at 10.87 GHz, which is fed into LO port of the DPMZM. Fig. 8 illustrates the fundamental signal and IMD_3 components. The SFDR of the proposed method is measured to be 93dB.Hz $^{2/3}$ for a given optical condition, which meets minimum requirement of 72 dB.Hz $^{2/3}$ reported in Ref [143], and it also demonstrates a 3.5 dB SFDR improvement when compared to the reported SFDR in Ref. [132]. The proposed system configuration represents a cost-effective microwave photonic mixer that can be deployed for up and down conversion around in RoF transmission systems.

4.4 Summary

Throughout the experimental analysis, our data determines an innovative microwave photonic mixer, incorporating an-all optical 10.87 GHz microwave frequency generator. These have been projected on Brillouin Stokes utilizing a single laser source. To demonstrate the performance of the proposed optical mixing for IMD_3 measurement, two tones RF input signals at 13.00 GHz and 13.01GHz are down converted to IF_1 at 2.13 GHz and IF_2 at 2.14 GHz, respectively. The lower IMD_3 is measured at 2.12 Hz and upper IMD_3 is measured at 2.15 GHz. The measured phase noise of the optically generated microwave signal at 10.87 GHz is -109 dBc/Hz at 15MHz offset. The proposed analog configuration is used to down-convert the incoming RF signal whilst demonstrating high SFDR performance of 93dB.Hz$^{2/3}$ with low cost, low complexity while using a single laser as a carrier and for RF generation. This meets the minimum requirement of 72 dB.Hz $^{2/3}$ reported in Ref [143], and also demonstrated a 3.5 dB SFDR improvement when compared to the reported SFDR in Ref. [14]. We have developed and implemented a cost-effective microwave photonic mixer structure for RoF transmission systems, where the CW lasers are used as a Brillouin pump for generating the RF optically and as the optical carrier for the DPMZM, simultaneously. This new technique reduces the complexity of RoF transmission systems when deploying multiuser systems with ultra-high bandwidth capacities. The proposed photonic mixer has also been used to down-convert the incoming microwave signal. This new structure can also be used as an all-optical microwave photonic up converter for RoF and antenna remoting around 11 GHz. Future work will be on using this new technique at a higher frequency. To the best of our knowledge, these types of photonic mixers have not been reported in the literature. This research work has proposed novel method to realize microwave photonics mixing in all optical structure, which greatly help to realize future wireless and communication systems in all optical structure. This will remove the problem electronic domain bottleneck problem by realizing all optical microwave photonics systems structure for future electronic warfare and wireless communication systems.

Chapter 5

5 Proposed Apparatus and Method for Reducing Distortions of an Optical Signal (Patent: GB2567646)

5.1 Introduction

Dynamic range is very important performance matrix for any radar and wireless communication systems. Dynamic range is the ability of a receiver to process a range of input powers from the antenna. If the signal is too weak, it cannot be detected as it will buried in noise, whereas, if the received signal power is too high, it will saturate the receiver and spur occurs [16] . Among others unwanted components in a received signal, distortion has great influence on receiver dynamic range. Distortion causes the original signal's shape alteration. This patent relates generally to an apparatus and method for reducing distortion in an optical signal to improve the dynamic range of a microwave photonic systems.

The proposed method was conceived for photonic links used with ultra-wideband photonic radio frequency receivers in electronic warfare (EW) systems, though the invention may have other applications such as for removing distortion in long-haul telecommunication cables. Current non-photonic EW receivers using RF filtering have a typical dynamic range is about 50 dB[144]. Dynamic range is the ratio of the highest signal level a circuit , components, link, or a system can handle to the lowest signal level expressed in (dB)[145]. Photonic links achieve a slightly better dynamic range for the same frequency range and bandwidth without filtering. Photonic RF links therefore provide a promising route for providing improved dynamic range for EW receivers.

The dynamic range of a photonic RF signal is also limited by the amount of optical modulation (typical 4%) [146]. That can be applied by an optical modulator modulating the optical beam to carry a received RF signal before distortion products derived though the modulation process begin to dominate. The objective of the invention (patent) is to improve the dynamic range of the photonic RF signal for microwave photonic systems. While there are numerous components and architecture that have been used to created microwave photonic links, the four components are dominant that enable the effective used are: low noise, high power diode, low loss electrooptic modulators with low drive voltage, high- power, highly linear photodiodes, and low Amplified Spontaneous Emission (ASE) Erbium Doped Fiber Amplifier (EDFA) [17]. To improve the dynamic range, over the last decade DARPA has invested in numerous programs aimed specially to the improvement and maturation of these first three components [17].

Many techniques have been reported using COTs photonic devices in literature to improve the dynamic range of photonic RF signal. Using polarization modulator (PoIM) where destructive combination of the distortion signal in the electrical domain which is realized using a PoIM with its output split into two channels [147]. Using four- wave mixing effect in a highly nonlinear fiber was demonstrated in ref [148]. Predistortion linearization technique is demonstrated to achieve 7.9 dB SFDR improvement [149]. Another scheme is used to improve the dynamic range of the RF photonic signal based a DPMZM with electrical phase shifter to completely supress IMD3 [150]. Series phase modulation and band pass filtering technique [151], using digital linearization technique to improve dynamic range of wide band photonic RF link [152]. Recently, Brillouin scattering in optical fiber has attracted great attention of microwave photonic research community, where Brillouin's anti-stoke is used as very narrow powerful optical notch filter to remove distortion from an optical signal.

Brillouin scattering is a form of inelastic optical light scattering arising from optical inhomogeneity within the light carrying medium. Thermal motion of molecules inside the optical medium cause local density fluctuations that lead to formation of acoustic vibrations within the optical material. Such waves represent acoustic phonons. The interaction of incident light with these phonons results in Brillouin scattering.

Spontaneous Brillouin scattering is caused by natural thermal fluctuations within the optical medium. However, when the intensity of a light beam propagated through the medium is sufficiently high, variations in the electric field of the light beam can induce acoustic vibrations within the material. Scattering caused by these induced acoustic waves is known as Stimulated Brillouin scattering (SBS). The change in optical frequency of scattered light from the frequency of the incident beam is called a Stokes shift. Scattered light that is shifted to lower frequencies are denoted as stokes components and light scattered to higher frequencies as anti-Stokes components. Anti-Stokes scattering results from acoustic waves travelling towards the incident light, while Stokes scattering results from acoustic waves that are retreating from the incident light. The Stokes shift of Brillouin scattered light (Brillouin shift) is equal to the frequency of the acoustic wave within the optical material. In silica optical fibers the typical value of the stokes shift of Brillouin scattered light from incident light having a wavelength of ~1.55 um, is 10.8 GHz. This is a result of the acoustic velocity in silica (V=5900 m/s) and refractive index n=1.46 of silica.

In an application of SBS, a first weak beam carrying a signal is propagated through an optical material in a first direction and a second light beam of optical power enough to effect SBS is propagated through the optical material in an opposite direction. By arranging the counterpropagating beams to be appropriately phased matched and with frequencies separated by the Brillouin shift for the optical medium, the interference wave (commonly referred to as a Dynamic Brillouin grating) formed by the interacting beams strongly stimulates acoustic waves in the optical material that vary in periodicity with the signal. The rating acts, though stimulated Brillion scattering, to reflect a portion of the signal back towards the first beam source [153]. In this research, a novel method is proposed by exploiting SBS's anti-stokes to suppress distortion of modulation product and harmonics generated by an optically modulated signal. In this method a length of optical fiber is used as very powerful optical notch filter to suppress modulation products while the signal is propagated through the optical fiber. This method improves dynamic range of an RF photonic link and optically modulated microwave photonic signals.

5.2 Principle Method

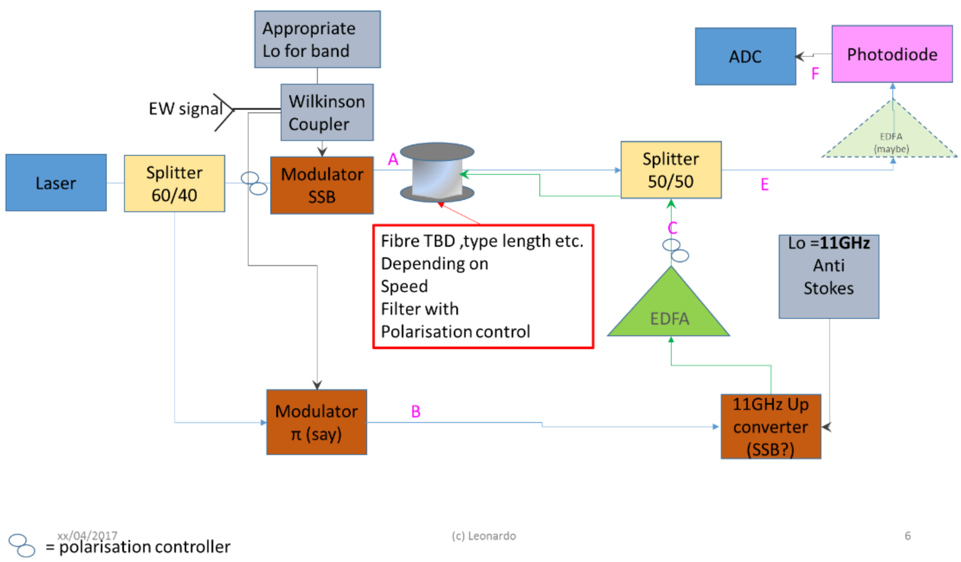

Figure 5.1 Proposed patent structure

Figure 5.1, illustrates a distortion removal apparatus for use with a RF receiver, e.g. a wide band receiver adapted to receive EW signals of frequencies between 1Khz – 100GHz. In a first aspect, there is provided apparatus for reducing distortion in an optical signal, the apparatus comprising: a coherent light source; an optical fiber; an optical modulator for modulating a first coherent light beam to carry a signal and propagate the modulated coherent light beam along the optical fiber; means to generate a dynamic Brillouin grating in the optical waveguide using stimulated Brillouin scattering by propagating a second light beam modulated to carry the signal through the optical fiber in an opposite direction to the first light beam; the optical frequency of the first beam and second beam differing to satisfy the Brillouin condition; and characterised in that the first and second light beams have different fundamental to distortion product ratios. Because the first and second beams have different fundamental : distortion product ratios (namely the ratio of amplitude of the fundamental to amplitude of largest amplitude distortion product) the dynamic Brillouin grating will act to preferentially reflect one of the fundamental or the distortion products in the signal over the other. Depending on the chosen arrangement of the apparatus, either the beam transmitted through the grating or that reflected from the grating will have reduced RF distortion products compared with modulated light beam before incidence with the grating. As such the apparatus provides an efficient means of reducing or removing distortion products introduced through the process of modulating the light to carry the signal, providing an output signal having higher spectrally free dynamic range compared with existing optical and electronic linkages used with RF receivers.

The second beam may be of sufficient optical power to bring about stimulated Brillouin scattering in order to form the grating. The second beam may be of higher optical power than the first beam. The apparatus may comprise an optical receiver arranged to receive the portion of the first light beam that has propagated through the grating. Alternatively, the optical receiver may be arranged to receive the portion of the first light beam that has reflected from the grating. In one arrangement the second beam has a higher frequency (shorter wavelength) than the first beam (e.g. through upconverting the second beam) by a magnitude substantially equal to the anti-stokes frequency shift, the second beam has a smaller fundamental distortion ratio than the first beam, and an optical receiver arranged to receiver the portion of first light beam transmitted through the grating, i.e. travelling in the direction of the first beam. Alternatively, though less preferred, the second beam may have a lower frequency than the first beam (e.g. through down converting) by the stokes frequency shift, the second beam has a smaller fundamental : distortion ratio than the first beam, and the optical receiver is arranged to receive the portion of the first beam that is scattered(reflected) by the grating, i.e. travelling in the opposite direction to the first beam. A perceived disadvantage of the second arrangement is that spontaneous Brillouin Scattering may reduce the quality of the output. Because the amplitude of the distortion products in the output optical signal are substantially reduced compared with the fundamental, e.g. such that amplitudes of the largest distortion products are below the noise floor, the optical modulator can be set to operate at a higher modulator index (optionally near 100%), thereby improving signal to noise ratio of the output signal. The apparatus may be used as an optical link for a RF receiver. In such an embodiment, the amplifier of the RF receiver used to amplifier the signal fed to the optical modulator will typically produce at least some distortion products that align with the distortion products created during optical modulation. As such the apparatus will further advantageously act to reduce/substantially remove distortion products derived from the amplifier as well as from the optical modulator.

The apparatus may comprise a coherent light source with a first modulator to modulate the coherent light from the light source to provide the first light beam. The apparatus may comprise a second modulator arranged to modulate coherent light (e.g. a portion of the coherent light from the coherent light source, in which case the apparatus may further include a splitter) to generate the second modulated light beam. Alternatively, the second modulated light beam could be generated by modulating coherent light source. In order that the second light beam has a lower ratio of fundamental: distortion product, the second modulator may be detuned compared with the first modulator. The second modulator may be tuned to substantially towards null biasing point V_{π}. A first light beam imposed with both the fundamental and unwanted distortion products, is propagated through an optical waveguide in a first direction. A second light beam with a ratio of the amplitude of fundamental to amplitude of larges distortion product that is lower than the equivalent ratio of the first light beam, is propagated into the optical waveguide so as to travel in an opposite direction to the first beam. The second light beam is frequency shifted with respect that of the first beam by the anti-Stokes frequency for the waveguide material.

Because the second beam has a higher ratio of distortion products to fundamental compared with the first beam, the grating preferentially reflects distortion products over fundamental. As such the portion of the first light beam that passes through the grating has distortion products with reduce amplitude relative to fundamental compared with the first beam before incidence with the grating. The apparatus may include an optical-electric transducer arranged to receive the portion of the first beam that transmitted through the grating. If the second beam is of enough optical power the amplitude of all distortion products can be removed to below the noise floor such as to provide the output with a very high spectrally free dynamic range. The optical power of the beam needed to generate an SBS grating will depend on the optical medium used which can be straightforwardly determined through empirical experimentation. The polarization of first and second beams need to be suitable controlled to generate the grating. Such control is taught in thesis [154] mentioned above, but will be known to those skilled in the art. This novel method generates very sharp optical notch filer automatically based on the signal's modulation products. In other word, it is auto tuned notch filter method, which are automatically generated by the modulation product itself. This novel method develops a smart distortion suppression method which based of my knowledge has not been reported before in the literatures. Based on this novel method, a UK patent has been granted and currently being in patent granting process in USA.

5.3 Simulation and Analysis

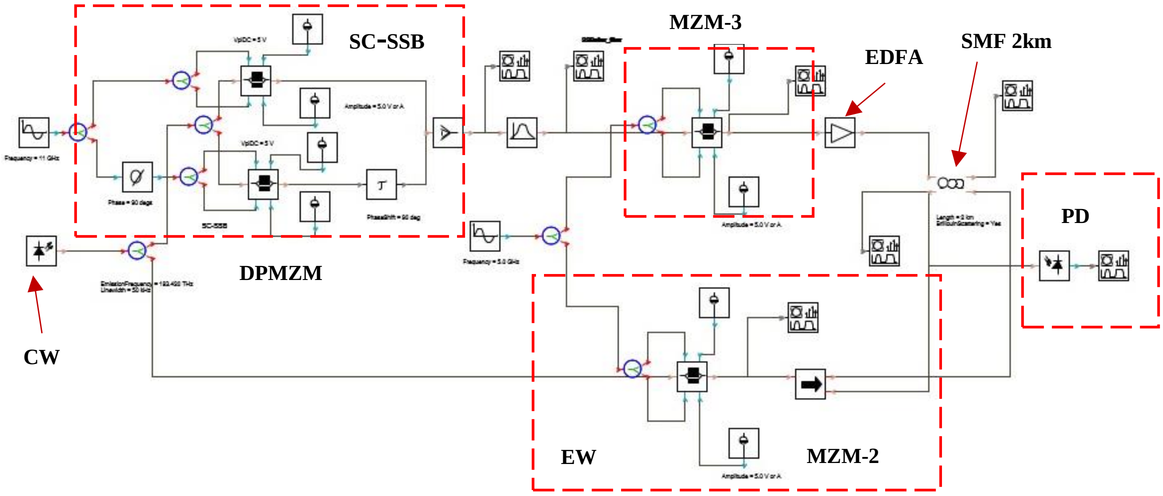

Figure 5.2 Simulation configuration of the patent

The simulation configuration shown in Figure 5.2 is setup based on the proposed patent structure as shown in Figure 5.1. The Continuous Wave (CW) laser with 193.420 THz frequency at 20mW power is spitted by an optical fork, where light from arm of the fork (splitter) is propagated to a Dual Parallel Mach Zehnder Modulator (DPMZM). The DPMZM is derived by 11 GHz RF signal, so that the upper sideband of the suppressed carrier single sideband (SC-SSB) falls in anti-Stokes and lower sideband of the SC-SSB falls in Stokes frequency signal of the Brillouin scattering. In the simulation, the lower side band of the SC-SSB is used as shown in Figure 5.3 to evaluate the anti-Stoke suppression effect on the optical sideband of the MZM-2 as shown in Figure 5.2.

