Investigation of Stimulated Brillouin Scattering Effects in Radio over Fiber Distribution Systems

By

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save an to the extent that such work has been cited and acknowledged within the text of my work.

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Abstract

Because of the emerging demand for bandwidth, future wireless access networks are likely to use high frequency microwave signals as the access media. Hence, radio-frequency (RF) signals need to be processed and transmitted with higher bandwidth in many applications. However, the attenuation of RF signals in traditional transmission media increases rapidly when the frequencies of the signal increase. On the other hand, optical fiber has emerged as an alternative and promising transmission medium in which RF modulated optical carriers can be transmitted and distributed with very low loss. This kind of hybrid radio/fiber system or Radio over Fiber (RoF) system provides good synergy between optics and radio.

This thesis first introduces optical and radio communication systems, and provides a review of the RoF systems for wireless access networks. The research then explores the effects of Stimulated Brillouin Scattering (SBS) in RoF distribution networks, and shows that it can seriously degrade the performance of radio-over-fiber systems in which a high transmission power is required. The work then goes onto look at how pre-filtering of the optical microwave signal can simultaneously perform Single Sideband (SSB) filtering to overcome the effects of signal fading due to dispersion, in addition to reducing the effect of SBS on signal transmission. Subsequently, the thesis investigates how to overcome the SBS effect by changing the modulation depth of the optical microwave signal. These experiments show that increasing the modulation index may increase the Brillouin threshold, as it is primarily the carrier power that induces the SBS effect due to its narrow linewidth. In this way we can further reduce the limitations on system performance due to SBS.

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Abbreviations and acronyms

A/D	Analogue to Digital
ACI	Adjacent Channel Interference
ACL	R Adjacent Channel Leakage Ratio
AM	Amplitude Modulation
AMPS	Advanced Mobile Phone Service
APD	Avalanche Photodiode
ASK	Amplitude Shift Keying
AT&T	American Telephone and Telegraph
BASK	Binary Amplitude Shift Keying
BER	Bit Error Rate
BERT	Bit Error Rate Tester
BPSK	Binary Phase Shift Keyed
BRZ	Bipolar Return to Zero
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver Stations
CATV	Cable Television
CDMA	Code Division Multiple Access
CID	Caller Identification
CN	Core Network
CW	Continuous Wave
DCF	Dispersion Compensated Fiber
DFB	Distributed Feed Back
DH	Double Heterostructure
DSF	Dispersion Shifted Fiber
DSL	Digital subscriber lines
DSP	Digital Signal Process
EA	Electroabsorption
EAM	Electro Absorption Modulator
ECL	External Cavity Laser
EDA	Electronic Design Automation

EDFA	Erbium Doped Fiber Amplifier
EDGE	Enhanced Data rates for GSM Evolution
EHF	Extremely high frequency
E/O	Electronic/optical
EOM	Electro-optic modulator
EIR	Equipment Identity Register
EMI	Electromagnetic Interference
ESN	Electronic Serial Number
FCC	Federal Communication Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward error correction
FM	Frequency Modulation
FP	Fabry Perot
FSK	Frequency Shift Keying
FWM	Four Wave Mixing
GFSK	Gaussian frequency shift keying
GHZ	Gigahertz
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile-Communications
HCA	Hybrid Coax Air
HCMTS	High Capacity Mobile Telephone System
HFC	Hybrid Fiber Cable
HFR	Hybrid Fiber Radio
HLR	Home Location Register
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IM	Intensity Modulation
IMD	Inter Modulation Distortion
IM-DD	Intensity modulated direct detection
IP	Internet Protocol
IR	Infrared

ILD	Injection laser diode
ISM	Industrial, Scientific and Medical
KHz	Kilohertz
LAN	Local Area Networks
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diodes
LLC	Logical link control
MASER	Microwave Amplification by Stimulated Emission of Radiation
ME	Mobile Equipment
MIMO	Multiple-input multiple-output
MQW	Multiple quantum well
MHz	Megahertz
MMF	Multi-Mode Fiber
MS	Mobile Station
MZ	Mach-Zehnder
MZM	Mach Zehnder Modulator
NRZ	Non Return to Zero
OOK	On Off Keying
OSSB	Optical single sideband
OEO	Opto-electronic oscillator
ODSB	Optical double sideband
OSI	Open system interconnection
OFDM	Orthogonal frequency division multiplexing
PC	Personal Computer
PCM	Pulse Code Modulation
PI	Power vs. Current
PIN	P-type, Intrinsic, N-Type
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
PHY	Physical
PON	Passive Optical Networks
PSK	Phase shift keying
QAM	Quadrature Amplitude Modulation

QoS	Quality of service
QPSK	Quaternary Phase Shift Keying
R&D	Research and Development
RAF	Remote Antenna Feeding
RF	Radio Frequency
RFI	frequency interference
RoF	Radio over fiber
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RZ	Return to Zero
SCM	Sub-Carrier Multiplexing
SEL	Surface emitting laser
SSB	Single sideband
SOA	Semiconductor optical amplifier
SCM	Sub-carrier multiplexing
SID	System Identification
SMSR	Side Mode Suppression Ratio
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SMF	Single Mode Fiber
SSMF	Standard Single Mode Fiber
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
USIM	User Services Identity Module
UWB	Ultra wideband
VLF	Very low frequency
VLR	Visitor Location Register
WAN	Wide Area Networks
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength division multiplexing
WI-MUX	Wavelength-interleaved multiplexer
WI-OADM	Wavelength-interleaved optical add-drop multiplexer

WLAN	Wireless local area network
WPAN	Wireless personal area network
WMAN	Wireless metropolitan area network
XPM	Cross Phase Modulation

Thesis overview

This thesis is divided into six chapters and its layout is as follows:

Chapter 1 gives an introduction to the optical fiber communication and the radio frequency communications. The basic concepts and the components used in the communication systems are described. Then we explain why the increasing bandwidth demand of wireless services encourages the combination of the optical fiber and the radio frequency communications.

Chapter 2 gives the detailed overview of the radio over fiber (RoF) distribution networks. The components, techniques and the architectures available for those networks are described. In this chapter, we discuss the RoF technology in some detail, and the modulation techniques used in RoF systems. We also discuss how to overcome chromatic dispersion effects in RoF systems, techniques to improve optical spectral efficiency, and the nonlinearity problems encountered in RoF systems.

Chapter 3 describes the method we proposed, which is pre-filtering, to reduce the SBS nonlinear effect in RoF transmission systems. In this chapter, we investigate the possibility of performing SSB filtering to simultaneously overcome the effects of dispersion and SBS in the transmission fibre. The results show that the pre-filtering can filter out one side band as well as reduce the effect of SBS.

Chapter 4 is the further investigation of overcoming the SBS effect by changing the modulation depth of the optical microwave signal. The experiments showed that increasing the modulation index increases the Brillouin threshold, as it is primarily the carrier power that induces the SBS effect due to its narrow linewidth. Thus, to further reduce the limitations on system performance due to SBS, it may be advantageous to ensure that any optical filter used at the central station not only generates a Single-Sideband-Signal to overcome dispersive fading, but also maximizes the modulation depth to reduce SBS effects.

Chapter 5 gives a brief summary of the thesis and presents some conclusions.

Chapter 1

Optical Communications and Radio Communications

1.1 Fundamental of optical fiber communications

Communication is the transmission of information from one point to another. Optical fiber communication is a technology that uses glass (or plastic) fibers to transmit data. An optical fiber cable consists of a bundle of glass threads, each of which is capable of transmitting messages modulated onto light waves [1]. Telecommunication networks based on optical fiber communications have become a major information-transmission system, with high-capacity optical fiber links encircling the globe in both terrestrial and undersea installations.

Fiber optics is a medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, fiber optics is not electrical in nature. Like any communication system, a basic fiber optic system consists of a transmitting device, which generates the light signal; an optical fiber cable, which carries the light; and a receiver, which accepts the light signal transmitted.

The transmitting device, or transmitter, usually consists of a semiconductor laser or LED (Light Emitting Diode) [2][3], modulated by an electrical information source. The modulated light from the source is then coupled into an optical fiber channel through which it is transmitted. At the fiber end, it is detected at the receiver, which generally consists of a photodetector, an amplifier and a signal-processing circuit.

1.1.1 Transmitters

There are two kinds of optical sources: LED and laser diode [4]. LEDs have broad spectral width and their output is incoherent. On the other hand, the laser diodes' output is coherent and highly monochromatic; hence they are generally used for systems requiring bandwidth greater than approximately 200 MHz. There are three kinds of generally used lasers [3]: FP (Fabry-Perot) laser, DFB (Distributed- feed-back) laser and VCSEL (Vertical Cavity Surface-emitting Laser) laser [5], which is a new laser structure that emits laser light vertically from its surface and has a vertical laser cavity.

Laser diodes have some advantages over LEDs, which make them popular when used in modern transmission system [3]. Among those advantages, we introduce three main ones. The first one is faster response time, which means greater modulation rates and higher data transmission rates. The second advantage is narrower spectral width of the output, which implies less dispersion-induced signal distortion. Last, but not the least, laser diodes have much higher optical power levels than LEDs. Hence we can couple higher signal power into a fiber with a laser diode and allow long transmission distances.

On the other hand, the laser diodes still have some drawbacks when compared with LEDs. First, their construction is more complicated than the LEDs, which is mainly because of the requirement of current confinement in a small lasing cavity. Then, the optical output power level is strongly dependent on temperature. This increases the complexity of the transmitter circuitry. If a laser diode is to be used over a wide temperature range, then either a cooling mechanism must be used to maintain the laser at a constant temperature or a thresholds-sensing circuit must be implemented to adjust the bias current with changes in temperature. The third one is that they are susceptible to catastrophic facet degradation that greatly reduces the device lifetime. The mechanical damage of the facets may arise after short operating times at high optical power densities.

Several key characteristics of laser diode determine their usefulness in a given application and we introduce them below in detail [6]:

Peak Wavelength: This is the wavelength at which the source emits the most power. It should be matched to the wavelengths that are transmitted with the least attenuation through optical fiber. The most common wavelengths employed are 1310 and 1550 nm.

Spectral Width: Ideally, all the light emitted from a laser would be at the peak wavelength, but in practice the light is emitted in a range of wavelengths centered at the peak wavelength. This range is called the spectral width of the source, and dependent on whether the laser is multimode or single mode, the spectrum width can vary from > 10 nm to < 0.01 nm.

Power: The best results are usually achieved by coupling as much of a source's power into the fiber as possible. The key requirement is that the output power of the source be strong enough to provide sufficient power to the detector at the receiving end, considering fiber attenuation, coupling losses and other system constraints. In general, lasers are more powerful than LEDs (e.g., 5 mW vs. 0.1 mW).

Bandwidth: A source should turn on and off fast enough to meet the bandwidth requirement of the system. The speed is given according to a source's rise or fall time, the time required to go from 10% to 90% of peak power. Lasers have faster rise and fall times than LEDs.

Figure 1-1 is the PI curve of a standard DFB laser, which is the relationship between optical output power and laser diode drive current. At low diode currents, only spontaneous radiation is emitted. Both the spectral range and the lateral beam width of this emission are broad like that of an LED. A dramatic and sharply defined increase in the power output occurs at the lasing threshold. As this transition point is approached, the spectral range and the beam width both narrow with increasing drive current. The final spectral width is reached just past the threshold point [4].

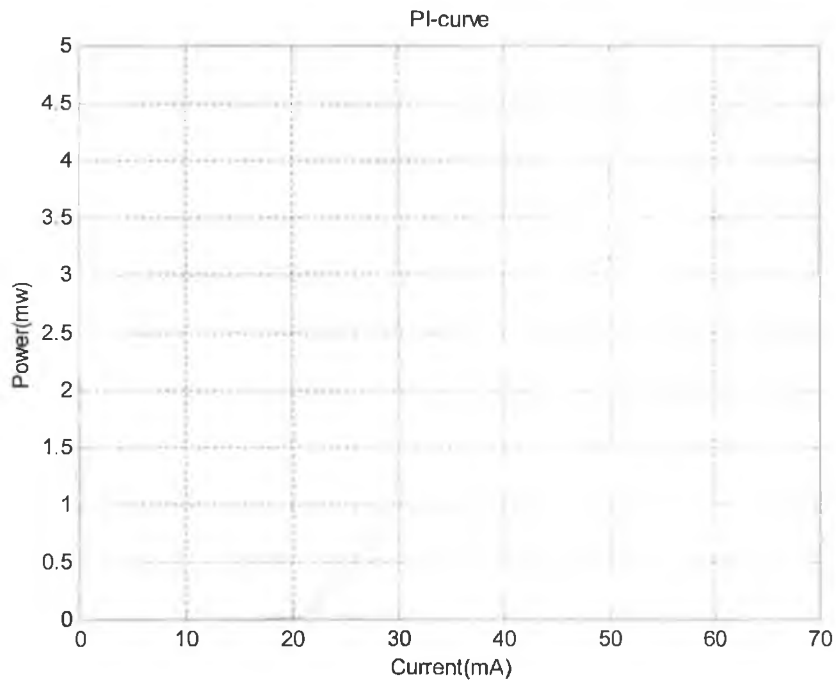

Figure 5-1: P-I curve of a DFB laser diode

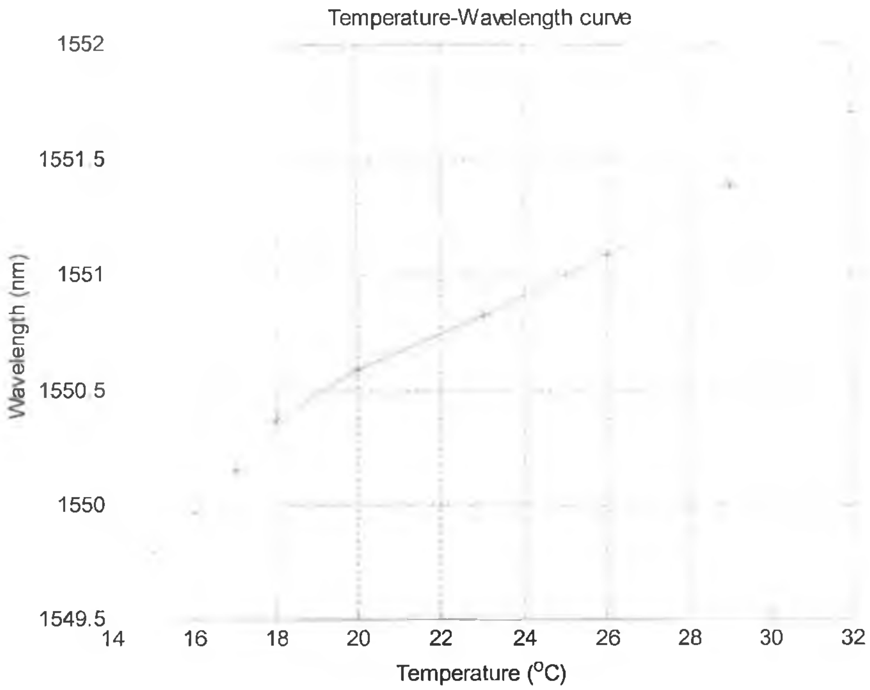

Figure 1-6: Wavelength vs. temperature

Figure 1-2 is the wavelength vs. temperature curve of the same laser. This Figure shows that when the temperature of the laser diode is increasing, the emitted light wavelength will increase [5].

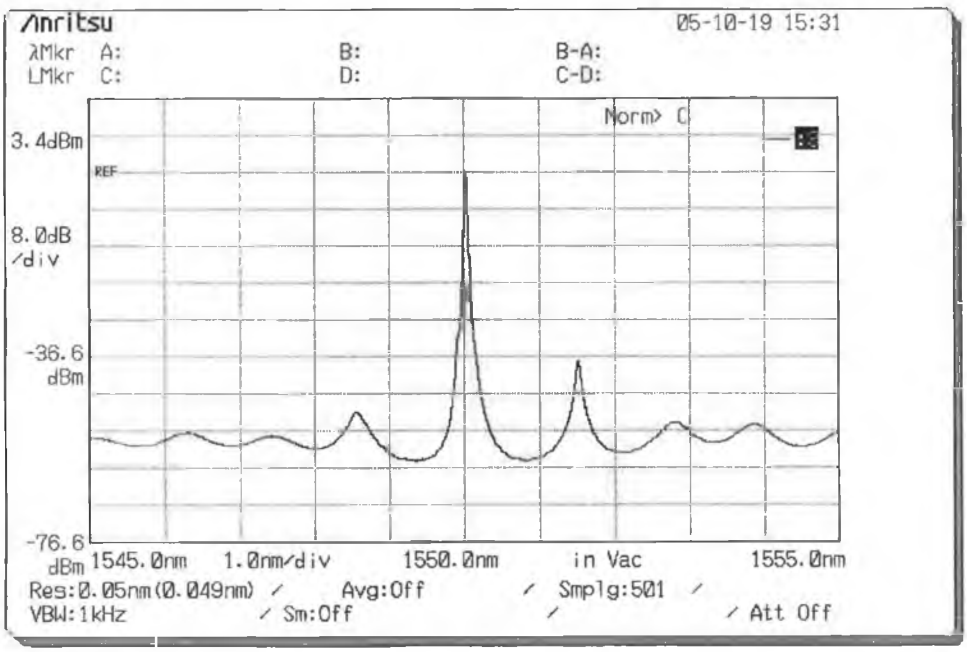

Figure 1-7: The spectrum of a single-mode CW laser

The spectrum of a single-mode CW laser is shown in the Figure 1-3, which gives us a basic concept of the spectrum. The Peak Wavelength is around 1550 nm and the spectral line width is measured to be 0.05 nm. But this is limited by the resolution of the Optical Spectrum Analyzer (OSA) that is used to measure the spectrum. In addition, another important parameter of the signal is the Side Mode Suppression Ratio (SMSR). The SMSR is a ratio between the output power emitted in the strongest mode and that emitted in the second strongest mode and is usually expressed in decibels. The spectrum shown in the Figure 1-3 has a SMSR value of 40 dB.

1.1.2 Optical receiver

An optical receiver is a device that detects an optical signal, converts it to an electrical signal, and processes the electrical signal as required for further use [8]. An optical receiver generally consists of a photodetector [3][4], an amplifier and the signal-processing circuit. Among the semiconductor-based photodetectors, the photodiode is used almost exclusively for fibre optical systems because of its small size, suitable material, high sensitivity, and fast response time. Generally we have two kinds of photodiodes, the PIN photodiode and the APD (avalanche photodiode)[9].

Two fundamental noise mechanisms, shot noise and thermal noise [10][11][12], lead to fluctuations in the current even when the incident optical signal has a constant power. The electrical noise induced by current fluctuations affects the receiver performance. In generally, for PIN photodiodes, the thermal noise currents of the detector load resistor and the active elements of the amplifiers circuitry are the dominant noise sources [13]. For APDs usually the thermal noise is of less importance and the shot noises dominate. An additional noise, known as "excess noise", is the multiplication noise, which describes the statisitical noise that is inherent with the stochastic APD multiplication process.

1.1.3 Channel

In an optical communication system, the channel is set up with single-mode or multimode optical fiber [12]. An optical fiber is a dielectric waveguide that operates at optical frequencies. This fiber waveguide is normally cylindrical in form.

The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the modes of the waveguide. Although many different configurations of the optical waveguide exist, the most widely accepted structure is the single solid dielectric cylinder. This cylinder is known as the core of the fiber and a solid dielectric cladding that has a lower refractive index surrounds the core.

In an optical fiber, if the refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary, then it is called a step-index fiber. In the second case, the core refractive index is made to vary as a function of the radial distance from the centre of the fiber. This type of fiber is graded-index fiber.

The attenuation of an optical fiber measures the amount of light lost between input and output [13]. It is dominated by absorption and scattering within the fiber. Sometimes other effects can cause important losses, such as light leakage from fibers that suffer from severe bending. Attenuation limits how far a signal can travel through a fiber before it becomes too weak to be correctly detected above the noise.

Another importan parameter of optical fiber is dispersion [14], which causes a broading of the data signal. There are generally two sources of dispersion. The first one is material dispersion, which comes from a frequency-dependent response of a material to waves. And the second one is waveguide dispersion [15], which is important only in single-mode fibers, caused by the dependence of the phase and group velocities on core radius, numerical aperture, and wavelength.

Fiber optics has several advantages over traditional metal communication lines. These advantages include:

Long distance signal transmission. The low attenuation and superior signal integrity found in optical systems allow much longer intervals of signal transmission than metallic-based systems. While single-line, voice-grade copper systems longer than a couple of kilometers require in-line signal repeaters for satisfactory performance, it is very usual for optical systems to go over 100 kilometers (km), with no active or passive processing. Emerging technologies promise even longer distances in the future.

Large bandwidth, light weight, and small diameter. Another significant advantage is that the fiber optic cables have a much greater bandwidth than metal cables, which means that they can carry more data. Fiber optic cables are also less susceptible than metal cables to interference. Furthermore, the fiber optic cables are much thinner and lighter than metal wires.

Non-conductivity and security. Another advantage of optical fibers is their dielectric nature. Since optical fiber has no metallic components, it can be installed in areas with electromagnetic interference (EMI), including radio frequency interference (RFI). Areas with high EMI include utility lines, power-carrying lines, and railroad tracks. All-dielectric cables are also ideal for areas of high lightning-strike incidence.

The dielectric nature of optical fiber makes it impossible to remotely detect the signal being transmitted within the cable. The only way to do so is by actually accessing the optical fiber itself. Accessing the fiber requires intervention that is easily detectable by security surveillance. These circumstances make fiber extremely attractive to governmental bodies, banks, and others with major security concerns.

1.1.4 Basic network information rates

Early applications of fiber optical transmission links were largely for trunking of telephone lines. These were digital links consisting of time-division-multiplexed 64 kb/s voice channels. In the North America, the fundamental rate is 1.544 Mb/s transmission rate known as T1 rate. It is formed by the time-division multiplexing of 24 voice channels, each digitised at a 64 kb/s rate. Framing bits are added along with these voice channels to yield the 1.544 Mb/s bit stream. The multiplexed rates are designed as T1 (1.544 Mb/s), T2 (6.312 Mb/s), T3 (44.736 Mb/s) and T4 (274.176 Mb/s). Similar hierarchies using different bit-rate levels are employed in Europe and Japan [4].

With the advent of high-capacity fiber optical transmission lines in the 1980s, service providers established a standard signal format called SONET (synchronous optical network) in North America and SDH (synchronous digital hierarchy) in other parts of the world [4]. These standards define a synchronous frame structure for sending multiplexed digital traffic over optical fiber trunk lines. Table 1-1 shows the commonly used SONET and SDH transmission rates.

SONET level	Electrical level	Line rate (Mb/s)	SDH equivalent
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-192	STS-192	9953.28	STM-64

Table 1-1. Commonly used SONET and SDH transmission rates

1.2 Fundamentals of radio communications

1.2.1 Radio frequency spectrum

Radio frequency (RF) refers to any frequency within the electromagnetic spectrum associated with radio wave propagation. When an RF current is supplied to an antenna, an electromagnetic field is created that is able to propagate through space [16][17].

When classified by frequencies, radio waves are expressed in kilohertz (KHz), megahertz (MHz) and gigahertz (GHz). RF signals range from extremely low frequency (ELF), to extremely high frequency (EHF). See Table 1-2 for the details of the radio frequency spectrum.

Band name	ITU band	Frequency	Wavelength	Example uses
Extremely low frequency (ELF)	1	3–30 Hz	100,000 km – 10,000 km	
Super low frequency (SLF)	2	30–300 Hz	10,000 km – 1000 km	
Ultra low frequency (ULF)	3	300–3000 Hz	1000 km – 100 km	
Very low frequency (VLF)	4	3–30 kHz	100 km – 10 km	Military communication
Low frequency (LF)	5	30–300 kHz	10 km – 1 km	Navigation, time signals, AM long wave broadcasting
Medium Frequency (MF)	6	300–3000 kHz	1 km – 100 m	AM broadcasts
High Frequency (HF)	7	3–30 MHz	100 m – 10 m	Short wave broadcasts and amateur radio
Very high frequency (VHF)	8	30–300 MHz	10 m – 1 m	FM and television broadcasts
Ultra high frequency (UHF)	9	300–3000 MHz	1 m – 100 mm	Television broadcasts
Super high frequency (SHF)	10	3–30 GHz	100 mm – 10 mm	Microwave devices, mobile phones, wireless LAN
Extremely high frequency (EHF)	11	30–300 GHz	10 mm – 1 mm	wireless communications

Table 1-2. Radio frequency spectrum

1.2.2 Antenna

Antennas are required for launching RF signals within radio communication systems. Electrons accelerating in the antenna generate radio waves. The most basic antenna is called "a quarter wave vertical"; it is a quarter wavelength long and is a vertical radiator. Typical examples of this type would be seen installed on motor vehicles for two-way communications. Technically the most basic antenna is an "isotropic radiator". This is an idea antenna that radiates in all directions, as does the light from a lamp bulb [18].

Depending upon how the antenna is orientated physically determines its polarisation. A vertical antenna is said to be "vertically polarised" while an antenna erected horizontally is said to be "horizontally polarised". Other specialized antennas exist with "cross polarisation", which have both vertical and horizontal components; and we can have "circular polarisation". Note that when a signal is transmitted at one polarisation but received at a different polarisation there exists a significant loss [19].

Antenna impedance is the ratio at any given point in the antenna of voltage to current at that point. Depending upon height above ground, the influence of surrounding objects and other factors, a quarter-wave antenna with a near perfect ground exhibits a nominal input impedance of around 36 ohms. A quarter wave antenna with drooping quarter wave radials exhibits nominal 50 ohms impedance, one reason for the existence of 50-ohm coaxial cable [20], to ensure good matching.

A half wave dipole antenna is nominally 75 ohms input impedance while a half wave folded dipole antenna is nominally 300 ohms. The two previous examples indicate why we have 75-ohm coaxial cable and 300-ohm ribbon line for TV antennas.

1.2.3 Radio Wave propogation in free space

Radio propagation is a term used to explain how radio waves behave when they are transmitted, or are propagated from one point on the Earth to another.

