SBS-based Tunable Microwave Photonic Notch Filter and Amplifier Simultaneously with Enhanced Gain, Bandwidth, and Polarisation Control up to 50 GHz

Mian Ali and Shyqyri Haxha, Senior *Member, IEEE*

***Abstract*— Stimulated Brillouin Scattering (SBS) based filters can provide high gain, narrow bandwidth, and wideband tunability, which are critical for modern radio frequency systems. However, it is important to optimise all performance parameters to obtain stable response over wideband along with high gain. We present a novel SBS-based Tuneable Microwave Photonics Notch Filter and Amplifier (TMWPNFA) configuration that can perform notch filtering, selective amplification or both simultaneously by exploiting additional Brillouin gain modes and using both SBS stokes and anti-stokes in single-mode fibre. The TMWPNFA amplification and notch suppression are shown for maximum of 50 GHz in Radio Domain, which is the highest reported tunability to our knowledge. The TMWPNFA exhibits high gain of ≃35dB by employing Radio Frequency Amplifier. The TMWPNFA achieves SBS gains from 24 to 4 dB over the range. The suppression achieved by TMWPNFA ranges from 12 to 3 dB. We demonstrated the SBS pump's RF Mixing approach for increasing the -3dB bandwidth of TMWPNFA to 35 MHz, resulting in greater separation of the amplification and suppression bands. The TMWPNFA phase noise distortion caused by SBS is measured to be < -8.6dBc/Hz at 125 kHz Spacing. The filter achieved sharp -3 dB bandwidth of 20 MHz and Q factor of 200 to 2500. The Degree of Polarisation of the SBS pump is shown to be the source of 6 dB gain control. It is shown that additional sound modes produced by SBS, separated by ≈2 x Bandwidth of SBS can be used for notch filtering while simultaneously achieving selective amplification. The proposed 50GHz TMWPNFA would provide unique benefits for satellite, aerospace and beyond communication technologies.**

***Index Terms*—Microwave Photonics, Tuneable filters, Stimulated Brillouin Scattering, Tuneable Microwave photonics filters, Optical filters**

I. INTRODUCTION

With the advancement in technology and the requirement of high data rates, the need for complex and capable communication systems is increasing. Traditional microwave communication systems has many limitations, which is where microwave photonics come into play [1]. Filters and amplifiers play integral part in any communication system. Microwave Photonic filters (MWPF) have many advantages over traditional microwave filters like configurability, high Q, tunability and immunity to electromagnetic noise. MWPF will play a significant role in aerospace satellite communication, defense, 6G and beyond. Electronic filters such as Kalman have explored and reported for measurement applications [2]. MWPF can help reduce size and power consumption compared to traditional filters. These MWPF have attained the attention since size and power constraints are critical for aerospace and satellite application. At the same time MWFP has shown to work up to 10's of GHz covering almost all major satellite and Radar bands. There are various commercial MWPF filters. In case of Fiber Bragg Grating, they offer a wide bandwidth of few GHz. The Mach Zehnder Interferometer and Fabry-Perot Filters have periodic passbands restricting desired band selections [3].

A tunable single bandpass MWPF based on a Fabry-Perot semiconductor optical amplifier is demonstrated in [4]. The MWPF has a tuneability of 40 GHz and bandwidth from 99 MHz to 18.3 GHz. However, the reported [4] filter exhibits a low Q, wider pass band, and extreme environmental sensitivity. Stimulated Brillouin scattering (SBS) is caused by thermal fluctuation in a material when light passes through it. It is one of the main characteristics to decide the upper optical power input limit in a communication system. MWPFs based on SBS provide many advantages over other photonic filters such as tuneability, high Q, and narrow bandwidth [5]. Broadband measurements are also performed using SBS's filter-based configurations that use Mach Zehnder Modulator [6]. Photonics-based sensors that utilize Brillouin for measurements [7]. These SBS-based MWPFs exhibit high gain and narrow bandwidth in the MHz range [8-9]. MWPFs based on SBS using Single Sideband (SSB) or Double Sideband (DSB) with suppressed carrier modulation have shown drift bias problems [8-9]. However, this does not affect the RF frequency or line width, and the drift problem can be solved by employing the bias controller with the modulator. SBS-based MWPF with dual-band and fixed frequency interval of 2.434 GHz is demonstrated [10]. The filter has shown a gain of 20dBm. A technique to generate a tunable SBS pump using fixed a laser is presented [11]. This filter has been shown to select and amplify phase-modulated signals using a tunable pump generated by an intensity modulator. An efficient microwave photonic filter with large out-of-band rejection and low loss has been demonstrated [12]. SBS-based MWPF are reported to have low loss, immunity to electromagnetic interference, potential tunability, and configurability [13]. A bandwidth-reconfigurable tunable microwave photonic filter based on SBS is presented [14]. The bandwidth varies using vectoral modulating pumps resulting in bandwidth tuneability from 20 to 500 MHz. However, the frequency tuneability is only demonstrated up to 20GHz. A

Mian Ali is with the Microwave Photonics and Sensors (MPS) research group, Royal Holloway, University of London, TW20 0EX (e-mail: mian.ali.2019@live.rhul.ac.uk).

Shyqyri Haxha is head of MPS research group at Royal Holloway, University of London, TW20 0EX (email: Shyqyri.Haxha@rhul.ac.uk)

narrowband single-pass filter is demonstrated using multiple pumps to generate a single wide narrowband [15]. A very high Q factor of 2412 is achieved. However, this narrow band produces adjacent amplification bands that can be tuned using bandwidth control of loss bands. Another area of interest for SBS-based Microwave photonics filters is size and optical fiber length reduction. An experimental study and demonstration of arsenic trisulfide (As_2S_3) has shown a suppression of 23 dB [16], but these chips are difficult to produce and not commercially available. An MWPF which utilizes a tunable laser to generate a widely tunable SBS pump is reported in [17]. The reported gain was 35 dB, and tuning range was demonstrated up to 20 GHz. An ultra-narrow 114 Hz SBS filter with rejection ratio of 20dB is shown. The filter has achieved a tuneability of 20 GHz [18].

This research presents a Tunable Microwave Photonics Notch Filter and Amplifier (TMWPNFA) with an operating principle to perform amplification or notch filtering based on pure Brillouin modes in an optical fiber medium. Brillouin modes enable the filter to be utilized as Tunable Microwave Photonic Amplifier which amplifies signals of interest (SOI). Simultaneously, the same filter can be employed as a notch filter, suppressing any undesirable signals in the channel. In a recent paper [19], we described an SBS-based tunable microwave photonic filter. It can select and amplify signals with the highest Q of 1240 and a maximum gain of 69 dB [19]. The setup includes a tunable laser pump, an RF mixer and an RF amplifier. The filter is demonstrated up to 32GHz tunable frequency range. It is found that the use of tunable laser pump affects the phase noise figure of amplified signal due to the wavelength instability of lasers. However, in this study, we employed a fixed laser-based SBS pump that ensures the phase noise figure of the amplified signal is within acceptable limits. The findings of the phase noise measurements are given and analyzed. This paper also discusses the impact of pump polarisation. The operating principle of the proposed filter is based on the fact that SBS excites multiple modes in optical fiber or in other optical waveguide mediums [11]. Three modes dominate in single mode fiber. In this paper, we have used the properties of those modes for selective amplification and notch filtering. The first and the dominating mode is used for amplification while the 2nd and 3rd Brillouin modes are exploited for suppression.