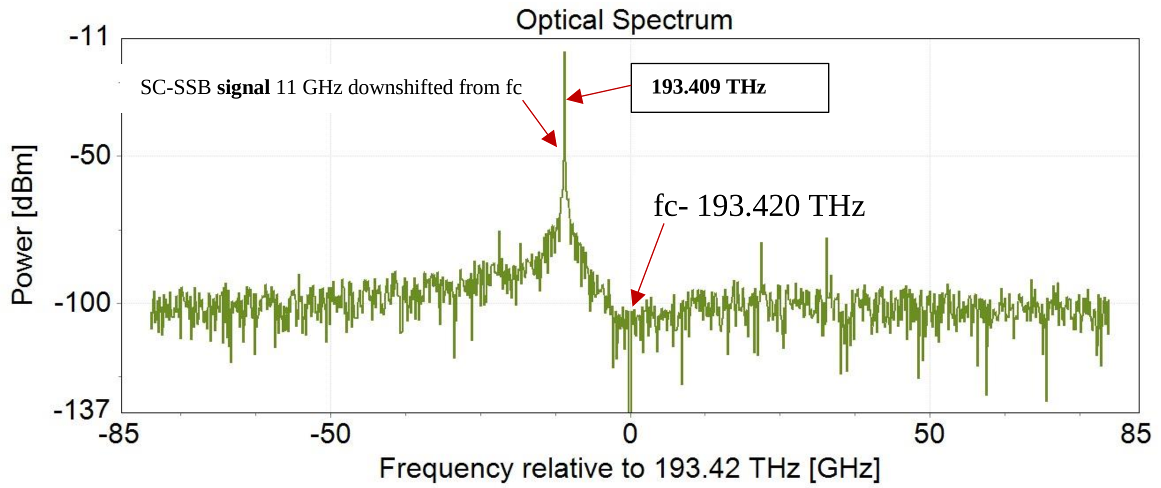

Figure 5.3 Optical supress carrier lower single side band signal

The lower sideband of the SC-SSB at 193.409 THz is working as a Brillouin pump and injected into MZM-3 as shown in Figure 5.3. The MZM-3 works as Brillouin suppressor and modulated by EW signal of 5 GHz biased at NULL operating point at DC 5V. The modulated signal form MZM-3 is amplified by an optical amplifier (EDFA) to generate enough Stimulated Brillouin Scattering (SBS) threshold so that when modulated signal is propagated through 2km single mode fiber (SMF) Brillouin Stokes and anti-Stoke is generated. The output of the MZM-3 is observed in optical spectrum analyser (OSA) as shown in Figure 5.4. It is clear from Figure 5.4 the effect of SBS anti-Stokes on optically modulated signal. The sideband of the modulated signal is suppressed by 10 dB. It worth to note that, anti-stokes is not observed on OSA as it is propagated toward the same direction of the Brillouin pump signal. However, the effect of the anti-Stokes can be seen on the modulated sidebands as both side band were suppressed by 10 dB.

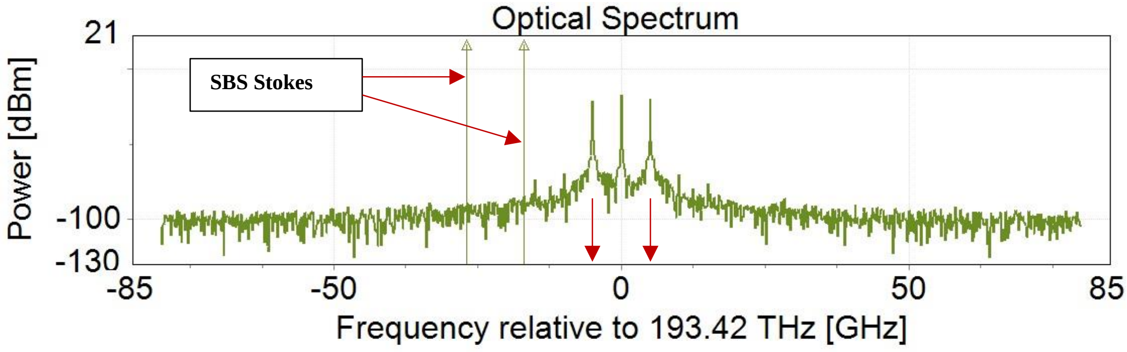

Figure 5.4 SBS Stokes are generated by two modulated sideband of the MZM-3

50% Light from lower arm of the optical fork (splitter) is propagated to MZM-2working as EW modulator and driven by 5 GHz RF signal biased at NULL operating point at DC 5V. The output of the MZM-2 is observed on OSA on the simulation shown in Figure 5.5 is

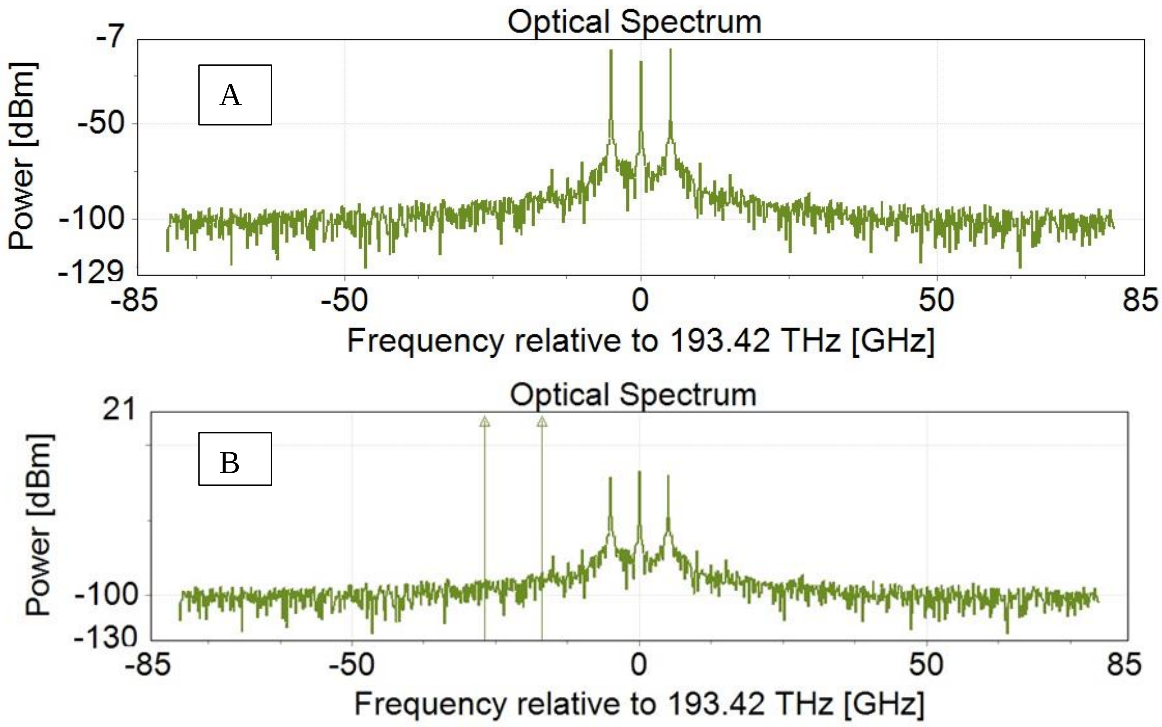

Figure 5.5 The output of the MZM-2 before SBS suppression (A), and, after SBS suppression (B)

propagated via an optical isolator through the 2km SMF fiber working as Brillouin gain medium. When the modulated signal form MZM-2 is propagated through 2km fiber the side bands of the modulated signal is suppressed by 10 dB due to SBS anti-Stokes suppression effect as shown in Figure 5.5. As a result, Null biased optical modulated sidebands are suppressed and becomes quadrature biased modulated side bands. This is shown by overlapping the image A and B of the Figure 5.5. As shown in Figure 5.6, where 10 dB suppression is evident.

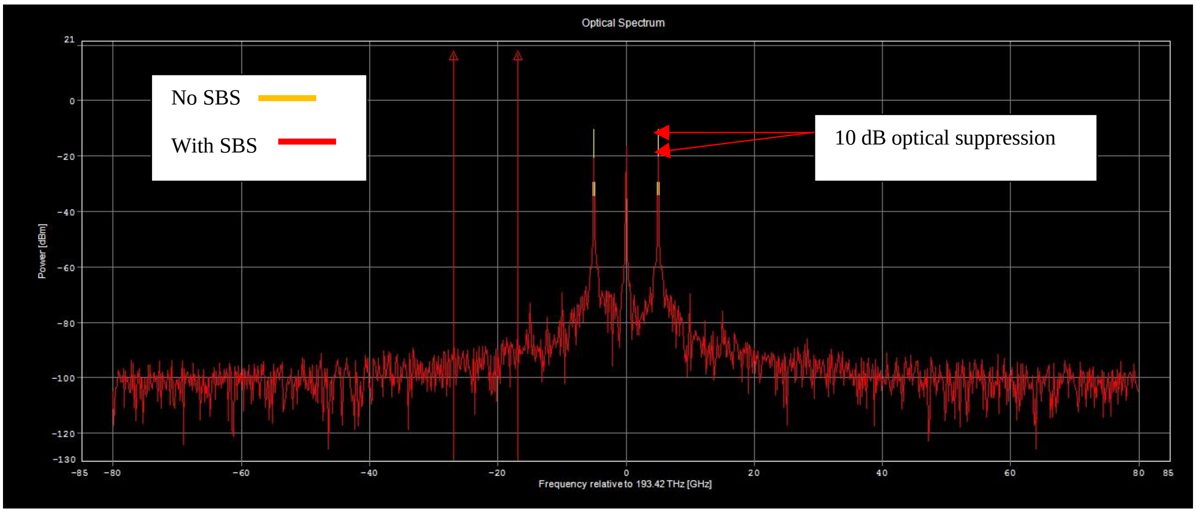

Figure 5.6 Merging image A and B from Figure 5.5

To observe the effect of the suppression in RF domain, the suppressed sidebands of the MZM-2 is injected on a PD according to the setting configuration as shown Figure 5.2 and observed on the RF spectrum analyser on the simulation. The output of the RF spectrum analyser is shown in Figure 4.7 which shows when there no SBS effect in image (A) the second order harmonic of the fundamental RF signal 10 GHz. The fundamental RF signal is 5 GHz. However, when both side bands in Figure 5.5 is suppressed by Brillouin anti-Stokes, the optically modulated signal biased as null becomes like quadrature biased signal. Hence, fundamental and second harmonics are observed in Figure 4.7 (B).

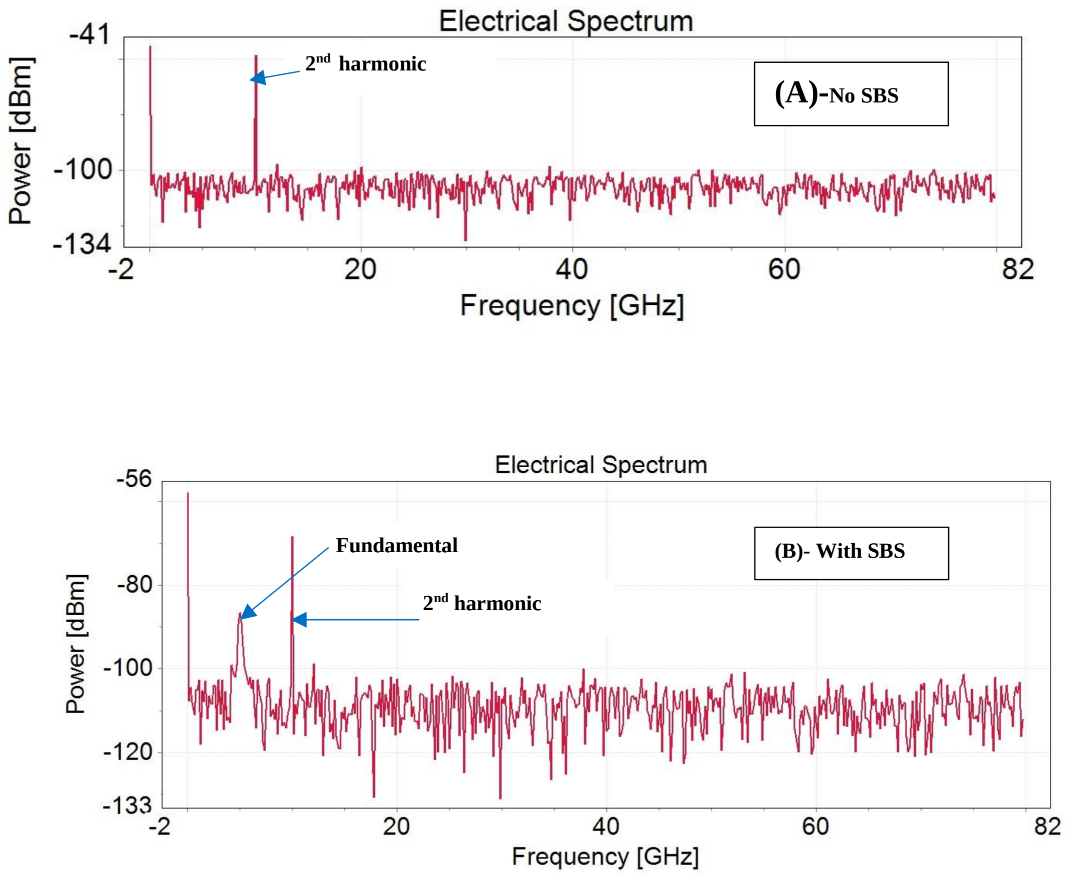

Figure 5.7 RF spectrum analyser shows the PD output without SBS (A) and with SBS effect (B)

The RF output of the photo detector (PD) with and without Brillouin effect is overlapped on each other by simulation as shown in Figure 5.8. Interestingly, the noise floor has also suppressed by 10 dB as shown in Figure 5.8.

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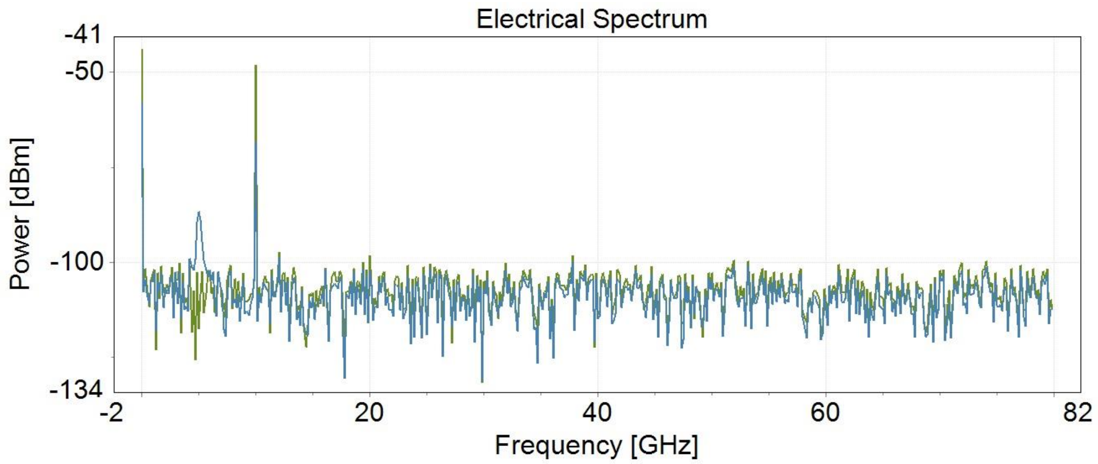

Figure 5.8 Overlapping of PD output with and without Brillouin effect

In this section, MWP down conversion is simulated using conventional structure with optical amplifier (EDFA) such as Erwin H.W. Chan et.al model [129] and [128]. Then down conversion is simulated using proposed patent structure where SBS Stokes are used to amplify modulated side bands (LO and RF) before the photo detector. 20 dB RF dynamic range of the down converted signal has been improved compared to conventional MWP down conversion structure [129]. Unlike EDFA, Brillouin selective sideband amplification only selectively amplify the modulated sidebands and leave noise floor unamplified, thanks to the selective sideband characteristic of the SBS Stokes. However, EDFA amplifies modulation sidebands along with the noise floor. Hence, using EDFA to amplify weak modulated sidebands before the photo detector deteriorate dynamic range by adding more noise on the signal. Moreover, Amplified Spontaneous Emission (ASE) noise generated by the EDFA is also problematic to achieve high dynamic range of the photonic mixers. The proposed patent offers MWP mixing structure which is self-aligned to selectively amplify modulated sidebands by exploiting SBS Stokes gain characteristic and circumvented the inherent noise problem of the EDFA for future RADAR and wireless communication systems.

5.3.1 Simulation Setup

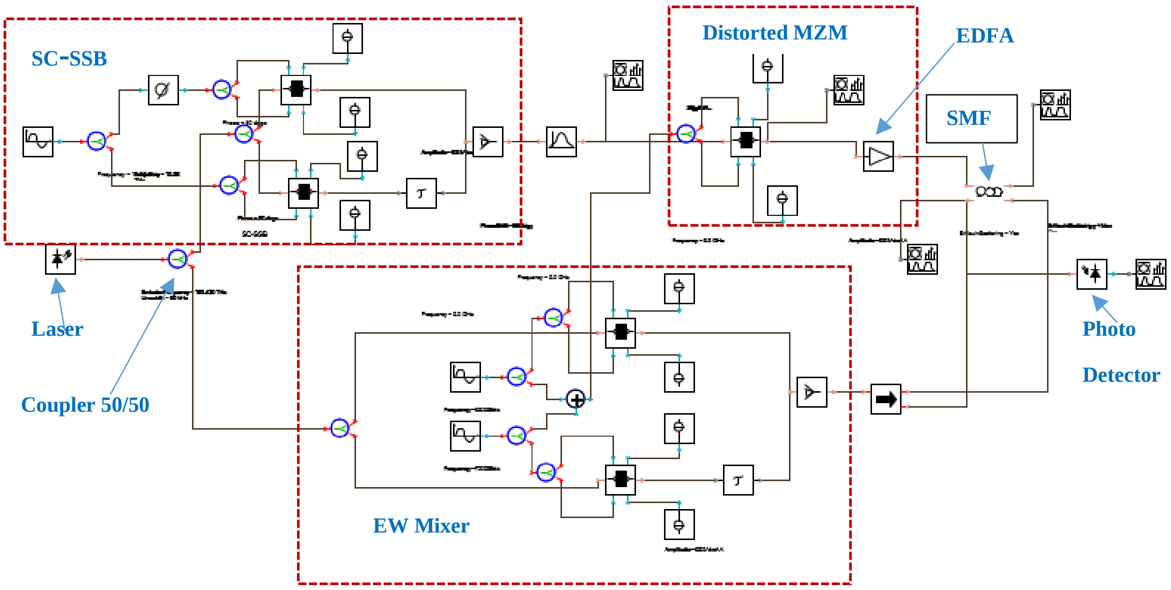

Figure 5.9 Simulation setup of the patent as auto tuned BSSA

The proposed structure is simulated according to Figure 5.9. Laser with 193.420 THz frequency at 20dBm power with -150 dB/Hz Relative Intensity Noise (RIN) is split by a 50/50 coupler. The linewidth of the laser is 100 KHz. The upper arm to the coupler is propagated to a DPMZM which works as Suppressed Carrier-Single Side Band (SC-SSB) Modulator. The SC-SSB modulator is driven by 11 GHz RF signal, so that lower side band of the SC-SSB is fall on Brillouin stokes frequency and upper sideband falls on anti-Stokes Brillouin shift where both side bands are used as Brillouin pump. In the simulation, for amplification of the modulated side bands, the upper side band at 193.431 THz is use as Brillouin pump.

Light upper sideband (193.411 THz) from the output of the SC-SSB is propagated through optical Bandpass Filter (BF) to suppress the optical carrier frequency (193.420 THz) fully and allow the upper sideband of the SC-SSB at 193.431 THz to propagate into single MZM working as a distorted MZM. The MZM working as distorted MZM is driven by combining LO and RF signal from EW mixer as shown in Figure 5.9. To suppress the carrier of the distorted MZM is biased at null operating point at 5V DC. The output of the suppressed carrier distorted MZM is shown in Figure 5.10.