In free space, all electromagnetic waves (radio, X-rays, visual, etc) obey the inverse-square law which states that an electromagnetic wave's energy strength is proportional to $1/(x^2)$, where x is the distance from the source. Doubling the distance from a transmitter means the energy strength is reduced to a quarter, and so on.

Radio propagation on Earth is not only affected by the inverse-square model, but by a number of other factors determined by its path from point to point. This path can be a direct line of sight path or an over-the-horizon path aided by reflection from the ionosphere. A variety of phenomena make radio propagation more complex and somewhat unpredictable.

Before electromagnetic energy in the form of radio waves propagates outward from a transmitting antenna, the high frequency radio wave will be propagated inside the transmitter and the receiver with transmission lines. In the next sub-section, we will discuss the limitation about the traditional transmission media when they are used to transfer RF signals.

1.2.4 Limitation of traditional transmission media - propagation phenomenon of traditional transmission lines

RF links serve important functions in many applications such as communications, signal processing and radar functions. However, at high frequencies, microwave signals transmitted over the coaxial cables experience extremely large attenuation [4]. Thus using the traditional media for transmission of microwave and millimeter wave signals is not feasible.

In wireless communication systems, transmission lines are essential components since they are employed to connect transmitters to receivers or antennas, acting as resonant elements in oscillators and filters, used for impedance matching in mixers and amplifiers, and so on.

Circuit analysis assumes that the electrical wavelengths are much bigger than the physical dimensions of a network. Unfortunately, this condition is not fulfilled for microwave signals. Thus a transmission line has to be considered as a distributed-parameter network, where the magnitudes and phases of voltages and currents can change over the length of the line. Here we will begin the analysis of transmission lines with a circuit model for an incremental length of line.

Since transmission lines usually consist of two parallel conductors, a transmission line may be schematically represented as a two-wire line. As shown in Figure 1-4, a short segment dx of transmission line is modeled as a lumped-element circuit. In this figure, the definition and unit of R, L, G and C are as below:

R: series resistance per unit length, in Ω/m.
G: shunt conductance per unit length, in S/m.
L: series inductance per unit length, in H/m.
C: shunt capacitance per unit length, in F/m.

R represents the resistance due to the finite conductivity of the conductors and L represents the total self-inductance of the two conductors. G is the result of the dielectric loss in the material between the conductors and C is due to the close proximity of the two conductors. Hence, R and G represent loss.

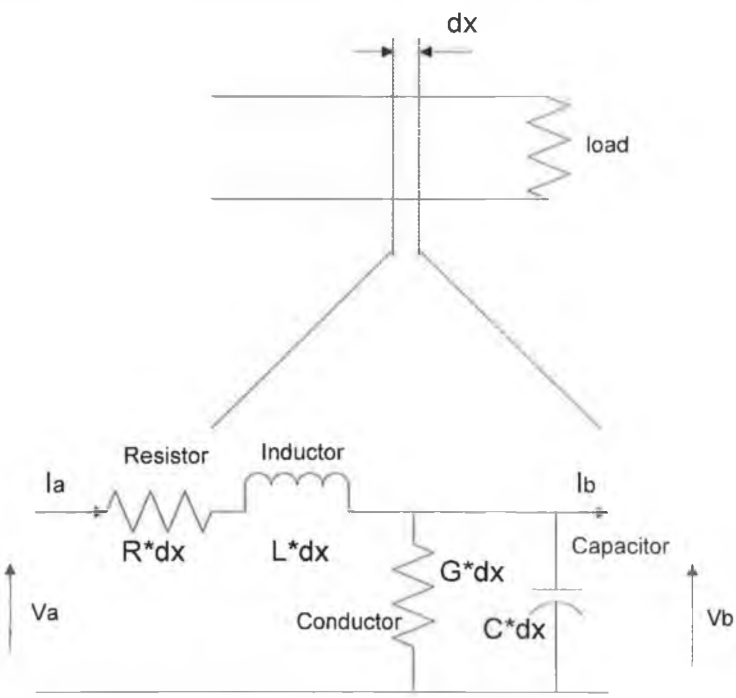

Figure 1-8: Lumped-element equivalent circuit of a transmission line

The wave equation for either Voltage V or Current I are given below:

$$\frac{d^2V(x)}{dx^2} - \gamma^2 V(x) = 0, \tag{1-1}$$

$$\frac{d^2I(x)}{dx^2} - \gamma^2 I(x) = 0, \tag{1-2}$$

where γ is the complex propagation constant and it is expressed as:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}, \tag{1-3}$$

in which ω represents the frequency, α is the attenuation constant and β is the phase constant. This expression shows that the attenuation constant α is proportional to the frequency ω.

From equation (1) and (2) we can obtain travelling wave solutions:

$$I(x) = \frac{V_0^+}{Z_c} e^{-\gamma x} - \frac{V_0^-}{Z_c} e^{+\gamma x}, \tag{1-4}$$

$$V(x) = V_0^+ e^{-\gamma x} + V_0^- e^{+\gamma x}, \tag{1-5}$$

where Z_c is the impedance of the propagation line, $V_0^+ e^{-\gamma x}$ represents forward solution and $V_0^- e^{+\gamma x}$ represents for the backward solution.

Let us assume sinusoidal signals are transmitted in the line, therefore, from (1-4) and (1-5) we get the formula for the input impedance:

$$Z_{in} = Z_c \frac{Z_l + jZ_c \tan(\beta l)}{Z_c + jZ_l \tan(\beta l)}, \tag{1-6}$$

where Z_l is the impedance of the load.

If βl <<1 then tan(βl)~0. In this case $Z_{in} \approx Z_l$, which conducts the usual limit:

When $l > \lambda / 20$, we should take into account the propagation effect of lines, while when $l < \lambda / 20$, there is no need to consider it. From the above it can be seen that, when the transmission frequency approaches up to 5 GHz, 2mm is the maximum length for which conductors can be considered as simple connections!

After analyzing the propagation phenomenon through the traditional coaxial cables above, we know that the attenuation is proportional to the frequency, which imposes a bandwidth limit for high-speed electrical transmissions. On the other hand, optical fiber communications have shown up to overcome the drawbacks of traditional electrical transmissions since with optical fiber the attenuation is only about 0.2 dB/km and it is independent of data rate. Thus it is of interest to employ optical fiber for transmission RF signals since the optical fiber can handle higher and higher demands of RF signal transmission.

1.2.5 Introduction of current wireless standards

Wireless communications is entering a new phase where the focus is shifting from voice to multimedia services. Present consumers are no longer interested in the underlying technology; they simply need reliable and cost effective communication systems that can support anytime, anywhere, any media they want. The driving force for this development is the expected dramatic increase of demand for broadband services over the next decade [19]. In 1990 the Institute of Electrical and Electronics Engineers (IEEE) formed working group 802.11 to develop a standard to govern local area network (WLANs). Since then the standards for personal area networks (WPAN) and the wireless metropolitan area network (WMAN) have been added to the standard group. Since these standards are demanding higher and higher bandwidths, higher bandwidth media is demanded for new wireless services, hence there has been an increasing emphasis upon research on radio over fiber (RoF) technology over the past few years.

Here we introduce the latest IEEE standards of wireless access networks, including the WLAN, the WPAN and the WMAN. From these latest standards we can see the demand for higher and higher bandwidth, which may result in the need to transmit the RF data signals through optical fiber form central stations to remote sites.

IEEE 802.11: Wireless Local Area Networks (WLAN) standard

The IEEE 802.11 Wireless local area network (WLAN) standard covers both the medium access control (MAC) sub-layer and the physical (PHY) layer of the open system interconnection (OSI) network reference model. In 1997, IEEE provided three kinds of options in the PHY layer, which are an infrared (IR) baseband PHY, a frequency hopping spread spectrum (FHSS) radio and a direct sequence spread spectrum (DSSS) radio. All these options support both 1 and 2Mbps PHY rates. In 1999, the IEEE has developed two high rate extensions: (1) 802.11b based on DSSS technology, with data rates up to 11Mbps in the 2.4GHz band, and (2) 802.11a, based on orthogonal frequency division multiplexing (OFDM) technology, with data rates up to 54Mbps in the 5GHz band. In 2003, the 802.11g standard that extend the 802.11b PHY layer to support data rates up to 54Mbps in the 2.4GHz band has been established. In addition, several other 802.11 standardization activities are ongoing. 802.11h aims to enhance 802.11a with adding indoor and outdoor license regulations for the 5GHz band in Europe. The 802.11n is a new task group that proposes a high-throughput amendment to the 802.11 standard. It will support at least 100Mbps rate, as measured at the interface between MAC and higher layers. It may choose multiple-input multiple-output (MIMO) antenna and adaptive OFDM as main PHY technologies. At the MAC sub-layer, 802.11e will extend to enhance the quality of service (QoS) performance of 802.11 WLAN. The 802.11f defined an Inter-Access Point protocol to allow stations roaming between multi-vendor access points [20] [21].

IEEE 802.15: Wireless Personal Area Networks (WPAN) standard

The IEEE 802.15 Working Group for Wireless Personal Area Networks (WPAN) was formed to develop standards for short-range wireless networks. This group is closely following the emerging industry specifications such as Bluetooth and Ultra wideband (UWB). Below the details of Bluetooth and the UWB are described.

Bluetooth. Bluetooth is designed to operate in a noisy and potentially interfered radio frequency environment. It allows any sort of electronic equipment - from computers and cell phones to keyboards and headphones - to make its own connections. In the ISM band (The Industrial, Scientific and Medical radio bands which originally reserved internationally for non-commercial use of RF electromagnetic fields for industrial, scientific and medical purposes), a set of 79 hop carriers separated by 1 MHz has been defined. A binary Gaussian frequency shift keying (GFSK) modulation scheme is applied in order to reduce cost and device complexity and a symbol rate of 1 Mb/s can be achieved for an occupied bandwidth of about 1 MHz [22].

UWB. A UWB system transmits signal across a much wider frequency band than conventional systems. The bandwidth of the UWB signal is at least 25% of the center frequency. Thus, a UWB signal centered at 2 GHz would have a minimum bandwidth of 500 MHz, and the minimum bandwidth of a UWB signal centered at 4 GHz would be 1 GHz. The most common technology for generating a UWB signal is to transmit pulses with durations less than 1 nanosecond [23]. The UWB RF signals typically have short ranges in outdoor and indoor environments since the power level is regulated to –41 dBm/MHz across most part of the 3.1 to 10.6 GHz spectra. Although UWB is typically in short ranges, the RoF networks can distribute the RF signals into the rooms of homes or offices [24].

IEEE 802.16: Wireless Metropolitan Area network (WMAN) standard

IEEE Standard 802.16 was for wireless metropolitan area network (WMAN). The standard was approved in 2001, addressing frequencies from 10 to 66 GHz, where extensive spectrum is currently available worldwide. A newer project completed an amendment denoted IEEE 802.16a at 2003. This document extended the air interface support to lower frequencies in the 2–11 GHz band, including both licensed and license-exempt spectra. Compared to the higher frequencies, such spectra offer the opportunity to reach many more customers with less expense, although at generally lower data rates. It suggests that such services will be oriented toward individual homes or small to medium-sized enterprises [25].

802.16, the latest entry in the wireless networking technology pantheon, is an up and coming contender as a wireless alternative to digital subscriber lines (DSL), cable modems, leased lines, and other broadband network access technologies. Intel has already pledged to develop a silicon product based on the 802.16 standard, and it claims equipment based on its chips will have a range of up to 30 miles and the ability to transfer data, voice, and video at speeds of up to 70 Mbps.

1.2.6 RoF technology meets the demand of increasing bandwidth

New wireless subscribers are signing up at an increasing rate demanding more capacity while the radio spectrum is limited. As a result, wideband radio links will become more prevalent in today's communication systems. In traditional systems, RF signals are transmitted and distributed electronically via electrical coaxial cables and waveguides. Nevertheless, due to the large attenuation of these media, RF transmission encounters big problems at Super high frequencies and Extremely high frequency (as we already know, the wireless communication spectrum occupies from the SHF to the EHF).

On the other hand, it is well known that optical fibers have become pervasive in telecommunication systems, whether in traditional fixed line networks, or wireless networks of the future. Although the two technologies are different, we can see how their individual advantages may be utilized as telecommunication network architectures evolve to merge the two. To satisfy the increasing demand of wireless spectrum, the high capacity of optical networks should be integrated with the flexibility of radio networks.

RoF is a very effective technology for integrating wireless and optical access. It combines the two media; fiber optics and radio, and is a way to easily distribute broadband radio frequency signals over fiber. Large distances between the Base Station (BS) and the antenna sites are possible and the overall network topology can be cost-optimized beyond what is possible with traditional feeder cabling.

1.3 Conclusion

In this chapter, we introduced the fundamental of the optical fiber transmission and the radio frequency transmission, discussed their advantages and disadvantages. Then, the introduction about the wireless communication is presented.

Since the wireless subscribers are signing up at an increasing rate, and the service is shifting from voice to video, the demand for bandwidth keeps rising. Radio over Fiber (RoF) technology should be important for the distribution of high capacity data signal. This kind of RoF system provides good synergy between optics and radio. Furthermore, it is an efficient means for these two seemingly disparate technologies to merge. In the following chapter, we will introduce the RoF systems and the components used in these systems in detail, and discuss the benefits of RoF systems.

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Chapter 2

Overview of Radio over Fiber distribution networks

In this chapter, we examine the main radio over fiber (RoF) techniques and their applications. First, an introduction of RoF is given, followed by a detailed description of the components (oscillators, transmitters and receivers) used in the RoF systems. In the third section, the modulation techniques are presented. Then we introduce the efforts to overcome chromatic dispersion effects in RoF transmission systems. The fifth section shows the use of advanced techniques in RoF systems. Finally, we end with the emerging applications of RoF technology.

2.1 What is RoF technology

The concept of Radio over Fiber (RoF) means to transport information over optical fibre by modulating the light with the radio signal. It is a technology used to distribute RF signals over analog optical links [1]. This modulation can be done directly with the radio signal or at an intermediate frequency. RoF is the integration of wireless and optical networks and it is a potential solution for increasing capacity and mobility as well as decreasing costs in the access network. It offers the advantages of low loss, huge bandwidth, high security, and immunity to electromagnetic interference. The RoF systems are expected to use frequencies ranging from around 2.5 GHz up to 60 GHz. Frequencies from 18 GHz and above are especially attractive for high capacity networks due to the large bandwidth available for data transfer.

In such RoF systems, broadband microwave data signals are modulated onto an optical carrier at a central location, and then transported to remote sites using optical fiber. The base-stations then transmit the RF signals over small areas using microwave antennas [2]. In addition, since it enables the generation of millimetre-wave signals with excellent properties, and makes effective use of the broad bandwidth and low transmission loss characteristics of optical fibers, it is a very attractive, cost-effective and flexible system configuration.

RoF can be used in the backbone of a wireless access network. Such a technology is expected to play an important role in present and future wireless networks since it provides an end user with a truly broadband access to the network while guaranteeing the increasing requirement for mobility. By using this technology, the capacity of optical networks can be combined with the flexibility and mobility of wireless access networks. RoF systems shift the system complexity away from the remote base station antenna and toward a centralized radio signal processing installation. In a RoF link, laser light is modulated by a radio signal and transported over an optical fiber medium. The modulation may occur at the radio signal frequency or at some intermediate frequency if frequency conversion is utilized.

The RoF technology enables the generation of millimetre-wave signals with excellent properties. Those signals can easily be distributed via optical fibers, since a major advantage of a RoF system is its low transmission loss rate, especially for long distance and at high frequencies [2]. For optical fiber communications, the low attenuation windows at 1.3 um and 1.55 um have bandwidths around 0.1 um. If these optical bandwidths are converted to frequency range, it is approximately equivalent to a total bandwidth of 30000 GHz [3].

The basic configuration of an analog fiber optic link consists of a bi-directional interface containing the analog laser transmitter and photodiode receiver located at a base station or remote antenna unit, paired with an analog laser transmitter and photodiode receiver located at a radio processing unit. One or more optical fibers connect the remote antenna unit to the central processing location.

As shown in Figure 2-1, future millimeter wave access networks are likely to employ an architecture in which signals are generated at a central control station and then distributed to remote sites using single-mode optical fibers. Signals are generated at a central control station and then distributed to remote sites using single-mode optical fibers. The control station, which can feed many remote sites, is responsible for optical-electrical (o/e) and electrical-optical (e/o) conversions, as well as up-conversion, down-conversion, and processing of the electrical data signals. At the remote sites, only o/e and e/o converters are employed; the o/e converters convert optical signals received from the control station to RF signals and then forward them using the antennas to the end users; the e/o converters convert the RF signals from the antennas to optical signals that are then transmitted to the control station. Such an architecture should prove to be highly cost efficient, since it allows sharing the transmission and processing equipments (located in the central control station) between many remote sites [4].

Note that the RoF system is an analog transmission system since it distributes the RF data signals directly on an optical carrier. But the radio system itself may be digital because the radio carrier can be modulated with digital modulation schemes to carry digital signals, such as phase shift keying (PSK), quadrature amplitude modulation (QAM) and code division multiple access (CDMA) [5].

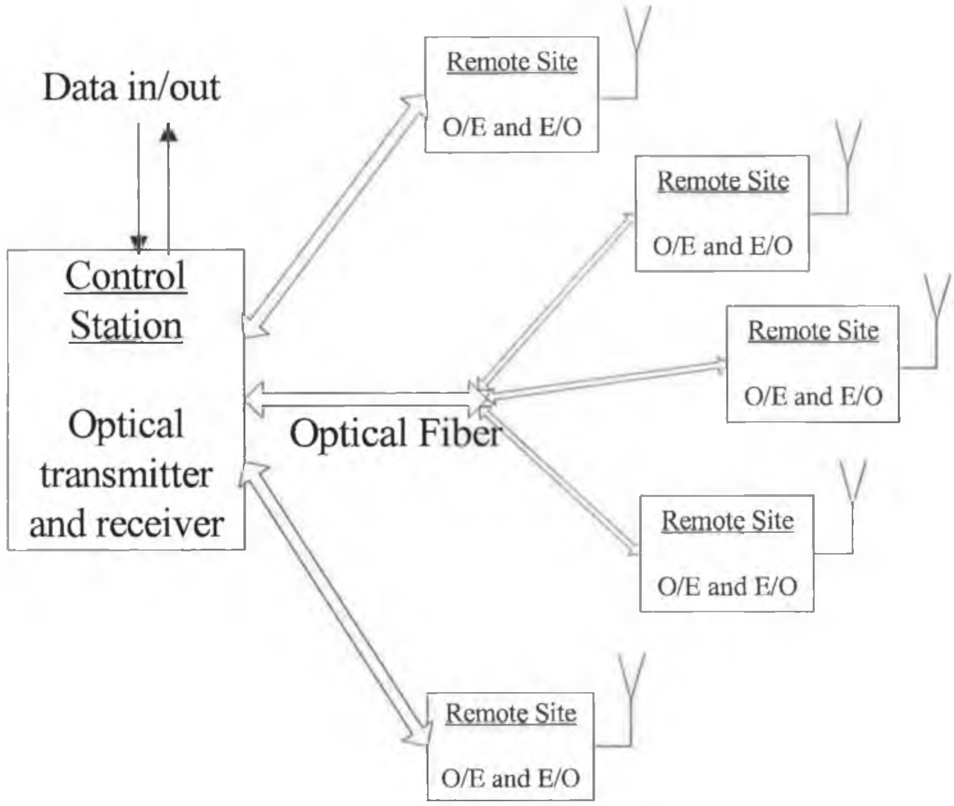

Figure 2-1: A basic RoF system structure

2.2 Components in RoF transmission systems – oscillators, transmitters and receivers

Oscillators, transmitters and receivers are three important components in the RoF distribution system, since they can build the basic point-to-point structures as the media for the data transmissions.

2.2.1 Oscillators

High quality RF oscillators play an important role in RoF systems providing reference signals to establish or select particular transmission channels. Unfortunately, traditional electronic RF oscillators cannot meet all the requirements of RoF systems since these systems involve RF signals in both optical and electrical domains. Note that the definition of optical domain RF signal is an optical wave modulated by a signal at RF, or an optical sub-carrier at RF.

Opto-electronic oscillator (OEO) is an alternative class of oscillators compared with traditional electronic RF oscillators since it meets the special requirements for RoF systems by generating RF signals in both optical and electrical domains [6]. The most common OEO is an active feedback loop in the form of a single loop oscillator based on converting the continuous light energy from a pump laser to stable and spectrally pure RF signals [7]. The OEO is characterized by significantly low noise and very high stability, as well as other functional characteristics that are not achieved with the electronic oscillator.

2.2.2 Optical transmitters

As for optical transmitters, we are primarily interested in injection laser diodes (ILD). ILD's output is coherent and highly monochromatic, and these devices can have modulation bandwidths up to 40 GHz [8]. The common commercially used laser diodes include Fabry-Perot (FP) lasers, distributed feedback (DFB) lasers and surface emitting lasers (SEL) [3].

On the other hand, wavelength tunable transmitters, which can change their output wavelengths based on the driving currents or temperatures, are attracting more and more attention. Figure 2-2 shows a star access network set up by a tunable transmitter. In the configuration of this star network, each remote site has a fixed optical filter to select out the wavelength channel destined for it, and the central control station would require a tunable transmitter that can generate N wavelengths (where N is the number of the remote sites).

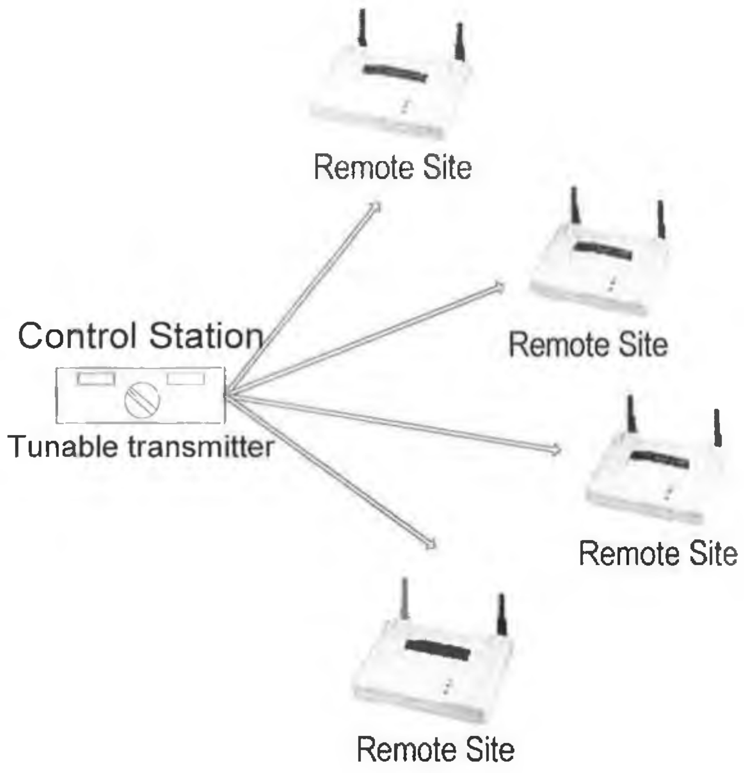

Figure 2-2: Basic structure of a RoF system

Clearly the use of wavelength tunable transmitters at central locations is very beneficial in simplifying the overall RoF networks and reducing the component requirements at the central control locations. Depending on the capacity requirements at any specific time at each remote site, the tunable transmitters could be configured to allocate the dynamically available bandwidth between the different remote sites. We anticipate that an architecture of this type would make network upgrade far easier than a system in which one transmitter with fixed wavelength at the central station is shared in a time division multiple access protocol between network remote sites.

2.2.3 Optical receivers

Generally, an optical receiver consists of an optical detector, usually a photodiode, and an amplifier. The main requirements for the receiver are that it should convert the optical signals to electrical signals efficiently [3]. In the digital applications, the developments of these detectors have evolved around on-off operations. For analog applications, these detectors have to incorporate additional design to ensure high linear dynamic range operation that is essential for the requirement of low distortion.

The characteristic 3-dB cut-off frequency of an optical detector is very important for many analog and digital applications. Notice that the characteristic 3-dB cut-off frequency can vary with optical power in some structures. In the worst case it can be greatly reduced at high power [2].

We know that the quality of the detected signals can be degraded due to the presence of noise. Noise can arise at the transmitter, at the electrical and optical amplifiers, and at the receiver. The addition of noise degrades the signal-to-noise ratio, and ultimately limits the performance of receivers [9]. Recently, great attention has been paid to ensure maximum signal-to-noise ration over a wide range of the detectors' internal resistances [10].

2.3 Modulation techniques used in RoF distribution systems

Modulation is the process of translating an outgoing data stream into a form suitable for transmission on the physical medium. In RoF distribution systems, two types of modulation techniques have been developed to modulate data signals onto the optical carrier, which are direct modulation and external modulation. Direct modulation is the most commonly used method, primarily because it is less expensive and simpler. However, the useful bandwidth of direct modulation is limited by the laser relaxation resonance. We call the frequency before the laser gets stabilized the relaxation oscillation frequency. Many solid-state lasers exhibit relaxation oscillations. As a result, the laser output power oscillates with large amplitude in general either when the laser is first turned on, or when the laser is suddenly perturbed. Relaxation oscillations are caused by interplay between the inversion of the electronic occupation and the intra-cavity signal and pump power.

For the commercially available laser diodes under free-running operation, the cut-off frequencies are usually about 10 GHz, which means that we are normally unable to use higher frequency RF carriers in order to generate high-frequency carrier signal [11]. Another problem with direct modulation of the laser transmitter with the RF data signal is that a change in the laser current also results in a change in the optical frequency, which is called chirping, resulting in frequency modulation on the intensity modulation. This can cause problems for transmission of the optical RF data signals over fiber.

On the other hand, in externally modulated systems, the intensity modulation of an optical carrier is obtained via a modulator connected in series with the laser. Compared with directly modulated laser links, the major advantages of external modulation links include higher speed, higher efficiency, and lower chirp.