A SBS-based filter with tunable range of 40 GHz that can perform amplification and filtering simultaneously was presented [12]. However, this was accomplished using SBS amplification and changing modulator bias points. However, we have proposed a novel SBS-based TMWPNFA that can amplify and suppress without reconfiguring the experimental setup i.e., changing the bias point of modulator [12]. This SBS-based approach is novel compared to many SBS-based filters that perform suppression/notch filtering by modifying the RF Mixing/ Modulation of the Pump. The proposed experimental setup can perform selective amplification, notch filtering, or both. The operation of the filter and tuning equations are described in detail. We have also shown unique filter bandwidth control using the RF Mixing technique. Another unique and important contribution is quantifying the proposed system's phase noise figure and polarisation control. This proposed system can provide significant benefits for optical subsystems required for all-optical signal processing, like up-conversion/down-conversion for measurement application [20], intermodulation distortion products [21] and future aerospace technologies[22]. The proposed filter can lay the foundation or be part of communication systems well over 50 GHz to THz communication system proposed [23], it can select or suppress noise or SOI in the THz range; while only limited by component availability such as Mach Zehnder Modulator, photodetectors and RF sources. The recent research also focuses on all Brillouin processing [24], where this work can help design such systems for high frequency and high data rate communications systems. This paper presents a unique configuration of TMWPNFA along with the operating principle that simultaneously exploits SBS for selective gain amplification and notch filtering. Based on the requirements, the proposed design employs an RF mixing approach, which can enhance and reduce the bandwidth of the TMWPNFA amplification and suppression regions. The proposed system design in this study may employ many independent pumps that can be expanded to select or suppress various signals separately. Previously published research [11, 25] claims that the stokes are used only for amplification while the anti-stokes for suppression. However, it is shown in this work that both stokes and anti-stokes can be applied for amplification and filtering. Also, the proximity of amplification and suppression bands also presents challenges while deploying SBS-based filters in the field for wideband amplification. These challenges and possible resolutions are presented. The TMWPFA capable of amplifying and suppressing frequencies up to 50 GHz is reported by exploiting the presented principle. To the best of our knowledge, this is the highest reported tunability achieved by an SBS-based filter and was realized by exploiting both stokes and anti-stokes for amplification and filtering. This technique used Mach Zehnder Intensity Modulator (MZIM) with an operating range of 40 GHz to generate an SBS pump that can amplify signals up to 51 GHz. As far as we are aware, this is the first time a relationship and working principle of SBS stokes and anti-stokes is shown as both notch filter and selective amplifier. This opens a door for future experimental configurations that utilize this combination to suppress noise signals such as harmonics while still amplifying Signal of Interest (SOI). It can be performed by employing multiple pump signals. The use of a Radio Frequency Amplifier is also presented. This results in an additional gain. Lastly, the pump polarisation and noise figure for amplification are explored. The high Q, narrow bandwidth, dual operation of filtering, and amplification makes this configuration very attractive for applications requiring precise selection, suppression, and amplification such as aerospace application and advanced communication systems. The main advantages of the proposed TMWFPA are widely tunable range, notch filtrating, high gain, selective amplification, low phase noise figure, and gain control. Thus, this configuration can help selectively amplify signals and measure SOI in optical channels.

II. Setup and Operating Principle

The operating principle of TMWFPA is based on SBS gain modes spectra in SMF. The Experimental configuration of TMWPNFA is illustrated in Fig. 1. The pump signal generates the stokes and anti-stokes. Either stokes or anti-stokes can amplify and/ or filter the RF SOI. The laser output (Gooch & Housego EM4) is split using 50/50 Fiber coupler (TW1550R5F1) 1x2 into two fiber paths. One path generates SBS's pump signal, and the other path for the SOI/ probe signal. The probe signal is produced by phase modulator (Thorlabs's LN27S). The pump signal is produced by Thorlabs's LN05S-FC MZIM. While DC bias is controlled using DC bench power supply. After which an exponential increase in Brillouin scattering happens, the Brillouin threshold is measured to be 12 dBm for this system. The MZIM modulates the carrier laser using an RF signal. The RF input of MZIM is fed from the RF source . The TMWPNFA is tuned to achieve amplification and/or filtering by controlling this RF source. The pump's carrier is suppressed using the DC bias control in MZIM. It prevents the pump's carrier signal from producing its own SBS. Double Side Band modulation- suppressed carrier (DS-SC) signal produces the suppression and amplification bands. An EDFA is used to amplify the DS-SC signal. This amplification allows the DS-SC to break the Brillouin threshold and produce SBS in SMF. The tuning is achieved by tuning the pump signal. The SBS produced is 10.816 GHz apart from the pump's DS-CS signal, called Brillouin shift. The RF response of the proposed TMWPNFA is shown up to 50 GHz due to the limitation of components utilized. The response is only limited due to the RF bandwidth of components. Otherwise, this configuration can work even beyond 100 GHz, limited only by photonic components bandwidth.

By deploying Radio Frequency Amplifier (RFA) (HP 8349A) after SBS amplification, an additional 20 dB gain is induced in amplified SOI. RFA should be deployed after SBS amplification to achieve this additional gain. The probe signal is amplified/ filtered by SBS when its wavelength matches the Brillouin signal generated by the pump. The Phase Shifter (PS) can be deployed as well after the RF source in the case of the Dual Parallel Dual Drive Mach Zehnder Modulator (DPDDMZM) to generate phase modulation [19]. However, for Intensity Modulation (IM) or Phase Modulation (PM), no PS is required. The modulator's output is passed through an Thorlabs's IOH- 1550APC Optical Isolator (OS). In this case, the OS protects the modulator by blocking any light travelling towards the modulator output, mainly the pump signal. The probe signal enters the SMF via the isolator. The pump signal enters the SMF from the other end of SMF. Pump and Probe signals travel in opposite direction in the SMF. The amplified probe signal exits the circulator at point 3. The Photodetector