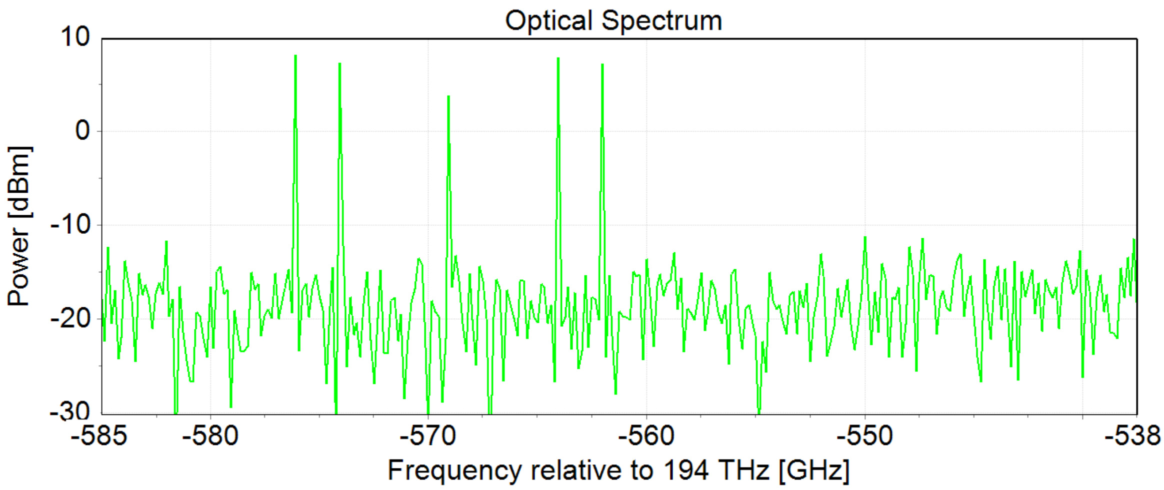

Figure 5.10 Optical spectrum analyser showing the output at distorted MZM

The modulated signal from the distorted MZM is amplified by an EDFA to achieve enough SBS threshold (The power at the output of the EDFA is measured at 26.41 dBm) and propagates through 2km SMF fiber. Here SMF is working as Brillouin gain medium, hence, counter propagated Brillouin Stokes and anti-Stokes frequency are generated. Both Stokes anti-Stokes frequencies are fall on to LO and RF frequencies of the EW mixer. As a result, when LO and RF signal is propagated through SMF, the LO and RF frequencies are selectively amplified by both Stokes have already generated by LO and RF form the distorted MZM. The amplified LO and RF sidebands by the SBS Stokes are shown in Figure 5.11.

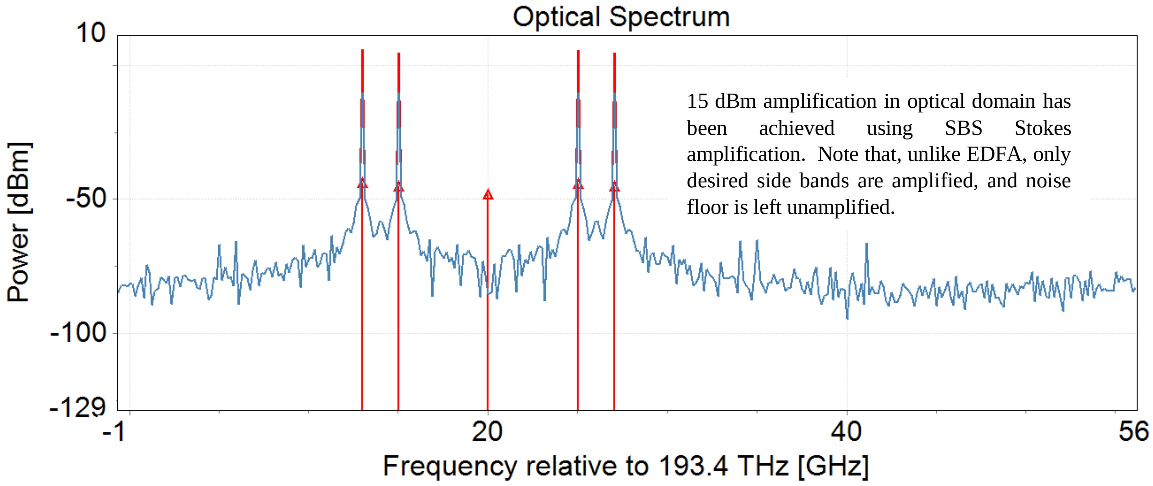

Figure 5.11 Amplified LO and RF signal by SBS Stokes at the input of the photo detector

It shown in Figure 5.11, that only LO and RF signals are amplified by the SBS Stokes. 15 dBm amplification in optical domain has been achieved. It is worth to state that, unlike optical amplifier EDFA, the light energy by SBS Stokes are only centred on LO and RF and noise floor is not amplified. As a result, better dynamic range is achieved, which will be discussed in result and discussions section coming next.

5.3.2 Result and Discussions

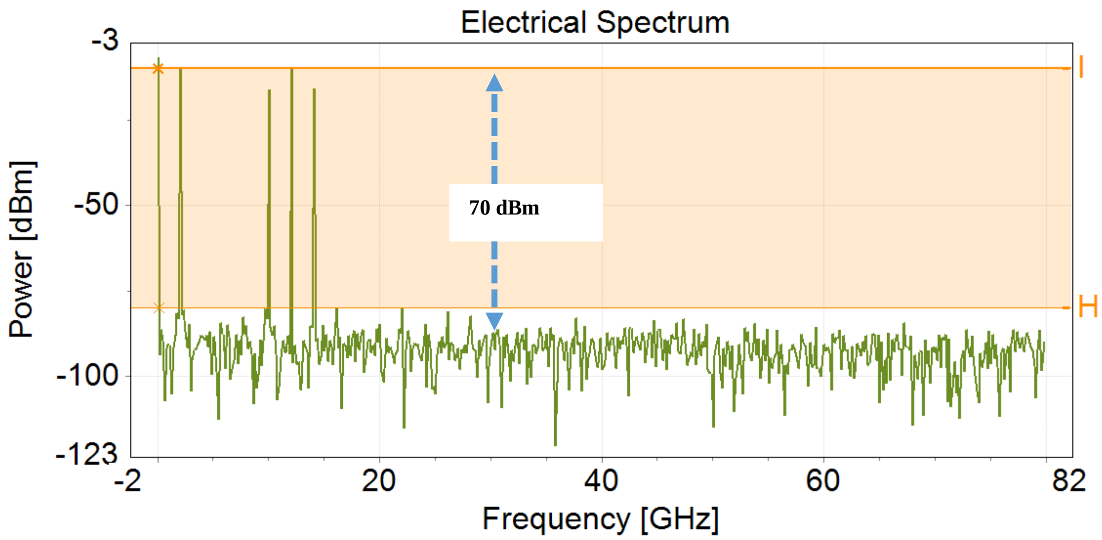

Figure 5.12 RF analyser showing the demodulated signal the photo detector output to the patent

Finally, the demodulated signal at the output of the photo detector is observed on RF spectrum analyser as shown in Figure 5.12 which shows 70 dBm dynamic range of the down converted IF signal. To benchmark the patent, the proposed microwave photonic structure is simulated according to E Chan et.al. in ref [129] as shown in Figure 5.13.

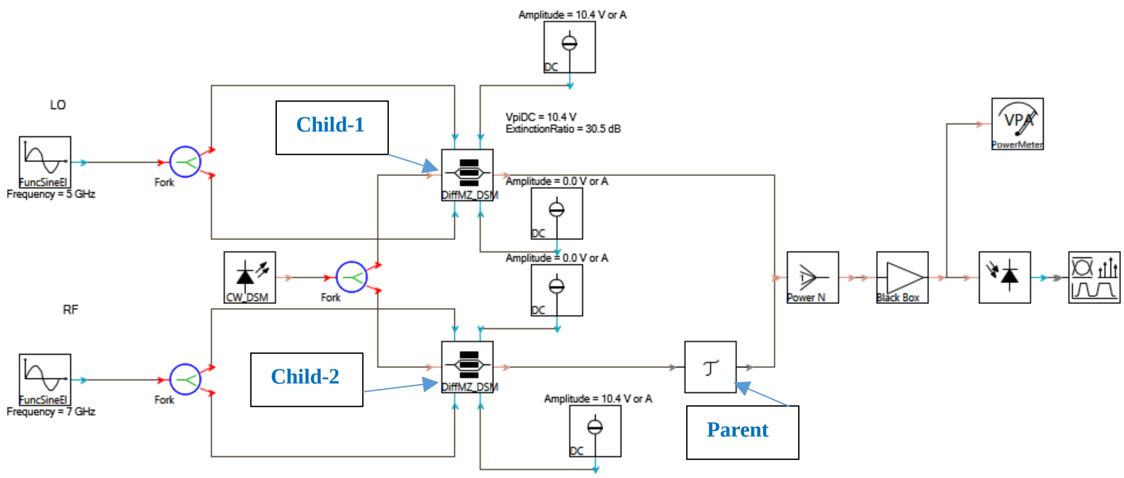

Figure 5.13 Simulation of E Chan et.al. photonic down converter

In simulation in Figure 5.13, CW laser with 193.100 THz at 20 dBm power is injected into an IQ modulator. The upper arm to the IQ modulator is driven by 5 GHz LO signal and lower arm of the IQ modulator's arm is driven by 7 GHz RF signal. To suppress the optical carrier, both child-1 and child-2 modulator of the IQ modulator are set to null biasing point. The null biasing is set to DC 10.4 V. The extinction ration of the child-1 and child-2 modulator was set to 30 dB. The insertion loss of the IQ modulator is 8.4 dB. The parent of the IQ modulator is simulated by using time delay and phase shifted by 180^0 to further suppress the optical carrier. The modulated sidebands from the output of the IQ modulator is amplified by an optical amplifier EDFA, prior to propagate on the photodetector. The output of the photo disconnected to an RF spectrum analyser to observe the demodulated signal as shown in Figure 5.14

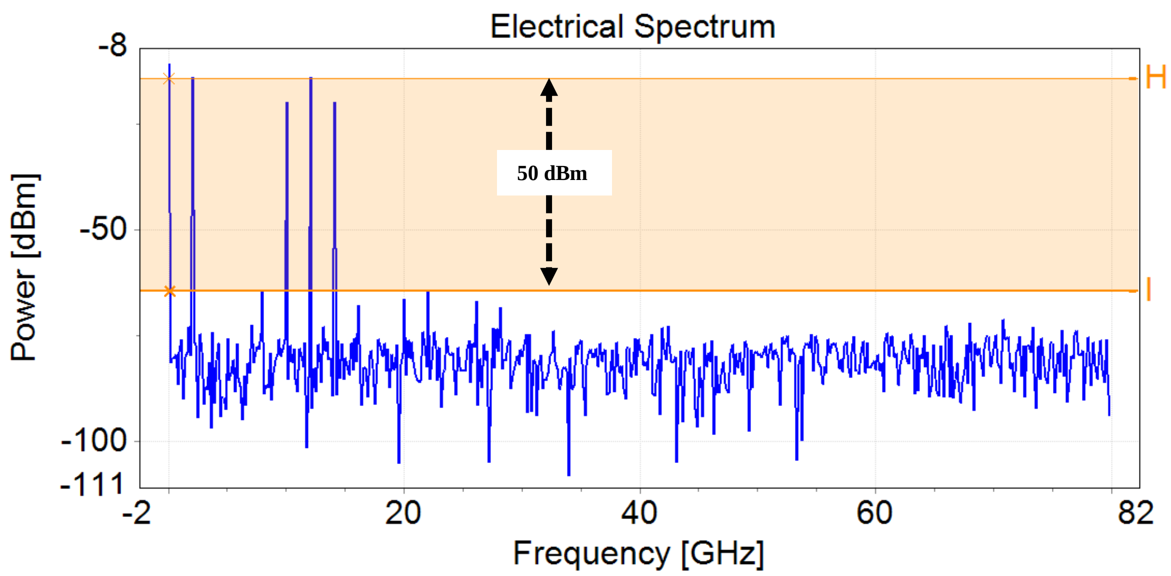

Figure 5.14 Dynamic range of E Chan et.al. photonic downconverter using EDFA[129]

The obtained results in Figure 5.14, show 50 dB dynamic range has been achieved. It is worth to be noted that, using EDFA to amplify weak LO and RF sidebands prior to the photo detector in a photonic mixer structure amplify noise along with modulated sideband. Hence, dynamic range is deteriorated. Furthermore, ASE noise of the EDFA adds further noise to the noise floor and dynamic range of the photonic mixer is greatly deteriorated.

Although, the EDFA is used in the proposed patent structure, the beauty of the proposed patent structure is that, the EDFA is used to generate the SBS threshold power, not to amplify the weak demodulated sidebands (LO and RF). Moreover, in the patent structure, the high power amplified optical signal is counter propagated to the opposite direction of the photo detector. As a result, the demodulated signal is not amplified by the EDFA and the ASE of the EDFA has no effect on the signal and the noise floor.

In the proposed patent structure, the weak demodulated signa is amplified by the SBS Stokes. The beauty of the SBS Stokes is that, the energy from SBS Stokes is only transferred to the

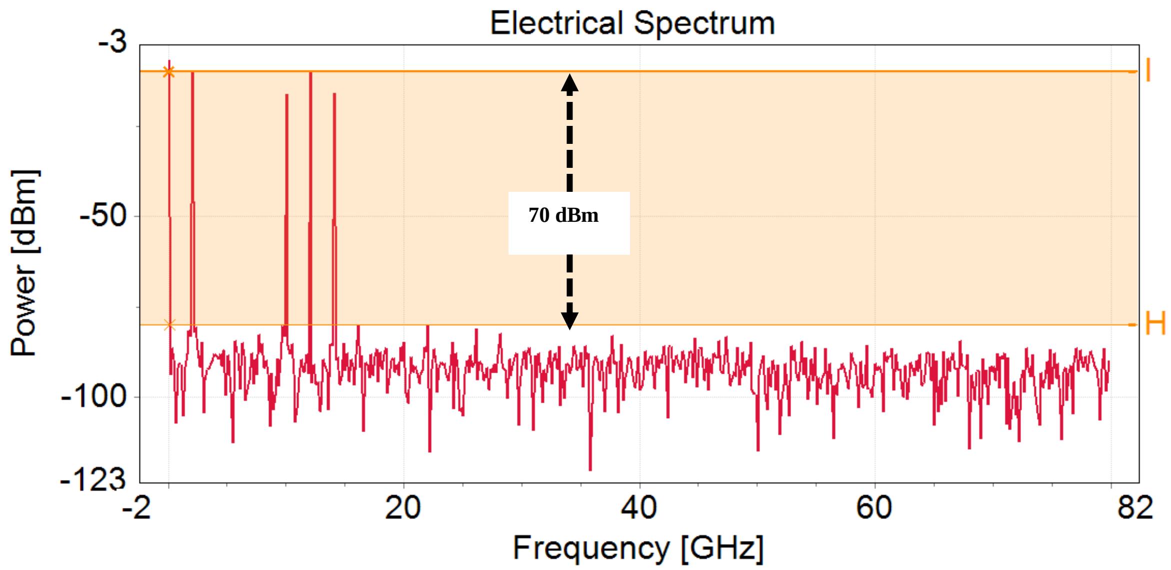

Figure 5.15 Dynamic range of the Patent

weak modulated side bands not into the noise floor. As a result, only the modulated sidebands are amplified, and noise floor is left untouched. Hence, dynamic range is greatly improved.

The obtained results of the proposed patent mixer at the photodetector output is shown in Figure 5.15, where 70 dB dynamic range has been achieved. This is 15 dB improvement compare to

E Chan mixer in ref [129]. Both results, E Chan et.al mixer and proposed patent are superimposed for analysis purpose as shown in Figure 5.16.

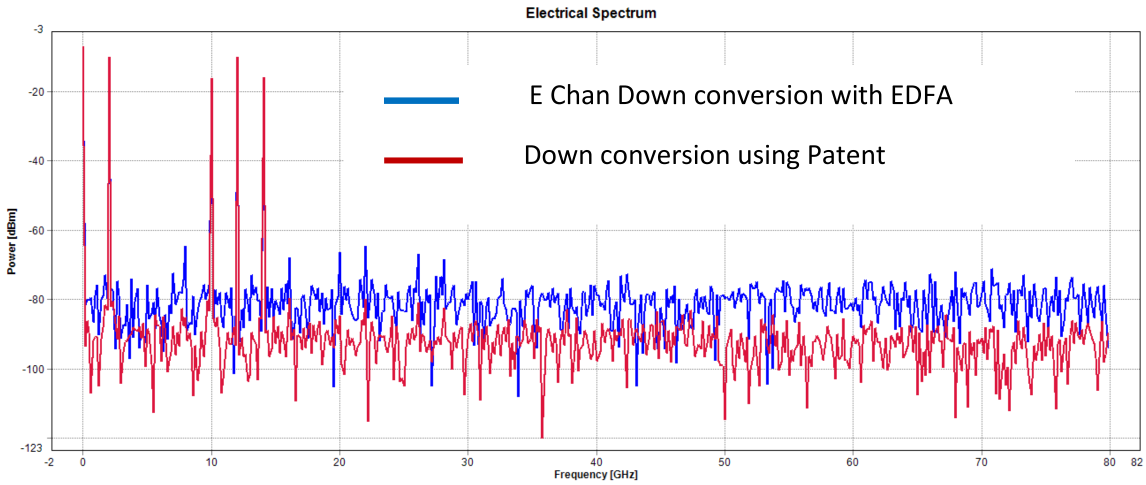

Figure 5.16 Comparison of E Chan downconverter with patent down converters shows noise floor was not amplified by the proposed patent structure. Hence SFDR improvement by 15 dB.

It is shown in Figure 5.16, that proposed patent structure only amplifies the signal and noise floor was not amplified by the proposed patent structure. However, E Chan et.al. mixer structure has amplified noise floor by 15 dB along with the signals as shown in Figure 5.17.