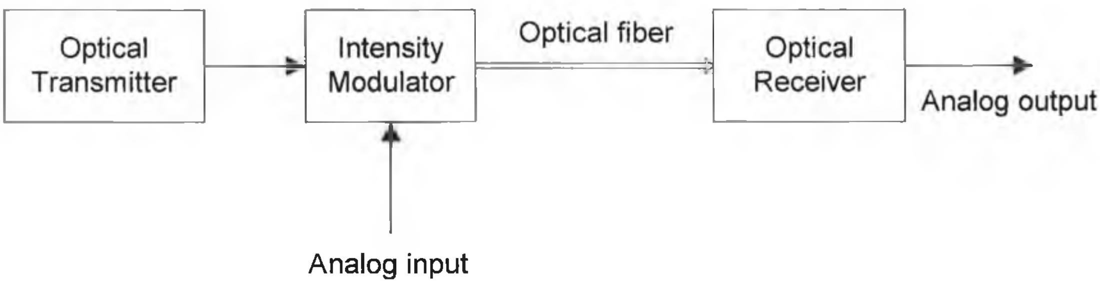

Figure 2-3: IM-DD transmission system (external modulation)

If the optical detector employs direct detection, this type of link is referred to as intensity modulated direct detection (IM-DD), which is the simplest and most cost-effective of the available link types. The optical communication systems based on IM-DD are very popular [12]. Figure 2-3 shows the basic structure of an IM-DD transmission system (external modulation).

For the IM-DD system shown in Figure 2-3, if we assume s(t) denote the analog signal to be transmitted, the optical power at the output of the intensity modulator is [3]:

$$P_o = P_m(1 + ms(t)), \qquad (2\text{-}1)$$

where P_m is the mean optical power and m is the modulation depth.

Two types of external modulators have been extensively studied: Mach-Zehnder (MZ) modulators and electroabsorption (EA) modulators. They are important components for RoF systems because of the maturity of the related technologies. Below we will describe these two modulators in more detail.

2.3.1 Mach-Zehnder (MZ) modulator

The MZ modulator has been in wide use for both analog and long-distance digital applications at this time. Specially, $LiNbO_3$ MZ modulators are widely used because they are relatively tolerant to fabrication errors and can be optimised for low or high frequencies [13]. The simplest form of the $LiNbO_3$ MZ modulator is shown in Figure 2-4 [2].

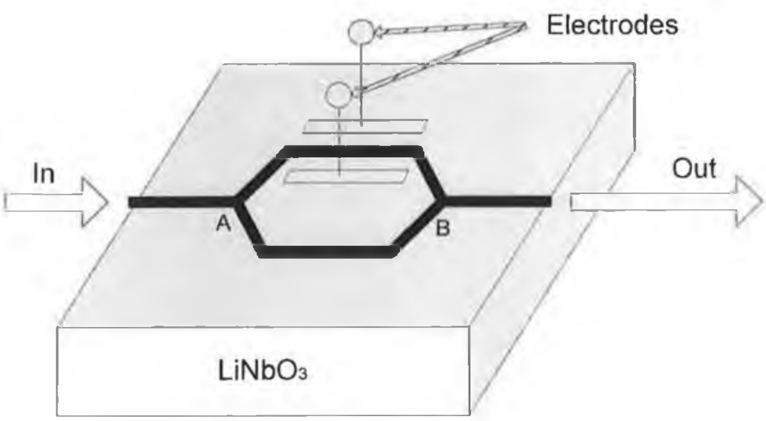

Figure 2-4: Mach-Zehnder (MZ) modulator

As shown in Figure 2-4, the MZ modulator basically consists of two Y junctions. The first one splits the incoming signals into two arms and one of the arms runs between two electrodes. The modulating signal is applied to the electrodes and generates a changing electrical field, changing the refractive index so that the phase of the light passing through the modulation arm will be varied. Hence the phase modulation is converted into intensity modulation after combining the light from both arms of the MZ modulator using the second Y junction.

Note that the total phase difference between the arms will influence the output power. If the lights from the two arms are in phase, they add to form the fundamental mode, thus the output power is at the maximum level. If the lights from the two arms are out of phase, they add in the output Y-branch to form the second order mode. This mode is not guided by the single mode output waveguide, so the power is radiated into the substrate and the output power is at the minimum level [2].

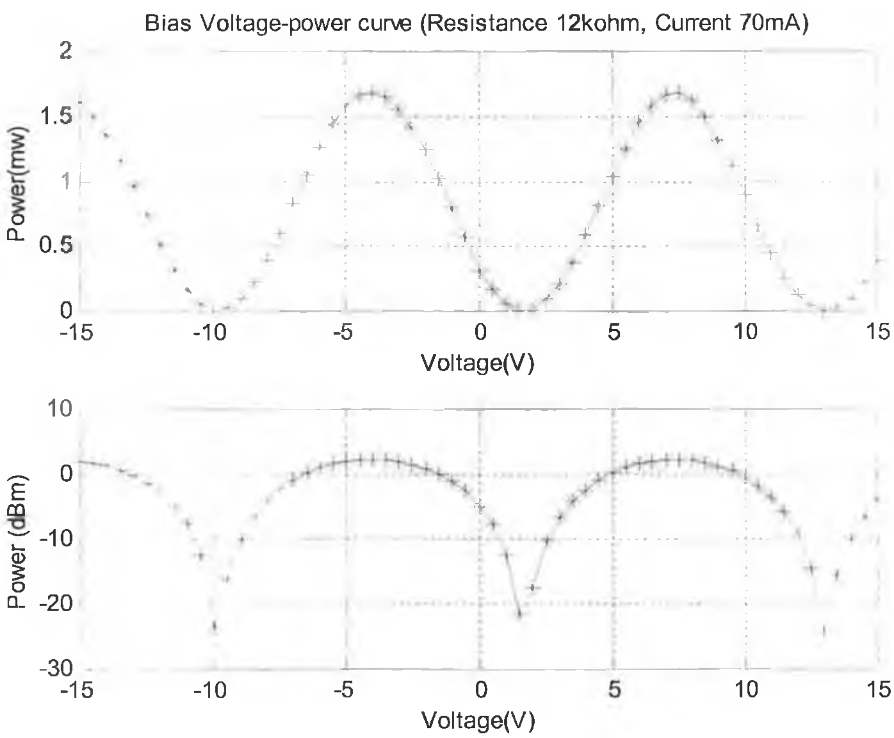

Figure 2-5: DC-bias voltage vs. optical power of a 10 Gb/s MZ modulator

Advanced designs can have two electrode pairs. Hence the two arms can be modified by different signals independently, thus amplitude and phase can be modulated separately in a MZ modulator [14].

More advanced and complicated devices based on MZ modulator also exist, e.g. multi-channel array-type polymeric MZ modulators [15], which can be suitable for wavelength division multiplexing (WDM) networks.

In Figure 2-5 we present the transfer characteristic (DC-bias voltage vs. optical power curves) for a typical OC192 10 Gb/s MZ modulator.

2.3.2 Electroabsorption (EA) modulator

The EA modulators are intensity modulators like the MZ modulators, but they work on EA effect instead. The EA effect means the optical absorption coefficient changes according to the electric field. In an EA modulator, an applied electric field shifts the absorption band edge in such a way that the material becomes opaque to the light at the wavelength of interest. Hence an EA modulator is a semiconductor optical waveguide device in which the degree of optical absorption can be controlled by an applied voltage, and it can only be built in a semiconductor material [2]. It is the modulator of choice for medium speed. Therefore EA modulators have emerged as a viable analog modulator also.

An EA modulator typically consists of a multimode waveguide that contains the multiple quantum well (MQW) structures. It is shown in Figure 2-6 a typical waveguide structure for EA modulators. The waveguide mode is propagating in the z-direction. At its input and output, the waveguide is coupled to single mode fibers. Note that the MQW region is the only undoped region shown as the "*i*" region in figure 2-6; other semiconductor layers are either *p* or *n* doped. A DC bias electric field and a superposed RF electric field are applied to the MQW layers in the x-direction. Since the formation of electron-hole pairs in the quantum well enhances the optical absorption effect, as the electrical field increases, the overlap of the electron and hole wave functions is reduced; thereby decreasing the optical output power [2].

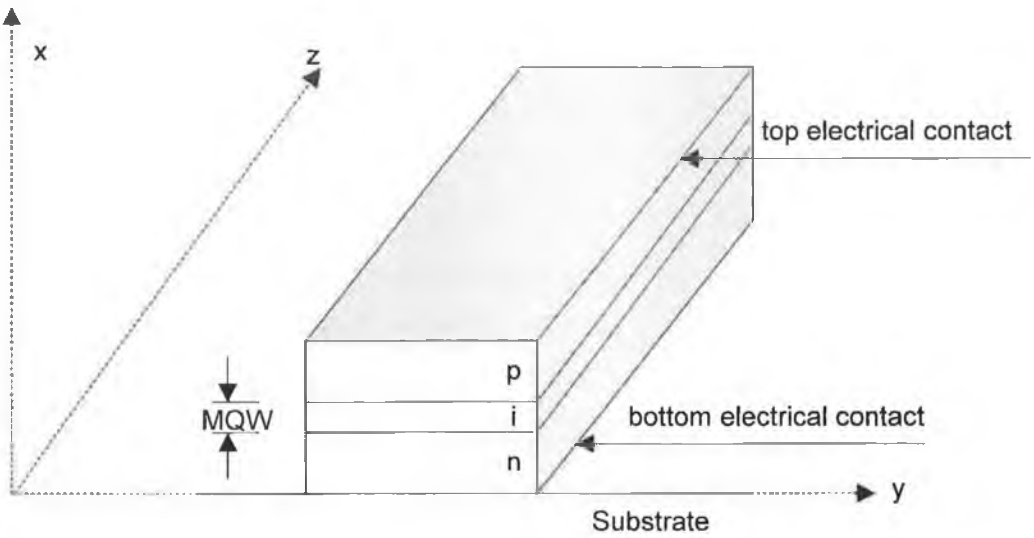

Figure 2-6: The basic structure of an EA MQW modulator

The primary advantages of the EA modulators compared with the MZ modulators in RoF systems are their compactness and their integrability with lasers [16]. We know that EA modulators are typically less than 1mm long, while MZ modulators are normally centimeters long.

Note that the nonlinearity of a modulator can cause distortions and reduce the dynamic range of a RoF system. In a MZ modulator, the transfer curve is a sinusoidal function and is relatively independent of the input optical and RF signal power. Therefore, the dynamic range can be improved by linearization technologies. Unfortunately, an EA modulator has a nonlinear transfer function that is strongly dependent on input optical wavelength and power, which makes linearization fairly difficult and limits the dynamic range of the RoF systems using EA modualtors [17].

In Figure 2-7, we present the transfer characteristic (DC-bias voltage vs. optical power curves) of a typical EA modulator. The transfer characteristic of a MZ modulator is different; the output optical power increases when the input DC bias voltage becomes higher.

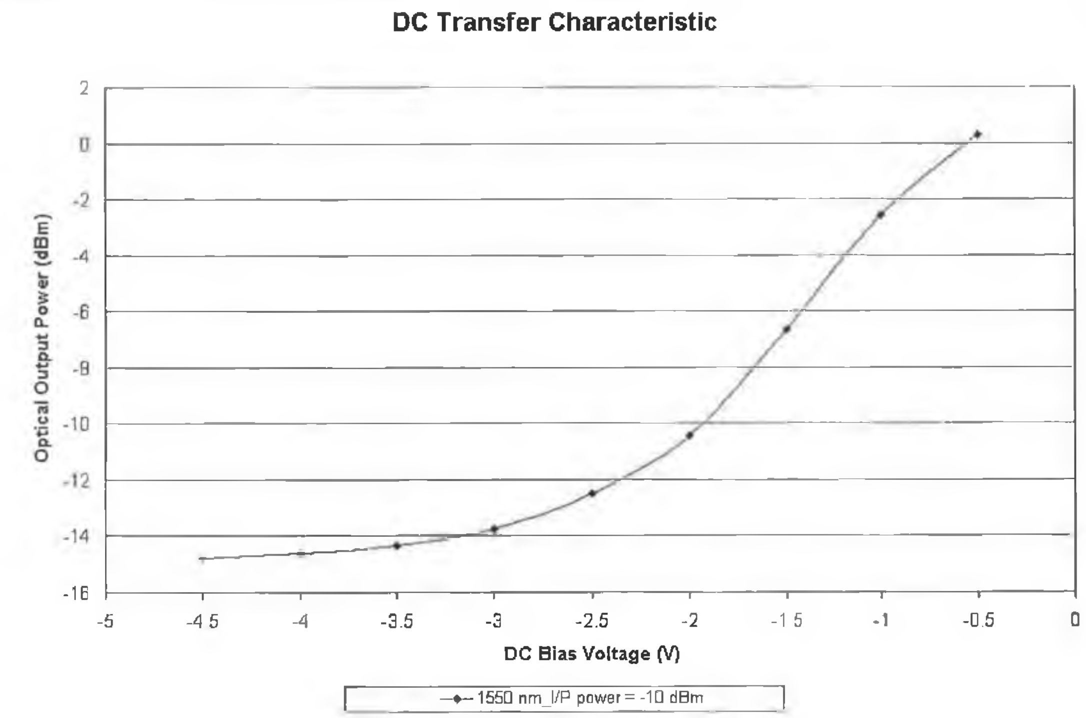

Figure 2-7: DC-bias voltage vs. optical power of an EA modulator

2.4 Chromatic dispersion effects on the transmission of RoF signals

After the generation of the optical RF data signal at the transmitter of a RoF system, it is then necessary to transmit the signal over fiber to the remote antenna site. The main problem encountering during transmission of the RF data signal over fiber is due to the chromatic dispersion of the fiber. Chromatic dispersion (CD) is the broadening of an input optical signal as it travels along the length of the fiber [18]. It is important to consider group delay before an explanation of CD because of their mathematical relationship. Group delay is defined as the first derivative of optical phase with respect to optical frequency while chromatic dispersion is defined as the second derivative of optical phase with respect to optical frequency. These quantities are represented as follows:

$$Group\_Delay = \frac{\partial \phi}{\partial \omega}, \tag{2-2}$$

$$Chromatic\_Dispersion = \frac{\partial^2 \phi}{\partial \omega^2}. \tag{2-3}$$

Where ϕ presents the optical phase and ω is the optical frequency.

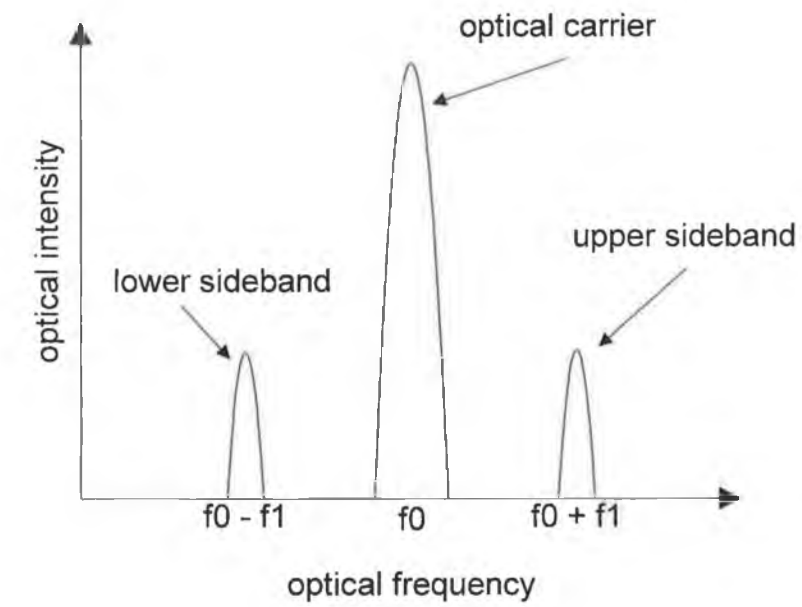

Figure 2-8: The optical spectrum of double sideband

CD consists of both material dispersion and waveguide dispersion. Both of these phenomena occur because different wavelengths will propagate at different speeds along the length of the fiber.

In conventional intensity modulation to generate optical RF data signals, the optical carrier is modulated to generate an optical signal with double sideband (DSB) [19]. Let us assume the frequency of the optical carrier is f0 and the frequency of the RF signal that needs to be modulated onto the optical carrier is f1, the optical spectrum of the DSB signals is displayed in Figure 2-8. However, if the signals are transmitted over the fiber, CD causes each sideband to experience different phase shifts depending on the fiber-link distance and modulation frequency, producing a phase difference between the two beat signals generated at the detector. When the phase difference is π, the RF signals will be completely cancelled out. As the RF frequency or fiber-link distance increases, this effect is even more severe and limits the system performance [18].

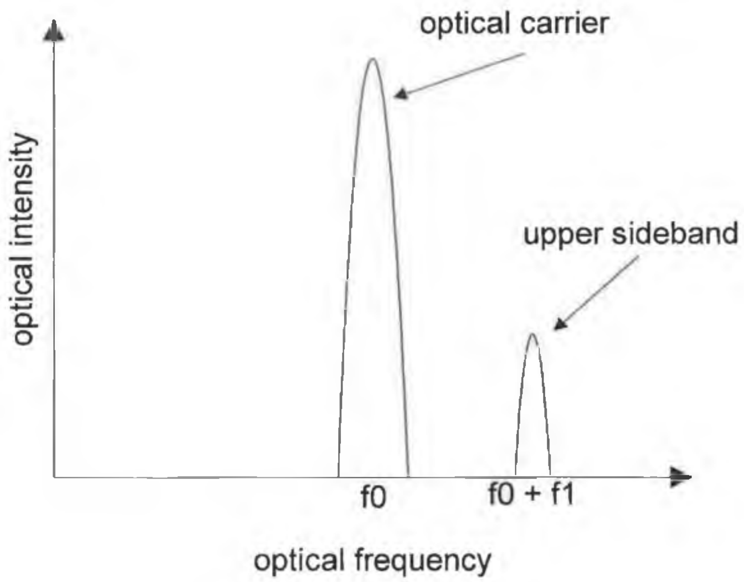

Figure 2-9: The optical spectrum of single sideband

Since CD makes upper and lower sidebands experience different phase shift, it is a critical problem for RF transmission. It has been shown that this phenomenon can significantly limit the transmission distance in IM-DD link operated above 20GHz. For example, in an externally modulated fiber link operated at 20 GHz, the detected RF power degrades 3 dB for a distance of 6 km; while operated at 60 GHz, the detected power degrades 3 dB for only 0.7 km [20]. At 60GHz, with a standard single-mode fiber of dispersion 18 ps/km.nm, a 1 dB penalty is induced after less than 500m transmissions, and the received signal is completed extinct after 1 km [21].

CD effects can be reduced and almost totally overcome in RoF systems by eliminating one sideband to produce an optical carrier with single sideband (SSB) modulation [22], which is called optical single sideband (OSSB) transmission. See

Figure 2-9 for the optical spectrum of the SSB by eliminating the lower sideband. Therefore, transmission of the optical carrier and just one of the sidebands prevents interference and the associated RF power fading. There have been multiple technologies to implement the OSSB transmission. They can be classified into two categories: OSSB modulation methods and filtering methods. These methods make use of Mach-Zehnder modulators [23][24], semiconductor optical amplifiers (SOA) [25], fixed fiber Bragg gratings [26] and wavelength-self-tunable single-sideband filters [27] separately. Table 2-1 shows the classification of these techniques and the details of them are described below.

OSSB modulation methods		Filtering methods	
Employing Mach-Zehnder modulators	Employing Semiconductor Optical Amplifier	Employing Fixed Fiber Bragg Grating	Employing Wavelength-self-tunable single-sideband filter

Table 2-1. Techniques to implement OSSB transmission

2.4.1 Employing Mach-Zehnder modulators

OSSB generation can be achieved by using an external modulator with a negative chirp. The simplest design is based on a dual-electrode MZ modulator. As we already knew, it has two electrodes that can be independently driven so as to vary the chirp parameter of the modulator. When both arms are modulated and the RF phase difference on the two arms is $\pi/2$, one sideband can be cancelled out to generate only one sideband and a carrier [23].

The main drawback of these OSSB modulators is that they rely on nonstandard designs; hence, their deployment could lead to cost or availability limitations. On the contrary, it would be highly desirable to implement OSSB modulation using the simple single-electrode MZ modulator. This technique is based on the application of a novel concept of bi-directional operation of traveling-wave electro-optic modulators (EOM) [24]. Furthermore, it provides suppression of the optical carrier when the modulator is biased for minimum transmission; hence enhancing the optical modulation depth.

2.4.2 Employing Semiconductor optical amplifiers (SOA)

Another way to overcome the CD problem is to use semiconductor optical amplifiers (SOA). In SOA, the phase modulation occurs by a variation of the carrier density due to the change of optical power. This scheme uses the phase modulation effect in a SOA which results $\pi/2$ phase difference between the amplitude and phase terms of modulated optical signals [25]. It is relatively simple to implement, as it requires only a SOA and an electrical phase shifter. And this method provides signal amplification as SOA inherently functions as an amplifier and can be implemented as an integrated device [25].

2.4.3 Employing Fixed fiber Bragg gratings

In RoF incorporating WDM / sub-carrier multiplexing (SCM) star networks, microwave data signals are modulated onto various optical carriers at a central control station, and then distributed to remote sites using optical fibers. In such a system, one optical filter at every remote site will be required to select one of the wavelength channels carrying a specific SCM data signal. Experiments showed that, although the optical signals are DSB, the correct positioning of a Bragg filter at the receiver base-station could not only select one of the wavelength channels, but also eliminate one of the sidebands [26].

2.4.4 Employing Wavelength-self-tunable single-sideband filters

Because the fixed filter has to be critically tuned to the optical carrier frequency, a solution to this limitation has been proposed in the form of self-tunable filters. The self-tunable filter is a wavelength-indepent OSSB filter and it relies on the photo refractive effect in an iron-doped indium phosphide (InP: Fe) crystal [27].

The principle of the device is to take a part of an optical double sideband (ODSB) signal to generate three dynamic Bragg gratings inside the bulk crystal via the photorefractive effect, note that these Bragg gratings can diffract independently of the carrier and one sideband. Simultaneously, the second part of the ODSB signal is injected into the gratings under the appropriate Bragg angle whose value is dictated by the modulation frequency, hence the operating frequency is set to the desired millimeter-wave value by simply adjusting the signal injection angle. In this way, two Bragg conditions are reached that lead to the diffraction of an OSSB signal made up of the carrier and the lower sideband of the input signal [27].

2.5 Advanced transmission techniques in RoF systems

2.5.1 WDM technique

WDM is a high-speed digital communication technique that simultaneously transports optical signals of different wavelengths over a single strand of fiber. WDM creates different channels by dividing a frequency band into smaller bands. In the commonly used 1550nm wavelength area, when the frequency difference is 100GHz, the wavelength difference is about 0.8 nm. The latest version of WDM, Dense WDM (DWDM), achieves higher capacity by dividing a wavelength-band into even more channels. Note that ultra-dense WDM with the channel spacing comparable to the data rate is commonly referred to as optical frequency-division multiplexing (OFDM).

The capability to deal with the large amount of data capacity of the WDM/DWDM transmission technique can be applied to the millimeter-wave RoF systems [28]. With the use of WDM/DWDM method in RoF systems, a different wavelength channel may be employed to feed each remote site, which offers a number of advantages in terms of simplified upgrade and management of the radio networks [29].

2.5.2 SCM technique

Optical SCM is a modulation scheme where multiple signals are multiplexed in the RF domain and transmitted on a single optical carrier [30]. This technique is basically a radio-frequency multiplexing technique that implies a second level of multiplexing: the spectrum is divided into bands/channels with a central carrier or frequency, which are also divided in sub-bands/sub-channels with its corresponding sub-carriers. One attractive feature of SCM is that it provides a way of exploiting the huge bandwidth potential of high-speed lasers using conventional and established microwave techniques. And SCM may act as a means of realising simple and economical multi-channel systems that have the ability to support a wide range of analog and digital services; hence it has found widespread applications.

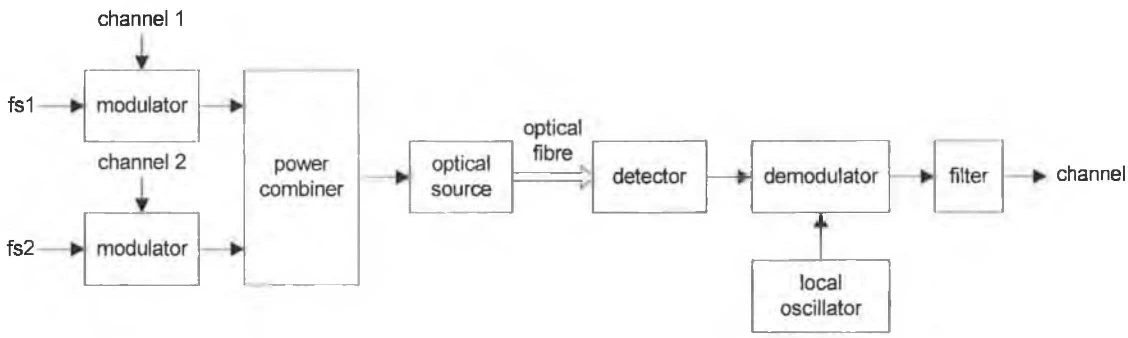

Figure 2-10: Sub-carrier multiplexing (SCM) system

Figure 2-10 illustrates the example block diagram of a SCM system. In this system we have two SCM signals modulated to an optical wave at the frequency f0. The optical spectrum of this system is shown in Figure 2-11.

WDM combined with SCM is a practical and attractive way to increase the channel capacity in existing optical fibers [31]. Since SCM systems can be combined with WDM/DWDM networks, it provides a flexible platform for high-speed optical transport networks to utilize the bandwidth of single-mode fibers [32].