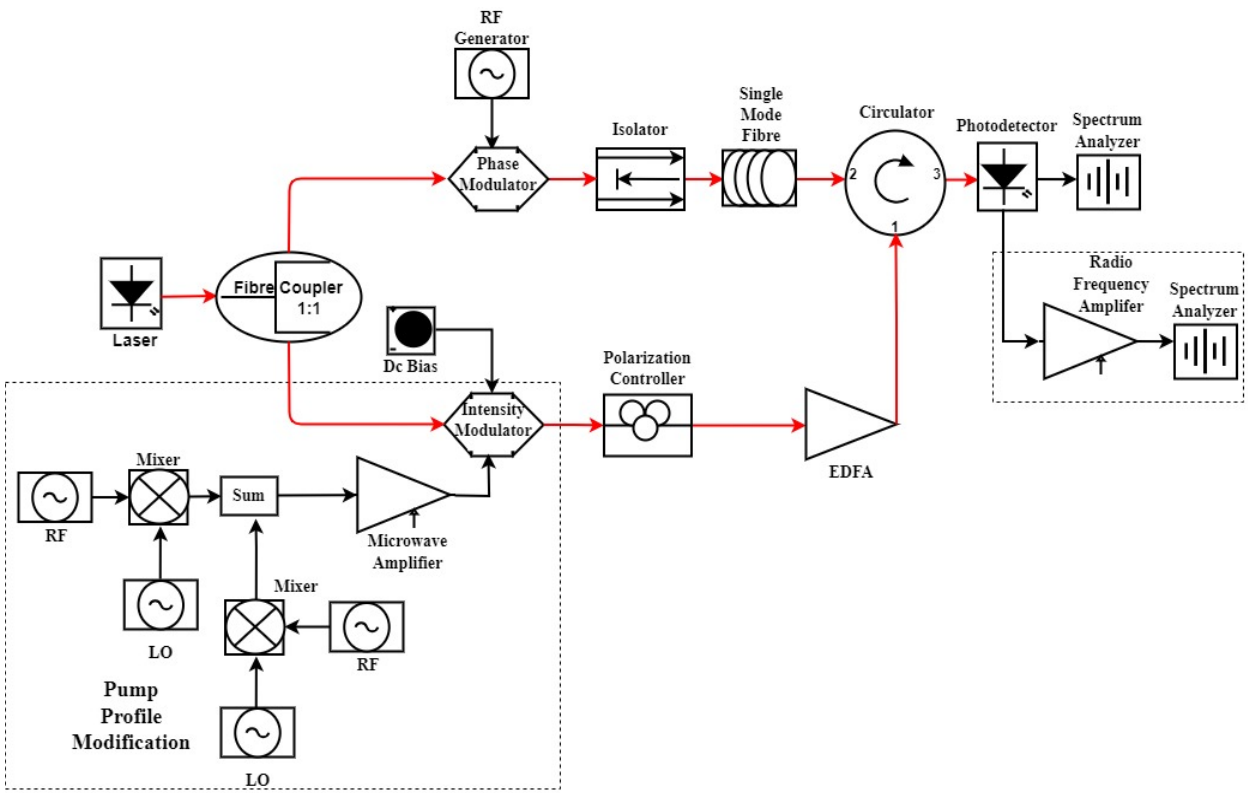

Fig. 1. Tunable Microwave Photonics Filter and Amplifier (TMWPNFA) based on Stimulated Brillouin Scattering (SBS) consisting of fixed laser, MZIM, Phase Modulation, Optical Isolator, SMF, circulator, RF generators, Spectrum analyzer, RF mixer, RF summer, RFA, EDFA, Polarization Controller , DC bias control and Photo Detector

converts the amplified probe signal back to the RF domain. The additional gain can be achieved by utilizing the RFA after the SBS gain.

This experiment employed a four-port 67 GHz R&S ZNA67 Vector Network Analyzer (VNA) and a 50 GHz R&S FSW50 Spectrum Analyzer. This cutting-edge technology is used to generate and evaluate high-quality RF transmissions. The spectrum analyzer FSW50 is used for the signal analysis. The PD employed is Thorlabs's DXM50AF. The kits, modulators and PD employed in this experiment use 1.80mm type RF connectors for RF coupling. VNA is utilized to generate an RF Probe signal and to determine notch suppression. Pump tuning is accomplished with a separate 40 GHz HP 8350B RF source. The same technique is followed for filtering except with addition of two-times bandwidth of Brillouin is added in tuning. The spectrum analyzer is used to analyze the pump and probe signals. The pump signal is controlled via a polarisation controller (Keysight's N7784B) and EDFA (Thorlabs's EDFA100S). The pump signal's profile is modified by mixing RF with a square wave signal of 1 MHz to 5 MHz frequency. The RF Mixer is RF MARKI mixer M10418NA. The State of polarization is viewed using Thorlabs's polarimeter PAX1000IR2. The EDFA amplifies the pump to generate the SBS. The primary SBS amplification is controlled by varying the EDFA's current.

The pump signal from the EDFA enters the circulator (Thorlabs 6015-3-FC) at point 1 and then leaves at point 2, then it enters SMF at point 2, opposite to probe in SMF (Silica based SMF fibre). Both signals need to be injected from opposite ends of SMF. Most of the SBS produced in SMF is in the opposite direction to the pump. Traditionally, SBS is used for amplification. It is also reported that the SMF-28 medium has both an amplification and a suppression effect of SBS bordering each other due to various SBS modes in SMF. Either one of them can be used depending on the application and requirement.

The working principle of TMWPNFA for filtering and amplification is shown in Fig. 2. The SBS is caused by vibrational sound waves in a medium. The SMF has multiple sound modes, and some of them overlap to cause amplification, and some will cause suppression. The relationship between amplification and filtering is related to the bandwidth of the SBS. This suppression is because, at the spectrum, sound modes overlap to create suppression. Nevertheless, the filtering achieved through SBS is almost half of the amplification achieved in the same vicinity. The Pump Brillouin and probe signals produced in optical domain by IM and PM are related by Eq. 1 [17].

$$f_C - f_{Pr} = f_C \pm f_{RF} \pm f_B \qquad (1)$$

Where f_C, f_{RF}, f_B and f_{Pr} are the fixed laser carrier frequency, Pump RF signal frequency, Brillouin shift, and Probe RF frequency, respectively. The SBS stokes and anti-stokes produced in SMF by pump signal (f_{RF}) are downshifted and upshifted by Brillouin shift (f_B) with respect to Pump as shown in Fig. 2a. In order for amplification/ Suppression to occur, the probe signal (f_{Pr}) has to interact with these Brillouin anti-stokes or stokes as shown in Fig. 2b. It is worth noting that both DS-SC sidebands can be used for TMWPNFA operation. For the sake of simplicity, only one sideband is considered in the following equation. DPDDMZM can accomplish Single Sideband Modulation(SSB) for pump signal. The Eq. 1 can be simplified and written as Eq. 2 [11].

$$f_{Pr} = f_{RF} \pm f_B \qquad (2)$$

According to Eq. 2, both Stokes and anti-stokes can be used for amplification and suppression. The transfer function of SBS based gain filter is expressed as [26]:

$$H(f) \propto G(f) exp\,[j\varphi(f)] - 1 \qquad (3)$$

G and φ represent the gain and phase difference of the filter. The relationship between gain and SBS gain in the medium is directly proportional. Additionally, the phase shift of the RF signal applied is represented by -1, indicating that the relationship is normalized. This normalization is since both sidebands and the carrier can express SBS gain or loss. The filter gain is directly proportional to the Brillouin gain of the medium, i.e., fibers such as HNLF or Chalcogenide glass fiber will result in more gain due to the higher Brillouin gain of the medium. This relation also shows that PM signals will be amplified more than IM signals. The SBS gain spectra follows the Lorentzian function [21], which is determined by the length of the optical fibre L, pump power P_p, effective refractive index n_{SBS} and Brillouin shift V_B, and Brillouin gain of the medium g_o.

$$G = exp\left\{\frac{\eta_{SBS} g_O P_P L}{2} \frac{(\frac{\Delta V_B}{2})^2}{(f_C - f_P - V_B - f)^2 + (\frac{\Delta V_B}{2})^2}\right\} \qquad (4)$$

The SBS gain is maximum when the polarization of the probe is aligned with that of the pump [28]. That is why a polarisation controller is utilized to control the gain. The Full Width at Half Maximum (FWHM) of the SBS has standard values ranging from 20 to 25 MHz. The 3dB bandwidth of TMWPNFA is found to be 20 MHz and the 40dB bandwidth to be 25 MHz. The FWHM is represented by BWSBS. This filtering/suppression band is produced due to multiple sound modes in SMF, which causes the PM signal to be suppressed. Brillouin shift, which in SMF is around 10.81 GHz, is used to upshift and downshift the stokes and anti-stokes. Amplification and suppression are produced when the probe signal falls on either the upshifted or downshifted Brillouin signals, as seen in Fig. 2.

This amplification and filtering bands in SMF-28 fiber is related to BWSBS, which can be regarded as bandwidth of TMWPNFA. For obtaining notch filtering using proposed TMWPNFA, the Eq. 2 can be rewritten as following:

Stokes: $f_{Pr} = f_{RF} - f_B - 2BW_{SBS}$ (5)

Anti-Stokes: $f_{Pr} = f_{RF} + f_B - 2BW_{SBS}$ (6)

Notch filtering occurs adjacent to Brillouin gain spectra in SMF for both stokes and anti-stokes. It is due to secondary sound modes that are produced in SMF because of SBS. The most dominant effect due to Brillouin modes is used for amplification. The second dominant effect produced in SMF, which is almost half as powerful as amplification, is used for suppression. This property enables the SMF-28 to function as both a filter and an amplifier at the same time or alternatively. Combining these two in SMF opens the possibility of many amplifications. Fig. 2 depicts the adjacent filtering band, pump generation, probe signal amplification, and suppression using both stokes and anti-stokes.