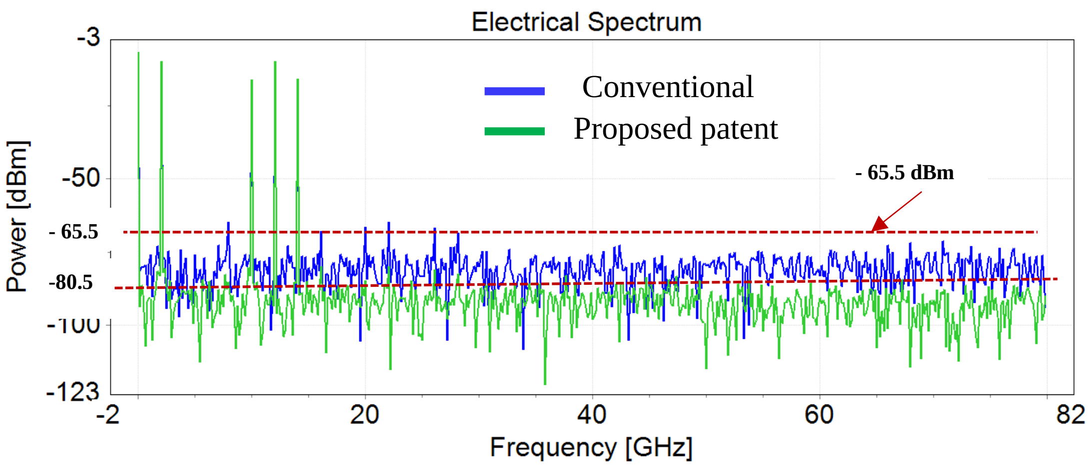

Figure 5.17 Noise floor improved by 15 dB compare to using EDFA

it is worth to note that 15 dB improvement in optical domain is equivalent to 30 dB improvement in electronic domain. Hence, this proposed method has greatly improved dynamic range of the RF photonic link as well as any microwave photonic systems.

5.4 Experimental work

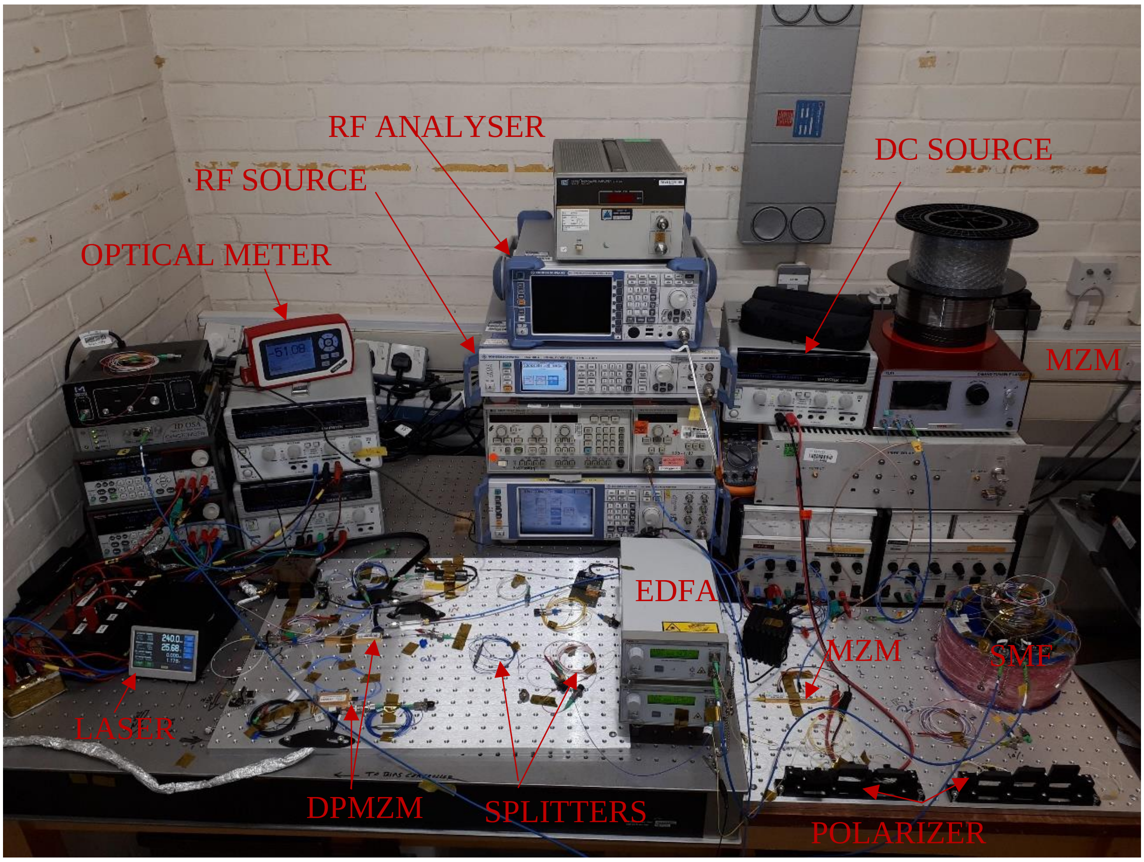

Figure 5.18 Experimental setup for patent

The experimental work has been setup based on schematic in Figure 5.1. Laser light 18 dBm is split by 60/40 optical splitter (Thorlabs-TN1550R5A1), where 40% of the laser light is propagated towards modulator SSB (DPMZM-Axenic -aXsd-2050). The insertion loss of the DPMZM is 7 dB and V_{π} (null voltage) is 8V DC. The DPMZM is biased for SC-SSB modulation. The DPMZM is driven by EW signal from the antenna. 60% light from the other arm of the optical splitter is propagated to (Axenic -aXsd-2040), where the modulator is biased at null and driven by same EW signal as DPMZM. The output of the modulator π is upshifted by 11 GHz by another DPMZM (Axenic -aXsd-2050). This upshifting is required to generate SBS anti-Stokes which fall on modulator SSB (upper modulator) harmonics band. After upshifting the modulated signal is amplified by EDFA (EDFA100P) and propagated via another 50/50 optical splitter into the one end of the SMF fiber. As a result, Brillouin Stokes and anti-Stokes effect is generated in the fiber. When optically modulated EW signal is propagated through the same fiber, all its harmonics are fall on the previously generated anti-Stokes band in the fiber. As a result, most of harmonics are suppressed and only modulated fundamental side bands are propagated toward a photodetector via another EDFA. Finally, the photodetector converts the optical signal into electric signal and sent towards an ADC, where, low speed electric circuitry-based microwave system processes the signal for further analysis. As a result, dynamic range of the EW signal improved greatly.

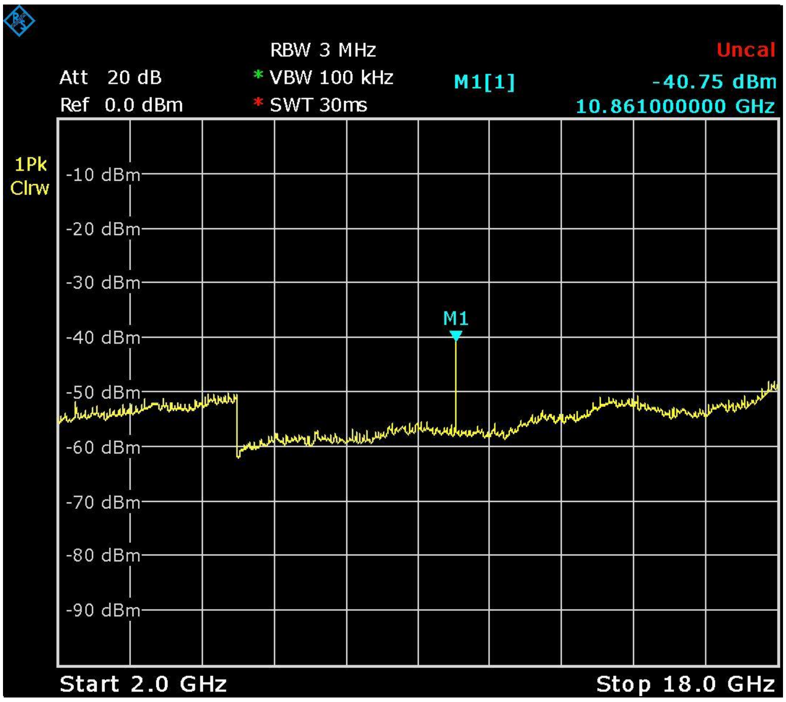

Figure 5.19 RF spectrum analyser shows SBS Stokes shift at 10.86 GHz

Figure 5.9, shows RF analyser (Rode & Schwarz) the Brillouin Stokes frequency shift at 10.86 GHz at -40.75 dBm. The resolution bandwidth of the RF analyser is set to 3 MHz, while vide bandwidth (VBW) is 100 KHz. The sweep time of the RF analyser is set to 30ms. The Brillouin frequency shift is measured using heterodyning technique. In heterodyning technique, laser frequency and SBS Stokes frequencies bit together at a photodetector to generate SBS frequency signal in RF domain. The linewidth of the SBS Stokes and anti-stokes is very important parameter to determine the Q factor of the SBS anti-Stokes which working optical notch filter in the proposed method. The line width of the SBS Stokes frequency is measured using RF spectrum analyser. The line width is measured around 12 MHz as shown in Figure 5.20.

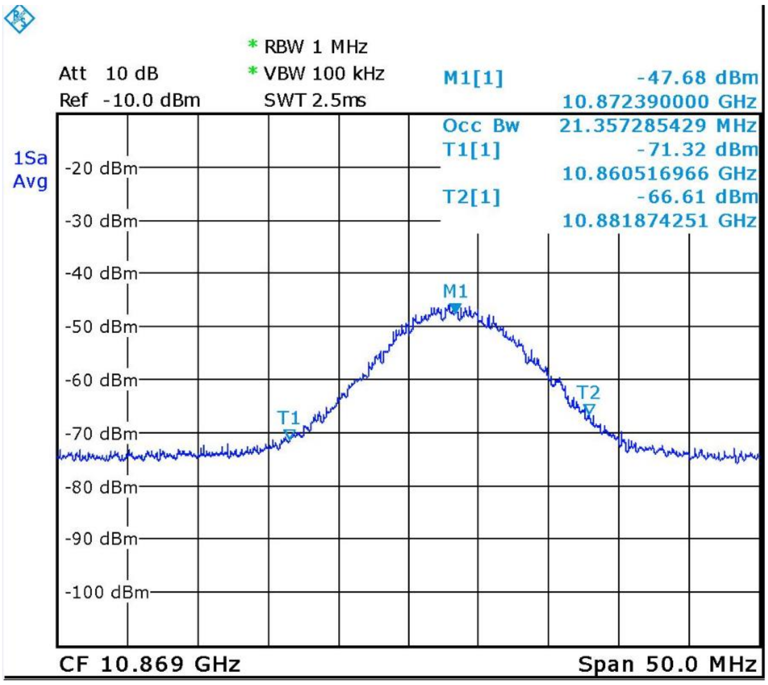

Figure 5.20 RF analyser shows SBS stokes linewidth of 12 MHz

The linewidth of the SBS anti-Stokes can be varied from (10-12) MHz depending on the bandwidth of the EW signal. Typical radar signal bandwidth is 10-20 MHz and SBS notch effect is the perfect platform to suppress distortion for any radar signal. It is worth to state that the linewidth of the SBS Stokes an anti-Stokes is material dependent where acoustic mode of the different material dictates how big the SBS Stokes and anti-stokes linewidth. Hence, fiber made of different material can be used to obtain desired SBS linewidth.

The optical output of the upper modulator is observed on Optica Spectrum analyser (OSA) as shown in Figure 5.21. The optical frequency of the SC-SSB signal is 193.408 THz. This signal works as optical domain sidebands of the EW signal.

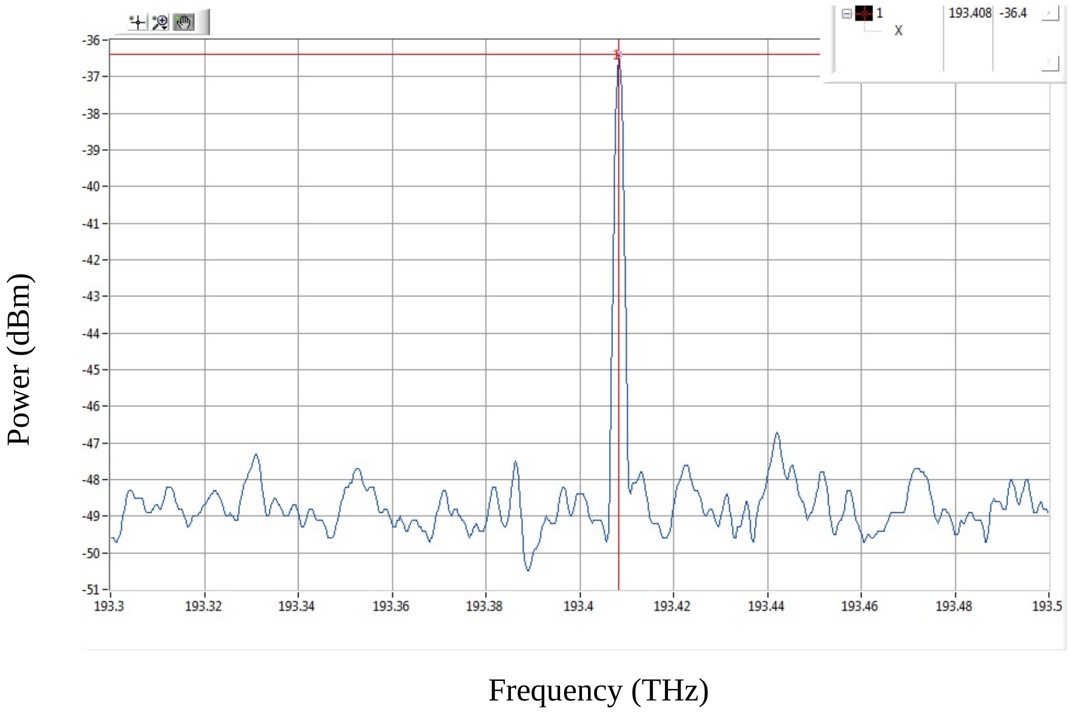

Figure 5.21 Optical spectrum analyser show the SC-SSB signal

The carrier of the SC-SSB signal is suppressed fully by biasing the DPMZM in such that only upper sideband should be coming out from the SC-SSB modulator. The optical carrier signal is not required after modulation and can be generated at the photodetector during demodulation. Finally, the distortion remove signal is observed before the photodetector in optical domain as shown in the schematic diagram in Figure 5.1. According to the proposed patent's method, when wireless or EW signal propagates through the optical fiber, the SBS notch effect in the fiber should suppress most of the distortion from the signal. The fundamental sidebands of the optically modulated signal should not be affected by this notch filtering effect. The beauty of this proposed method is that not additional optical signal processor is not required. This novel

method used optical fiber simultaneously as an RF photonic link and a very powerful microwave photonic notch filter. Hence, EW signal is processed in real time on the fly.

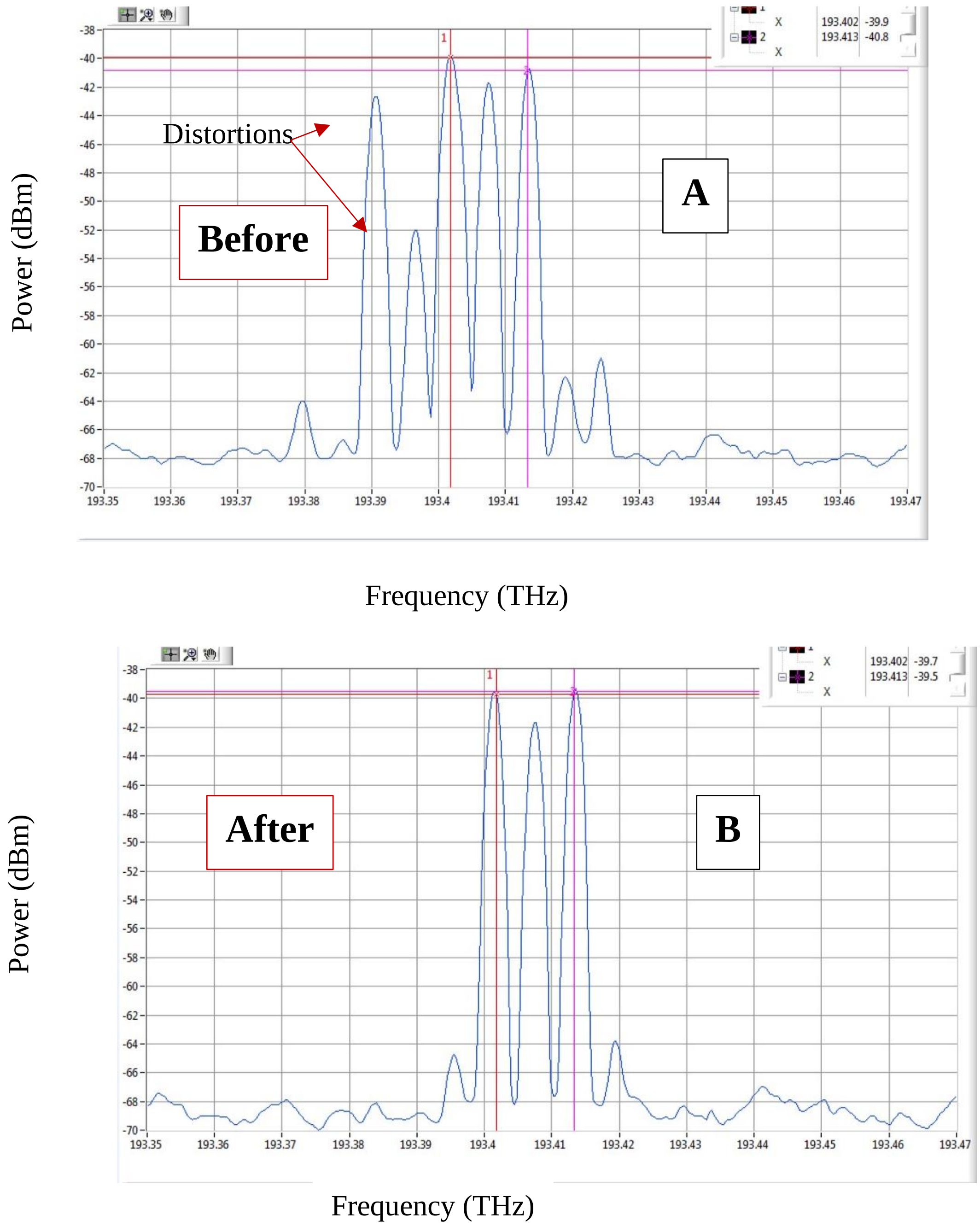

Figure 5.22 Optical spectrum analyser shows EW signal with distortion (A); EW signal without distortion suppressed by the proposed method

This is the demand of future EW and wireless communication systems. Figure 5.22 shows optical spectrum of the signal both with distortion and after distortion removal using the proposed method. 24 dB distortion suppression has been achieved in optical domain. This is equivalent to about 40 dB suppression in RF domain

5.5 Summary

A novel method has been proposed and patented to achieved 70 dB dynamic range, which is 15 dB more than current [155] photonic mixer structure with EDFA. The beauty of the proposed method is that, it only selectively suppresses distortion from the modulated signal as shown in Figure 5.22. Using conventional RF photonic filter this would be very difficult task to achieve as it is very difficult to realize very sharp high Q effect using conventional microwave photonic filter. This method selectively suppress distortion from the optically modulated signal. 24 dB suppression has been achieved in optical domain which is about 40 dB in RF domain. The proposed patent structure suppresses distortion form signal smart way which contribute greatly to achieve high dynamic range for future EW and wireless communication systems. In this method, a length of optical fiber is used simultaneously as an optical signal transmission medium as well as a very powerful microwave photonic signal processor. This method is able to process high bandwidth high frequency microwave photonic signal on the fly in real time, which is the demand for future wireless and radar communication systems. Future work will be focused on using chalcogenide optical fiber instead of single mode fiber to minimize fiber length for EW application where latency is problematic. Chalcogenide fiber has very high Brillouin gain coefficient. This allow using 5m fiber rather than 2 km to be used as a Brillouin medium. This will greatly help to integrate SBS systems in small footprint. Further SBS systems size can be reduced by using Chalcogenide glass cube instead of chalcogenide fiber. The chalcogenide glass cube size would be 2-3 cm and will replace 5 m chalcogenide fiber, hence, potential implementation on photonics chip. There is no doubt that SBS method would be unified all in one microwave signal processing solution for future radar and wireless communication systems.