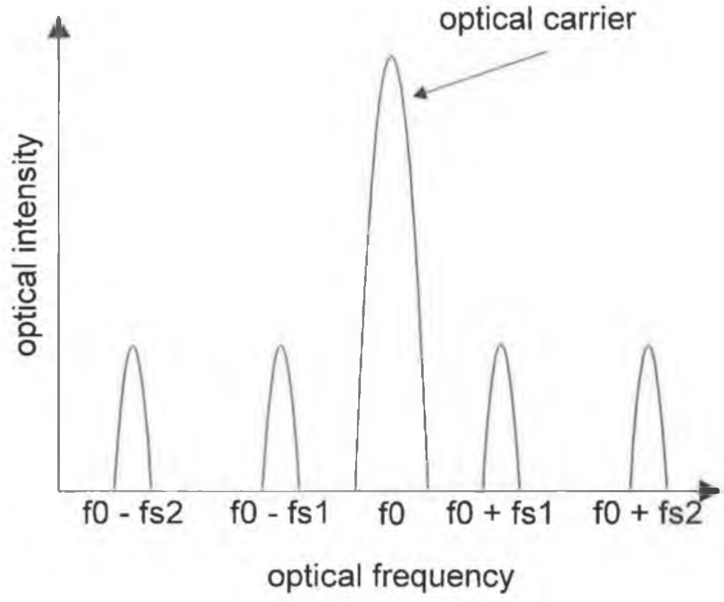

Figure 2-11: The optical spectrum of sub-carrier multiplexing (SCM)

2.5.3 Wavelength interleaving method

Because the bandwidths of the subcarrier-multiplexed signals are much narrower than the carrier frequencies [33], it is difficult to fully utilize the optical spectra in WDM/SCM RoF systems. Hence Wavelength interleaving is a promising scheme to increase the optical spectral efficiency in RoF systems.

In a wavelength-interleaved RoF system, the multiple WDM channels and their corresponding OSSB are multiplexed together via a wavelength-interleaved multiplexer (WI-MUX). In this way, wavelength interleaving allows spacing less than twice the highest modulation frequency for every channel. The interleaved channels are then optically transported to the antenna remote site and the remote site selects the desired optical carrier and the corresponding sideband using a wavelength-interleaved optical add-drop multiplexer (WI-OADM) [34].

Wavelength interleaving allows an optical network to achieve a spectral efficiency greater than what can be obtained with standard WDM channel spacing of 50, 100 or 200 GHz. But we should note that, in a RoF system using small channel spacing, the risk of interference is high, thus a sharp cut-off of the demultiplexing filter is a requirement [35].

2.6 RoF applications

RoF technology has been successfully demonstrated in a variety of applications, especially in wireless access networks. It is well known that broadband wireless access is regarded as one promising technology to achieve broadband multimedia services. As the demand for broadband services such as video/audio on demand and mobile computing increases, so does the need to develop high bandwidth wireless access networks. Therefore, next generation wireless access systems should operate in the high frequency band. Those future networks are likely to use microwave radios, operating at frequencies from 10 GHz up to 100 GHz as the access media. In order to develop this type of network it is anticipated that optical fibers will be required for distributing the microwave data signals from a central control station to the remote sites.

RoF technology can be implemented with all types of wireless network applications currently in use, such as wireless personal area network (WPAN), wireless local area network (WLAN) and wireless metropolitan area network (WMAN). For these wireless networks, generally the basic optical trunk topology can be star, ring or mesh networks.

Since the bandwidths of optical fibers are immense, and the optical techniques of WDM/DWDM are well evolved, one fiber can serve very different services simultaneously and these different services can be transmitted via different wavelengths. On the other hand, the data generated by those services and dependent on their origins (mobile or fixed wireless access networks) and formats (narrowband or broadband), would be converted on different RF carriers. Thus RoF can be regarded and applied as a transfer network of universal use.

In Figure 2-12, a multi-service system is schematically shown in which the optical trunk network may be a star, ring or mesh network. This RoF network thus serves different kinds of wireless access applications based on the different demands for the bandwidths, distances and power supplies. We demonstrated in this figure a multi-service RoF network, which is composed of a WAPN, a WLAN and a WMAN.

In a hybrid radio/fiber network, the transfer is realized via RoF technology. The ideal physical layer should be composed of two sub-layers: conventional wireless sub-layer and the optical sub-layer. The optical sub-layer would be a transparent layer positioned below the wireless sub-layer, and one fiber-based network example is Passive Optical Networks (PON). As such it would operate transparently with both current and future wireless standards [36].

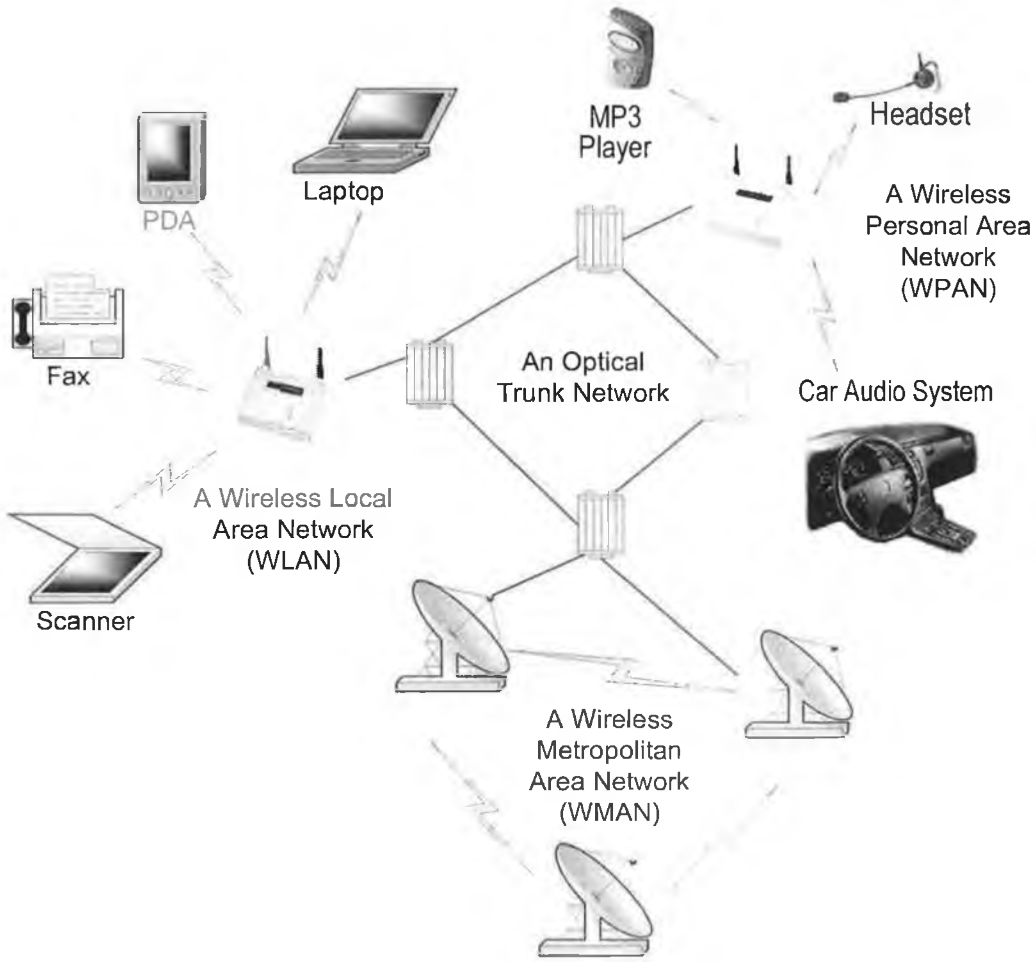

Figure 2-12: A multi-service RoF network

On the other hand, since there have been a lot of copper cables already set up in current communication networks, a transitional measure of RoF is to utilize some of the existing cables by the combination of the optical fibers and the cables - Hybrid Fiber Cable (HFC). HFC is to replace the long cascade cable trunks with optical fibers and keep the residential area cables. This technique can be established to be a competitive means to support wide varieties of narrowband and broadband services to residential users [37]. Narrowband applications include high-speed data, telephone, and interactive video services and broadband applications include broadcasting multi-channel digital TV in HFC networks [2].

One example of HFC-based applications is Hybrid Coax Air (HCA) radio channel. It provides low cost networks for distribution of RF signals, and is introduced in relation to wireless applications [38]. In order to simplify the wireless systems, the authors in [38] propose to build hybrid networks that provide wireless access by carrying signals over the existing Community Antenna Television (CATV) infrastructure implemented at the HFC architecture. With this structure, the IEEE 802.11 WLAN signals [39] are coupled together with CATV data and transmitted using optical fiber from the CATV centre to optical nodes. At these optical nodes they are launched into the coaxial cables and sent to antennas where they are forwarded over the air to the end users.

2.7 Conclusion

Future communication expectations are very likely to expand their optical fiber infrastructures more and more into the wireless access networks. RoF transmission systems, characterised by having elements of free-space radios and optical fibers, are expected to find an increasing role in telecommunication networks over the next decade, due to their abilities to provide operational benefits in a variety of applications such as a wireless periphery to an optical fiber network infrastructure.

Since the broadband wireless access is regarded as an excellent technology to combine with the RoF technology to build the next generation RF networks, in the preceding sections, we have provided a comprehensive up-to-date survey of RoF technology. In this chapter, a brief explanation on the technical background for understanding how RoF systems are implemented - starting from components and ending with applications - were described.

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Chapter 3

Transmission limitations due to dispersion and non-linearity in Radio-over-Fiber distribution systems

As we already know, when the signals are transmitted over fiber, chromatic dispersion causes each side band to experience a different phase shift. If the phase difference at the receiver equals π , the two side bands interfere destructively causing fading of the received RF signal. Using an optical filter to filter out one side band can thus reduce chromatic dispersion effects.

Another problem in RoF systems may come from Stimulated Brillouin Scattering (SBS). SBS is an interaction between light and sound waves in the fiber, which causes frequency conversion and reversal of the propagation direction of the light. It is the decay of an incident (pump) light wave into a frequency-downshifted (Stokes) light wave and an acoustic wave [1].

SBS severely limits the optical power that could be transmitted through a fiber and it is detrimental for optical communication systems. It can also be reduced by the filtration carried out at the transmitter (pre-filtering). Since the optical filter functions to eliminate one sideband and induces insertion loss (about 2 dB), the optical power to be launched into the transmission fiber falls sharply and so does the risk of SBS. In this chapter, we investigate the possibility of performing SSB filtering to simultaneously overcome the effects of dispersion and SBS in the transmission fiber. The results show that the pre-filtering can filter out one side band to overcome dispersive fading effects, as well as reduce the effect of SBS.

3.1 Chromatic Dispersion Induced Fading Effect

Chromatic dispersion is the broadening of an input optical signal as it travels along the length of the fiber. Chromatic dispersion phenomenon occur because different wavelengths propagate at different speeds along the fiber. The concept to consider when talking about chromatic dispersion should be optical phase.

Chromatic dispersion caused fading of the microwave signals is a critical problem for RF transmission. It can be reduced and almost totally be overcomed in RoF systems by eliminating one sideband to produce an optical carrier with single sideband (SSB) modulation [4], which is called optical single sideband (OSSB) transmission. Therefore, transmission of the optical carrier and just one of the sidebands prevents interference and the associated RF power fading. In addition, it is possible to employ optical filtering at the remote site to eliminate one side band after signal transmission and improve the quality of signal significantly [7].

3.2 Nonlinear effects

Normally light waves or photons transmitted through a fiber have little interaction with each other, and are not changed by their passage through the fiber (except for absorption and scattering). However, there are exceptions arising from the interactions between light waves and the material transmitting. These processes generally are called nonlinear effects because their strength typically depends on the square (or some higher power) of electric field strength. This means that nonlinear effects are weak at low powers, but can become much stronger when light reaches high intensities. This can occur either when the power is increased, or when it is concentrated in a small area-such as the core of an optical fiber [8]. Even though the nonlinearities in optical fibers are small, they may accumulate as light passes through many kilometers of fiber.

Nonlinear effects are comparatively small in optical fibers transmitting a single optical channel. They become much larger when dense wavelength-division multiplexing (DWDM) packs many channels into a single fiber. DWDM puts many closely spaced wavelengths into the same fiber where they can interact with one another. It also multiplies the total power in the fiber.

Several nonlinear optical effects normally limit the optical power level that can be employed in RoF distribution systems. This limitation may cause difficulties in RoF systems that require large transmission powers, such as un-amplified links with large distances between central and remote sites, or systems in which optical splitters are used at certain points in the link to serve multiple remote sites. The non-linear effects responsible for this limitation include Stimulated Brillouin and Raman Scattering (SBS and SRS), Self-Phase Modulation (SPM), cross-phase modulation and Four-Wave Mixing, etc. In the following section, the main nonlinear effects in fiber will be introduced.

3.2.1 Self-phase modulation

Self-phase modulation is the change of phase in optical pulse due to the change in refractive index caused by the pulse. Since the refractive index of glass varies slightly with the intensity of light passing through it, so changes in signal intensity cause the speed of light passing through the glass. This process causes intensity modulation of an optical channel to modulate the phase of the optical channel that creates it, which is called self-phase modulation.

When the optical power rises and falls, these phase shifts also effectively shift the frequencies of some of the light; the shifts are in opposite directions at the rising and falling parts of the pulse. The overall result is to spread the bandwidth of the optical channel.

The spectral broadening caused by self-phase modulation produces dispersion-like effects, which can limit data rates in some long-haul communication systems, depending on the fiber type and its chromatic dispersion. For ultrashort pulses (pulse lasts less than one picosecond) with very high peak powers, self-phase modulation can be very strong, generating a broad continuum of wavelengths [8].

3.2.2 Cross-Phase modulation

Cross-Phase modulation is a nonlinear phase changing due to power variations in adjacent channels. It can strongly impact system performances. Systems carrying multiple wavelength channels are vulnerable to cross phase modulation as well as self-phase modulation. In this case, variations in the intensity of one optical channel cause changes in the refractive index and affect other optical channels. These changes modulate the phase of light on other optical channels, in addition to self-phase modulation of the same channel [8].

3.2.3 Four-wave mixing

Four-wave mixing is a nonlinear effect arising from a third-order optical nonlinearity, and it is a phase-sensitive process. Normally multiple optical channels passing through the same fiber interact with each other very weakly. However, these weak interactions in glass can become significant over long fiber-transmission distances. The most important is four-wave mixing in which three wavelengths interact to generate the fourth one. Four-wave mixing is one of a broad class of harmonic mixing or harmonic generation processes. The phenomenon is that two or more waves combine to generate waves at a different frequency that is the sum or difference of the signals that are mixed. Second-harmonic generation (or frequency doubling) is common in optics; it combines two waves at the same frequency to generate a wave at twice the frequency (half the wavelength). This can happen in optical fibers, but the second harmonic of the 1550 nm band is at 775 nm, far from the communications band, so it doesn't interfere with any signal wavelength [8].

Four-wave mixing may accumulate especially when chromatic dispersion is very close to zero. As we know, pulses transmitted over different optical channels at different wavelengths will stay in the same relative positions along the length of the fiber if the signals experience near-zero dispersion. This amplifies the effect of four-wave mixing, and builds up the noise signal. This problem led to abandonment of zero dispersion-shifted fibers, and the zero-dispersion point has to be moved out of the erbium-fiber amplifier band from 1530 to 1625 nm.

3.2.4 Stimulated Raman scattering

Stimulated Raman scattering (SRS) is a nonlinear effect in fiber-optical transmission that results in signal amplification if optical pump waves with the correct wavelength and power are launched into the fiber. When light waves interact with molecular vibrations in a solid lattice, the Stimulated Raman scattering occurs. In simple Raman scattering, the molecule absorbs the light, then quickly re-emits a photon with energy equal to the original photon, plus or minus the energy of a molecular vibration mode. This has the effect of both scattering light and shifting its wavelength. When a fiber transmits two suitably spaced wavelengths, stimulated Raman scattering can transfer energy from one to the other. In this case, one wavelength excites the molecular vibration, and then light of the second wavelength stimulates the molecule to emit energy at the second wavelength. The Raman shift between the two wavelengths is relatively large, which is about 13 terahertz (100 nm in the 1550-nanometer window), but it can produce some crosstalk between optical channels. In addition, it can deplete signal strength by transferring light energy to other wavelengths outside the operating band [8].

3.2.5 Stimulated Brillouin Scattering Effect

Stimulated Brillouin scattering (SBS) is a nonlinear scattering effect based on acoustic phonons. It occurs when the incident pump wave generates acoustic waves through the process of electrostriction and the sound waves cause vibrations in the glass lattice that makes up the fiber core [9]. In other words, SBS occurs when signal power reaches a level sufficient to generate tiny acoustic vibrations in the glass [8]. This can occur at powers as low as a few milliwatts in single-mode fiber. Acoustic waves may change the density of a material, and thus alter its refractive index. The resulting refractive-index fluctuations can scatter light, which is called Brillouin scattering. Since the light wave being scattered may generate the acoustic waves itself, the process is called stimulated Brillouin scattering.

Brillouin scattering directs part of the signal back toward the transmitter and effectively increasing attenuation. As input power increases, the fraction of power scattered in the opposite direction rises sharply, and the fiber essentially becomes saturated. The small frequency shift effectively confines the effect to the optical channel generating the effect at present channel spacing, so it does not create crosstalk with other channels. However, it does limit the maximum power a single length of fiber can transmit in one direction.

In this chapter we focus on investigating the SBS effect and propose a method to overcome the SBS effect since it is likely to have the lowest threshold in systems employing lasers with narrow linewidths. Once the Brillouin threshold is reached, SBS occurs in the fiber, reflecting parts of the input powers launched into the optical fiber and the power is converted into the backward-traveling light, which is named the Stokes wave [10]. The SBS process induces optical power fluctuations that may degrade the Q factor and consequently the bit error rate (BER) of an optical communication system. As a result, SBS limits the performance of RoF systems and the fiber-input power should normally be kept below the Brillouin threshold [11].

As we already know, SBS occurs due to acousto-optic fluctuations in the fiber. The incident pump wave generates acoustic waves through the process of electrostriction, which in turn causes a periodic modulation of the refractive index [12]. Once the Brillouin threshold is reached, a large part of the pump power is transferred to the Stokes wave [13]. The effect is strong when the light pulse is long (allowing a long interaction between light and the acoustic wave), or the laser linewidth is very small.

The process of SBS can be described classically as a parametric interaction among the incident pump wave, the Stokes wave, and the acoustic wave. The pump-induced index grating scatters the pump light through Bragg diffraction [13]. Scattered light is downshifted in frequency because of the Doppler shift associated with a grating moving at the acoustic velocity. Hence, a Stokes wave is generated downshifted from the frequency of the incident pump wave and the frequency shift is determined by the nonlinear medium.

The same scattering process can be viewed quantum-mechanically as if annihilation of an incident pump photon creates a Stokes photon and an acoustic phonon simultaneously. Since both the energy and the momentum must be conserved during each scattering event, the frequencies and the wave vectors of the three waves are related by

$$\varpi_A = \varpi_p - \varpi_s \,. \tag{3-1}$$

$$k_A = k_p - k_s \,, \tag{3-2}$$

Where ϖ_A, ϖ_p and ϖ_s are the frequencies of the acoustic wave, the incident pump wave and the Stocks wave; k_A, k_p and k_s are the wave vectors of the acoustic wave, the incident pump wave and the Stocks wave, respectively [12].

In a single-mode optical fiber the only relevant directions are only the forward and the backward directions. When the scattering angle θ = *pi,* the shift reaches the maximum value. Therefore, the one-dimensional guiding nature of optical fibers only allows observation of the Stokes wave in the backward direction. The frequency difference between the incident wave and the Stokes wave υ_B is given by

$$\upsilon_B = \frac{2nV_A}{\lambda_p}, \tag{3-3}$$

where λ_p, n, and V_A are the wavelength of the incident pump, the refractive index of the core, and the sound velocity inside the material, respectively [14]. If we use the values appropriate for silica fibers, such as V_A = 5.96 km/s and n=1.45, we obtain υ_B = 11.1 GHz at λ_p = 1.55 µm [15].

The criterion for the Brillouin threshold is arbitrarily defined as the input optical pump power (P_{fiber}) at which the backward Stokes power (P_{Stokes}) is equal to P_{fiber} at the fiber input [16]. If the pump laser is assumed to have a finite linewidth of Δv_P, and the Stokes wave linewidth is given by Δv_B, then the Brillouin threshold for Continuous Wave (CW) light is given by [17]:

$$p_{thr}^{CW} \approx 21\frac{A_{eff}K}{g_o L_{eff}}(\frac{\Delta v_B + \Delta v_P}{\Delta v_B}), \tag{3-4}$$

where L_{eff} is the effective interaction length given by

$$L_{eff} \equiv (1-e^{-\alpha L})/\alpha, \tag{3-5}$$

A_{eff} is the effective core area of the fiber, α is the fiber loss (dB/m), g_o is the peak Brillouin gain coefficient (g_o= 4.6*10^{-11} m/W), L is the length of the fiber, and K is the polarization factor ($1 \le K \le 2$), which accounts for polarization scrambling between the pump and the Stoke waves [11].

In the case of narrow linewidth with $\Delta\nu_B \geq \Delta\nu_P$, (3-6) can be reduced to (for CW light):

$$p_{thr}^{CW} \approx 21\frac{A_{eff}K}{g_o L_{eff}}. \qquad (3\text{-}6)$$

Under proper conditions (generally when the optical power reach 10 dB), SBS will be the dominant nonlinear process since the Brillouin threshold is so low for practical use. It converts the transmitted signal in the fiber to a backward scattered one, decreasing the quality of the signals that are transmitted in the fiber, and thus sets a limit on the total fiber injected power [12].

3.3 Simulation with VPItransmission 5.5

In this section, we use VPItransmissionMaker 5.5, which is photonic design simulation software to simulate a RoF distribution system. Using these simulations can allow us to understand some of the basic limitations of radio-over-fiber distribution systems. Indeed, since using the simulation parameters can easily change the simulation environments, we can obtain results that are difficult to get with experiments.

3.3.1 The simulation set-up

The simulation set-up is shown in the Figure 3-1. A 155.520 Mbit/s NRZ data signal (passed through a low-pass filter to minimize the bandwidth of the data) is first mixed with an 18 GHz carrier to generate binary phase-shift keyed (BPSK) data signal that is used to directly modulate a single mode laser diode with wavelength around 1550 nm. The optical signal is then launched into a 12 km optical fiber reel. At the receiver, the signal is then detected and down-converted to base-band data using another mixer and the 18 GHz carrier. Finally the resulting data is monitored on an oscilloscope. We use two optical power meters in the simulation set-up to measure the power to be propagated in the fiber and the power at the photodiode.

This simulation set-up was a post-attenuator, an attenuator is placed after the optical fiber reel, so that the optical power propagated in the fiber reel is generally high, and the optical power at the photodiode will fall down to an appropriate range which is suitable for the linear regime of the photodiode.

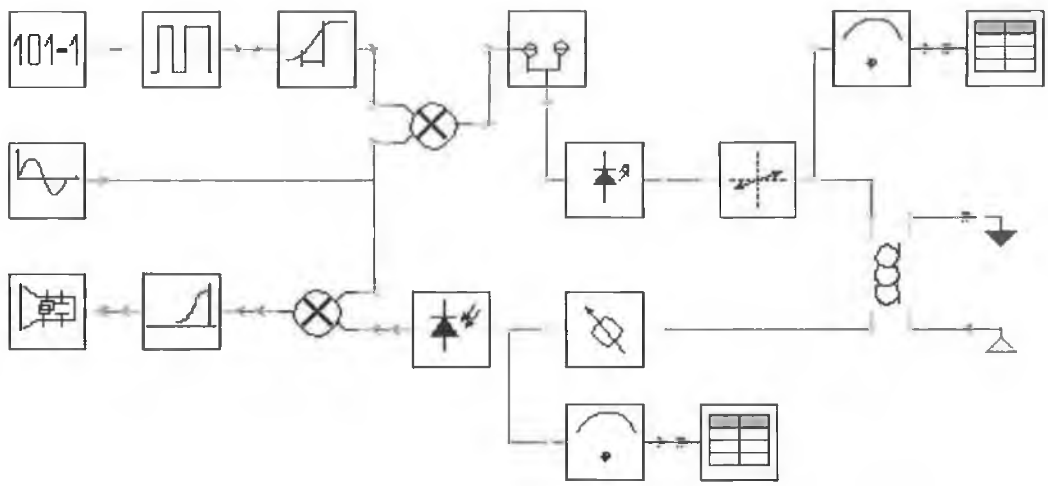

Figure 3-1: The simulation set-up with post-attenuator

3.3.2 Global Parameters set up

In order to run the simulation, first we set some global parameters for the simulation environment.

(1) Bit rate default
We have defined the data signal at the speed at 155.520 Mbit/s.

(2) Sample rate default
Since higher sample rate may lead to more accurate result, we tend to choose high sample rate. On the other hand, the CPU speed limitation brings us a restriction to the set-up. In this simulation, we choose 2^{10} times of bit rate, which is 1024 *163e6 bits/s = 166912 e6 Hz.

(3) Time window

From bit rate we can get the time for a bit to pass through, which is 1/bit rate. We should set the time window big enough for the software to get enough signal information to analyze, and we still suffered from the CPU limitation of the computer (If we set the time window large, it will take long time for the computer to get the simulation result). The trade-off time window, we set it as 128/bit rate.

(4) Sample Mode Center

This parameter is the set-up of the wavelength. Since we simulate on the wavelength 1550 nm, we get 193.1e12 Hz by converting this value to Hz.

3.3.3 Individual device parameters set-up

Setting the parameters of the individual devices.

(1) Sine wave generator

Sine wave generator is used as our carrier wave, which generates a high frequency sine wave to be mixed with our data signal to move the spectrum of the base band signal to high frequency band. Here we set the frequency as 18e9 Hz, which is exactly 18 GHz.

(2) NRZ coder

The NRZ coder is an important device in the simulation since it is the source of the data. It generates Non-return-to-zero data in the shape of square wave, which will be compared with the result data passing through the transmission system to get the result of Bit Error Rate (BER). We define the data speed for the NRA coder as 155.520 Mbit/s.

(3) Optical attenuator

We set the attenuation as 10 dB for the optical attenuator. During our simulations, no mater where we place the optical attenuator (in front of the fiber reel or after the fiber reel), we will not change this value. In this way the results of different simulations can be compared.