III. Results and Discussion

The proposed TMWPNFA is tested up to 50 GHz for RF amplification & notch filtering. The operating ranges of components, which in this case were the RF Sources and Optical Modulators, limit the proposed TMWPNFA tunability to further higher frequencies. Fig. 3b shows the original 40 GHz probe signal recovered by the Photodetector. As shown, the power level of the probe is -60 dBm without SBS interaction. The frequency of the probe signal is 40 GHz. The noise floor is at -85 dBm. The probe amplification is achieved by tuning the SBS anti-stokes to fall on the probe signal is shown in Fig. 3c. The signal is amplified to -43 from -60 dBm which means a gain of 17 dB. By using Eq. 3 for anti-stokes amplification, the pump RF frequency is determined as:

$$f_{Pr} = f_{RF} + f_B$$
$$\because f_{Pr} = 40\ GHz, f_B = 10.817\ GHz$$
$$f_{RF} = 40\ GHz - 10.817\ GHz$$
$$= 29.183\ \text{GHz}$$

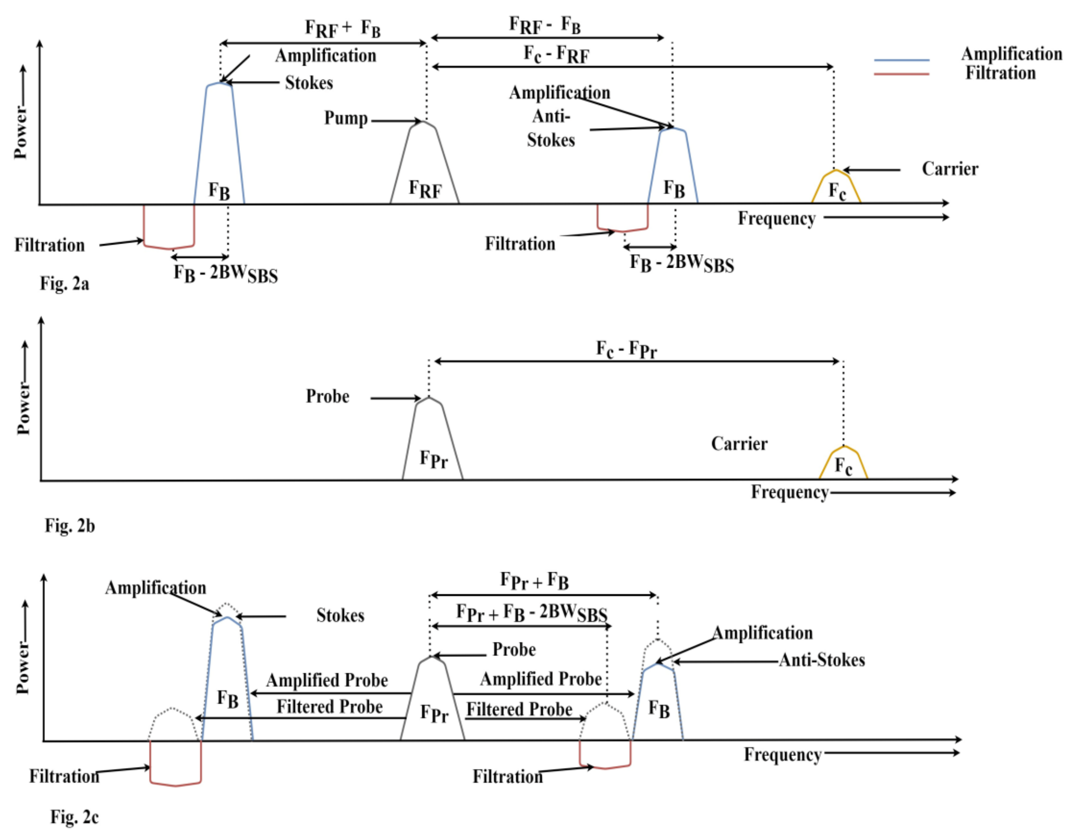

Fig. 2. Working Principle of TMWPNFA for probe filtrating & amplification: (a) RF signal generates stokes and anti-stokes of SBS. The amplification and notch filtering bands are adjacent to each other, related by the bandwidth of SBS signal produced. (b) SOI signal to be amplified or suppressed. (c) The process of suppression or amplification is achieved by tuning pump signal to cause the stokes or anti-stokes to fall exactly on SOI

Fig. 3a shows the same pump frequency of 29.183 GHz for notch filtering/ suppression. As discussed before, the suppression band is located at -$2BW_{SBS}$ meaning, 39.95 GHz. When the probe frequency is changed to 39.95 GHz, it results in a signal to suppress from -60 to -70 dBm, achieving 10 dB suppression. This technique achieves pure SBS-based suppression rather than changing the bias control of the modulator as done in some SBS-based filters [12]. This rejection property can be used to suppress noise signals, & interference in the communication channel. The 3dB bandwidth of TMWPNFA is 20 MHz, and 40 dB bandwidth is 25 MHz. By using Eq. 6 for anti-stokes filtering, pump or probe frequency can be determined. While in this case, probe frequency is calculated using 29.817 GHz pump frequency as:

$$f_{Pr} = f_{RF} + f_B - 2BW_{SBS}$$
$$\because f_{RF}=29.183 \text{ GHz}, f_{B=}10.617\ GHz, BW_{SBS} = 25\ MHz$$
$$f_{Pr} = 29.817\ GHz + 10.817 \text{ GHz} - 2(0.025) \text{ GHz}$$
$$f_{Pr} = 39.95 \text{ GHz}$$

The use of RFA following SBS amplification provides an appealing alternative for applications that need more gain. The amplification comes at the price of a lower Spurious-Free Dynamic Range (SFDR). The reduced SFDR happens because RFA increases the phase noise components, which are already amplified slightly by SBS. It is compromise that can be made if more amplification is required. The amplification of SBS and RFA are shown in Fig. 4. The 12 GHz probe signal frequency is shown in Fig. 4a. It is a phase-modulated signal with -35dBm power. The bandwidth shown in the figure is 200 MHz. Turning on the SBS pump amplifies The probe signal to a -21 dBm power level. The resulting probe signal is shown in Fig. 4b. Some phase noise harmonics exist in the noise floor, which can be reduced by lowering the SBS amplification. An RFA amplifier is used for additional gain, as shown in Fig. 4c, resulting in a the probe signal being further amplified to -5 dBm, resulting total gain of 30 dB. In Fig. 4, the SFDR of enhanced SOI by SBS is lowered to 30.5 dBc when amplified further by RFA. For lower frequencies, the TMWPNFA has achieved gain of 35dB.

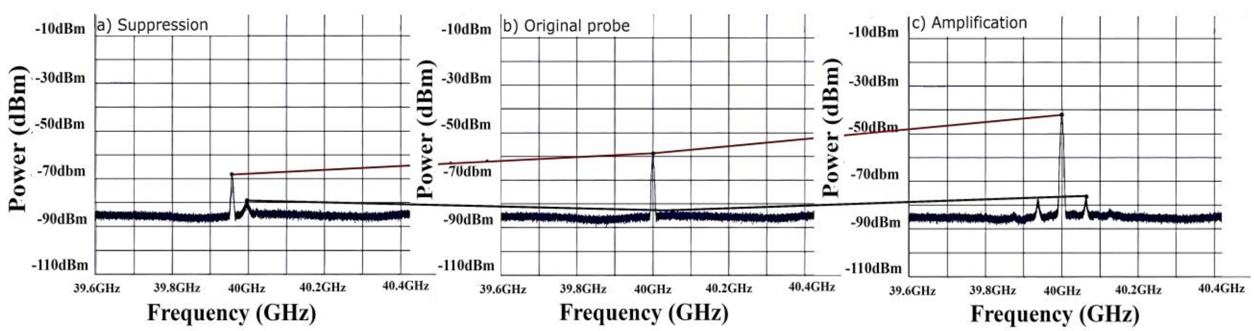

Fig. 3. 40 GHz probe signal amplification and suppression using SBS tunable pump a) 10dB suppression of 39.95 GHz probe signal by using pump's frequency of 29.183 GHz b) the original probe signal having -60 dBm power level c) the probe signal after amplified by using same 29.193 GHz pump. The probe achieved 17 dB amplification. These results shows that suppression band exist 2BWSBS apart to the amplification band