Chapter 6

6 Proposed Brillouin Selective Sideband Amplification

6.1 Introduction

Amplification is an essential signal processing task in radar and wireless communication systems to improve dynamic range. Conventional optical amplifiers are not able to distinguish between signal and noise and amplifies signal and noise simultaneously. Hence, amplifying noise same time with signal degrades SNR. Brillouin Selective Sideband Amplification (BSSA) is a very powerful amplification technique [131] where desired signal is selectively amplified while noise is kept unamplified. Hence, BSSA greatly improves dynamic range of microwave photonic systems. In Brillouin amplification [156], an optical pump with a frequency of υ_p entering a length of optical fiber generates an acoustic grating moving in the direction of the pump, which gives rise to backscattering of the optical pump. The frequency of the backscattering light is down shifted due to Doppler effect, from the pump [156]. In other words, acoustic wave can cause variation of the density of the optical fiber in which they travel. The density variation can affect optical gratings. Scattering of light by such acoustic grating is called Brillouin scattering [157]. BSSA has been used for selective carrier amplification [158][159] where modulated carrier is amplified before detection by a narrowband BSSA which enhances SNR. A future improvement is achieved by combining wide and narrow-band quantum amplifiers. That would have been very difficult task to achieve in pure electronic domain. The reason is that in electronics domain, it is impossible to design narrow band amplifier like SBS stokes.

This research proposed a novel method based on BSSA, where the modulated side bands of an optically modulated signal is selectively amplified to improve the dynamic range of a modulated signal sideband in a photonic system. This method is auto tuned and to the best of my knowledge has not been reported in the literatures. The novelty of this method is that it is auto tuned to modulated sideband to selective amplification and left noise unamplified. As a result, the photodetector is not saturated by the unwanted amplified optical signal and dynamic range of a microwave photonics systems are greatly improved.

6.2 Principal method

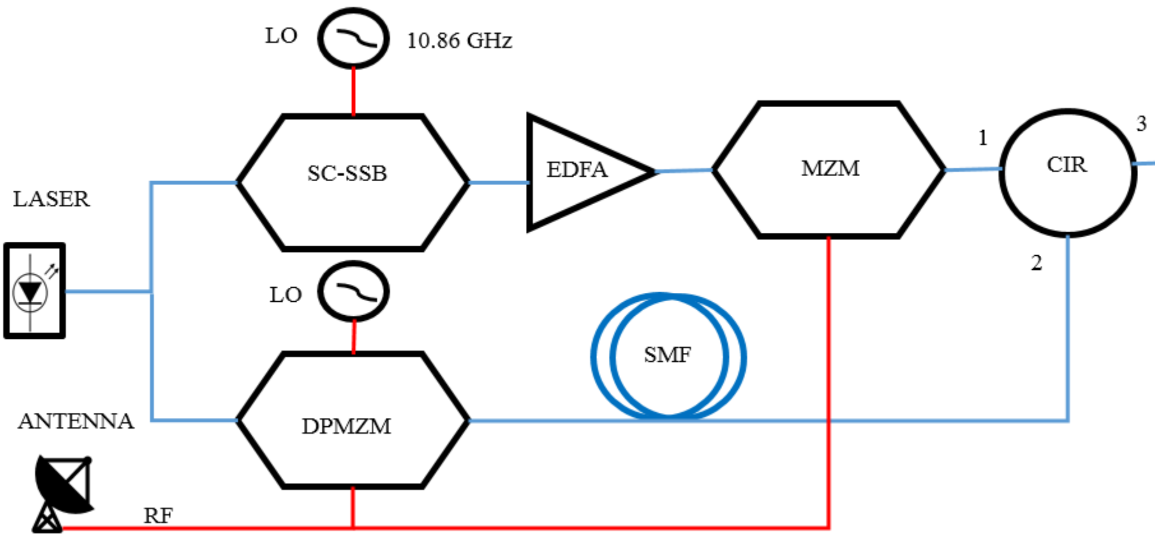

Figure 6.1 Schematic diagram of BSSA; LO: Local Oscillator; SC-SSB: Supress Carrier Single Sideband; EDFA: Erbium Doped Fiber Amplifier; CIR: Circulator; SMF: Single Mode Fiber

Light from laser is spilt by 50/50 by an optical splitter. Light form one arm of the splitter is propagated to Suppress Carrier Single Side band (SC-SSB) and the light from other arm of the optical splitter is propagated to Dual Parallel Mach Zander Modulator (DPMZM). SC-SSB is driven by 10.86 GHz local oscillator RF signal to generate single side band optical signal. The purpose of the SC-SSB is to upshift laser frequency by 10.86 GHz, this allows MZM sidebands to generate Brillouin Stokes which calls on EW signal's sidebands. The upper sideband is used to shift laser signal by 10.86 GHz. Light from SC-SSB is propagated into EDFA to amplify the SC-SSB weak output signal. The output EDFA is connected to the input of the single MZM. The RF signal from the antenna drives DPMZM and MZM simultaneously. Light from MZM is propagated via an optical Circulator (CIR) port-1 to port-2 to the one end of the Single Mode Fiber (SMF) and generates Brillouin Stokes frequency is generated inside the SMF. When optically modulated RF signal from DPMZM output is propagated through the same SMF, the side bands of the modulated signal is amplified by the Brillouin Stokes frequency gain which was already generated by the modulated signal from MZM. The sidebands of the modulated signal rom DPMZM is always fell on the Stoke frequencies generated by MZM as both DPMZM and MZM are driven by the same RF signal as shown Figure 6.1 . As Brillouin Stokes fall only on the side band of the DPMZM, hence, only sidebands are amplified while noise kept unamplified. This novel method greatly enhances SNR and greatly improves dynamic range of the microwave photonics systems. The photodetector is not saturated by the unwanted amplified noise. The photodetector has limited input power limit, conventional optical amplifiers saturate the photo detector with unwanted noise as they are not able to selectively amplify only the desired modulated side bands signal.

Furthermore, manufacturing photodetector with high input power capability is costly and research intensive. Further integrating this method on chalcogenide glass will be capable to achieve the same results as very high input power photoreactor would achieve. Hence, this method would bring cost down greatly by not using very expensive high input power photodetector for future microwave photonics system. This method has potential to improve dynamic range more than 40 dB using chalcogenide glass cube as a Brillouin gain medium. This would not be possible using conventional optical amplifier. Hence, it greatly contributes not only realizing RF systems in optical domain but greatly improve dynamic range of any RF system yield by future EW systems.

6.3 Simulation

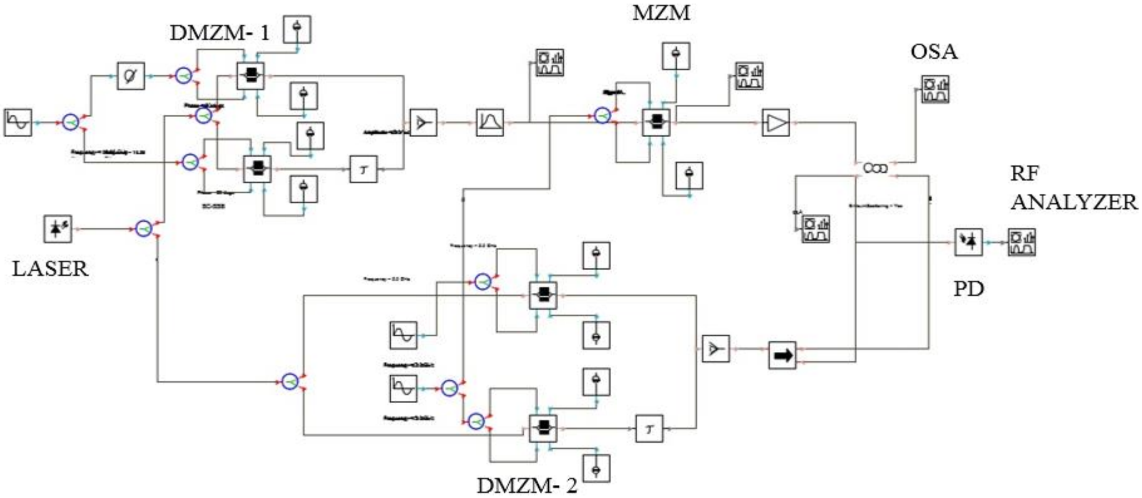

Figure 6.2 BSSA simulation

Prior to experimental work, simulation as shown in Figure 6.2, is performed based on the schematic diagram shown in Figure 6.1. industry standard VPI-photonic software is used for simulation. In the simulation as shown in Figure 6.2, first light from laser is split 50/50 by and optical splitter. Light from upper arm of the splitter propagated to an optical modulator (DPMZM-1). The DPMZM-1 is driven by a 11 GHz RF signal to upshift the laser frequency by Brillouin shift of 11 GHz. The simulated DPMZM-1 is built using two single MZM in push pull orientation, these are also called child modulators. The DPMZM-1 is biased at null and quadrature to generate SC-SSB at the output. The SC-SSB signal is then propagated towards MZM input, where the MZM is also biased at null to suppress the carrier and driven by the same LO as DPMZM-2. It is worth to state that, both modulator MZM and DPMZM-2 are driven by the same LO to make the proposed method auto tuned. The output of the MZM is amplified by EDFA to generate enough threshold power for SBS. The amplified light (18 dBm) from the output of the MZM is propagated through the 2 km optical fiber SMF towards the DPMZM-2. An isolator is used to guard the DPMZM-2 by the high optical power generated from MZM. Laser light from the bottom arm of the optical splitter is propagated towards DPMZM-2 where it is driven by two local oscillators (LO), one LO is used to imitate RF signal form an antenna where other LO drives both MZM and DPMZM-2. The DPMZM-2 is biased at null and quadrature, where both chid are biased at null and parent at quadrature.

Modulated signal form DPMZM-2 output is propagated towards the optical fiber 2km (SMF), while it propagated through the 2 km fiber, the sidebands of the modulated signal are fall in the same frequencies of the Brillouin Stokes frequencies which are already generated by the high power MZM sideband . AS a result, both modulated side bands are amplified selectively, and noise is not amplified. Finally, selectively amplified modulated sideband from the other end of the optical fiber is propagated toward a photo detector (PD) and converted to RF signal. It is worth to state that, the PD has limited input power limit which is around 10 dBm for currently commercially available PD in the market. The problem with conventional optical amplifier is that it saturates PD with amplified noise along with signal, as it is not able to distinguish between noise and signal. The noise it unwanted in any communication and radar application. The novelty of this proposed method is that it selectively amplifies signal from noise and not kept unamplified. As a result, PD is not saturated with amplified noise and desired modulated sideband are fully amplified to achieve desired dynamic range. Hence, this method greatly enhances the dynamic range of any RF photonics link and microwave photonics systems on the fly in real time while signal is propagated through the optical fiber for future radar and wireless communication systems. The results of the simulation are evaluated in the next section.

6.3.1 Simulation results

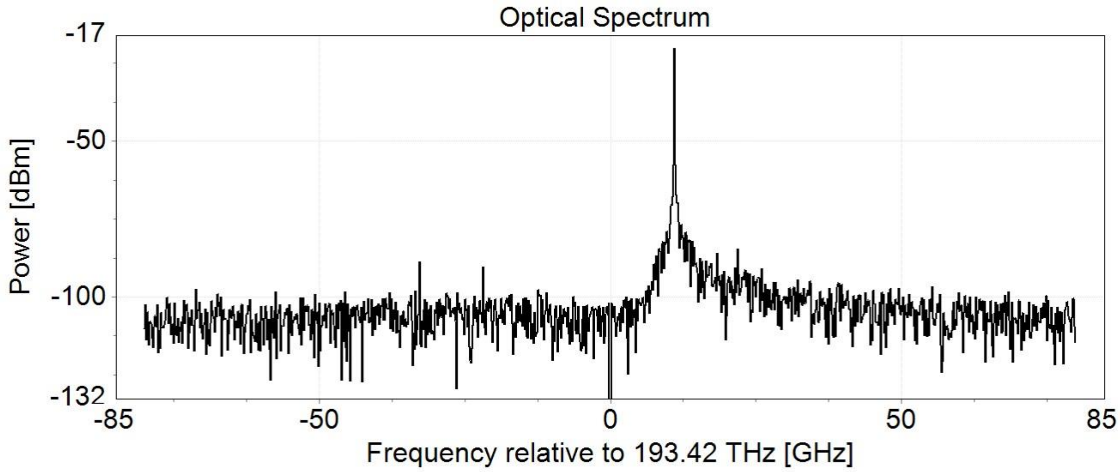

Figure 6.3 SC-SSB signal at DPMZM -1 output

Figure 6.3 shows the simulated output signal which shows SC-SSB signal is generated by DPMZM-1. The purpose to the SC-SSB is to upshift laser signal by 10.86 GHz. This allows the EW signal sideband falls on Brillouin Stokes which is generated by MZM. The output of the DPMZM is further amplified by an EDFA. Here, EDFA is used to amplify the SC-SSB weak signal which is working as a Brillouin pump as shown in Figure 6.3. The output signal form the EDFA is injected into a single MZM. Here, MZM is working as a double Brillouin pump as shown in Figure 6.4. Double Brillouin pump is required to generate two Brillouin Stokes frequency so upper and lower modulator side band are simultaneously amplified. It is worth to note that the MZM and lower DPMZM are driven by same RF signal form the antenna as shown in the schematic diagram in Figure 6.1. However, MZM has 11 GHz upshifted optical signal in the input compare to the lower DPMZM. This is purposely done so that the generated Brillouin Stoke effect by the MZM is fallen on Rf sidebands of the optically modulated RF signal form bottom DPMZM as shown in the schematic diagram in Figure 6.1.

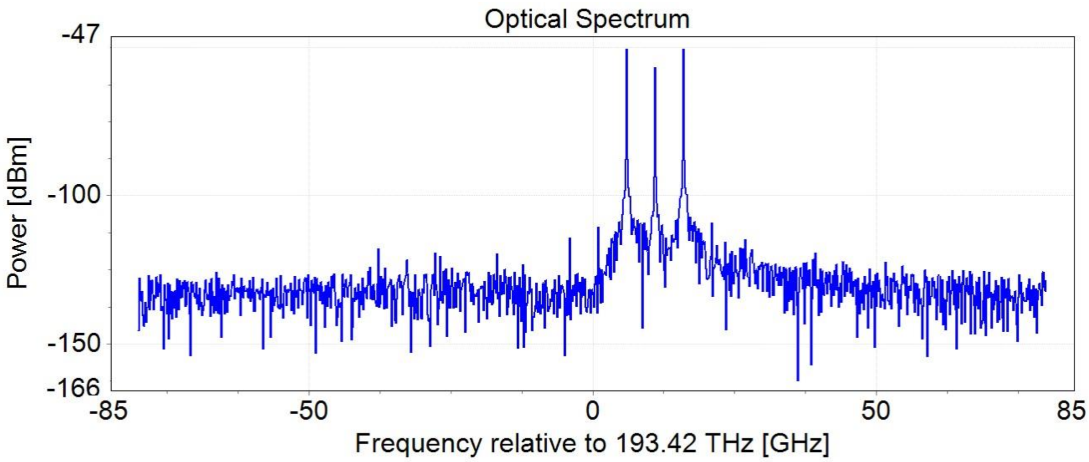

Figure 6.4 Simulated output signal at MZM output

The MZM signal is shown in Figure 6.4. It is worth to state that, the output signal form MZM is working in the method as a Brillouin pump. Both sideband of the MZM output signal as shown in Figure 6.4, generates two Brillouin Stokes as shown in Figure 6.5, which work as sharp high Q Brillouin selective side band amplifier to selectively amplify DPMZM output signal sidebands. The beauty of this method is that the noise is not amplified. This phenomenon is shown in Figure 6.5 where three small sharp blue lines represents Brillouin Stokes frequencies. The characteristic of the SBS Stokes frequencies are they have only 10 MHz which behaves like very sharp high Q optical amplifiers. Hence, only desired signal is amplified, and noise is left unamplified. As a result, it helps photo detector not to be saturated by the unwanted amplified noise. Furthermore, this sharp amplification has no effect on the phase of the modulated sidebands from bottom DPMZM as shown in Figure 6.1. The side bands of the MZM are tuneable by the local oscillator signal. Hence, Brillouin Stokes can be generated to amplify any desired modulated sidebands of the DPMZM. Furthermore, it is auto tune to the received RF signal form the antenna. Tuning RF signal to different band automatically tune the MZM sideband such a way so that the generated SBS Stokes automatically fall on optically modulated sidebands of the DPMZM as shown in Figure 6.1.