(4) Fiber reel

The "fiber reel" acts as the transmission channel in our simulation; hence it is a very important device. We choose this "UniversalFiber" because it offers us to change the Brillouin scattering effect, which can be chosen to set as "on" or "off". Furthermore, we set the length of the fiber reel as long as 12 km.

3.3.4 Simulation and Results

First, let us examine the spectrum. In the simulation, we put an Optical Spectrum Analyser (OSA) after the ideal linear polarizer, and get the spectrum of the optical microwave signal generated by direct modulation of the laser (shown in the figure 3-2). The spectrum of the optical signal shows a standard double-sideband-signal (DSB) with 18 GHz distances between the carrier and the sidebands, which is due to the carrier frequency (18 GHz) of the sine wave generator.

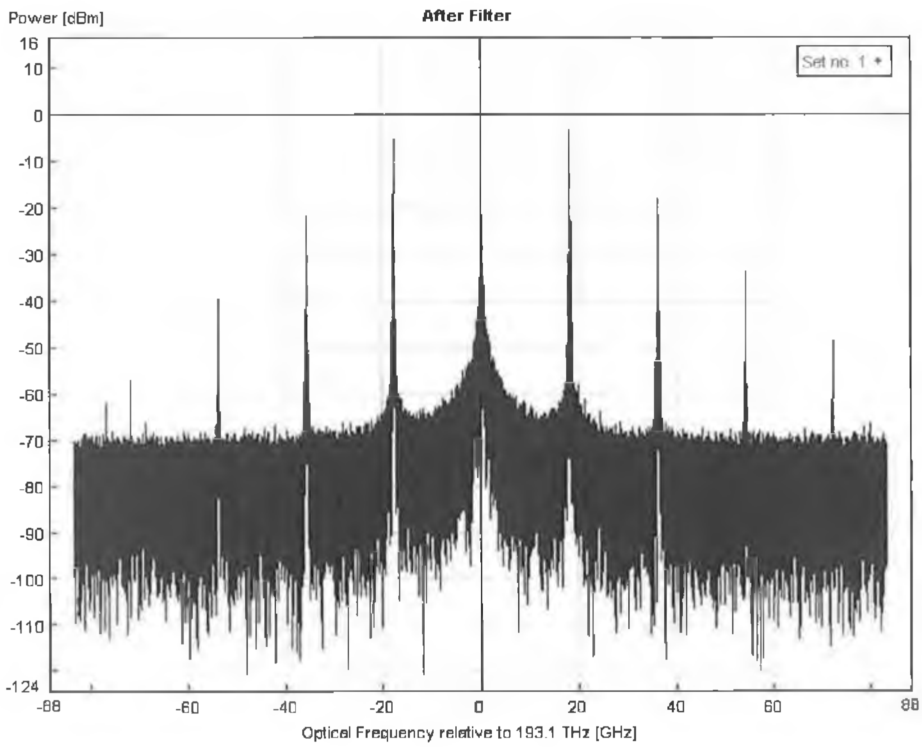

Figure 3-2: Optical Spectrum of the carrier and sidebands

In the RoF systems, since the generated optical microwave signals are usually in the DSB format (as in this case), the two sidebands will propagate through the fiber with different speed and cause dispersion fading effects. Figure 3-3 is a graph from VPI, which shows how the received RF power of a DSB signal (18 GHz carrier) varies with propagation through different lengths of standard fiber. As we can see, after propagation through specific lengths of fiber the RF power is significantly reduced due to dispersive fading. To overcome this effect we may use an optical filter to generate a single-sideband-signal

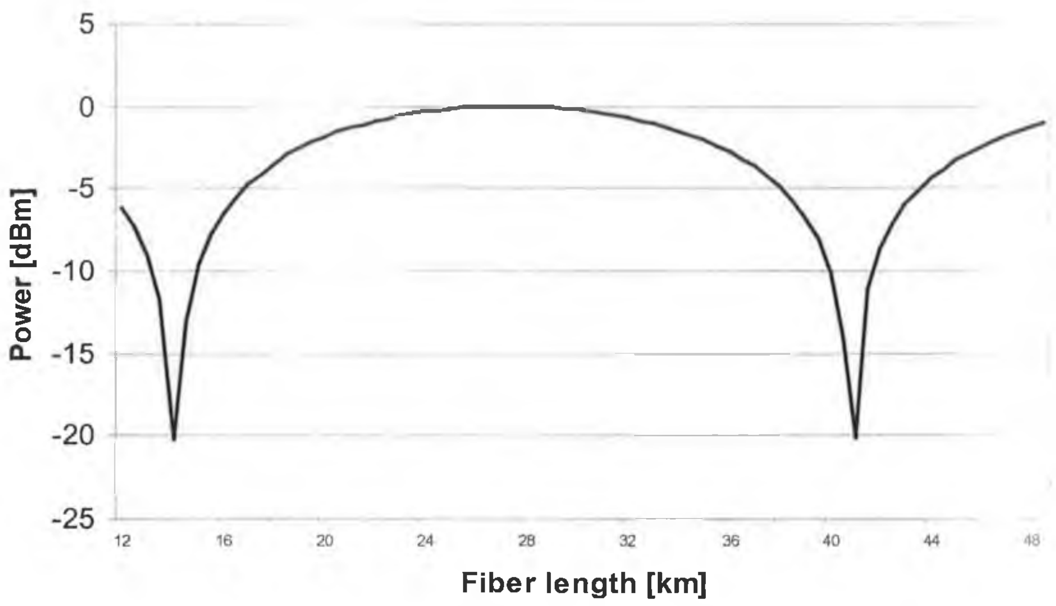

Figure 3-3: Dispersive fading effect

When we consider the SSB effect, during the simulation we can change the situation by setting the SBS parameter of the fiber reel "off" or "on. The simulated result eye-diagram is shown below in the Figure 3-4 and Figure 3-5. At both cases the power of the optical microwave signal to be launched into the fiber reel is 14.3 dBm, which is high enough to induce the SBS effect.

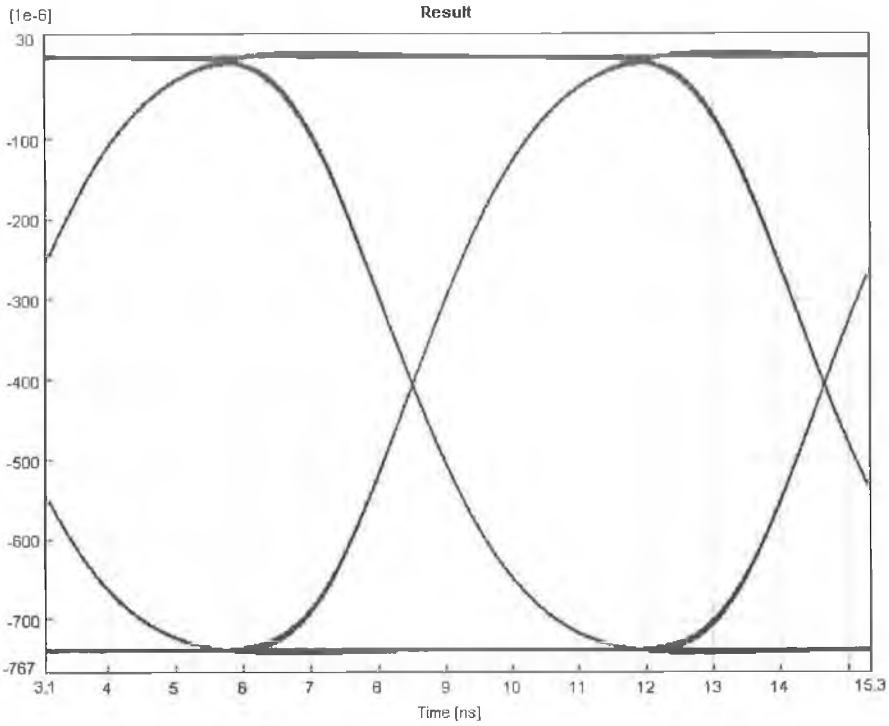

Figure 3-4: The eye-diagram results without the SBS at 14.3 dBm

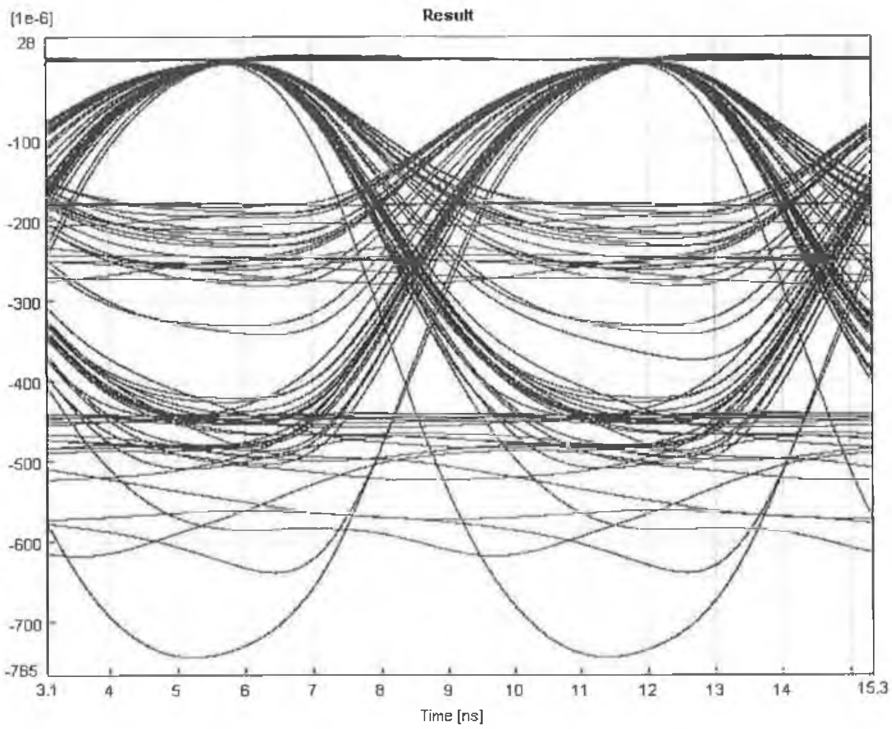

Figure 3-5: The eye-diagram results with the SBS at 14.3 dBm

When we set the SBS parameter "off", the result eye-diagram is shown in the Figure 3-4. In this case, the detected optical power is 1.9 dBm, which is suitable for the photodiode. The eye is perfectly open in this Figure, indicating the potential for a very low Bit Error Rate (BER).

Then we set the SBS parameter of the fiber reel "on", the result eye diagram is noise margin shown in the Figure 3-5. In this case, the received optical power decreases to –2.3 dBm, which is due to the optical power consumed by the SBS effect and transmitted back through the fiber.

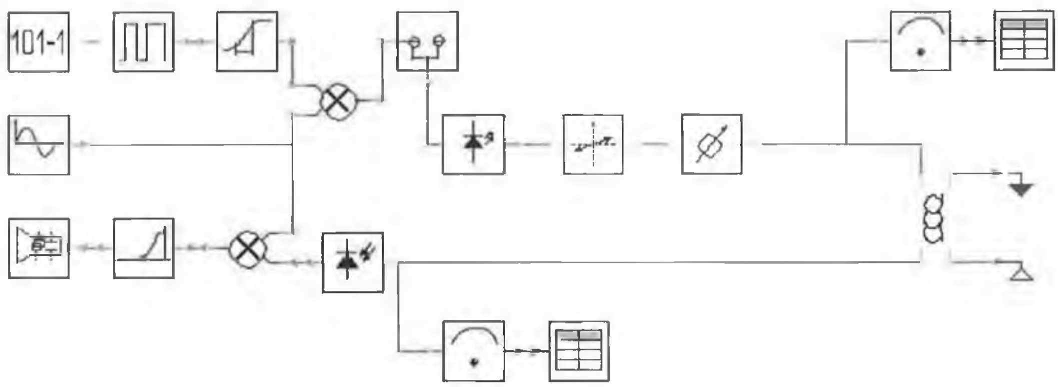

Figure 3-6: The simulation set-up with pre-attenuator

Then we move the attenuator (10 dB attenuation) to the transmitter, and put it just before the optical fiber reel, as shown in Figure 3-6. In this case, the optical power launched into the optical fiber decreases to just 4.3 dBm because of the attenuator.

The simulated result eye-diagram is shown below in the Figure 3-7 and Figure 3-8. At both cases the power to be launched into the fiber reel is 4.3 dBm, which is due to the attenuator and this power is lower than the Brillouin threshold.

When we set the SBS parameter "off", the result eye-diagram is shown in the Figure 3-7. In this case, the detected optical power is 1.9 dBm. When we set the SBS parameter "on", the result eye-diagram is shown in the Figure 3-8. In this case, the detected optical power is 1.9 dBm as well, which is the same as the case of Figure 3-7, which means SBS consumes no optical power.

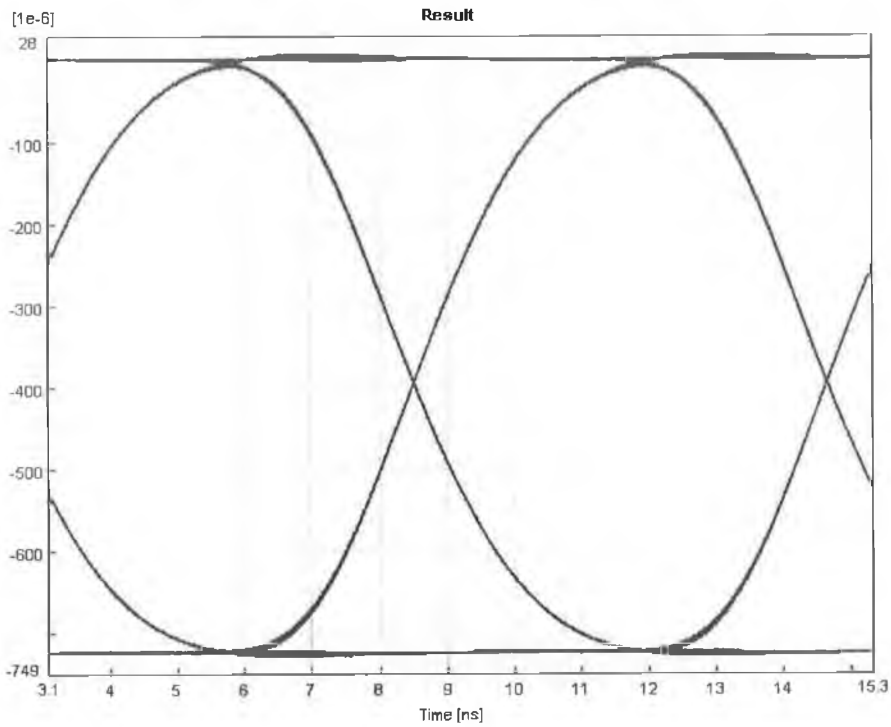

Figure 3-7: The eye-diagram results without the SBS at 4.3 dBm

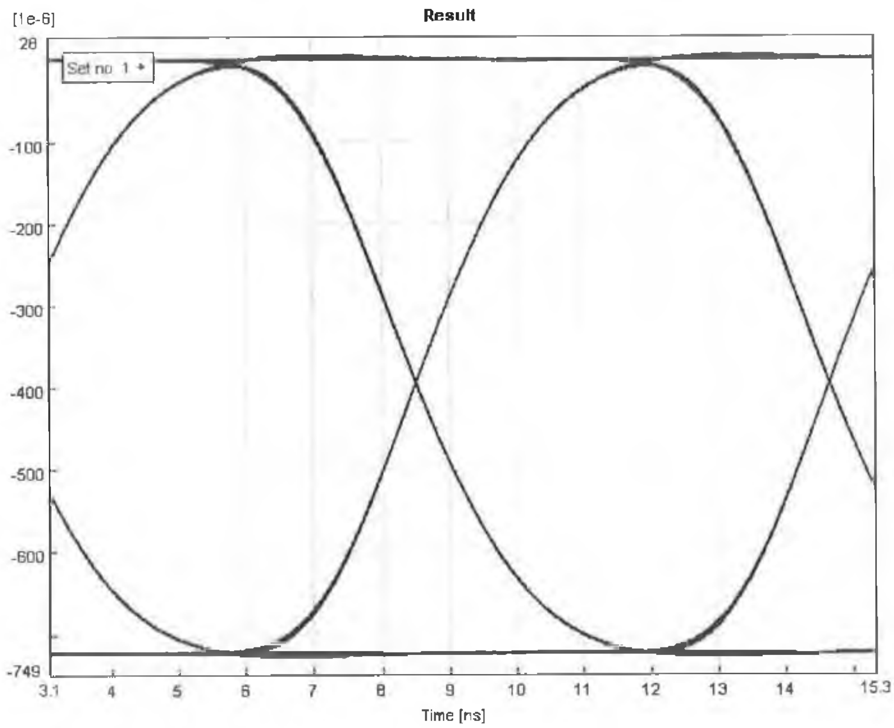

Figure 3-8: The eye-diagram results with the SBS at 4.3 dBm

The Figure 3-7 and Figure 3-8 do not show any significant differences, both eye-diagrams are clean and clear. This basic simulation clearly shows the effect that SBS can have on the performance of Radio-over-Fibre distribution system, and tells us that it is necessary to keep the power below the Brillouin threshold to ensure that SBS does not degrade system performance.

3.4 Experiment setup and results

In this section, we experimentally investigate the possibility of performing optical filtering on an optical microwave signal to simultaneously overcome the effects of chromatic dispersion by generating a single-sideband-signal (SSB), and reduce the SBS noise in the transmission fiber. The system performance is verified for SSB pre-filtering and compared with the case where the filtration is performed at the receiver (post-filtering).

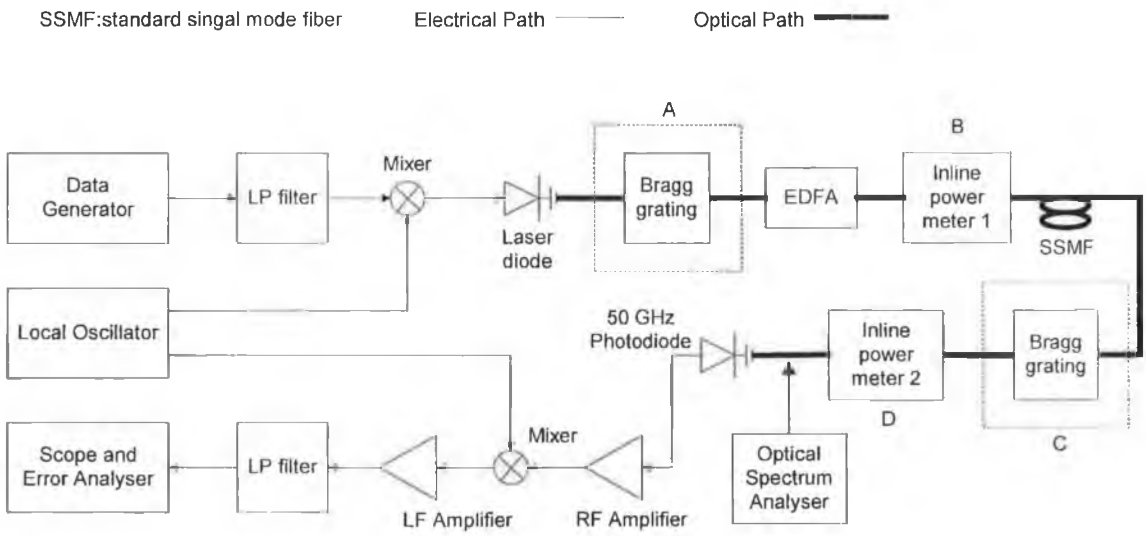

Figure 3-9: The experiment set up

The experimental set up used is shown in the Figure 3-9. A 155.520 Mbit/s NRZ data stream from an Anritsu pattern generator is initially passed through a 117-MHz low-pass filter to minimize the bandwidth of the data signal (generally we choose the filter with 75% bandwidth of the signal to keep most of the signal pass the channel). Then the signal is mixed with a RF carrier of 18 GHz to generate binary phase-shift keying (BPSK) data signal that is used to directly modulate a single mode laser diode. The emission wavelength of the laser (around 1550 nm) can be slightly altered and set to specific values by the temperature control of the diode, and the optical signal is amplified using an erbium-doped fiber amplifier (EDFA) before being launched into the optical fiber reel. At the receiver, the detected signal is initially amplified with a RF amplifier and then downconverted to a baseband signal using a mixer and the 18GHz local oscillator. Finally, the resulting NRZ data signal is amplified with a low frequency (LF) amplifier and then filtered before being monitored on a 50 GHz oscilloscope.

In this experiment, we use two inline power meters with built-in tunable attenuators (at positions B and D) to monitor and adjust the optical power launched into the fiber reel and the photodiode, respectively. At positions A and C, we place the Bragg grating (optical filter) according to the experiment demands. The generated optical microwave signal is transmitted over 12.7 or 25.4 km of standard single mode fiber, depending on the required experimental conditions (two standard single-mode fiber reels of dispersion around 17 ps/km.nm at 1550 nm, each one 12.7 km). In addition, the fiber grating used has a transmission profile (band-stop filter) as shown in Figure 3-10. It is a Band-Pass optical filter if used in reflection mode.

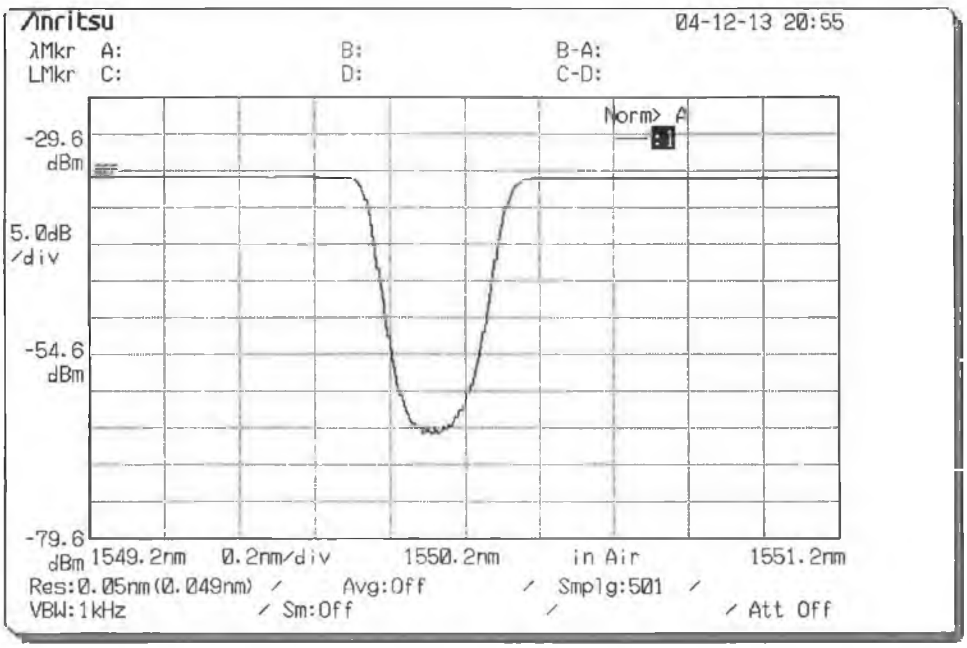

Figure 3-10: Frequency response of the Bragg filter used in transmission method

3.4.1 Measure Brillouin Threshold

In order to initially measure the Brillouin threshold, we do not use any Bragg grating in the system, which means that there are only fiber patchcords at the position A and C. In this experiment, we use one fiber reel of 12.7 km, which is long enough to show the effect of SBS.

We change the optical power launched into the fiber reel by changing the attenuation of inline power 1 and read the optical power value from it. After the optical signal propagating through the 12.7 km long fiber reel, we adjusted the attenuation of the inline power meter 2 to keep the optical power to be launched into the photodiode constant at 3 dBm. For the laser diode, we set the bias current at 60 mA to guarantee that it works in the linear regime. From the eye-diagram shown on the oscilloscope we get the Q factor according to the definition of Q:

$$Q = \frac{v_H - v_L}{\sigma_L + \sigma_H}, \qquad (3\text{-}7)$$

where v_H and v_L represent the voltage level of "1" signal and "0" signal; and σ_L and σ_H is the standard deviation of the noise amplitude for "1" and "0" signals.

In Figure 3-11 we see that the Q factor degrades sharply when the optical power launched into the fiber reel reached around 12.5 dBm. Since the degradation of Q factor begins at the SBS threshold, we know that for our experimental set-up, the SBS threshold is about 12.5 dBm.

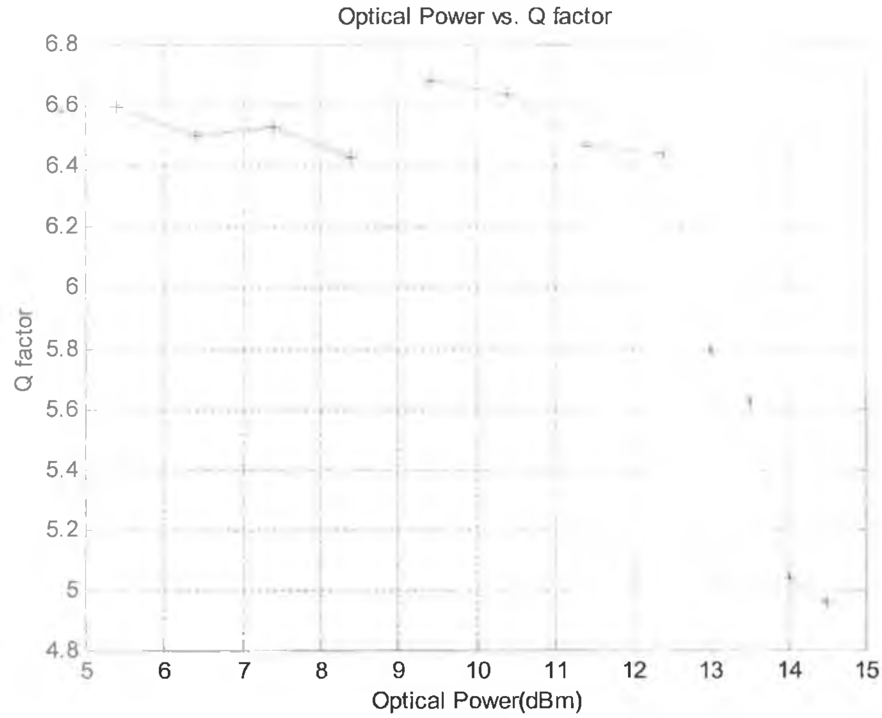

Figure 3-11: Optical power launched into the fiber reel vs. Q factor

In Figure 3-12 and figure 3-13, we show two eye-diagrams at two different Q factors to show the SBS effect on eye-diagrams. The different eye-diagrams suffer from different grade of SBS effects. When the SBS effect is more severe, the eye bears more noise, as shown in Fig. 3.13.