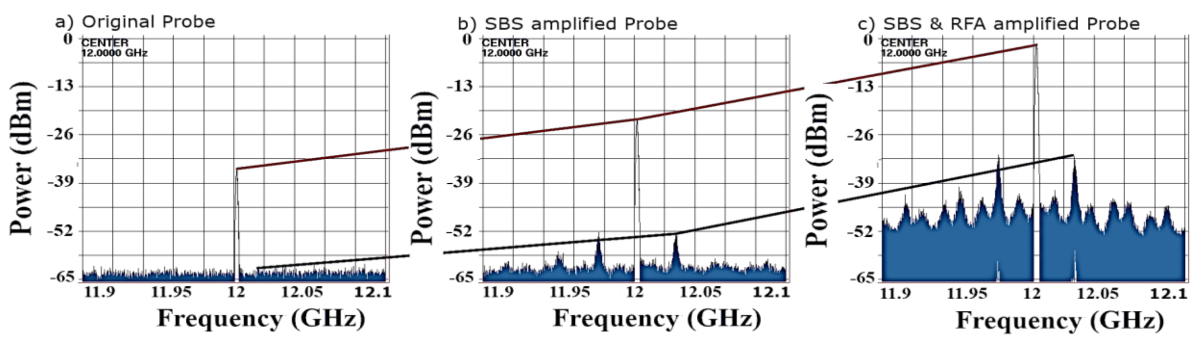

Fig. 4. SBS and RFA Gain of 12 GHz PM Signal a) 12 GHz original probe signal b) amplification of 12 GHz with SBS. The probe is amplified by 21 dB. c) the second stage amplification of amplified probe signal with RFA. The total gain achieved is 30 dBm. However, the RFA amplification increase the noise floor resulting in decreased SFDR

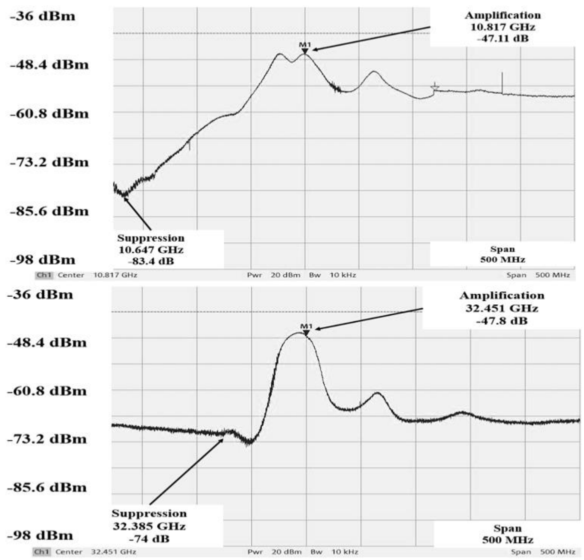

Fig. 5. TMWPNFA filtering & amplification bands for stokes and anti-stokes of 21.63 GHz pump, a stokes centered at 10.817 GHz produce higher response vs the anti-stokes at 32.451 GHz

The TMWPNFA notch suppression and amplification for both stokes and anti-stokes are shown in Fig. 5. The frequency of the Phase Modulation (PM) Radio Frequency (RF) is adjusted within the range of 10.567 to 11.057 GHz. The response of the photodetector is then measured by employing a Vector Network Analyzer (VNA). The amplification band for stokes is cantered at 10.817 GHz. The Brillouin bandwidth is 35 MHz, with the suppression band starting after 70 MHz. The signal with a frequency of 10.817 GHz undergoes amplification resulting in -44.298 dB. The 10.647 GHz signal is suppressed to -83.4 dB. The Anti-Stokes bands, which exhibit amplification, are centred at a frequency of 32.451 GHz. The amplification is observed at a level of -47.8 dB, while a suppression of -74 dB is achieved. These differences in gains and suppression can be seen in Fig. 7, which shows that the 10 GHz probe has higher gains and suppression than the 30 GHz probe. The Fig. 5 shows the duality of SBS-based TMWPNFA. These bands' bandwidth can be increased using RF mixing and multiple pump signals adjacent to each other, which will be beneficial if the signal of interest has a wide bandwidth or another signal must be amplified, which lies at suppression band. It is shown that the SBS amplification bandwidth is increased to 35MHz, and the resultant separation between amplification and suppression bands also increases with the increase of bandwidth.

The amplification for 50 GHz SOI is shown in Fig. 6. The signal power is at -47 dBm with -10 dB attenuation enabled on the spectrum analyzer. The red trace shows the amplified SOI. The signal is amplified to -43 dBm. SBS stokes are used for the amplification. If signal was moved to 49.95, it faces suppression of 3 dB. The operating range of the components accounts for low signal output level and amplification at 50 GHz. At 50 GHz, the PM has high insertion losses, and the photodetector sensitivity is also limited. If high amplification and suppression is needed at 50 GHz, a high bandwidth PM, MZIM and photodetector are required. With the current setup, the photodetector will produce limited response for high frequencies and small suppression can help to suppress high frequency unwanted signals.

Nonetheless, the TMWPNFA amplified the signal by 4 dB. The Q factor of TMWPNFA is calculated to be 2500 for 50GHz response and -3dB bandwidth of 20MHz. Filters with a Q factor of 200 or higher are considered narrow bandwidth filters. That means the TMWPNFA has a very high Q factor. The Proposed TMWPNFA notch filtering and amplification are shown in Fig. 7.

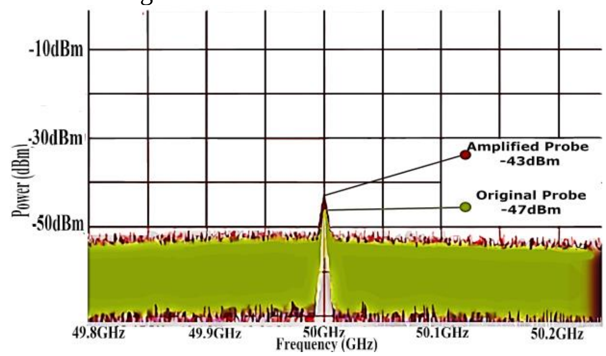

Fig. 6. 50 GHz probe signal amplification with 10 dB Attenuation. The signal is amplified by 4 dB

An amplification of 23 dB, 18 dB, 14 dB, 13 dB, 21 dB, 22 dB, 13 dB, & 4 dB is accomplished for 4 GHz, 8 GHz, 12 GHz, 20 GHz, 30 GHz, 36 GHz, 40 GHz, & 50 GHz probe frequencies, respectively. Similarly, suppression of 11 dB, 12 dB, 10 dB, 7 dB, 6 dB, 5 dB, 6 dB, & 3 dB is attained for 4 GHz, 8 GHz, 12 GHz, 20 GHz, 30 GHz, 36 GHz, 40 GHz, & 50 GHz probe frequencies, respectively. These results are without employing RFA. The tuneability of the TMWPNFA can be increased by using high bandwidth MZIM, photodetector and another high RF source. Currently, OPTILAB's 50GHz phase modulator is available off the shelf, however most of higher frequency modulators are still in development stages. Similarly the photodetector are available in limited bandwidth.