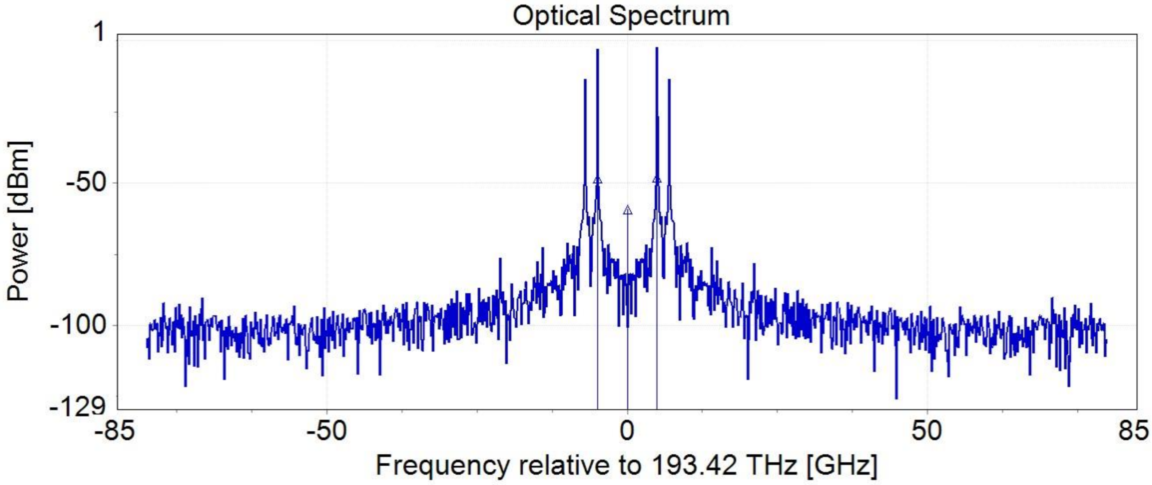

Figure 6.5 Simulated optical spectrum analyser shows EW signal form DPMZM-2 output falls on SBS Stokes generated by MZM signal

Figure 6.6 shows, simulated RF spectrum analyser where amplified signal from DPMZM is shown in electronic domain. It is evident from Figure 6.6, that 15 dB improvement of signal to noise floor by the proposed Brillouin selective sideband method. Unlike conventional optical amplifier, this method does not amplify noise and desired signal same time. It selectively amplifies the modulated sideband in optical domain prior to incident on the photo detector as shown in simulation result in Figure 6.5. The green signal in Figure 6.6, represents the conventional optical amplifier signal where noise and signal are indigenously amplified. The blue signal represents the amplified signal by the proposed Brillouin selective side band application where only sidebands are selectively amplified, and noise is kept unamplified.

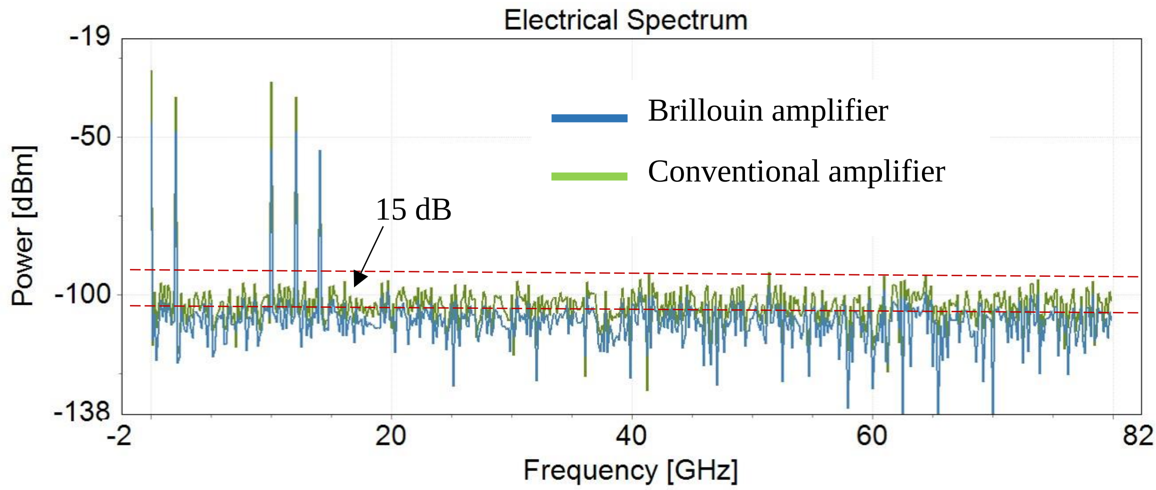

Figure 6.6 Simulated RF spectrum analyser shows of 15 dB noise floor improvement compared to conventional optical amplifier shown by the red dashed lines.

The dynamic range can be improved more than 15 dB by using longer length of optical fiber. The problem of using very long optical fiber impose delay in radar signal. However, using longer optical fiber is possible in telecommunication. Furthermore, using optical fiber with different material with high Brillouin gain coefficient does not require longer optical fiber for this proposed method. The proposed method can easily be integrated on a photonic chip where a cube shape 2-3 cm chalcogenide glass can be used as very high Brillouin gain medium instead of optical fiber. The is enormous potential of SBS to be used as an unified microwave photonic signal processor for generation of mm wave RF signal to very high frequency high Q smart amplifier (proposed method) to very high Q microwave photonic notch filter to very powerful optical time delay for future quantum computer memory to future photonic radar. The beauty of this proposed method is using a length of optical fiber as very powerful smart optical amplifier which greatly enhance the dynamic range of the microwave photonic systems.

6.4 Experimental work

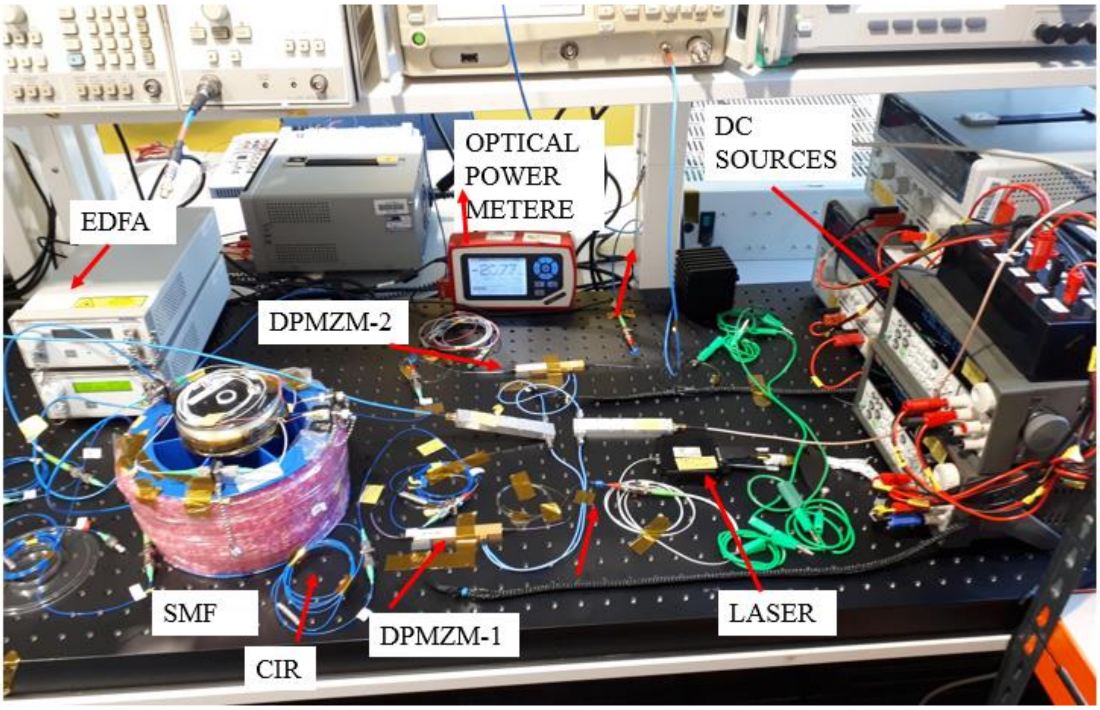

Figure 6.7 Experimental setup for BSSA

Experimental work has been setup based on the schematic diagram illustrated in Figure 6.1 and the simulation based in Figure 6.2. Light from laser is split 50/50 by laser operating at 1549.948 nm (193.421THz), with a narrow linewidth of 50 kHz (Thorlabs-SFL 1550 S) and optical power of 18 dBm, connected to an optical splitter (Thorlabs PN1550R5A1). Light form upper arm of the optical splitter is propagating to DPMZM-1, where the DPMZM-1 is biased to generate SC-SSB output signal. The upper DPMZM is driven by10.86 RF signal generated by Rode and Schwarz RF source. In this experimental work Gallium arsenide (GaAs) based (Axenic -aXsd-2050) are deployed due to their advantages for and satellite communication systems. The 3-dB bandwidth of the DPMZM is 50 GHz with the insertion loss of 10 dB. The half-wave voltage $V\pi$ for the child-1 and child-2 modulators are around 10 V-DC, and for the parent modulator $V\pi$ is 12 V-DC. In such RoF transmission systems, it is necessary to suppress the carrier. Within this experiment, in order to minimize the carrier, we optimized the bias voltages of the DPMZM. Our measurements show that the optimized DPMZM bias voltages to minimize the carrier are at; Vb1 = 6.50 V, Vb2 = 11.85 V and Vb3 = 1.85 V. These bias voltage values are proven to achieve a large carrier suppression of 45 dB, resulting in a down-converted IF signal of 2.13 GHz [95]. SC-SSB signal form is amplified by EDFA (Thorlabs-100P) and inject into MZM input. The output power of the EDFA is 18 dBm. EDFA is used to generate enough threshold power for MZM to generate SBS Stokes frequency. Light from MZM output is propagated through one end of the SMF-28 fiber where the fiber length is 2km and loss is 0.22 dB /km. While light from MZM is propagated through the SMF-28 fiber, Brillouin Stokes frequency is generated in the SMF and counter propagated towards CIR port-2.

Light from the lower arm of the optical splitter is propagated to the lower DPMZM-2, where it is driven by RF signal from the antenna. The RF signal from the antenna simultaneously drives DPMZM-2 and DPMZM. The modulated optical signal form DPMZM-2 is propagated through SMF-28 fiber to the CIR (Thorlabs CIR1550 PM) port-t to port-3 to be further processed by low speed electronics circuitry-based systems. While modulated optical signal is propagated through the optical fiber (SMF-28), the sideband of the modulated signals falls on the same frequency of the already generated two Brillouin frequencies by the MZM sidebands. As a result, both sideband of the DPMZM -2 is selectively amplified by the both SBS Stokes frequencies as shown in Figure 6.8. Here, both SBS Stokes work as very sharp high Q optical amplifier. Unlike conventional amplifier, Brillouin SBS Stokes only amplify the desired signal which is mixed with noise and interferences. This greatly improves SNR and dynamic range of any microwave photonics systems. The experimental result as shown on an optical spectrum analyser capture in Figure 6.8 validates the simulation result as shown in Figure 6.5. it is shown from the experimental result of the optical spectrum analyser in Figure 6.8, that SBS Stokes effect selectively only amplify the modulated sideband and kept noise unamplified. This approach does not saturate photo detector by amplifying noise.

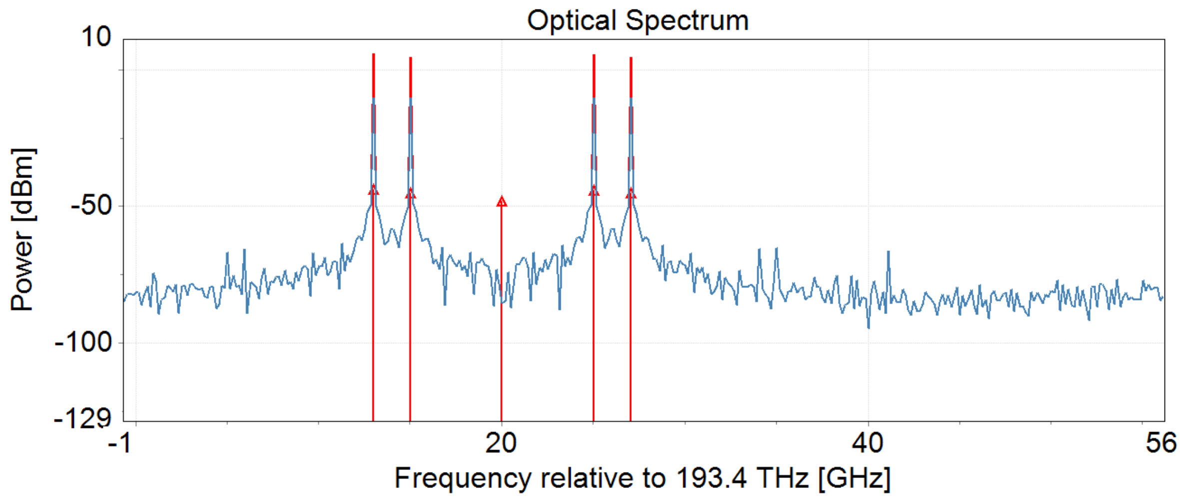

Figure 6.8 Optical spectrum analyser shows DPMZM-2 signal is selectively amplified by the two SBS Stokes frequency generated by the MZM

The photo detector has very limited input optical power handling capability which is around 10 dBm for most of the commercially available photodetectors.

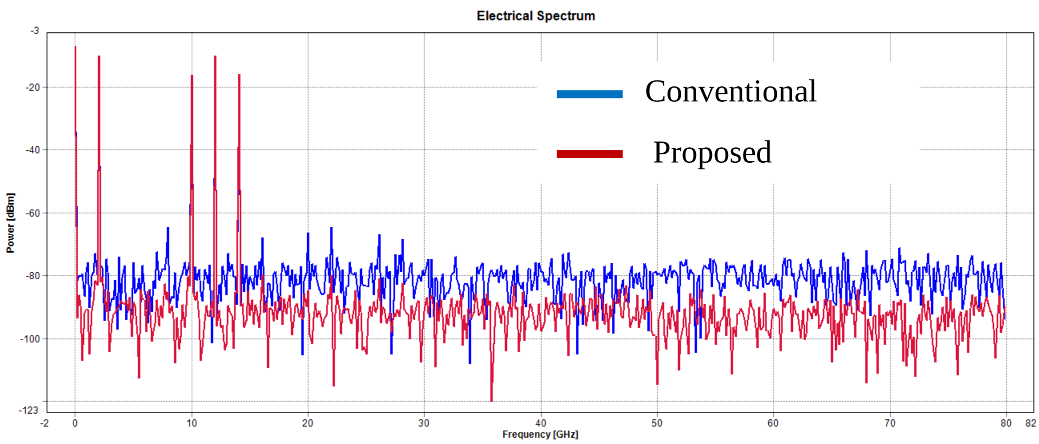

Figure 6.9 RF analyser shows 15 dB dynamic improvement by the proposed method

Finally, the amplified light from CIR-port 3 is incident on a photodetector (PD). The output of the PD is observed on a RF spectrum analyser (Rode and Schwarz) as shown in Figure 6.9.

It is observed from Figure 6.9, the received signal by the PD has greatly improved compared to conventional optical amplifier. The conventional optical amplifier in blue colour amplified signal and noise simultaneously where the proposed method only amplifies the selective sidebands and noise is left unamplified. The novelty of this method is that, it only selectively amplifies the desired sideband of the optical modulate signal, not noise, prior to reach at the photo detector. Hence, the photodetector does not saturate with noise power. Only desired signal is incident on the photodetector. As a result, dynamic range of the RF photonic link and microwave photonic systems are greatly enhanced by 15 dB as shown in Figure 6.9 .

6.4.1 Summary

A novel method of selective sideband amplification of microwave photonic signal using Brillouin Stokes frequency gain has been demonstrated. 15 dB SNR improvement has been achieved compared to conventional optical amplifier. This novel method allows an optical fiber to simultaneously work as a photonics link and a selective sideband amplifier. This will allow to process signal in real time on the fly which is the demand for future radar and wireless communication systems. Photodetector with high input power is required to achieve high dynamic range of any microwave photonic systems. This is because, using conventional optical amplifier to amplify signal also amplify noise along with signal. Hence, when this amplified signal with amplified noise is incident on the photodetector, the photodetector is saturated by unwanted amplified noise as the photodetector has limited input power taking ability. Using photodetector with high input power rating can solve this problem. However, photodetector with high input power rating is very expensive. This method solves this problem by selectively amplifying the desired modulated sidebands, not the noise. Hence, photodetector is not saturated with unwanted amplified noise. As a result, cheap photo detector with low input power rating is not saturated and greatly improves dynamic range and cost for high bandwidth microwave photonic system for electronic warfare and wireless communication systems.

Chapter 7

7 Conclusion and Future Work

7.1 Conclusions

Future radar and wireless communication systems require microwave photonics systems with high dynamic range and a powerful microwave photonics signal processor. In this thesis, this issue has been addressed by exploiting Stimulated Brillouin Scattering (SBS) in optical fiber as very powerful unified microwave photonic signal processor.

The background theory of the thesis is conducted in **chapter 2**. The theoretical, simulation and in-depth experimental work of generation of SBS in optical fiber has been demonstrated in **chapter 3**.   This would greatly help anyone to understand the behaviour and characteristic of the SBS prior to exploiting it for microwave photonic signal processing. **In chapter 4**, a novel method of generating high frequency RF signal has been proposed by exploiting SBS Stokes frequency gain, which beats with optical carrier frequency using heterodyning technique. This allows to realize microwave photonics mixing in all optical system configurations. This method greatly helps to overcome electronic bottleneck problem in electronics domain by realizing all optical microwave photonics system. This work has been published in IEEE access.

In chapter 5, another novel method has been proposed to suppress nonlinearity generated by modulation product from any optical modulator. This proposed method has significantly improved dynamic range of any microwave photonics systems by 15 dB. A UK patent (**GB2567646**) has been granted based on this work.

In chapter 6, another a novel method to selectively amplify high frequency microwave signal from noise has been proposed by exploiting SBS Stoke gain. In this novel method desired microwave signal is amplified selectively. This approach is smarter and more efficient comparing to conventional optical amplifier. Unlike conventional optical amplifier which amplify noise along with desired signal, the proposed SBS amplifier only amplifies desired signal selectively. This greatly improves signal to noise ratio which in turn greatly improves conversion efficiency of the optical modulator. Improvement of 15 dB SNR has been achieved. This approach greatly enhances wireless and Radar systems performances.

7.2 Future work

This research has great potential to use SBS as a unified microwave photonics signal processor. In order to improve the performance and integration to photonic chip level, further, investigation is required. The main focus of this thesis was to use Stimulated Brillouin Scattering (SBS) in fiber as a very powerful microwave photonic signal processor. Single Mode Fiber (SMF) was used as a proof of concept experimental work.