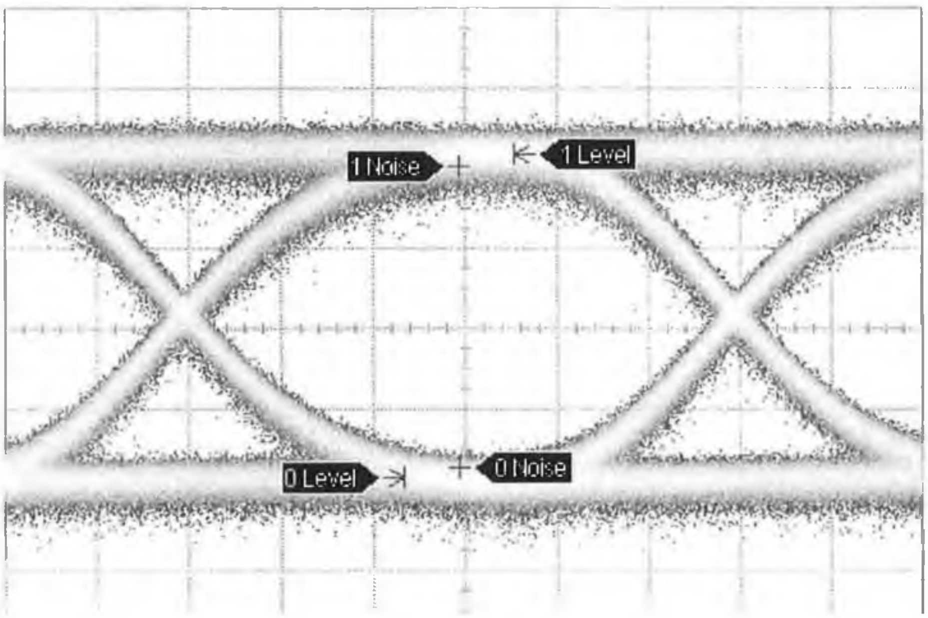

Figure 3-12: Eye-diagram of Q factor 7

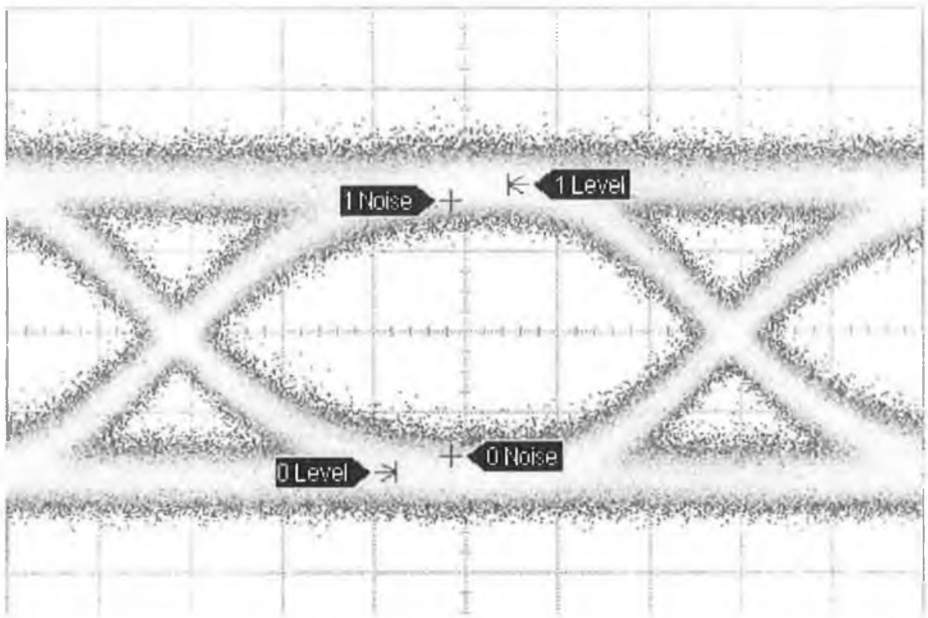

Figure 3-13: Eye-diagram of Q factor 4.6

3.4.2 Effect of Dispersive Fading and SBS

In the RoF systems, although the generated optical microwave signals are usually in the DSB format, optical filters may be employed at the receiver (post-filering) to convert the DSB signals to SSB format and eliminate the dispersion fading effects in the fiber. Indeed such a filter could simultaneously demultiplex the desired wavelength channel in RoF WDM systems [1]. Here we propose and demonstrate how the position of the optical filter can influence the performance of a RoF system due to SBS.

In order to investigate the dispersive fading effect and the SBS effect simultaneously, we set up the experiment without any Bragg grating in the system and change the pump power of the EDFA to keep the optical power launched into the fiber reel at 12.5 dBm (shown on the inline power meter 1). At the receiver, we adjusted the attenuation of the inline power meter 2 to keep the optical power launched into the photodiode at 0 dBm.

From experiments, we found that, when the transmission distance is set to around 25 km, the dispersive fading effect is the most serious. Hence we connected two fiber reels of 12.7 km together to get the required transmission length.

In order to measure the optical spectrum, an Optical Spectrum Analyser (Anritsu MS 9717A) is employed just before the photodiode. The result is displayed in Figure 3-14.

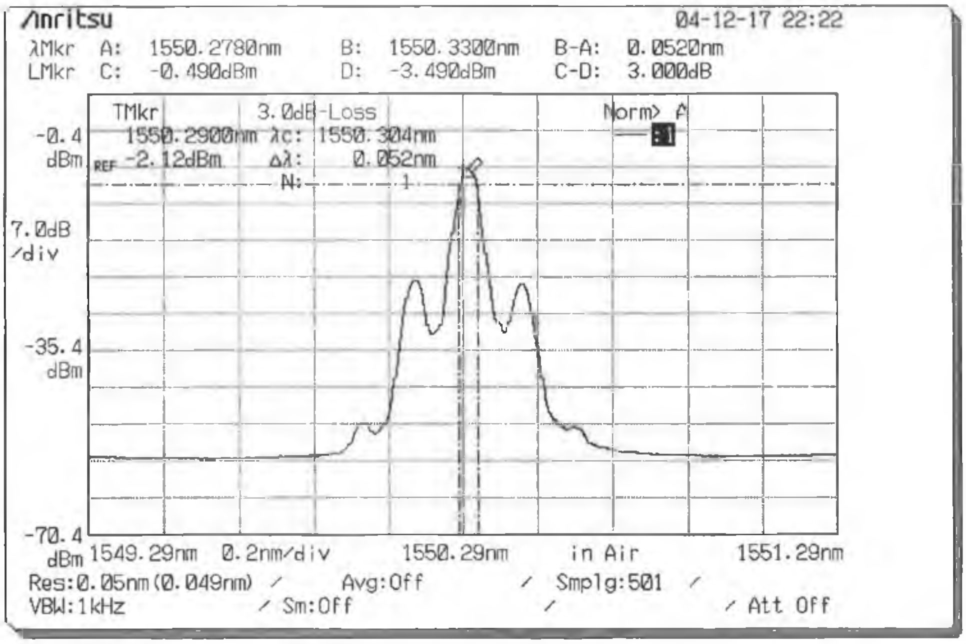

Figure 3-14: The DSB optical spectrum just before the photodiode

The optical spectrum is shown as Double Side Band signal (DSB), which causes signal fading as we have mentioned before. In this case, the phase difference between the two side bands is around π , which induces almost complete fading of the receiver RF signal after the receiver. As for this experiment, the eye-diagram shown from the oscilloscope is displayed in Figure 3-15, which verifies our prediction of a closed eye due to the dispersive fading effect. In addition, because of the influence of SBS, even when the eye is closed, severe noise is also clearly shown on the eye-diagram.

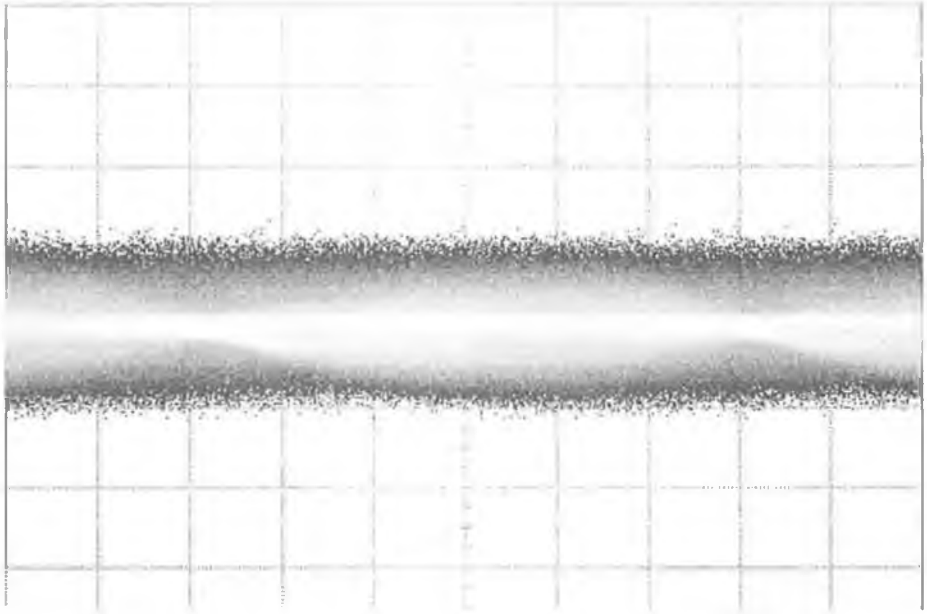

Figure 3-15: The eye-diagram of the received DSB signal shown on the oscilloscope

3.4.3 The System with Post-filtering

To overcome the dispersive fading effect shown above, it is necessary to employ an optical filter somewhere in the system to generate a single-sideband-signal (SSB). This filter can generally be at the transmission or reception side, post- or pre-filtering respectively. In order to measure the effect of the post-filtering, we place the Bragg grating at the position "C" in Figure 3-8. The optical power launched into the 25 km fiber reel is kept at 12.5 dBm and the optical power launched into the photodiode is kept at 0 dBm as before. The optical spectrum of the received signal from the Optical Spectrum Analyser is shown in Figure 3-16. The 25 km transmission length makes the SBS effect more severe, and is also the length at which dispersive fading would greatly reduce the received RF power of a DSB signal. The received eye-diagram is shown in Figure 3-17. From this figure it can be seen that the quality of the signal is poor and the eye is very noisy (Q factor is 2.7 in this case). Although, it should also be noticed that in comparison with Figure 3-15, we are able to achieve an open eye as the optical filter eliminates the dispersive fading problem.

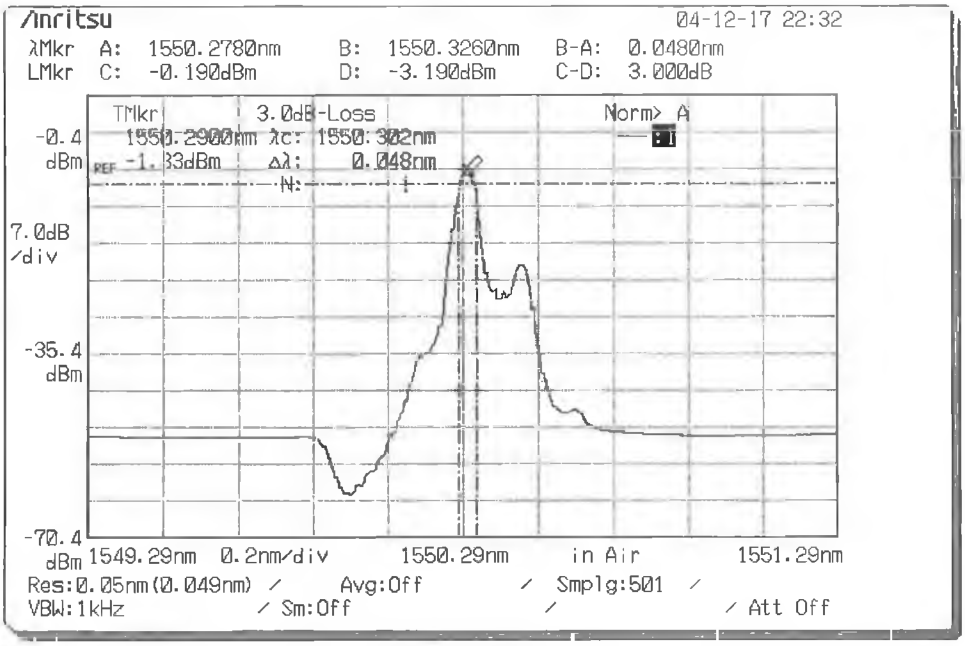

Figure 3-16: The optical spectrum before the photodiode in the case of post-filtering

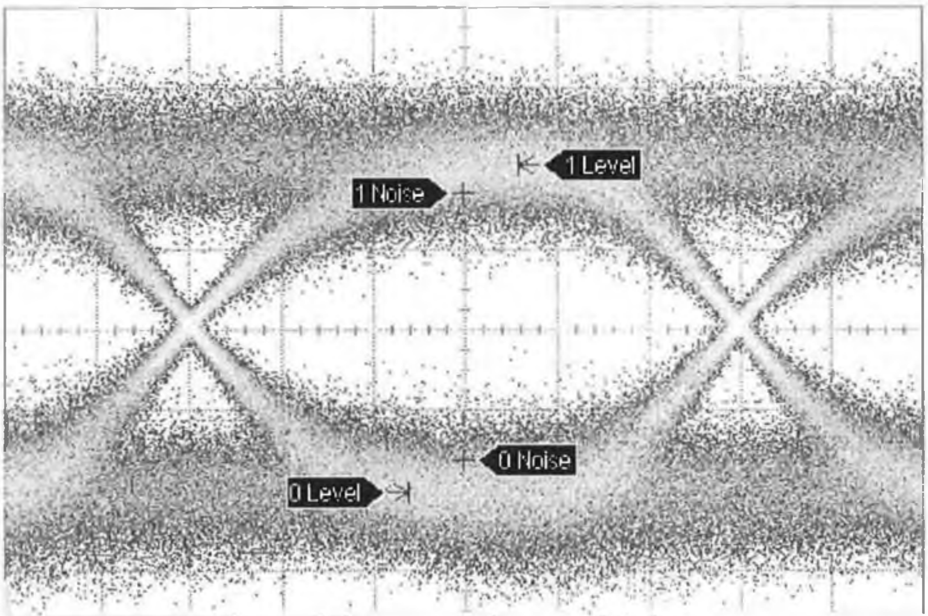

Figure 3-17: The eye-diagram of the post-filtering system

From Figure 3-17 we can see that the signal has been converted into the SSB format using the Bragg grating. It shows also the SBS effect at about the 11GHz distance from the optical carrier. The optical power of the carrier fluctuates because of the effect of SBS, which is not shown in this time-average spectrum, but can be realized if we investigate the inline power meter 2. Since the down-converted signal is the beat result between the fluctuated carrier and the side band, severe noise is induced into the signal, as shown by the received eye in Fig 3.17.

3.4.4 The System with Pre-filtering

In the case of pre-filtering, since the optical filter eliminates one side band and has a certain insertion loss, the optical power launched into the fiber is reduced greatly. By placing the insertion loss of the filter at the central station instead of the remote site, the SBS effect in a Radio-over-Fiber distribution system could be alleviated. In order to measure the effect of pre-filtering, we move the Bragg filter to the position "A" in Figure 3-8. Although the optical power before the Bragg filter is still kept at 12.5 dBm (after the EDFA), after passing through the Bragg filter, the inline power meter 1 shows that the optical power launched into the fiber reel decreases to 7.0 dBm.

As before, we adjust the attenuator value of the inline power meter 2 to make sure the optical power to be launched into the photodiode kept at 0 dBm and we examine the optical spectrum before the photodiode, which is presented in Figure 3-18.

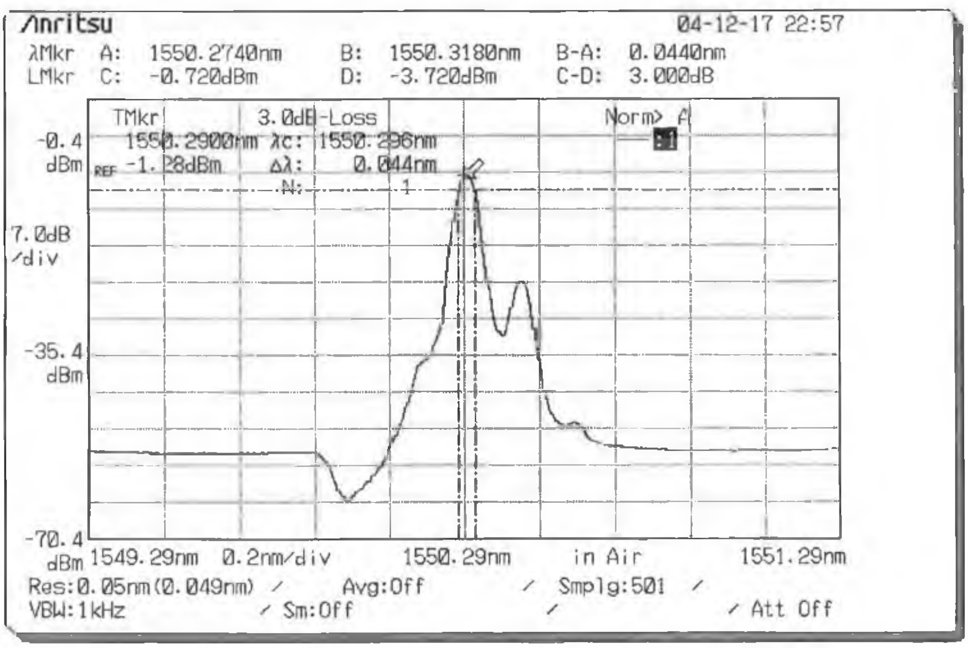

Figure 3-18: The optical spectrum in front of the photodiode in case of pre-filtering

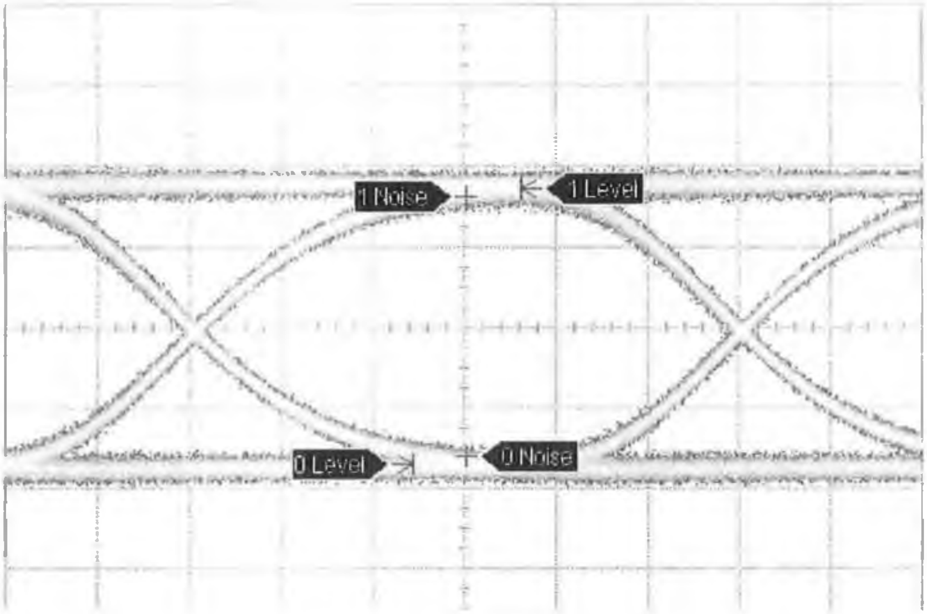

Figure 3-19: The eye-diagram of the pre-filtering system

Since the optical power launched into the optical fiber is lower than the SBS threshold, the optical spectrum shows a smooth profile between the carrier and the sideband, and we successfully avoid the effect of SBS. In this case, we get a clear and clean eye-diagram for the received data signal, shown in figure 3-19. The Q factor of this case is 9.9; the improvement in systems performance is essentially caused by the insertion loss of the optical filter employed before transmission.

3.5 Conclusion

In this chapter, we investigate the effects of dispersion and non-linearity of the performance of a Radio-over-Fiber distribution system. We propose and demonstrate that by performing SSB filtering at the central station of a RoF distribution system, we can simultaneously overcome the effects of dispersion and SBS in the transmission fiber. The improvement in system performance using this technique is verified both by simulation and experiment.

With the simulation, we demonstrate the basic concept of how the SBS effect will influence the system performance. With the experiment, we demonstrated SSB pre-filtering and compared with the case where the filtration is performed at the receiver. Our experiments showed that by using the pre-filtering method we could not only obtain the required SSB transmission (to overcome dispersive fading), but also reduce the signal degradation caused by SBS (by reducing the signal power launched into the transmission fiber).

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Chapter 4

The Influence of Modulation Depth on Stimulated Brillouin Scattering Effects in Radio-over-Fiber Distribution Systems

As we have already seen, SBS may impose a limitation on the transmitted power in radio-over-fiber (RoF) distribution systems. By employing an optical filter at the transmitter that converts the optical microwave signal to Single Side Band (SSB) format to overcome dispersive fading, it is also possible to reduce the effect of SBS on system performance because of a reduction in transmitted power [1].

In this chapter we will further investigate the SBS effect. We find that the modulation depth of the optical-microwave data signal may influence the Brillouin threshold. Hence by changing the modulation depth by employing an optical filter at the transmission side of the RoF distribution systems, we can further improve the system performance.

4.1 Introduction

From the previous chapters, we know that depending on the RoF distribution system architecture, optical filtering may normally be employed in such systems either to convert a Double Side Band (DSB) signal to Single Side Band (SSB) format [2] to overcome dispersive fading of the RF signal in the fiber link [3], or to filter out one optical data channel if wavelength division multiplexing (WDM) technology is employed in the system. Indeed, it is possible to use one Bragg filter at the remote site to carry out both these functions simultaneously [4].

In this chapter we examine how the modulation index of the optical microwave signal will affect SBS in a radio-over-fiber distribution system. This work shows that by using an optical filter that not only generates a SSB signal at the transmitter, but also increases the modulation index of the data signal, the limitations due to SBS may be greatly reduced.

4.2 Basic experiment set-up

In the last chapter, we set up an experiment to figure out the SBS effect. Here we still use the same experiment set-up as our basic test bed that is shown in Figure 4-1. First we should be familiar with the experiment again: A 155.520 Mbit/s NRZ data stream from an Anritsu pattern generator is initially passed through a 117-MHz low-pass filter to minimize the bandwidth of the data signal. Then the signal is mixed with a RF carrier of 18 GHz to generate binary phase-shift keying (BPSK) data signal that is used to directly modulate a single mode laser diode that is biased around 60 mA and has an operating wavelength of 1550 nm. The optical signal is then amplified using an erbium-doped fiber amplifier (EDFA) before being launched into the optical fiber reel. At the receiver, the detected signal is initially amplified and then downconverted to a baseband signal using a mixer and the 18 GHz local oscillator. Finally, the resulting NRZ data signal is amplified before passing through a low-pass filter and monitored on a 50 GHz oscilloscope.

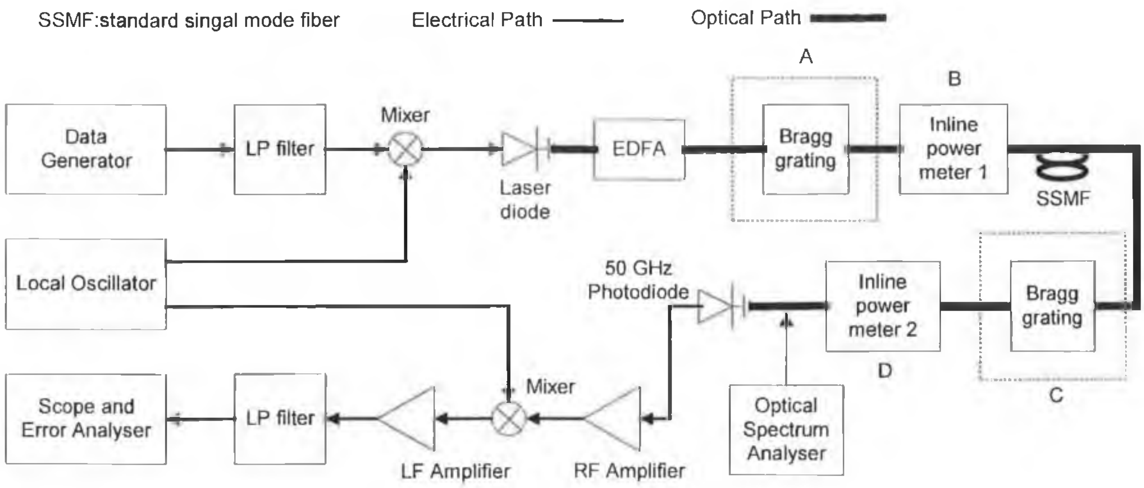

Figure 4-1: The experiment set up to measure the Brillouin threshold

In this experiment, we use two inline power meters with built-in tunable attenuators (at the positions B and D) to adjust and measure the optical power launched into the fiber reel and at the photodiode, respectively. At positions A and C, we place the Bragg filter according to the experimental demands. The generated optical microwave signal is transmitted over 12.7 km of standard single mode fiber, which is long enough to show the SBS effect.