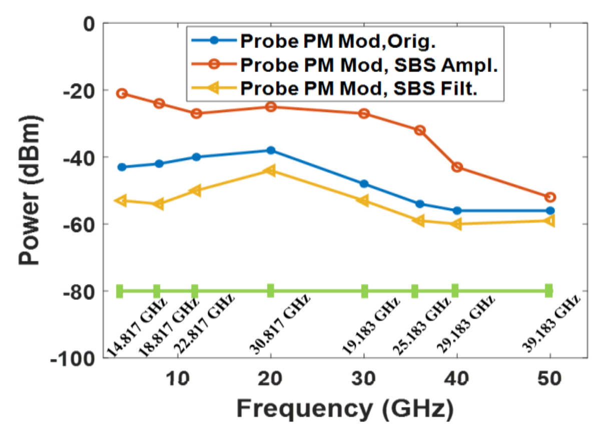

Fig. 7. TMWPNFA filtering & amplification response, pump frequency for amplification is shown on green line bar. Stokes is used for lower frequencies while anti-stokes is used for higher frequencies

High insertion losses of modulators for high frequencies and low photodetector sensitivity at higher frequencies can explain low amplification and filtering response for higher frequencies. The suppression achieved is much less than the amplification since SBS dominant causes amplification. The suppression results from a less dominant SBS mode in SMF. SBS amplification and notch filtering can be increased by deploying high Brillouin constant fibers such as chalcogenide glass fiber and highly nonlinear fibers. Using high-power EDFA such as rear earth elements Ytterbium doped EYDFA (OPTILABS's EYDFA-PA-37-BM) can cause a significant increase in amplification and filtering, which can also increase the bandwidth and distance between the centers of amplification and filtering bands. The bandwidth control of the TMWPNFA for 1 MHz and 5 MHz square wave local oscillator signals, is presented in Fig 8.

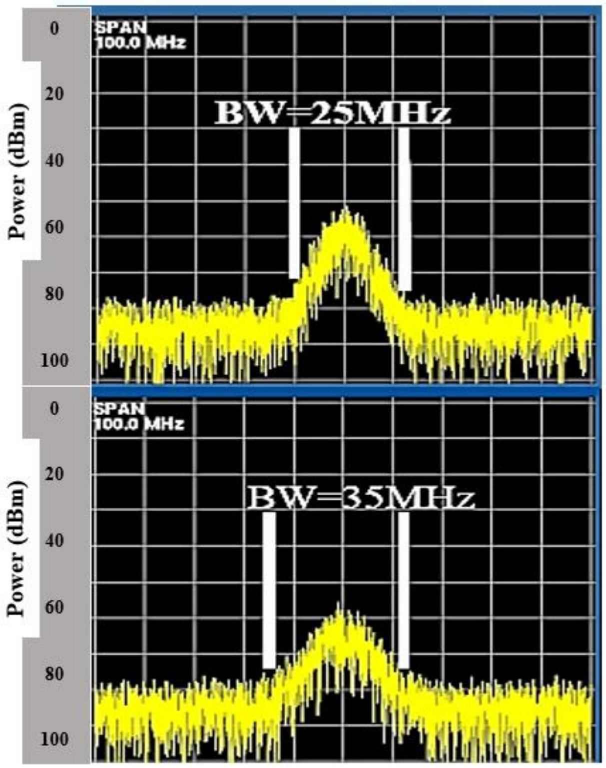

Fig. 8. The bandwidth of TMWPNFA increased to 35 MHz by mixing pump signal with 5MHz Square signal

The bandwidth of the SBS filter is set to 25 MHz by mixing it with a 1 MHz square wave. The square wave IF frequency is increased to increase the TMWFP bandwidth further. As shown in Fig. 8, the TMWFP bandwidth is increased from 25 to 35 MHz, which can be increased further if the frequency of the square is increased further and more Brillouin gain is achieved using longer-length fiber or high-power EDFAs. The presented configuration can be multiple LO signals added together to create a wideband amplification or suppression band or even independently tuned amplification/ suppression bands.

However, those results cannot be presented due to limitations of components such as EDFAs and longer lengths. The mixing can be extended to add more independent amplification and suppression bands with tunable bandwidth. Since the proposed filter can amplify and suppress multiple signals with tunable bandwidth and frequency, it would have great potential for future advanced communication systems where selective amplification or suppression is desired.

Even though it is not desired, it sometimes amplifies the adjacent signal when filtering. The bandwidth of the filter can be increased to avoid this from happening. There are numerous advantages to using a single laser for SBS-based amplification or filtering. The effect of SBS amplification on phase noise is shown in Fig. 9. The frequency of the probe signal is 9 GHz. The pointer is placed at 125 kHz from the probe signal's center, and the measurements are taken per Hertz. The probe signal exhibits a phase noise of -67.94 dBc/Hz without SBS amplification, as shown in Fig. 9a. After the SBS amplification is applied. The phase noise is increased to -59.30 dBc/Hz against power gain to -26 dBm from -42 dBm, as shown in Fig. 9b. The use of a separate tunable pump laser in a previously proposed configuration [9] caused issues with wavelength stability between the two lasers and resulted in amplified SOI with substantial phase noise.

The stability issues in multi-laser systems have been known for many decades. This also affects SBS filters designed using tunable and fixed lasers [19]. As both lasers' wavelength shifts during operation, the SBS generated by tunable lasers will also drift in frequency. This instability causes the amplification achieved using SBS to fluctuate; hence, the phase noise figure arises. The proposed solution for multi-system-based SBS filters involves using highly stable lasers and a frequency-locking mechanism. Furthermore, this study, utilized a cost-effective solution using one fixed laser for both pump and probe signals. This ensures that any change in the laser wavelength does not result in any drift, and the response at PD stays the same due to the same laser throughout the system. The above is necessary for the stable and improved phase noise response in the proposed TMWPNFA system configuration. By doing this, we could still achieve a 50 GHz tunable range. This indicates that SBS from the same laser source has a < -8.64 dBc/Hz effect on the noise figure. This is considerably lower as compared to the gain that is achieved by a tunable laser pump. This contributes to creating a low-cost SBS TMWPNFA solution rather than relying on expensive, highly stable separate lasers that may still negatively affect the probe signal phase noise. The pump polarisation state has also proved to play a crucial role in total gain by SBS. It should be noted here, if RFA is used, it will increase phase noise further. The phase noise of the 9 GHz signal was increase to -53.57 dBc/Hz, an addition of 5.73 dBc/Hz. This is an addition of The 9 GHz probe signal is amplified with two polarisation states, as shown in Fig. 10. The maximum gain achieved by controlling the pump polarisation to the right orientation is shown in Fig. 10b. The pump polarisation state is changed to left orientation, as shown in Fig.10a. This causes a decrease of 6 dB gain from -30 to -36 dBm. The pump's polarisation variation can control up to 6 dB of gain. The pump polarisation can be employed as an additional gain control for the SBS-based filters and amplifiers. The gain can be independent of pump polarisation by using polarisation maintaining fiber links between the laser, MZIM, EDFA, and circulator, and utilizing polarisation by maintaining SMF as an optical medium. That will ensure that the pump's polarisation is always maintained and that polarisation does not affect gain

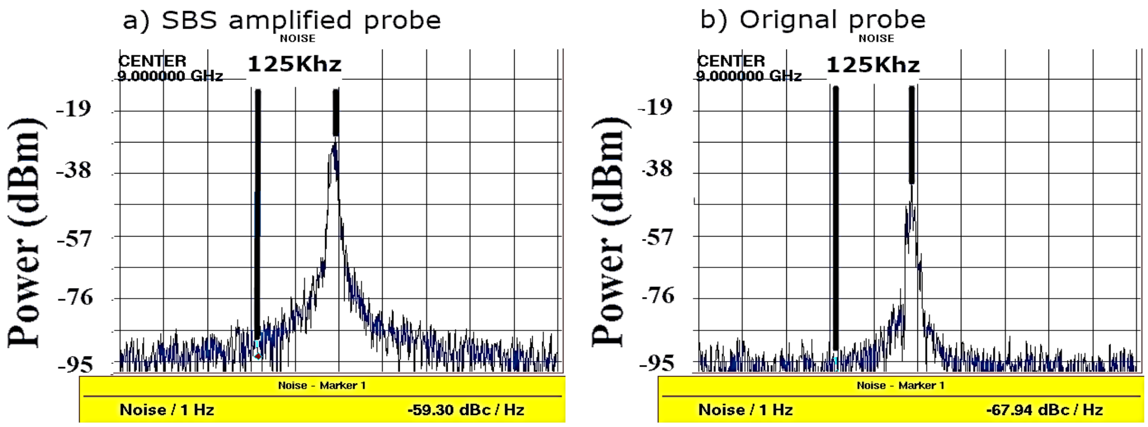

Fig. 9. Phase noise measurement of TMWPNFA for 9 GHz probe signal with bandwidth spacing of 125 kHz from probe/ SOI. a) phase noise measurement with 125 kHz spacing from the amplified SOI. the noise increased to -59.30 dBc/Hz from the original probe shown b) SOI with phase noise of -67.94 dBc/Hz with 125 kHz spacing from center