It will be more appropriate to integrate SBS medium on small photonic chip. Using optical fiber as a Brillouin medium is not appropriate to achieve this goal. Hence, using short length of chalcogenide fiber instead of 2km single mode fiber will greatly miniaturised the overall SBS microwave photonics systems. Further miniaturization is possible by using 2-3 cm Chalcogenide glass cube which will enable to implement SBS based signal processor on photonic chip. Brillouin gain medium with high Brillouin gain coefficient greatly reduces SBS pump's threshold power. It is very important to implement Brillouin gain medium on a photonic chip for system level integration in airborne and EW platform. Brillouin medium with very high Brillouin gain coefficient is very important to realize SBS signal processing on a photonics chip. Further research work needs to be performed on Brillouin gain medium with high Brillouin gain coefficient to integrate SBS on optical signal processor on chip.

In chapter 4, Brillouin Stokes are exploited to generate high frequency RF signal in all optical domain to realize all optical microwave photonics frequency mixing. Further investigation needs to be conducted to extend the proposed structure with tuneable capability to generate different range of high frequency RF signal in optical domain.

In chapter 5, Brillouin anti-Stokes notch effect is exploited to suppress interference from an optical signal. Brillouin Stoke also has potential to be used as a powerful microwave photonic notch filter. A further investigation may be required to explore the potential of the Brillouin Stokes gain as microwave photonic filter.

In chapter 6, Brillouin Stokes gain is exploited to selectively amplify microwave photonics signal where Brillouin anti-stokes frequency is not desired as some intelligence signal may be suppressed by the Brillouin anti-Stokes. This effect needs to be further investigated to analyse the Brillouin anti-Stokes effect on intelligence signal. Amplified Spontaneous Emission (ASE) generated by SBS Stokes gain, which influences the increased noise floor, this issue needs to be further researched. In sum, future, military and wireless application must require a unified microwave photonics signal processor and SBS is the right candidate to fulfil this demand and further research in SBS will make it reality.

8 References

[1] "VIII. A dynamical theory of the electromagnetic field," *Philos. Trans. R. Soc. London*, vol. 155, pp. 459–512, Jan. 1865.

[2] A. J. Schwab, "Maxwell, Hertz, and German Radio-Wave History," *Proc. IEEE*, vol. 86, no. 7, pp. 1312–1317, 1998.

[3] R. Y. Chiao, C. H. Townes, and B. P. Stoicheff, "Stimulated brillouin scattering and coherent generation of intense hypersonic waves," *Phys. Rev. Lett.*, vol. 12, no. 21, pp. 592–595, 1964.

[4] "Maxwell's equations and light." [Online]. Available: https://web.pa.msu.edu/courses/2000fall/phy232/lectures/emwaves/maxwell.html. [Accessed: 23-Dec-2019].

[5] "Electromagnetic Spectrum | NASA." [Online]. Available: https://www.nasa.gov/content/electromagnetic-spectrum. [Accessed: 13-Feb-2020].

[6] D. M. Pozar and J. Wiley, "Microwave Engineering Third Edition W WILEY," 2009.

[7] L.-T. Wang, Y. Xiong, and M. He, "Review on UWB Bandpass Filters," in *UWB Technology - Circuits and Systems*, IntechOpen, 2020.

[8] Edward I. Ackerman et.al, *Microwave Photonics Devices and Applications*. John Wiley & Sons, Ltd, 2009.

[9] P. Ghelfi, F. Scotti, D. Onori, and A. Bogoni, "Photonics for Ultrawideband RF Spectral Analysis in Electronic Warfare Applications," *IEEE J. Sel. Top. Quantum*

Electron., vol. 25, no. 4, Jul. 2019.

[10] A. Nirmalathas, “Microwave photonics-double magic [From the Guest Editor’s Desk],” *IEEE Microwave Magazine*, vol. 16, no. 8. Institute of Electrical and Electronics Engineers Inc., pp. 24–26, 01-Sep-2015.

[11] W. R. Babbitt *et al.*, “Extreme Bandwidth Analyzer and Correlator for spectrum analysis and direction finding,” in *IEEE Aerospace Conference Proceedings*, 2012.

[12] A. Khilo *et al.*, “Photonic ADC: overcoming the bottleneck of electronic jitter,” *Opt. Express*, vol. 20, no. 4, p. 4454, Feb. 2012.

[13] M. Pagani, “mattia pagani,” University of Sydney, Jan. 2016.

[14] S. Chen and J. Zhao, “The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication,” *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 36–43, 2014.

[15] J. B. Y. Tsui and J. P. Stephens, “Digital microwave receiver technology,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 699–705, Mar. 2002.

[16] “Microwaves101 | Dynamic Range.” [Online]. Available: https://www.microwaves101.com/encyclopedias/dynamic-range. [Accessed: 18-Sep-2020].

[17] R. W. Ridgway, C. L. Dohrman, and J. A. Conway, “Microwave photonics programs at DARPA,” *J. Light. Technol.*, vol. 32, no. 20, pp. 3428–3439, Oct. 2014.

[18] H. Lee, Aurangozeb, S. Park, J. Kim, and C. Kim, “A 6-bit 2.5-GS/s Time-Interleaved Analog-to-Digital Converter Using Resistor-Array Sharing Digital-to-Analog Converter,” *IEEE Trans. Very Large Scale Integr. Syst.*, vol. 23, no. 11, pp. 2371–2383, Nov. 2015.

[19] C. Caloz, S. Gupta, Q. Zhang, and B. Nikfal, “Analog signal processing,” *IEEE Microw. Mag.*, vol. 14, no. 6, pp. 87–103, 2013.

[20] R. Gomez-Garcia and A. C. Guyette, “Reconfigurable multi-band microwave filters,” *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 4, pp. 1294–1307, Apr. 2015.

[21] “Ultra Wideband Signals and Systems in Communication Engineering - M. Ghavami, Lachlan Michael, Ryuji Kohno - Google Books.” [Online]. Available: https://books.google.co.uk/books?hl=en&lr=&id=vX7eCq8TDp4C&oi=fnd&pg=PR5&ots=I02NgQAPPY&sig=dPxQK6cj4gZX5CVpn6eVfeVGcmw#v=onepage&q&f=false. [Accessed: 27-Nov-2020].

[22] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, “Microwave photonic signal processing,” *J. Light. Technol.*, vol. 31, no. 4, pp. 571–586, 2013.

[23] D. Marpaung, J. Yao, and J. Capmany, “Integrated microwave photonics,” *Nature Photonics*, vol. 13, no. 2. Nature Publishing Group, pp. 80–90, 01-Feb-2019.

[24] T. Schneider, M. Junker, K. L.-J. B, and undefined 2006, “Theoretical and experimental investigation of Brillouin scattering for the generation of millimeter waves,” *osapublishing.org*.

[25] M. Woodson *et al.*, “High-power high-bandwidth unitraveling-carrier photodiodes for high-frequency RF photonic links (Conference Presentation),” in *Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XII*, 2019, vol. 10917, p. 55.

[26] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nature Photonics*, vol. 1, no. 6. Nature Publishing Group, pp. 319–330, Jun-2007.

[27] “Relative Intensity Noise - an overview | ScienceDirect Topics.” [Online]. Available:

https://www.sciencedirect.com/topics/engineering/relative-intensity-noise. [Accessed: 22-Aug-2020].

[28] M. Faugeron *et al.*, "High-power tunable dilute mode DFB laser with low RIN and narrow linewidth," *IEEE Photonics Technol. Lett.*, vol. 25, no. 1, pp. 7–10, 2013.

[29] "Analogue optical links - theory and practice - IET Journals & Magazine." [Online]. Available: https://ieeexplore.ieee.org/abstract/document/1340337. [Accessed: 23-Aug-2020].

[30] M. Lee *et al.*, "Broadband modulation of light by using an electro-optic polymer," *Science (80-.).*, vol. 298, no. 5597, pp. 1401–1403, Nov. 2002.

[31] E. I. Ackerman *et al.*, "Signal-to-noise performance of two analog photonic links using different noise reduction techniques," in *IEEE MTT-S International Microwave Symposium Digest*, 2007, pp. 51–54.

[32] K. S. Giboney *et al.*, "Travelling-Wave Photodetectors with, 172-GHz Bandwidth and 76-GHz Bandwidth-Efficiency Product," *IEEE Photonics Technol. Lett.*, vol. 7, no. 4, pp. 412–414, 1995.

[33] T. H. Maiman, "Stimulated optical radiation in Ruby," *Nature*, vol. 187, no. 4736, pp. 493–494, 1960.

[34] N. Institution of Electrical Engineers. and L. L. Freris, *IEE proceedings. B, Electric power applications.*, vol. 120, no. 5. Institution of Electrical Engineers, 1980.

[35] J. E. Midwinter, "The start of optical fiber communications as seen from a U.K. perspective," *IEEE J. Sel. Top. Quantum Electron.*, vol. 6, no. 6, pp. 1307–1311, 2000.

[36] B. Jalali, P. Kelkar, and A. S. Bushan, "Microwave photonic signal processing," in *Asia-Pacific Microwave Conference Proceedings, APMC*, 2000, vol. 54, no. 2, p. 14.

[37] J. Capmany, G. Li, C. Lim, and J. Yao, “Microwave Photonics: Current challenges towards widespread application,” *Opt. Express*, vol. 21, no. 19, p. 22862, Sep. 2013.

[38] K. Clays and A. Persoons, “Hyper-Rayleigh scattering in solution,” *Phys. Rev. Lett.*, vol. 66, no. 23, pp. 2980–2983, Jun. 1991.

[39] M. Merklein *et al.*, “Stimulated brillouin scattering in photonic integrated circuits: Novel applications and devices,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 2, pp. 336–346, Mar. 2016.

[40] “Widely Tunable Single-Passband Microwave Photonic Filter Based on Stimulated Brillouin Scattering - IEEE Journals & Magazine.” [Online]. Available: https://ieeexplore.ieee.org/abstract/document/6025266. [Accessed: 05-Dec-2020].

[41] J. Capmany, B. Ortega, and D. Pastor, “A tutorial on microwave photonic filters,” *J. Light. Technol.*, vol. 24, no. 1, pp. 201–229, 2006.

[42] “Quality Factor | Q Factor Formula | Electronics Notes.” [Online]. Available: https://www.electronics-notes.com/articles/basic_concepts/q-quality-factor/basics-tutorial-formula.php. [Accessed: 19-Jan-2021].

[43] S. Preussler and T. Schneider, “Stimulated Brillouin scattering gain bandwidth reduction and applications in microwave photonics and optical signal processing,” *Opt. Eng.*, vol. 55, no. 3, p. 031110, Oct. 2015.

[44] “free-spectral range (FSR) | Photonics Dictionary® | Photonics Buyers’ Guide.” [Online]. Available: https://www.photonics.com/EDU/free-spectral_range_FSR/d4274. [Accessed: 20-Dec-2020].

[45] “G. P. Agrawal, Nonlinear Fiber Optics, Academic Press,... - Google Scholar.” [Online]. Available:

https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=G.+P.+Agrawal%2C+Nonlinear+Fiber+Optics%2C+Academic+Press%2C+Amsterdam+%282007%29.&btnG=. [Accessed: 20-Dec-2020].

[46] D. Marpaung, B. Morrison, R. Pant, and B. J. Eggleton, "Frequency agile microwave photonic notch filter with anomalously high stopband rejection," *Opt. Lett.*, vol. 38, no. 21, p. 4300, Nov. 2013.

[47] S. Hu, L. Li, X. Yi, and F. Teng, "Tunable dual-passband microwave photonic filter based on stimulated Brillouin scattering," *IEEE Photonics Technol. Lett.*, vol. 29, no. 3, pp. 330–333, Feb. 2017.

[48] H. Y. Jiang, D. Marpaung, M. Pagani, L. Yan, and B. J. Eggleton, "Multiple frequencies microwave measurement using a tunable Brillouin RF photonic filter," in *2015 11th Conference on Lasers and Electro-Optics Pacific Rim, CLEO-PR 2015*, 2016, vol. 4.

[49] J. Sancho *et al.*, "Tunable and reconfigurable multi-tap microwave photonic filter based on dynamic Brillouin gratings in fibers," *Opt. Express*, vol. 20, no. 6, p. 6157, Mar. 2012.

[50] I. Aryanfar *et al.*, "Reconfigurable microwave bandstop filter based on stimulated Brillouin scattering," in *2016 IEEE International Topical Meeting on Microwave Photonics, MWP 2016*, 2016, pp. 118–121.

[51] A. R. Chraplyvy, "Limitations on Lightwave Communications Imposed by Optical-Fiber Nonlinearities," *J. Light. Technol.*, vol. 8, no. 10, pp. 1548–1557, 1990.

[52] K. J. Blow and D. Wood, "Theoretical Description of Transient Stimulated Raman Scattering in Optical Fibers," *IEEE J. Quantum Electron.*, vol. 25, no. 12, pp. 2665–

2673, 1989.

[53] R. L. Carman, F. Shimizu, C. S. Wang, and N. Bloembergen, “Theory of stokes pulse shapes in transient stimulated Raman scattering,” *Phys. Rev. A*, vol. 2, no. 1, pp. 60–72, Jul. 1970.

[54] G. P. Agrawal, “Stimulated Raman scattering,” in *Nonlinear Fiber Optics*, Elsevier, 2019, pp. 297–354.

[55] “Cross-phase modulation - Wikipedia.” [Online]. Available: https://en.wikipedia.org/wiki/Cross-phase_modulation. [Accessed: 16-Sep-2020].

[56] M. N. Islam, J. R. Simpson, H. T. Shang, L. F. Mollenauer, and R. H. Stolen, “Cross-phase modulation in optical fibers,” *Opt. Lett.*, vol. 12, no. 8, p. 625, Aug. 1987.

[57] R. W. Tkach, A. R. Chraplyvy, F. Forghieri, A. H. Gnauck, and R. M. Derosier, “Four-Photon Mixing and High-Speed WDM Systems,” *J. Light. Technol.*, vol. 13, no. 5, pp. 841–849, 1995.

[58] R. L. Carman, R. Y. Chiao, and P. L. Kelley, “Observation of degenerate stimulated four-photon interaction and four-wave parametric amplification,” *Phys. Rev. Lett.*, vol. 17, no. 26, pp. 1281–1283, 1966.

[59] B. Fan, Z. Duan, L. Zhou, C. Yuan, Z. Y. Ou, and W. Zhang, “Generation of a single-photon source via a four-wave mixing process in a cavity,” *Phys. Rev. A - At. Mol. Opt. Phys.*, vol. 80, no. 6, p. 063809, Dec. 2009.

[60] W. Zou, X. Long, and J. Chen, “Brillouin Scattering in Optical Fibers and Its Application to Distributed Sensors,” in *Advances in Optical Fiber Technology: Fundamental Optical Phenomena and Applications*, InTech, 2015.

[61] L. Brillouin, “Diffusion de la lumière et des rayons X par un corps transparent

homogène," *Ann. Phys. (Paris).*, vol. 9, no. 17, pp. 88–122, Apr. 1922.

[62] "(No Title)." [Online]. Available: https://pdfs.semanticscholar.org/2a25/c54ac14b91579c67e59f0d0e20bdfb69f448.pdf. [Accessed: 23-Dec-2019].

[63] M. J. et. al. Damzen, *Stimulated Brillouin Scattering Fundamentals and Applications*. Bristol: IOP Publisher Ltd 2003, 2003.

[64] M. J. Damzen, *Stimulated Brillouin Scattering : M. J. Damzen : 9780750308700*. .

[65] E. P. Ippen and R. H. Stolen, "Stimulated Brillouin scattering in optical fibers," *Appl. Phys. Lett.*, vol. 539, no. 1972, pp. 25–28, Dec. 1972.

[66] M. J. et. al. Damzen, *Stimulated Brillouin scattering fundamental and application*. .

[67] "Brillouin - an overview | ScienceDirect Topics." [Online]. Available: https://www.sciencedirect.com/topics/engineering/brillouin. [Accessed: 31-Jan-2020].

[68] H. Yuan, Y. Wang, C. Zhu, Z. Zheng, and Z. Lu, "Investigation of sub-phonon lifetime pulse amplification in active frequency matching stimulated Brillouin scattering," *Opt. Express*, vol. 27, no. 12, p. 16661, Jun. 2019.

[69] G. C. Debney, R. P. Kerr, and A. Schild, "Solutions of the Einstein and Einstein-Maxwell equations," *J. Math. Phys.*, vol. 10, no. 10, pp. 1842–1854, Oct. 1969.

[70] K. Sanders, C. Dappiaggi, and T. P. Hack, "Electromagnetism, Local Covariance, the Aharonov-Bohm Effect and Gauss' Law," *Commun. Math. Phys.*, vol. 328, no. 2, pp. 625–667, Mar. 2014.

[71] "Gauss' Law for Magnetic Fields." [Online]. Available: http://www.maxwells-equations.com/gauss/magnetism.php. [Accessed: 02-Sep-2020].

[72] "Maxwell's Equations: Faraday's Law." [Online]. Available: http://www.maxwells-equations.com/faraday/faradays-law.php. [Accessed: 03-Sep-2020].

[73] "Maxwell's Equations: Ampere's Law." [Online]. Available: http://www.maxwells-equations.com/ampere/amperes-law.php. [Accessed: 03-Sep-2020].

[74] R. G. Harrison and D. Yu, "Stimulated Brillouin scattering 1 Chapter 0.1 STIMULATED BRILLOUIN SCATTERING NONLINEAR LIGHT SCATTERING Theory and experiment Contents 0.1.1 Stimulated Brillouin scattering."

[75] R. W. Boyd, J. J. Maki, and J. E. Sipe, "Local field effects in enhancing the nonlinear susceptibility of optical materials," in *Nonlinear Optics*, Elsevier, 1992, pp. 63–76.

[76] Y. R. Shen, Shen, and Y. R., "The principles of nonlinear optics," *wi*, 1984.

[77] I. P. Batra, R. H. Enns, and D. Pohl, "Stimulated thermal scattering of light," *Phys. Status Solidi*, vol. 48, no. 1, pp. 11–63, Nov. 1971.

[78] Ivan P. Kaminow and Thomas L. Koch, *Optical Fiber Telecommunications IIIA*. 1997.

[79] M. F. Ferreira, J. F. Rocha, and J. L. Pinto, "Analysis of the gain and noise characteristics of fibre Brillouin amplifiers," *Opt. Quantum Electron.*, vol. 26, no. 1, pp. 35–44, Jan. 1994.