4.3 The influence of the modulation depth on SBS effect

As we already know, in an optical communication system, if the pump laser is assumed to have a finite linewidth $\Delta\nu_P$, and if the Stokes wave linewidth is given by $\Delta\nu_B$, then the Brillouin threshold for Continuous Wave (CW) light is given by [5]:

$$p_{thr}^{CW} \approx 21\frac{A_{eff}K}{g_o L_{eff}}\left(\frac{\Delta\nu_B + \Delta\nu_P}{\Delta\nu_B}\right), \qquad (4\text{-}1)$$

where L_{eff} is the effective interaction length given by

$$L_{eff} \equiv (1 - e^{-\alpha L})/\alpha, \qquad (4\text{-}2)$$

A_{eff} is the effective core area of the fiber, α is the fiber loss (dB/m), g_o is the peak Brillouin gain coefficient (g_o = 4.6*10^{-11} m/W), and K is the polarization factor ($1 \le K \le 2$), which accounts for polarization scrambling between the pump and the Stoke waves.

From formula (4-1) we know that the linewidth $\Delta\nu_P$ of the laser strongly influences the Brillouin threshold: the wider the $\Delta\nu_P$, the higher the Brillouin threshold. Hence, narrower linewidth signals are more prone to SBS effects. In our RoF system, the linewidth of the optical carrier is much narrower than that of the sidebands (which are carrying the data). Therefore, the carrier signal is the main cause of SBS, and reducing the power of the carrier (increasing the modulation depth of the signal) may allow us to reduce the limitation caused by SBS. The modulation depth is expressed in terms of the carrier to sideband ratio (CSR), which is defined as the difference in the optical power between the carrier and a first-order sideband [6].

To investigate how the modulation depth will influence the Brillouin threshold, we improve on the experimental set-up and it is shown in the Figure 4-2. This experiment set-up is similar to the Figure 4-1; the only difference is that we keep the position of the Bragg filter at the transmitter of the RoF system. In this case, we place the EDFA after the Bragg filter so that we can easily increase the optical power launched into the optical fiber reel further. We will see, even when we have already pre-filtered the system, how the change of the modulation depth may increase the system performance further.

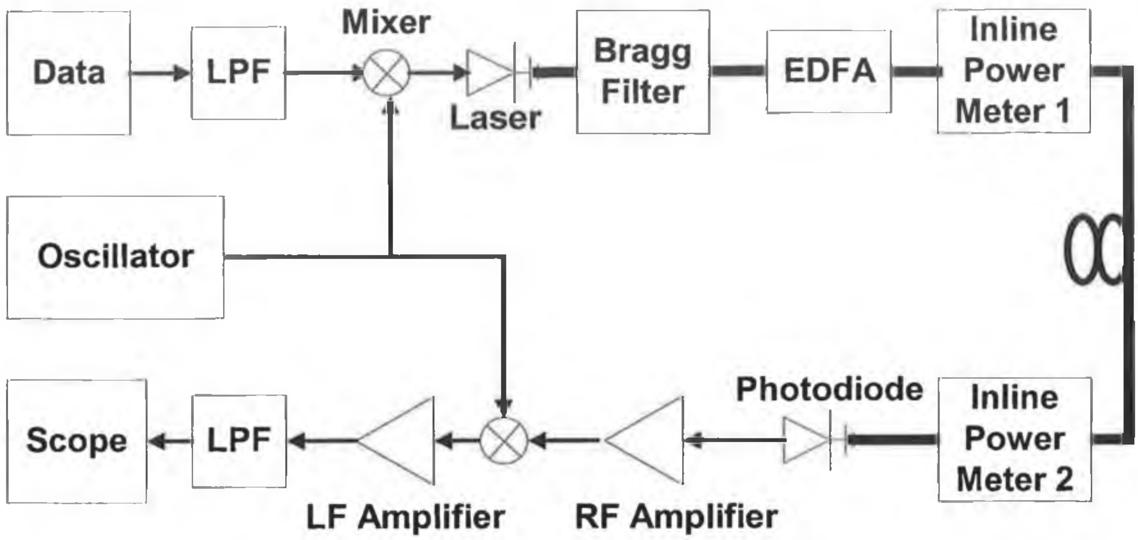

Figure 4-2: Experimental set-up to investigate the modulation depth effect

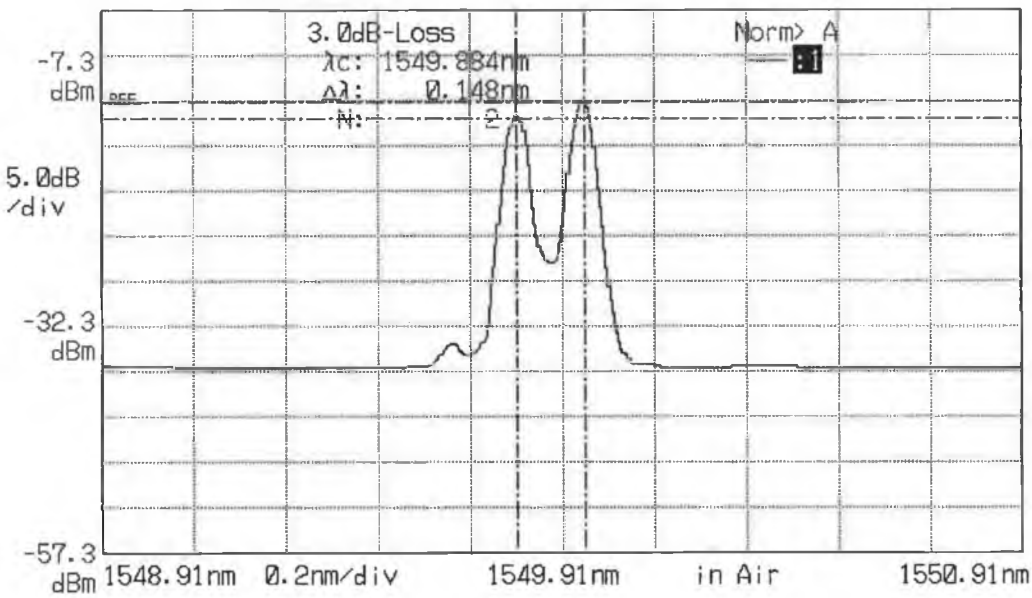

Figure 4-3: Spectrum of Carrier to Sideband Ratio 1.8 dB

To vary the modulation index of the generated optical microwave we use the same fixed Bragg filter that was employed earlier, and we use temperature control to vary the emission wavelength of the laser (the emission wavelength of the laser is varied with the change of the temperature) relative to the center of the filter stop band. By doing so we can obtain different values of CSR (i.e. different modulation depths). Figure 4-3, and Figure 4-4 show the spectrum of the signal with the CSR of 1.8 dB, and 23.6 dB respectively. We can also see that the filter converts the DSB signal directly after the laser to a SSB signal.

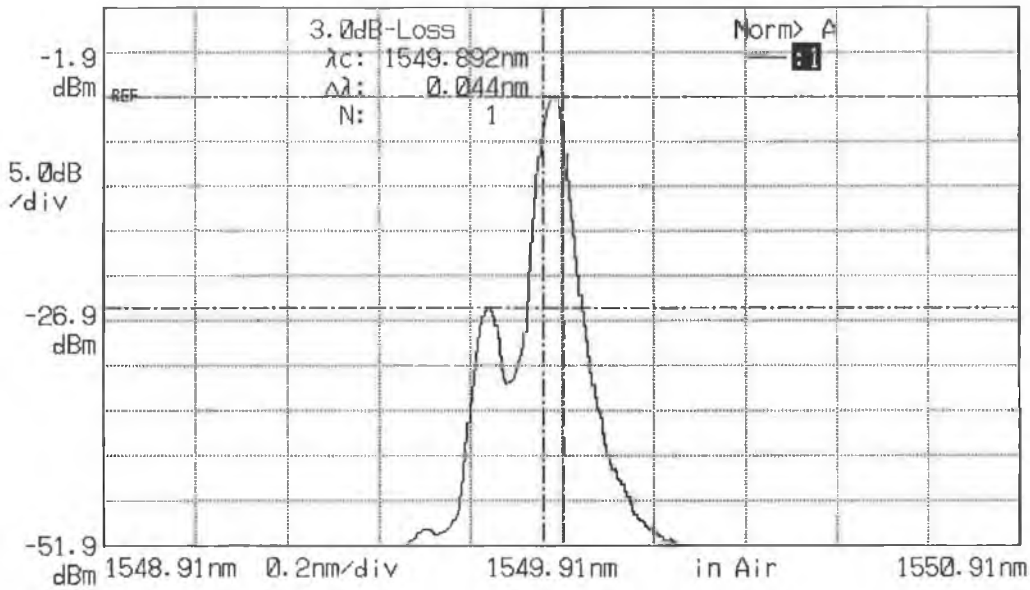

Figure 4-4: Spectrum of Carrier to Sideband Ratio 23.6 dB

4.3.1 Carrier to Sideband Ratio vs. Q factor

To investigate the impact of the CSR on the SBS threshold we used the experimental set-up as shown in Figure 4-2. The emission wavelength of the data signal was changed relative to the bandpass profile of the filter to vary the CSR, and a variable attenuator before the transmission fiber was used to keep the launched power constant as the CSR varied. We choose two different optical launch powers, 6 dBm and 12.5 dBm, and in both cases the variable attenuator before the detector is used to keep the received power constant at 0 dBm. Figure 4-5 shows how the Q factor of the received signal changes when the modulation index is varied for the two launched powers.

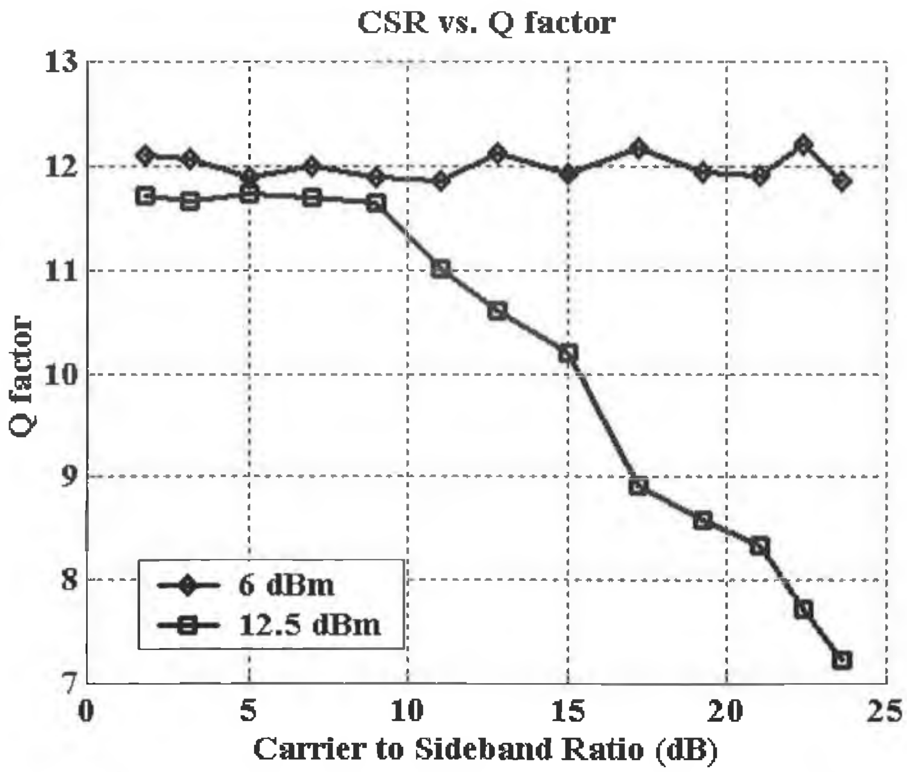

Figure 4-5: Carrier to Sideband Ratio vs. Q factor

Since 6 dBm is far below the Brillouin threshold, the CSR does not have any influence on the system performance. When the optical power is increased to 12.5 dBm, which was the initial Brillouin threshold measured for our system, the situation becomes different. In this case the higher the CSR, the worse the Q factor (the lower the Brillouin threshold). This result confirms that the carrier is the main cause of the SBS induced noise in RoF distribution systems. Hence, suppressing the carrier power to change the CSR reduces the effect of SBS on system performance, and allows us to maximize the transmission power.

4.3.2 BER vs. Received Power

To design a network, it is imperative to comply the system design with the BER requirement of the network. As we know, the Q-factor provides a qualitative description of the receiver performance because it is a function of the signal to noise ratio (optical). The Q-factor suggests the minimum Signal to Noise Ratio (SNR) required to obtain a specific Bit Error Rate (BER) for a given signal. As we can see, the higher the value of Q-factor, the better the BER [7].

Mathematically, Equation 4-3 gives the Q-factor of an optical signal [7].

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} , \qquad (4\text{-}3)$$

where I_1 is the value of the 1-bit current, I_0 is the value of the 0-bit current, σ_1 is the standard deviation of the 1-bit current, and σ_0 is the standard deviation of the 0-bit current. The relationship of Q-factor to BER is shown in Equation 4-4 [7].

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) , \qquad (4\text{-}4)$$

We know that the BER is difficult to calculate. For a given design at a BER (such as 10^{-12} and a line rate of OC-3, or 155 Mbps), the network would have one error in approximately 10 days. It would take 1000 days to record a steady state BER value. That is why BER calculations maybe quite difficult. On the other hand, Q-factor analysis is comparatively easy. From the Equation 4-4, we have the way to calculate the BER of the system from the Q factor value, which is easy to get from the oscilloscope.

In this section, we will measure the Q factor and the BER vs. the received power characteristic. By adjusting the temperature control of the laser, the wavelength of the laser was changed relative to the pass band of the filter, and the modulation depth of optical microwave signal is varied. In the experiment, we keep the optical power propagated through the fiber reel constant at 12.5 dBm, which is near the Brillouin threshold. For different CSR values, we measure the BER at different received powers by adjusting the built-in attenuator with the inline power meter 2.

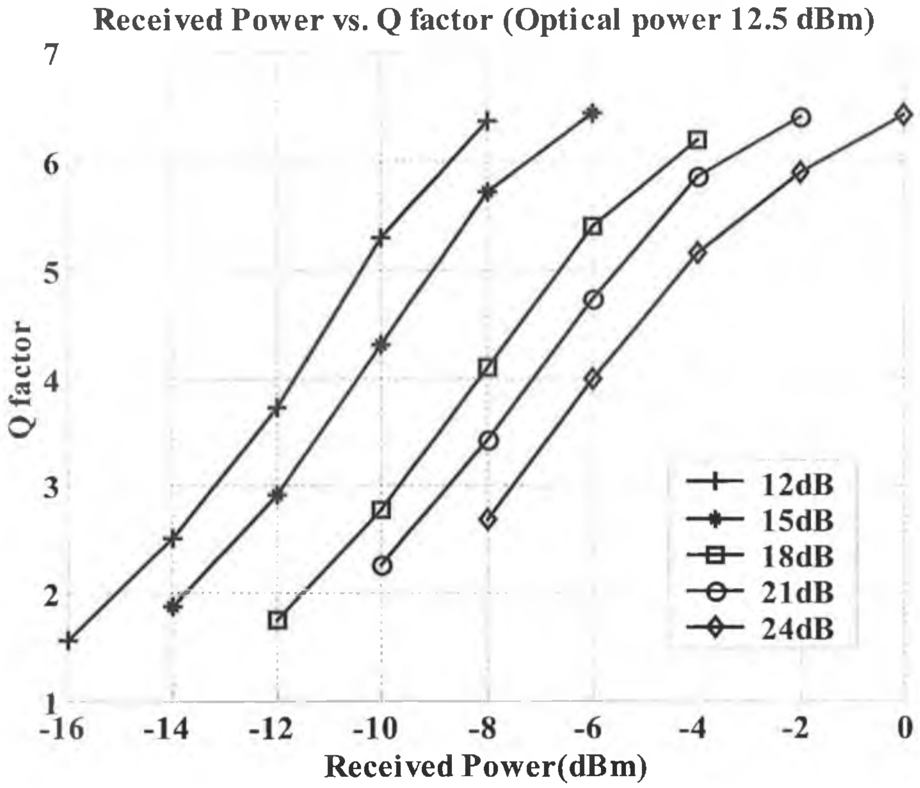

Figure 4-6: Q factor vs. Received Power

In order to investigate the influence of the modulation depth, we maintain the transmitted optical power at 12.5 dBm. The Q factor vs. received power curves for different values of CSR (12dB, 15dB, 18dB, etc) are shown in the Figure 4-6. From the data of Figure 4-6 we use the formula 4-4 to calculate and get the Bit Error Rate (BER) vs. received power curve as Figure 4-7.

From the Figure 4-6 and the Figure 4-7 it can be clearly seen that increasing the CSR value introduces a power penalty primarily due to a reduction in the power of the data sideband (which is carrying the information). However, for the case when the CSR is increased from 15 to 18 dB, the power penalty incurred is further increased due to the introduction of SBS. We know that by increasing the CSR value with the total optical power kept constant, more optical power is concentrated in the carrier. Since the linewidth of the carrier is much narrower than the sideband, and mainly responsible for the introduction of Brillouin threshold, as the CSR increases from 15 to 18 dB, the power in the carrier exceeds the Brillouin threshold. This results in a larger power penalty as the CSR goes from 15 to 18 dB. In this case (CSR increase from 15 to 18 dB) the carrier power exceeds the Brillouin threshold and the power penalty is as big as around 2.5 dB comparing with the 1.5 dB penalties among other curves. Therefore, this experiment shows that increasing of the CSR effectively decreases the Brillouin threshold, and reduces the optical power that could be transmitted in a radio-over-fibre distribution system.

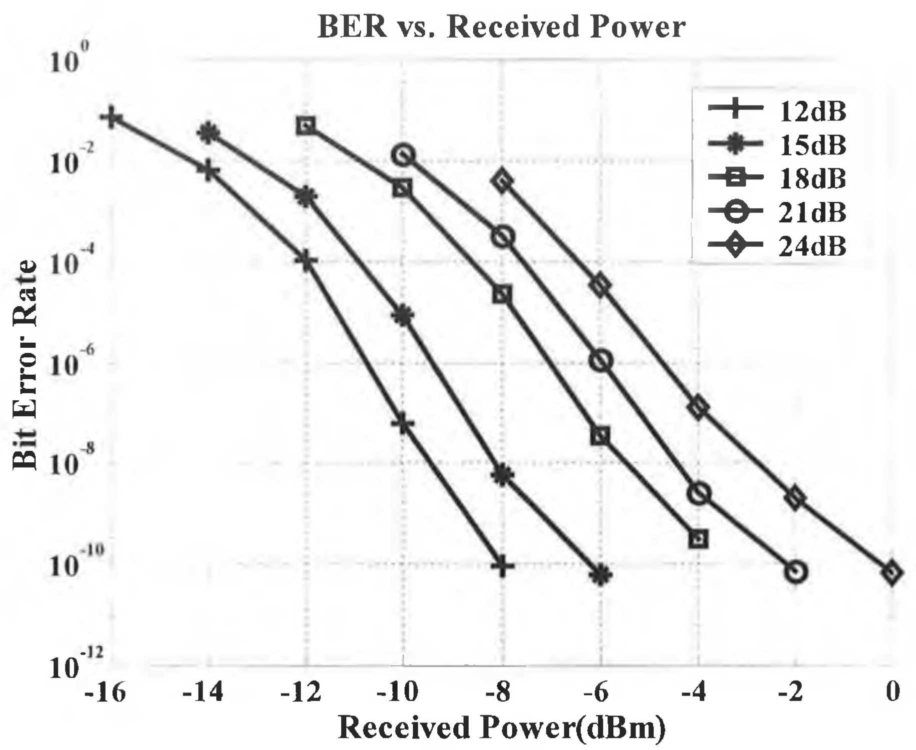

Figure 4-7: BER vs. Received Power

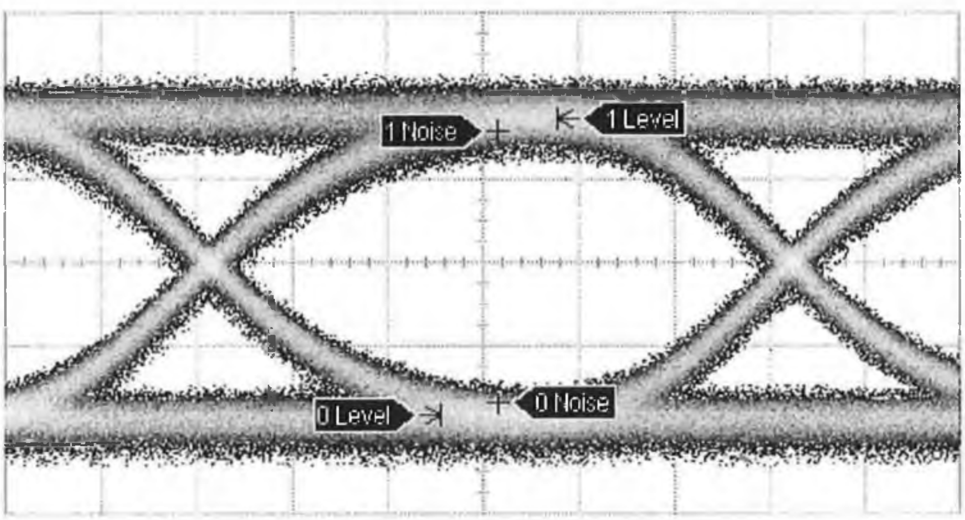

Figure 4-8: Eye diagrams when the received power is –8 dBm with CSR 15 dB

In order to further to demonstrate how SBS will degrade the signal to noise quality, in Figure 4-8, we show the eye-diagrams when the received power is –8 dBm with a CSR of 15 dB.

Fig. 4-9 shows the eye-diagrams when CSR increased from 15 dB to 18 dB (the received power is still at -8 dBm). The decrease of the eye amplitude is due to the decrease of the signal sideband power (as we know, when the CSR increases, the percentage of optical power decreases in the data carrying sideband, and increases in the carrier, as the total optical power is being kept constant). Furthermore, there is more noise shown with the eye when the CSR is 18 dB, which makes the signal Q factor decrease. This is because the SBS phenomenon begins to appear since the carrier power just exceeds its Brillouin threshold. Therefore, this experiment shows us the influence of different CSRs. By decreasing the CSR value, we may effectively increase the Brillouin threshold; therefore improve the system performance as well.

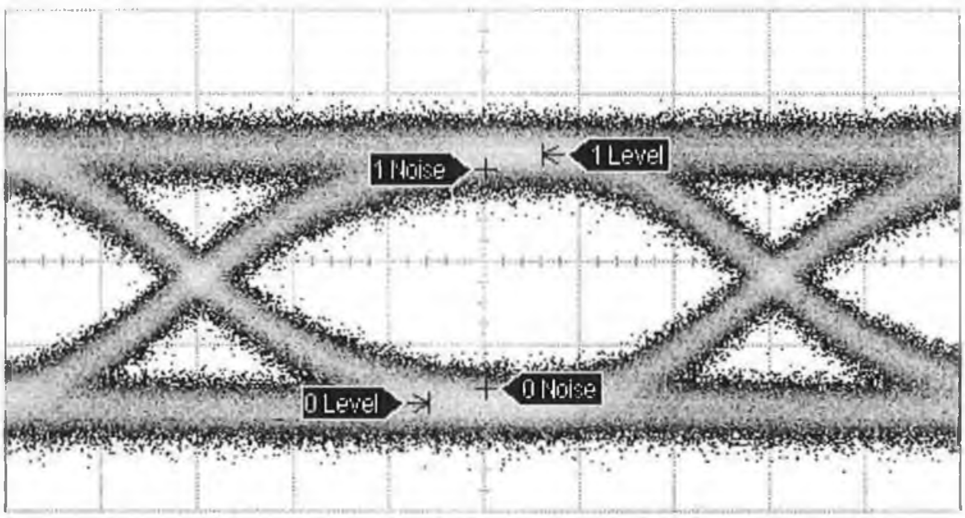

Figure 4-9: Eye diagrams when the received power is –8 dBm with CSR 18 dB

4.4 Conclusion

In this chapter, we investigated how the modulation depth of the optical microwave signal can affect the influence of SBS system performance. The experiment showed that increasing the modulation index increases the Brillouin threshold, as it is primarily the carrier power that induces the SBS effect due to its narrow linewidth. The increase in modulation depth can be achieved by employing an optical filter in the transmitter.

Thus, to further reduce the limitations on system performance due to SBS, it may be advantageous to employ an optical filter at the central station to increase the modulation depth of the signal. This solution is especially advantageous since the filter can fulfil two tasks simultaneously, i.e. to modify the CSR to raise the Brillouin threshold, as well as to convert the transmission signal to SSB format to overcome dispersive fading of the RF signal in the fiber link.

4.5 References

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Chapter 5

Conclusion

As the demand for broadband wireless services such as video-on-demand and mobile computing increases, the demand for bandwidth is growing constantly, forcing the carriers to look for new ways to increase the capacity of the networks. Hence, the need to develop high capacity wireless communication networks which are capable of delivering broadband signals to remote areas keep increasing. Because of the emerging demand for bandwidth, future wireless access networks are likely to use high frequency microwave signals as the access media. Many experts believe that radio is capable of delivering huge bandwidth, providing that remote sites can be engineered cheaply enough to enable operators to install thousands of them. Hence, radio-frequency (RF) signals need to be processed and transmitted with higher bandwidth in many applications. However, the attenuation of RF signals in traditional transmission media increases rapidly when the frequencies of the signal increase. On the other hand, optical fiber has emerged as an alternative and promising transmission medium in which RF modulated optical carriers can be transmitted and distributed with very low loss. The integration of wireless and optical networks is one potential solution for increasing both capacity and mobility. Such hybrid networks benefit from the advantages of both systems: optical fiber provides a high capacity medium with electromagnetic interference immunity and low attenuation, while radio will enable broadband data to be delivered to the end-users in a quick, flexible and inexpensive manner. This kind of hybrid radio/fiber system or Radio over Fiber (RoF) system provides good synergy between optics and radio.

Radio over fiber (RoF) systems is a very attractive option to realize such broadband networks. In these RoF systems, the microwave or millimeter wave data signals are modulated onto an optical carrier at a central location, and then distributed to remote sites using optical fiber. The remote site can then transmit the microwave signals over small areas using antenna. Such architecture should prove to be cost efficient since it allows sharing the transmission and processing equipment between many remote sites.