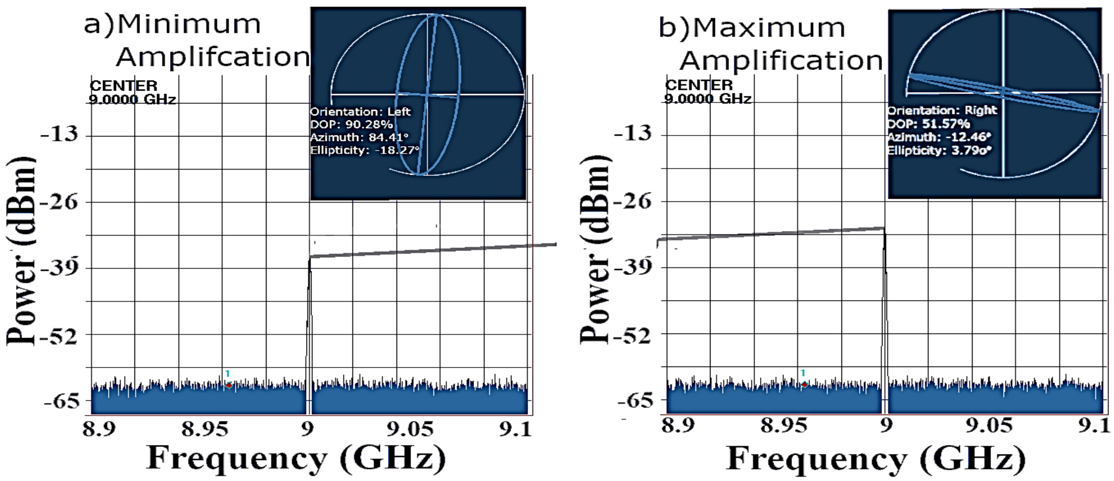

Fig. 10. Pump polarisation and gain control measurement of TMWPNFA for 9 GHz probe signal a) minimum amplification with left orientation of pump polarisation b) the maximum gain achieved with pump polarisation of right orientation. The control of polarisation resulted in 6 dB gain control

or filtering. The optical spectrum for the 9 GHz probe signal SBS amplification is shown in Fig. 11. The laser pump is centered at 193.406 THz. The red trace depicts the probe signal. The phase- modulated probe signal sidebands are centered at 193.415 THz and 193.397 THz. The pump signal is generated using MZIM biased at minimum, and RF signal of 19.817 GHz, causing the SBS induced amplification with stokes signal falling on probe 193.415 THz sideband. The black trace in Fig. 11 depicts the amplification of one of the sidebands by SBS stokes. However, the channel adds multiple harmonics and different stokes and anti-stokes of pump sidebands. This effect can be minimized by using an SSB-based pump. SSB can be performed using DPDDMZM. The filter response deviates over time due to the bias point shift of MZIM; this can be fixed by employing bias controller at a minimum. A PM with low insertion losses and a photodetector with high sensitivity for higher frequencies will ensure more gain for higher frequencies.

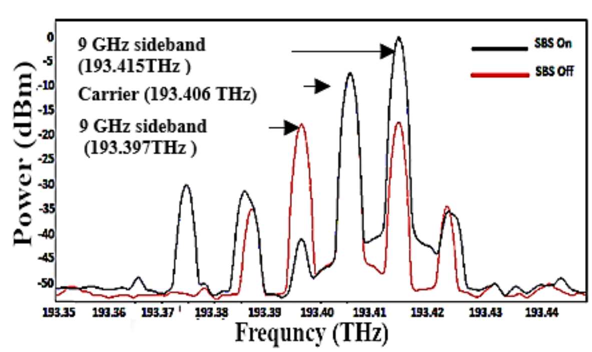

Fig. 11. Optical Spectrum Analysis, with SBS off both PM 9 GHz are at same amplitude, when SBS is turned on, upper amplitude is pushed to 0 from -20 dBm resulting in 20 dB gain

The comparison of the TMWPNFA with other recent work is presented in Table 1. The OSA scan resolution of 312.5 MHz limits the ability show spacing between carrier and bands, however the RF results are shown with correct bandwidth of SOI and SBS bands. The one main difference is using pure SBS modes to suppress SOI. This work explores the duality of SBS. Compared to previous work published before, the filters relay on SBS amplification and modulator bias points [12]. The bias point is changed to minimum, which reduces the RF output produced on PD [12]. The larger bandwidth is result of long length of optical fibres in proposed technology approx. 50KM [12]. SBS gain is directly proportional to length of fibre thus, more SBS is produced and resultant linewidth of SBS translates to wide bandwidth. The longer length of fibres result in SOI to experience large propagation delays. It also increase the size of filter. Nevertheless, the SBS is used to amplify the signal of interest [12]. The SBS filter presented in this paper amplifies the SOI. SBS is used to amplify the signal of interest [12]. The SBS filter presented in this paper amplifies the SOI. The reported filter also suppresses the any signal without changing the bias points. Although it can cause problem when amplifying or suppressing wideband signals. But, by widening the pump bandwidth along with use of multiple pumps close to each

Table 1 Comparison of TMWPNFA with previously published work

Reference	Tuning Range (GHz)	Gain (dB)	Polarisation gain control	Suppression (dB)	Bandwidth (3dB)	Phase Noise	Notes
This work	4 GHz - 50 GHz	≃35 dB (SBS & RFA) 24 to 4 (SBS)	≃6 dB	13 to 3 dB	20 MHz-35 MHz	<-8.6dBc/Hz	• SBS based amplification and suppression • No changes to modulator bias point to produce suppression • Highest reported tunable range using single laser • Small size, only 10KM fiber
SC- PD SBS [12]	4.5 GHz – 40 GHz	19 dB	Not Available (NA)	48 dB	14 MHz-59 MHz	NA	• Suppression achieved by reducing bias point to minimum thus causing whole response to be lower • 50KM fibre results in propagation delay and large size
Tunable Laser SBS [19]	4GHz – 32GHz	69 dB	NA	NA	25 MHz-35 MHz	>-20 dBc/Hz	• Using Tunable laser effects, the phase noise of the signal.
Dual Band CS-SSB injected disturbed feedback [29]	9 GHz – 39 GHz	29 dB	NA	NA	232 MHz	NA	• Did not achieve any suppression • Large bandwidth • Dual bands to select two signals • Use tuneable laser, results in unstable response
Dual Stage SBS with polarisation Modulation [30]	2.1 GHz-6.1 GHz	0.35 dB	NA	NA	7.7 MHz	NA	• Mentioned phase noise is decreased in system but didn't quantify • Two stages of 25 KM each is used to amplify signal which causes the signal to delay • Larger size due to 50KM of SMF fibres

other, the bandwidth of the amplification and suppression band can be increased, as presented in this work.