[80] A. El-Sherif, T. K.-O. letters, and undefined 2003, "High-peak-power operation of a Q-switched Tm3+-doped silica fiber laser operating near 2 μm," *osapublishing.org*, 2003.

[81] M. Merklein *et al.*, "Stimulated brillouin scattering in photonic integrated circuits: Novel applications and devices," *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 2, Mar. 2016.

[82] Z. Bai *et al.*, “Stimulated Brillouin scattering materials, experimental design and applications: A review,” *Opt. Mater. (Amst).*, vol. 75, pp. 626–645, Jan. 2018.

[83] T. Omatsu *et al.*, “The Current Trends in SBS and phase conjugation,” *Laser Part. Beams*, vol. 30, no. 1, pp. 117–174, Mar. 2012.

[84] X. Bao and L. Chen, “Recent Progress in Distributed Fiber Optic Sensors,” *Sensors*, vol. 12, no. 7, pp. 8601–8639, Jun. 2012.

[85] R. Pant, D. Marpaung, I. V. Kabakova, B. Morrison, C. G. Poulton, and B. J. Eggleton, “On-chip stimulated Brillouin Scattering for microwave signal processing and generation,” *Laser Photon. Rev.*, vol. 8, no. 5, pp. 653–666, Sep. 2014.

[86] W. Zhang and R. A. Minasian, “Widely tunable single-passband microwave photonic filter based on stimulated Brillouin scattering,” *IEEE Photonics Technol. Lett.*, vol. 23, no. 23, pp. 1775–1777, 2011.

[87] Y. M. Chang and J. H. Lee, “High-Q, tunable, photonic microwave single passband filter based on stimulated Brillouin scattering and fiber Bragg grating filtering,” *Opt. Commun.*, vol. 281, no. 20, pp. 5146–5150, Oct. 2008.

[88] “Photonic microwave filter with single bandpass response based on Brillouin processing and SSB-SC - IEEE Conference Publication.” [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5342708. [Accessed: 07-Sep-2020].

[89] A. Loayssa, J. Capmany, M. Sagues, and J. Mora, “Demonstration of incoherent microwave photonic filters with all-optical complex coefficients,” *IEEE Photonics Technol. Lett.*, vol. 18, no. 16, pp. 1744–1746, Aug. 2006.

[90] B. Vidal, M. A. Piqueras, and J. Martí, “Tunable and reconfigurable photonic microwave filter based on stimulated Brillouin scattering,” *Opt. Lett.*, vol. 32, no. 1, p.

23, Jan. 2007.

[91] W. Li, N. H. Zhu, and L. X. Wang, “Brillouin-assisted microwave frequency measurement with adjustable measurement range and resolution,” *Opt. Lett.*, vol. 37, no. 2, p. 166, Jan. 2012.

[92] J. Li *et al.*, “Photonic-assisted microwave frequency measurement with higher resolution and tunable range,” *Opt. Lett.*, vol. 34, no. 6, p. 743, Mar. 2009.

[93] M. Ganjali, S. Esmail Hosseini, K. Jamshidi, and D. Plettemeier, “Theoretical investigation of a photonic-assisted instantaneous frequency measurement with a tunable measurement range and resolution by adjusting the chirp parameter of an optical intensity modulator,” *Appl. Opt.*, vol. 58, no. 36, p. 9990, Dec. 2019.

[94] “High Resolution Optical Spectrum Analyzer - BOSA - Aragon Photonics Labs.” [Online]. Available: https://aragonphotonics.com/bosa-optical-spectrum-analyzer/. [Accessed: 10-Sep-2020].

[95] M. Alom, S. Haxha, and A. Aggoun, “Photonic mixer incorporating all-optical microwave frequency generator based on stimulated brillouin scattering using single laser source,” *IEEE Access*, vol. 8, pp. 37045–37051, 2020.

[96] R. Pant, D. Marpaung, I. V. Kabakova, B. Morrison, C. G. Poulton, and B. J. Eggleton, “On-chip stimulated Brillouin Scattering for microwave signal processing and generation,” *Laser Photon. Rev.*, vol. 8, no. 5, pp. 653–666, Sep. 2014.

[97] T. Borowski, M. Pasternak, and J. Pietrasinski, “The photonic radar: the situation today and the prospects for the future,” in *Radioelectronic Systems Conference 2019*, 2020, vol. 11442, no. 11, p. 52.

[98] Y. Peled, M. Tur, and A. Zadok, “Generation and detection of ultra-wideband

waveforms using stimulated Brillouin scattering amplified spontaneous emission," *IEEE Photonics Technol. Lett.*, vol. 22, no. 22, pp. 1692–1694, 2010.

[99] A. Byrnes *et al.*, "Photonic chip based tunable and reconfigurable narrowband microwave photonic filter using stimulated Brillouin scattering," *Opt. Express*, vol. 20, no. 17, p. 18836, Aug. 2012.

[100] T. F. S. Büttner *et al.*, "Phase-locked, chip-based, cascaded stimulated Brillouin scattering," *Optica*, vol. 1, no. 5, p. 311, Nov. 2014.

[101] W. Zou, Z. He, and K. Hotate, "Tunable fiber-optic delay line based on stimulated Brillouin scattering," *Appl. Phys. Express*, vol. 3, no. 1, p. 012501, Jan. 2010.

[102] H. Ju, L. Ren, X. Lin, J. Liang, and C. Ma, "Wide-range continuously-tunable slow-light delay line based on stimulated brillouin scattering," *IEEE Photonics Technol. Lett.*, vol. 25, no. 19, pp. 1920–1923, 2013.

[103] A. Loayssa and F. J. Lahoz, "Broad-band RF photonic phase shifter based on stimulated brillouin scattering and single-sideband modulation," *IEEE Photonics Technol. Lett.*, vol. 18, no. 1, pp. 208–210, 2006.

[104] M. Pagani, D. Marpaung, D. Y. Choi, S. J. Madden, B. Luther-Davies, and B. J. Eggleton, "Tunable microwave photonic phase shifter using on-chip stimulated Brillouin scattering," in *Conference on Lasers and Electro-Optics Europe - Technical Digest*, 2015, vol. 2015-Augus, no. 23, pp. 28810–28818.

[105] "Optical beamforming for phased array antennas using stimulated Brillouin Scattering - IEEE Conference Publication." [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5342686. [Accessed: 17-Sep-2020].

[106] M. Tur, "True time delay photonic beamforming: A review," in *2009 IEEE*

International Conference on Microwaves, Communications, Antennas and Electronics Systems, COMCAS 2009, 2009.

[107] W. Zhang and R. A. Minasian, "Ultrawide tunable microwave photonic notch filter based on stimulated brillouin scattering," *IEEE Photonics Technol. Lett.*, vol. 24, no. 14, pp. 1182–1184, 2012.

[108] B. Morrison *et al.*, "Tunable microwave photonic notch filter using on-chip stimulated Brillouin scattering," *Opt. Commun.*, vol. 313, pp. 85–89, Feb. 2014.

[109] D. Marpaung *et al.*, "Microwave photonic notch filter using on-chip stimulated Brillouin scattering," in *Pacific Rim Conference on Lasers and Electro-Optics, CLEO - Technical Digest*, 2013.

[110] S. Zheng, S. Ge, X. Zhang, H. Chi, and X. Jin, "High-resolution multiple microwave frequency measurement based on stimulated brillouin scattering," *IEEE Photonics Technol. Lett.*, vol. 24, no. 13, pp. 1115–1117, 2012.

[111] "OSA | Optical Spectrum Analyzer with Femtometer Resolution." [Online]. Available: https://www.osapublishing.org/abstract.cfm?uri=CLEO-2006-CMU1. [Accessed: 17-Sep-2020].

[112] "High Resolution Optical Spectrum Analyzer - BOSA - Aragon Photonics Labs." [Online]. Available: https://aragonphotonics.com/bosa-optical-spectrum-analyzer/. [Accessed: 17-Sep-2020].

[113] S. Azizan, M. Mohamad Shahimin, and S. A. Z. Murad, "Simulation of distributed fibre optic sensor for temperature and stress sensing," in *2011 IEEE Colloquium on Humanities, Science and Engineering, CHUSER 2011*, 2011, pp. 449–453.

[114] L. Wang, B. Zhou, C. Shu, and S. He, "Stimulated Brillouin scattering slow-light-

based fiber-optic temperature sensor," *Opt. Lett.*, vol. 36, no. 3, p. 427, Feb. 2011.

[115] M. Lee, Y. Zhu, D. J. Gauthier, M. E. Gehm, and M. A. Neifeld, "Information-theoretic analysis of a stimulated-Brillouin-scattering-based slow-light system," *Appl. Opt.*, vol. 50, no. 32, pp. 6063–6072, Nov. 2011.

[116] "The Development of Brillouin Scattering Distributed Optic Fiber Sensor--《Journal of Test and Measurement Technology》2002年02期." [Online]. Available: http://en.cnki.com.cn/Article_en/CJFDTotal-CSJS200202002.htm. [Accessed: 18-Sep-2020].

[117] H. Kee, G. Lees, T. N.-O. letters, and undefined 2000, "All-fiber system for simultaneous interrogation of distributed strain and temperature sensing by spontaneous Brillouin scattering," *osapublishing.org*.

[118] K. Hotate, M. T.-I. P. T. Letters, and undefined 2002, "Distributed fiber Brillouin strain sensing with 1-cm spatial resolution by correlation-based continuous-wave technique," *ieeexplore.ieee.org*.

[119] M. González-Herráez, K. Y. Song, and L. Thévenaz, "Optically controlled slow and fast light in optical fibers using stimulated Brillouin scattering," *Appl. Phys. Lett.*, vol. 87, no. 8, p. 081113, Aug. 2005.

[120] S. Chin *et al.*, "Broadband true time delay for microwave signal processing, using slow light based on stimulated Brillouin scattering in optical fibers," *Opt. Express*, vol. 18, no. 21, p. 22599, Oct. 2010.

[121] L. Thévenaz, "Slow and fast light in optical fibres," *Nature Photonics*, vol. 2, no. 8. Nature Publishing Group, pp. 474–481, Aug-2008.

[122] T. Schneider, M. Junker, and K.-U. Lauterbach, "Theoretical and experimental

investigation of Brillouin scattering for the generation of millimeter waves," *J. Opt. Soc. Am. B*, vol. 23, no. 6, p. 1012, Jun. 2006.

[123] A. W. Brown, J. P. Smith, X. Bao, M. D. Demerchant, and T. Bremner, "Brillouin Scattering Based Distributed Sensors for Structural Applications," *J. Intell. Mater. Syst. Struct.*, vol. 10, no. 4, pp. 340–349, Apr. 1999.

[124] K. Xu *et al.*, "Microwave photonics: radio-over-fiber links, systems, and applications [Invited]," *Photonics Res.*, vol. 2, no. 4, p. B54, Aug. 2014.

[125] D. Pérez, I. Gasulla, and J. Capmany, "Toward Programmable Microwave Photonics Processors," *J. Light. Technol.*, vol. 36, no. 2, pp. 519–532, Jan. 2018.

[126] A. Choudhary *et al.*, "Advanced Integrated Microwave Signal Processing with Giant On-Chip Brillouin Gain," *J. Light. Technol.*, vol. 35, no. 4, pp. 846–854, Feb. 2017.

[127] R. A. Minasian, "Photonic signal processing of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 832–846, Feb. 2006.

[128] F. Paloi, S. Haxha, T. N. Mirza, and M. S. Alom, "Microwave Photonic Downconversion with Improved Conversion Efficiency and SFDR," *IEEE Access*, vol. 6, pp. 8089–8097, Jan. 2018.

[129] E. H. W. Chan and R. A. Minasian, "Microwave photonic downconverter with high conversion efficiency," *J. Light. Technol.*, vol. 30, no. 23, pp. 3580–3585, 2012.

[130] G. A.-L. N. in Physics and undefined 2000, "Nonlinear Science at the Dawn of the 21st Century."

[131] X. S. Yao, "Brillouin selective sideband amplification of microwave photonic signals," *IEEE Photonics Technol. Lett.*, vol. 10, no. 1, pp. 138–140, Jan. 1998.

[132] C. S. C. S. Park, C. G. Lee, and C. S. C. S. Park, “Photonic frequency upconversion based on stimulated Brillouin scattering,” *IEEE Photonics Technol. Lett.*, vol. 19, no. 10, pp. 777–779, May 2007.

[133] Y. Shen, X. Zhang, and K. Chen, “Optical single sideband modulation of 11-GHz RoF system using stimulated brillouin scattering,” *IEEE Photonics Technol. Lett.*, vol. 17, no. 6, pp. 1277–1279, Jun. 2005.

[134] E. H. W. Chan and R. A. Minasian, “High conversion efficiency microwave photonic mixer based on stimulated Brillouin scattering carrier suppression technique,” *Opt. Lett.*, vol. 38, no. 24, p. 5292, Dec. 2013.

[135] X. S. Yao, “High-quality microwave signal generation by use of Brillouin scattering in optical fibers,” *Opt. Lett.*, vol. 22, no. 17, p. 1329, Sep. 1997.

[136] C. Zhang *et al.*, “Tunable DC-60 GHz RF Generation Utilizing a Dual-Loop Optoelectronic Oscillator Based on Stimulated Brillouin Scattering,” *J. Light. Technol. Vol. 33, Issue 13, pp. 2707-2715*, vol. 33, no. 13, pp. 2707–2715, Jul. 2015.

[137] H. Peng *et al.*, “Wideband tunable optoelectronic oscillator based on the deamplification of stimulated Brillouin scattering,” *Opt. Express*, vol. 25, no. 9, p. 10287, May 2017.

[138] X. Xie, H. Peng, and T. Sun, “Tunable DC-60 GHz RF generation based on a dual loop Brillouin optoelectronic oscillator Tunable DC-60 G Brillo,” 2014.

[139] Y. G. Shee *et al.*, “All-optical generation of a 21 GHz microwave carrier by incorporating a double-Brillouin frequency shifter,” *Opt. Lett.*, vol. 35, no. 9, p. 1461, May 2010.

[140] Y. Shen, X. Zhang, K. Chen, X. Zhang, and Y. Shen, “All-Optical Generation of

Microwave and Millimeter Wave Using a Two-Frequency Bragg Grating-Based Brillouin Fiber Laser," *J. Light. Technol. Vol. 23, Issue 5, pp. 1860-*, vol. 23, no. 5, p. 1860, May 2005.

[141] R. G. Walker, N. I. Cameron, Y. Zhou, and S. J. Clements, "Optimized gallium arsenide modulators for advanced modulation formats," *IEEE J. Sel. Top. Quantum Electron.*, vol. 19, no. 6, 2013.

[142] T. Schneider, M. Junker, and K.-U. Lauterbach, "Theoretical and experimental investigation of Brillouin scattering for the generation of millimeter waves," *J. Opt. Soc. Am. B*, vol. 23, no. 6, p. 1012, Jun. 2006.

[143] J. C. Fan, "Dynamic range requirements for microcellular personal communication systems using analog fiber-optic links," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8 PART 2, pp. 1390–1397, 1997.

[144] G. Gabrielli, R. A. Gualano, E. B. Aureliano Imparato, C. Mitrano, M. Pietrobono, and V. Cirella, "Spurious-free Ultra-wideband Downconveter in 3U Size for EW System," in *2019 PhotonIcs & Electromagnetics Research Symposium - Spring (PIERS-Spring)*, 2019, pp. 1695–1699.

[145] "Understanding Dynamic Range | Microwaves & RF." [Online]. Available: https://www.mwrf.com/technologies/test-measurement/article/21846555/understanding-dynamic-range. [Accessed: 07-Mar-2020].

[146] Z. Tang, Y. Li, J. Yao, and S. Pan, "Photonics-Based Microwave Frequency Mixing: Methodology and Applications," *Laser and Photonics Reviews*, vol. 14, no. 1. Wiley-VCH Verlag, p. 1800350, 01-Jan-2020.

[147] X. Chen, W. Li, and J. Yao, “Microwave photonic link with improved dynamic range using a polarization modulator,” *IEEE Photonics Technol. Lett.*, vol. 25, no. 14, pp. 1373–1376, 2013.

[148] H. Emami and M. Ashourian, “Improved dynamic range microwave photonic instantaneous frequency measurement based on four-wave mixing,” *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 10, pp. 2462–2470, 2014.

[149] J. A. MacDonald, M. V. Kubak, and A. Katz, “Wideband dynamic range improvement of microwave photonic links,” in *2005 IEEE Conference - Avionics Fiber-Optics and Photonics, AVFOP 2005*, 2005, vol. 2005, pp. 67–68.

[150] W. Jiang *et al.*, “A linearization analog photonic link with high third-order intermodulation distortion suppression based on dual-parallel Mach-Zehnder modulator,” *IEEE Photonics J.*, vol. 7, no. 3, Jun. 2015.

[151] B. M. Haas and T. E. Murphy, “Linearized downconverting microwave photonic link using dual-wavelength phase modulation and optical filtering,” *IEEE Photonics J.*, vol. 3, no. 1, 2011.

[152] T. R. Clark, M. Currie, and P. J. Matthews, “Digitally linearized wide-band photonic link,” *J. Light. Technol.*, vol. 19, no. 2, pp. 172–179, Feb. 2001.

[153] P. Le and E. R. Février, “Generation and application of dynamic gratings in optical fibers using stimulated Brillouin scattering THÈSE N O 5615 (2013) ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE Nikolay PRIMEROv,” 2013.

[154] N. PRIMERO, “Generation and application of dynamic gratings in optical fibers using stimulated Brillouin scattering,” vol. 5615, 2013.

[155] E. H. W. W. Chan and R. A. Minasian, “Microwave Photonic Downconverter with

High Conversion Efficiency," *J. Light. Technol.*, vol. 30, no. 23, pp. 3580–3585, Dec. 2012.

[156] G. Agrawal, "Nonlinear fiber optics: quantum electronics—principles and applications," 1989.

[157] "US6535328B2 - Methods and devices based on brillouin selective sideband amplification - Google Patents." [Online]. Available: https://patents.google.com/patent/US6535328B2/en. [Accessed: 24-Sep-2020].

[158] C. G. Atkins, D. Cotter, D. W. Smith, and R. Wyatt, "Application Of Brillouin Amplification In Coherent Optical Transmission," *Electron. Lett.*, vol. 22, no. 10, pp. 556–558, 1986.

[159] J. A. Arnaud, "R-5—Enhancement of Optical Receiver Sensitivities by Amplification of the Carrier," *IEEE J. Quantum Electron.*, vol. 4, no. 11, pp. 893–899, 1968.