By using multiple independent pumps, multiple signals can be amplified or/ and suppressed. Due to the EDFA output power and other component limitations, only the signal pump and a bandwidth expansion to 35 MHz are shown. The work presented in this filter uses a fixed laser compared to previous work published [19]. The filter phase noise figure is presented, showing that filter amplification has a much better phase noise figure. The tuneable range achieved with the proposed filter is up to 50 GHz while using commercially available 40 GHz MZIM. It is achieved while employing both stokes and anti-stokes of SBS as compared to previous work, claiming that both causes alternate effects (amplification and suppression). The wide tuneable range is because that amplification and suppression bands lie next to each other which is proved by experimentation and presented in this paper.

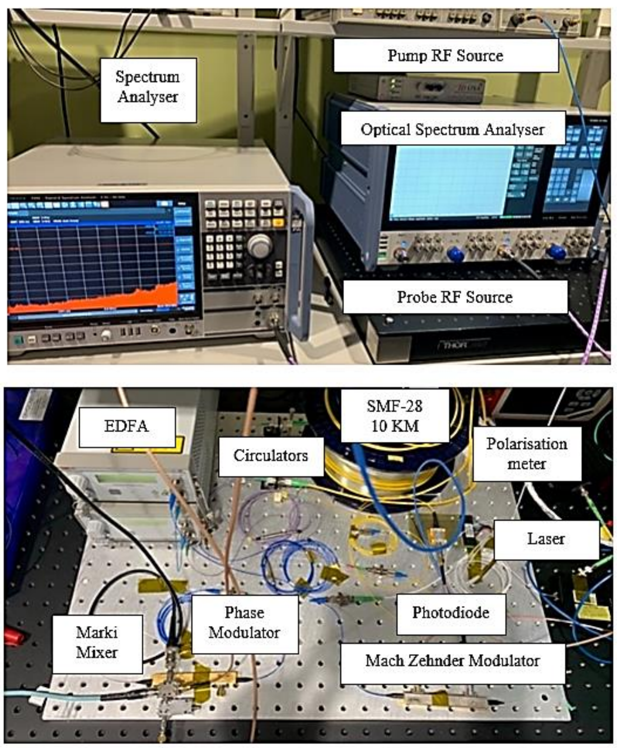

Fig. 12. TMWPNFA consists of EDFA, circulator, SMF fiber, fixed laser, couplers, modulators, RF sources and Marki mixer whereas Measurement Setup consists of VNA, RF Spectrum Analyzer, Optical Spectrum Analyzer and Polarimeter

The proposed TMWPNFA can be expanded into multiple series or parallel blocks. A system can be constructed to perform selective suppression of amplification, while leaving the system's overall response the same by employing such blocks. Another way to implement multiple bands is by using multiple pump signals in TMWPNFA. The existence of amplification and suppression bands next to each other can cause problems in practical systems. The suppression and amplification bands can be modified by modifying the pump profile, as demonstrated in previous research. This TMWPNFA has the potential to be expanded into reliable component for high data rate communication systems by miniaturing RF components and the addition of intelligent electronic circuitry that can control bias point of the modulator, make selection of pump frequencies and pump profile. This configuration can be further improved by employing a single sideband, carrier-suppressed SBS's pump signal, and highly nonlinear Chalcogenide fibres. The modulators are fabricated using lithium niobate. The SMF-28 fibre, circulators and couplers are made up of silica glass fibre. The EDFA contains erbium ions dopped silica fibre. The photonics system can be miniaturized to approx. 50 cm x 50 cm x 25 cm module board. However, the measuring setup containing VNA and pump RF setup will have to be miniaturised further in order to improve the package size.

IV. Conclusion

We have demonstrated an experimental configuration of the TMWPNFA filter system that can perform notch filtering/ suppression and amplification by exploiting multiple Brillouin modes in SMF. The operating principle, detailed explanation, and mathematical calculation for performing suppression and amplification using both stokes and anti-stokes of SBS are presented for the first time. It is shown that both stokes and anti-stokes can be utilized for both filtering and amplification. The amplification and filtering duality exist due to multiple modes present in SMF-28. The TMWPNFA demonstrates a high gain of $\simeq$35 dB by simultaneously employing SBS and RFA gain. The TMWPNFA configuration has demonstrated a highest suppression of $\simeq$13 dB and an amplification of $\simeq$22 dB. The 3dB bandwidth of TMWPNFA is 20 MHz. The paper also presents an RF mixing approach to increase the bandwidth of TMWPNFA's amplification/ Suppression bands to 35 MHz Using multiple pumps to develop the capability of multiple amplification and suppression bands with varying bandwidths is also proposed. The Q factor is calculated as from 200 to 2500 for 4 GHz to 50 GHz frequencies.

A fixed laser, Erbium-Doped Fibre Amplifiers (EDFA), an RF Amplifier (RFA), an RF Mixer, Optical couplers, Single Mode Fibre (SMF), Phase Modulator, and Intensity Modulators are used in the proposed TMWPNFA experimental configuration. The phase noise caused by amplification is reported to be -8.6 dBc/Hz at 125 kHz. The Pump polarisation state has been demonstrated experimentally to play a critical influence in overall gain by SBS. Pump polarisation is shown to be the source of 6dB gain control. Based on the proposed 50 GHz TMWPNFA, the SBS filters would benefit future measurement systems, 6G, Aerospace, and beyond communication technologies.

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Mian Ali is pursuing a PhD in Electronic Engineering from Royal Holloway, University of London. Before starting his doctorate, he was working as senior Lecturer in Electrical Engineering department, Bahria University for more than three years. He has completed his MSc Electronic Engineering with distinction from University of Bedfordshire, United Kingdom and achieved CGPA of 3.24/4 in Bachelor of Electrical Engineering with specialization in Electronics from Bahria University, Islamabad.

His research is focused on third order non linearities in optical medium and exploiting them for applications such as delay lines, filters, amplifiers, and control. Before beginning Doctorate, his research interest includes Microwave photonics, Optical non linearities, Artificial intelligence, Optical FDM, Optical MIMO systems, Speckle Pattern-based devices, and systems for cybersecurity applications. He has published Numerous conference and Journal papers based on Microwave Photonics, Antenna Design, Robotics, Internet of Things, Artificial Intelligence, and Bio Medical Devices.

Dr. SHYQYRI HAXHA (SM'14) received the MSc and PhD degrees from City University in London in 2000 and 2004, respectively. He has also obtained several world-class industrial trainings and diplomas such as Executive MBA Cambridge Judge Business School and Mini Telecom MBAs. He was awarded the SIM Postgraduate Award from The Worshipful Company of Scientific Instrument Makers in Cambridge for his highly successful contribution in research. Currently, he is a Reader, a Director of research and Knowledge Exchange Framework (KEF) at Royal Holloway, University of London, Department of Electronic Engineering Egham, Surrey, United Kingdom. He was also a Reader in Photonics in the Computer Science and Technology, University of Bedfordshire, Luton in the United Kingdom. Prior to these posts, he was a lecturer in Optic Communication at the School of Engineering and Digital Arts, University of Kent, Canterbury, United Kingdom.

Dr. Haxha founded and leads the Microwave Photonics and Sensors (MPS) group at Royall Holloway University of London. His expertise is in designing and optimising photonic and microwave devices and systems for applications in Sensor Technology (Medical and Environmental), Nanotechnology, and Telecommunication Systems. Dr Haxha research interests are in the areas of microwave photonics, photonic crystal devices, metamaterials, photonic crystal fibers, nano-sensors, optical sensors, surface plasmon polaritons (SPP), biosensors, ultra-high-speed electro-optic modulators, compact integrated optic devices, Optical CDMA, Optical FDM, and Optical MIMO systems. He has developed and demonstrated RF over fiber transmission systems for the aviation industry, including cybersecurity protection for commercial and defense applications. He is a Chartered Engineer (CEng), Senior Member of the Institution of Electrical and Electronics Engineers (Senior MIEEE), Fellow of the Higher Education Academy (FHEA), Editorial Board Member for MDPI journals and Associate Editor of IEEE Sensors Journal. He has been a keynote speaker of numerous world class conferences.