In this thesis, we first introduced optical communication systems and radio communication systems, then provided a review of the RoF systems for wireless access networks in chapter 2.

In chapter 3, we proposed a pre-filtering method to overcome the SBS nonlinear effect in RoF transmission systems and investigated the possibility of performing Single Sideband (SSB) filtering to simultaneously overcome the effects of dispersion and SBS in the transmission fiber. The experiment showed that the pre-filtering method can filter out one side band as well as reduce the effect of SBS, which is exactly what we anticipated. The reduction in SBS effect in this case is primarily due to the reduced signal power launched in the transmission fiber.

Furthermore, we investigated how to overcome the limitation on system performance caused by SBS effect by changing the modulation depth of optical microwave signals in Chapter 4. The experiments showed that increasing the modulation index increases the Brillouin threshold, as it is primarily the carrier power that induces the SBS effect due to its narrow linewidth. Therefore, by increasing the modulation depth of the optical microwave signal at the transmitter side of a Radio-over-Fiber distribution system, we can reduce the limitations on system performance due to SBS, and maximize the transmission power. This is important in systems that encounter large optical losses due to large transmission lengths between central station and remote, or the use of many optical splitters to feed the optical microwave signal to many remote sites.

We have thus shown that by correct use of an optical filter placed at the transmitter of the RoF distribution system, we may fulfill three tasks simultaneously:

1. Filter out one side band of the transmitted signal to generate a single-sideband signal, which will overcome the chromatic dispersion induced signal fading.
2. To induce insertion loss into the transmitted power, which way decrease the risk of SBS.
3. To change the modulation depth of the signal, thus reducing the power in the carrier (which is mainly responsible for SBS in the propagation of optical microwave signals). This will further increase the Brillouin threshold.

Appendix A – Matlab Code

Matlab code for Figure 1-1 and Figure 1-2:

```
%%%%%cd d:\linghu\work\data%%%%%
%Resistance : 12 k ohm
% PI (Power-Current) curve
% the temperature is set as correspondence to 12 kohm
% wavelength at 1550 nm
% unit for current: mA
% unit for Power_watt : mw
% unit for Power_dBm : dBm
% unit for Impedance : kohm
% unit for wavelength : nm

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%for PI
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Current = [5.02 8.30 11.01 14.00 17.10 19.46 20.99 21.46 22.02 22.52
23.10 23.62 25.19 27.07 30.31 33.08 36.07 39.26 42.32 45.30 48.25
51.56 55.05 59.25 62.50 65.16 66.79];
Power_watt = [ 0.000513 0.001041 0.001680 0.002807 0.004800 0.007466
0.01680 0.058 0.116 0.1679 0.2276 0.2823 0.4471 0.6467 0.9958 1.3
1.631 1.986 2.326 2.655 2.977 3.334 3.712 4.17 4.529 4.820 4.999];
Power_dBm = [-32.9 -29.84 -27.75 -25.52 -23.19 -21.27 -17.75 -12.37
-9.36 -7.75 -6.43 -5.49 -3.50 -1.89 -0.02 1.14 2.13 2.98 3.67 4.24
4.74 5.23 5.69 6.20 6.56 6.83 6.99];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%for Resistance-wavelength
curve%%%%%%%%%%%%%%%%%%%%%%%
Resistance = [8.07 9.01 10.01 11.00 12.00 13.01 14.02 15.02 16.00];
Temperature = [32 29 26 23 20 18 17 16 15];
Wavelength = [1551.71 1551.39 1551.09 1550.83 1550.59 1550.37
1550.15 1549.97 1549.79];

%%%%%%%%%%%%%%%%%%%%plot for PI
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
%subplot(2,1,1);
plot(Current,Power_watt);
title('PI-curve');
xlabel ('Current(mA)')
ylabel ('Power(mw)')
grid on;


%%%%%%%%%%%%%%%%plot for Impedance-Wavelength curve
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(2)
plot(Temperature,Wavelength,'*-');
title('Temperature-Wavelength curve at 58.11 mA');
xlabel ('Temperature (^oC)')
ylabel ('Wavelength (nm)')
grid on;
```

The Matlab-code for Figure 2-5:

```
%%%%%%cd d:\linghu\work\mzm10G%%%%%%%%%%%%%%%%%
%Resistance : 12 k ohm
% the temperature is set as correspondence to 12 kohm
% current 70 mA
% wavelength at 1550 nm
% unit for Power_watt : mw
% unit for Power_dBm : dBm
% unit for Impedance : kohm
% unit for wavelength : nm

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%for Bias-power
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Voltage = [-15 -14.5 -14 -13.5 -13 -12.5 -12 -11.5 -11 -10.5 -10 -
9.5 -9 -8.5 -8 -7.5 -7 -6.5 -6 -5.5 -5 -4.5 -4 -3.5 -3 -2.5 -2 -1.5
-1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5
10 10.5 11 11.5 12 12.5 13 13.5 14 14.5 15];
Power_watt = [1.61 1.50 1.35 1.16 0.962 0.740 0.521 0.326 0.171
0.055 0.0045 0.0241 0.0995 0.224 0.396 0.6 0.82 1.05 1.26 1.44 1.58
1.66 1.68 1.65 1.55 1.41 1.24 1.02 0.791 0.575 0.31 0.166 0.0561
0.00718 0.0181 0.0916 0.216 0.384 0.585 0.807 1.04 1.25 1.45 1.58
1.66 1.68 1.62 1.49 1.32 1.12 0.893 0.653 0.45 0.256 0.126 0.0359
0.00367 0.0285 0.102 0.227 0.395];
Power_dBm = [2.07 1.77 1.32 0.65 -0.17 -1.33 -2.81 -4.89 -7.61 -
12.63 -23.49 -16.24 -9.99 -6.53 -4.01 -2.23 -0.84 0.2 0.99 1.59 1.97
2.18 2.26 2.18 1.90 1.49 0.90 0.10 -1.04 -2.38 -5.06 -7.91 -12.40 -
21.56 -17.51 -10.36 -6.71 -4.11 -2.39 -0.88 0.15 0.98 1.60 1.99 2.21
2.24 2.11 1.72 1.22 0.48 -0.52 -1.82 -3.51 -5.90 -9.14 -14.40 -24.44
-15.5 -9.87 -6.54 -4.02];


%%%%%%%%%%%%%%%%%%%%plot for PI
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
subplot(2,1,1);
plot(Voltage,Power_watt, '*-');
title('Bias Voltage-power curve (Resistance 12kohm, Current 70mA)');
```

```
xlabel ('Voltage(V)')
ylabel ('Power(mw)')
grid on;

subplot(2,1,2);
plot(Voltage,Power_dBm, '*-');
xlabel ('Voltage(V)')
ylabel ('Power (dBm)')
grid on;
```

Below is the Matlab-code for Figure 4-5:

```
%%%%%%cd
d:\linghu\work\modeepth%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Resistance : 12 kohm
% the temperature is set as correspondence to 12 kohm
% the optical power set at the detector is 3 dBm
% wavelength at 1550 nm
% unit for Power_watt : mw
% unit for Power_dBm : dBm
% unit for Impedance : kohm
% unit for wavelength : nm

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
Depth = [1.8 3.2 5.0 7.0 9.0 11 12.8 15 17.2 19.2 21 22.4 23.6];

%% Without SBS, optical power 6 dBm.
SNR1 = [24.19 24.13 23.77 24.01 23.80 23.73 24.24 23.87 24.34 23.89
23.82 24.41 23.72];
Q1 = SNR1/2;

%BER1 = (exp((-0.5)*(SNR1.^2)))./(((2*pi)^0.5)*SNR1)


%% With SBS, optical power 12.5 dBm maximum.
SNR2 = [23.44 23.31 23.45 23.40 23.28 22.03 21.23 20.40 17.85 17.17
16.69 15.44 14.47];

Q2 = SNR2/2;

%BER2 = (exp((-0.5)*(SNR2.^2)))./(((2*pi)^0.5)*SNR2)


%%%%%%%%%%%%%%%%%%%plot for
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);
hold on;
plot(Depth,Q1, 'kd-');
```

```
plot(Depth,Q2, 'ks-');
grid on;
title('CSR vs. Q factor');
xlabel ('Carrier to Sideband Ratio (dB)');
ylabel ('Q factor');

legend ('6 dBm ', '12.5 dBm');
```

Below is the Matlab-code for Figure 4-6 and Figure 4-7:

```
%%%%%%cd
d:\linghu\work\modeepth%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Resistance : 12 kohm
% the temperature is set as correspondence to 12 kohm
% the optical power set at the detector is 3 dBm
% wavelength at 1550 nm
% unit for Power_watt : mw
% unit for Power_dBm : dBm
% unit for Impedance : kohm
% unit for wavelength : nm

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
power1 = [-8 -10 -12 -14 -16];
power2 = [-6 -8 -10 -12 -14];
power3 = [-4 -6 -8 -10 -12];
power4 = [-2 -4 -6 -8 -10];
power5 = [0 -2 -4 -6 -8];

SNR1 = [12.74 10.58 7.46 5.04 3.12];
SNR2 = [12.88 11.42 8.62 5.83 3.77];
SNR3 = [12.38 10.80 8.20 5.56 3.50];
SNR4 = [12.82 11.70 9.46 6.84 4.55];
SNR5 = [12.84 11.77 10.31 8.00 5.38];

Q1 = SNR1 /2;
Q2 = SNR2 /2;
Q3 = SNR3 /2;
Q4 = SNR4 /2;
Q5 = SNR5 /2;

%%%%%%%%%%%%%%%%%%%%%%%%%Bit Error
Rate%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
BER1 = (exp((-0.5)*(Q1.^2)))./(((2*pi)^0.5)*Q1);
BER2 = (exp((-0.5)*(Q2.^2)))./(((2*pi)^0.5)*Q2);
BER3 = (exp((-0.5)*(Q3.^2)))./(((2*pi)^0.5)*Q3);
```

```
BER4 = (exp((-0.5)*(Q4.^2)))./(((2*pi)^0.5)*Q4);
BER5 = (exp((-0.5)*(Q5.^2)))./(((2*pi)^0.5)*Q5);

%%%%%%%%%%%%%%%%%%plot for
curve%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1);
hold on;
plot(power1,Q1,'k+-');
plot(power2,Q2,'k*-');
plot(power3,Q3,'ks-');
plot(power4,Q4,'ko-');
plot(power5,Q5,'kd-');
grid on;
title('Received Power vs. Q factor (Optical power 12.5 dBm)');
xlabel ('Received Power(dBm)');
ylabel ('Q factor');
legend ('12dB','15dB','18dB', '21dB','24dB');
hold off;

figure(2);
semilogy(power1,BER1,'k+-');
hold on;
semilogy(power2,BER2,'k*-');
semilogy(power3,BER3,'ks-');
semilogy(power4,BER4,'ko-');
semilogy(power5,BER5,'kd-');

grid on;
title('BER vs. Received Power');
xlabel ('Received Power(dBm)');
ylabel ('Bit Error Rate');
legend ('12dB','15dB','18dB', '21dB','24dB');
hold off;
```

Appendix B – List of Publications

Refereed Journals

Ling Hu, Aleksandra Kaszubowska and Liam Barry, "Investigation of Stimulated Brillouin Scattering Effects in Radio-over-Fiber Distribution Systems", Elsevier Journal of Optics Communications, Vol. 255, Issues 4-6, 15 Nov. 2005, Pages 253-260.

A. Kaszubowska, L.P. Barry, P. Anandarajah and **L. Hu**, "Characterization of Wavelength Interleaving in Radio-over-Fiber Systems Employing WDM/SCM", accepted for publication in Journal of Optics Communications.

Refereed Conferences

Ling Hu, Aleksandra Kaszubowska and Liam Barry, "Pre-filtering on Signal Fading Effect for Radio-over-Fiber Distribution Systems." Paper 5825-49, Technical Proceedings, SPIE OPTO-Ireland, Dublin, Ireland, 4-6 April 2005.

Pre-filtering on Signal Fading Effect for Radio-over-Fiber Distribution Systems

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Abstract

With the increasing demand for broadband services, it is expected that radio over fiber (RoF) systems may be employed to provide high capacity wireless access networks. In this kind of system, microwave data signals are modulated onto various optical carriers at a central control station, and then distributed to remote sites using optical fibres.

A major problem with the system described above, is that standard amplitude modulation of the optical carrier generates Double Side-Band (DSB) signals. If such signals are transmitted over fiber, chromatic dispersion would cause each side band to experience a different phase shift depending on the fiber-link distance, modulation frequency, and fibre dispersion. If the phase difference at the receiver equals π, the two side bands would interfere destructively causing fading of the received signal. Chromatic dispersion effects can be reduced by eliminating one sideband to produce an optical carrier with a single sideband (SSB). This could be achieved by using an optical filter to filter out one side band.

Another problem comes in RoF systems may come from Stimulated Brillouin Scattering (SBS). SBS is an interaction between light and sound waves in the fiber, which causes frequency conversion and reversal of the propagation direction of light. Once the Brillouin threshold is reached, it is a process that leads to a dominant nonlinearity in single-mode optical fibre which can produce significant noise on the received optical signal. Therefore, it severely limits the optical power that could be transmitted through a fiber and it is detrimental for optical communication systems. SBS can also be reduced by the filtration carried out at the transmitter (pre-filtering). Since the optical filer functions to eliminate one sideband and induces insertion loss, the optical power to be launched into the transmission fiber falls sharply and so does the risk of SBS.

In this paper, we investigate the possibility of performing SSB filtering to simultaneously overcome the effects of dispersion and SBS in the transmission fibre. The system performance is verified for SSB pre-filtering and compared with the case where the filtration is performed at the receiver (post-filtering). The results show that the pre-filtering can filter out one side band as well as to avoid the effect of SBS by reducing the optical power launched into the transmission fibre.

Keywords

Radio over Fiber (RoF), Single Side Band (SSB), Stimulated Brillouin Scattering (SBS), Fibre Bragg Grating (FBG).

1. Introduction to Radio over Fiber (RoF)

RoF is a technology used to distribute RF signals over analog optical links. The RoF technology enables the generation of millimetre-wave signals with excellent properties. It offers the advantages of low loss, huge bandwidth, high security, and immunity to electromagnetic interference. For optical fiber communications, the low attenuation windows at 1.3 um and 1.55 um have bandwidths around 0.1 um. If these optical bandwidths are converted to frequency range, it is approximately equivalent to a total bandwidth of 30000 GHz [1].

The basic RoF system is a bi-directional analog fiber optic link and consists of a laser/photodiode pair at each site of the link, and transmitting and receiving antennas at the remote base stations. Signals are generated at a central control station and then distributed to base stations using single-mode optical fibers, as shown in figure 1. The control station, which feeds many base stations are responsible for optical-electrical (o/e) and electrical-optical (e/o) conversions, as well as up-conversion, down-conversion, and processing of the electrical data signals. At the remote base stations, o/e and e/o converters are employed. The o/e converters convert optical signals received from the control station to RF signals and then forward them using the antennas to the end users. On the other hand, the e/o converters convert the RF signals gotten from the antennas to optical signals that are then translated to the control station [2].

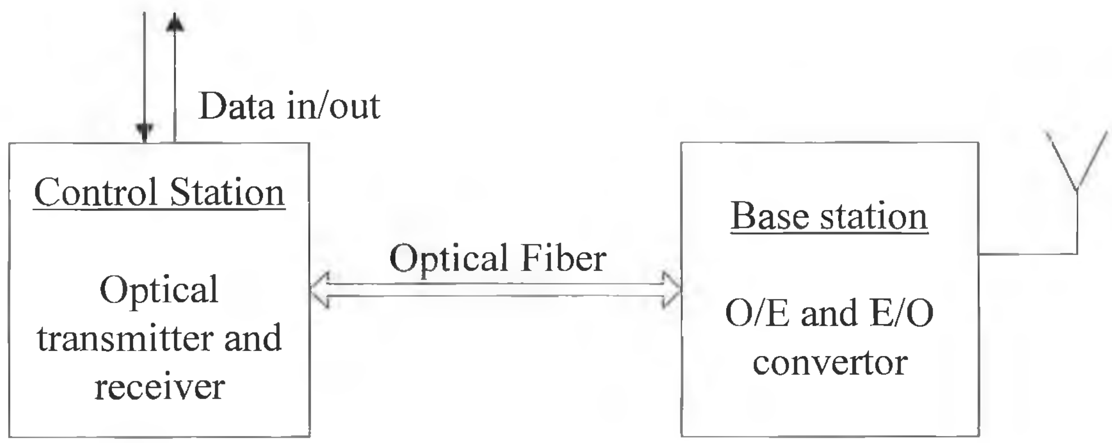

Figure 1. Typical layout of RoF system

2. Chromatic Dispersion Induced Fading Effect

Chromatic dispersion is the broadening of an input optical signal as it travels along the length of the fiber. Chromatic dispersion phenomenon occurs because different wavelengths will propagate at different speeds along the length of the fiber.

In conventional intensity modulation, the optical carrier is modulated to generate an optical signal with double sideband (DSB) [3]. If the signals are transmitted over the fiber, chromatic dispersion causes each sideband to experience different phase shift depending on the fiber-link distance and modulation frequency, producing a phase difference between the two beat signals generated at the detector. When the phase difference between the two sidebands is π, the RF signals will be completely cancelled out. As the RF frequency or fiber-link distance increases, this effect is even more severe and limits the system performance [4].

Since chromatic dispersion makes upper and lower sideband subcarrier experience different phase shift, it is a critical problem for RF transmission. It has been shown that this phenomenon can significantly limit the transmission distance operated above 20GHz. For example, in an externally modulated fiber link operated at 20 GHz, the detected RF power degrades 3 dB for a distance of 6 km; while operated at 60 GHz, the detected power degrades 3 dB for only 0.7 km [5]. At 60GHz, with a standard single-mode fiber of dispersion 17 ps/km.nm, a 1 dB penalty is induced after less than 500m transmissions, and the received signal is completed extinct after 1 km [6].

Chromatic dispersion effects can be reduced and almost totally overcome in RoF systems by eliminating one sideband to produce an optical carrier with single sideband (SSB) modulation [4], which is called optical single sideband (OSSB) transmission. Therefore, transmission of the optical carrier and just one of the sidebands prevents interference and the associated RF power fading. Experiment showed that, although the optical signals are DSB, the correct positioning of a Bragg filer at the receiver base-station could eliminate one of the sidebands and improve the quality of signal significantly [7].

3. Stimulated Brillouin Scattering (SBS) Effect

Stimulated Brillouin Scattering (SBS) is manifests due to acoustooptic fluctuations via electrostriction. The incident pump wave generates acoustic waves through the process of electrostriction, which in turn causes a periodic modulation of the refractive index [8]. Once the Brillion threshold is reached, a large part of the pump power is transferred to the Stokes wave [9].

The process of SBS can be described classically as a parametric interaction among the incident pump wave, the Stoke wave, and an acoustic wave. The pump-induced index grating scatters the pump light through Bragg diffraction [10]. Scattered light is downshifted in frequency because of the Doppler shift associated with a grating moving at the acoustic velocity. Hence, a Stokes wave is generated downshifted from the frequency of the incident pump wave and the frequency shifted is determined by the nonlinear medium.

The same scattering process can be viewed quantum-mechanically as if annihilation of an incident pump photon cerates a Stokes photon and an acoustic phonon simultaneously. Since both the energy and the momentum must be conserved during each scattering event, the frequencies and the wave vectors of the three waves are related by

$$\varpi_A = \varpi_p - \varpi_s \quad (1)$$

$$k_A = k_p - k_s \quad (2)$$

Where ϖ_A, ϖ_p and ϖ_s are the frequencies of the acoustic wave, the incident pump wave and the Stocks wave; k_A, k_p and k_s are the wave vectors of the acoustic wave, the incident pump wave and the Stocks wave, respectively [8].

In a single-mode optical fiber the only relevant directions are only the forward and the backward directions. When the scattering angle θ = π, the shift reaches the maximum value. Therefore, the one-dimensional guiding nature of optical fibers only allows observation of the Stokes wave in the backward and the frequency difference between the incident wave and the Stoke wave υ_B is given by

$$\upsilon_B = \frac{2nV_A}{\lambda_p}, \tag{3}$$

where λ_p, n, and V_A are the wavelength of the incident pump, the refractive index of the core, and the sound velocity inside the material, respectively [10]. If we use the values appropriate for silica fibers, such as V_A = 5.96 km/s and n=1.45, we can get υ_B = 11.1 GHz at λ_p = 1.55 um [8].

Under proper conditions SBS will be the dominant nonlinear process. It converts the transmitted signal in the fiber to a backward scattered one, decrease the quality of the signals that are transmitted in the fiber and thus sets a limit to the total fiber injected power [11].

4. Experimental setup and results

In this paper, we experimentally investigate the possibility of performing optical filtering to overcome the effects of chromatic dispersion and SBS simultaneously in the transmission fibre. The system performance is verified for SSB pre-filtering and compared with the case where the filtration is performed at the receiver (post-filtering).

The experiment we set up is shown in Figure 2. A 155.520 Mbit/s NRZ data stream from an Anritsu pattern generator is initially passed through a 117-MHz low-pass filter to minimize the bandwidth of the data signal. Then the signal is mixed with a RF carrier of 18 GHz to generate binary phase-shift keying (BPSK) data signals. The emission wavelengths of the lasers (around 1550 nm) can be slightly altered and set to specific values by the temperature control of the diodes. We use two inline power meters that include tunable attenuators (see the positions B and D) to show and adjust the optical power launched into the fiber reel and the photodiode, respectively. At positions A and C, we leave the places for the inserting of the Bragg grating (optical filter) according to the experiment demands. Some parameters for this experiment are:

Two standard single-mode fiber reels of dispersion around 17 ps/km.nm at 1550 nm, each one is as long as 12670 m.

Bragg grating (optical filter): JDS Uniphase TC 001211. The frequency response of the Bragg filter is shown in figure 3. It is a Band-Stop optical filter if used in transmission method instead of reflection method.

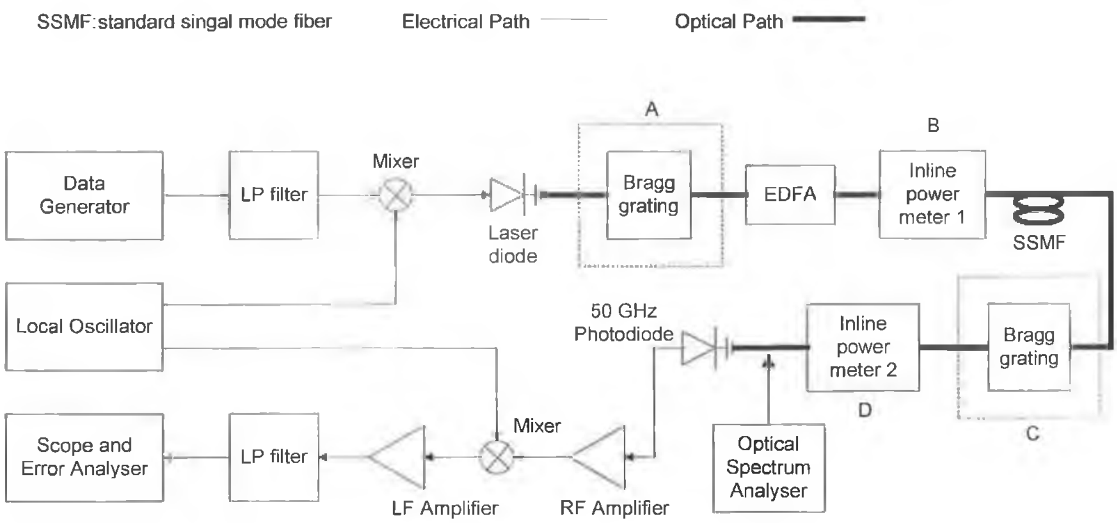

Figure 2. The experiment set up

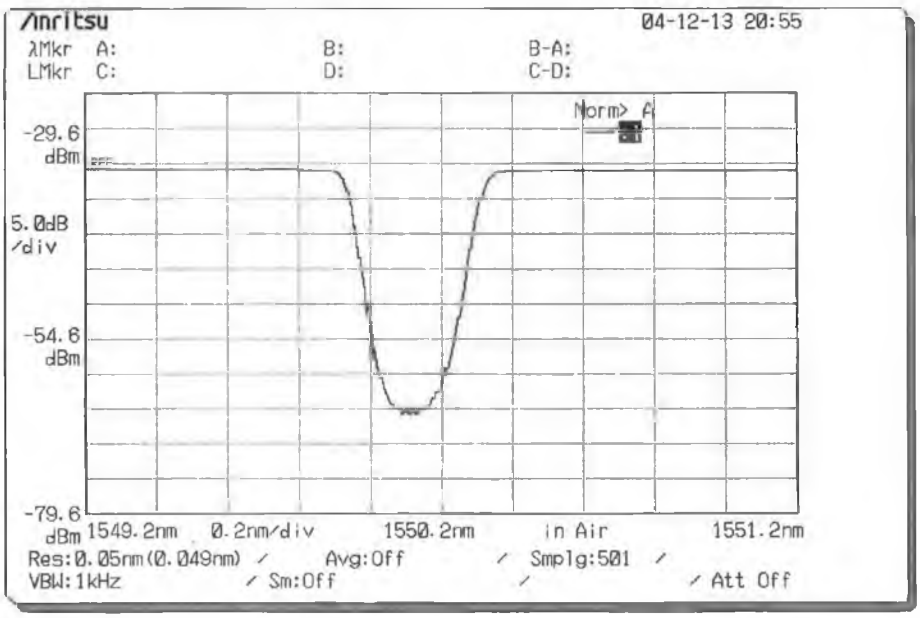

Figure 3. Frequency response of the Bragg filter used in transmission method

4.1 Measure Brillion Threshold

In order to measure the Brillion threshold, we do not need any Bragg grating in the system, which means that, at the position A and C, it is only fiber patch cords to be used. We make use of one fiber reel of 12670m, which is long enough to show the effect of SBS.

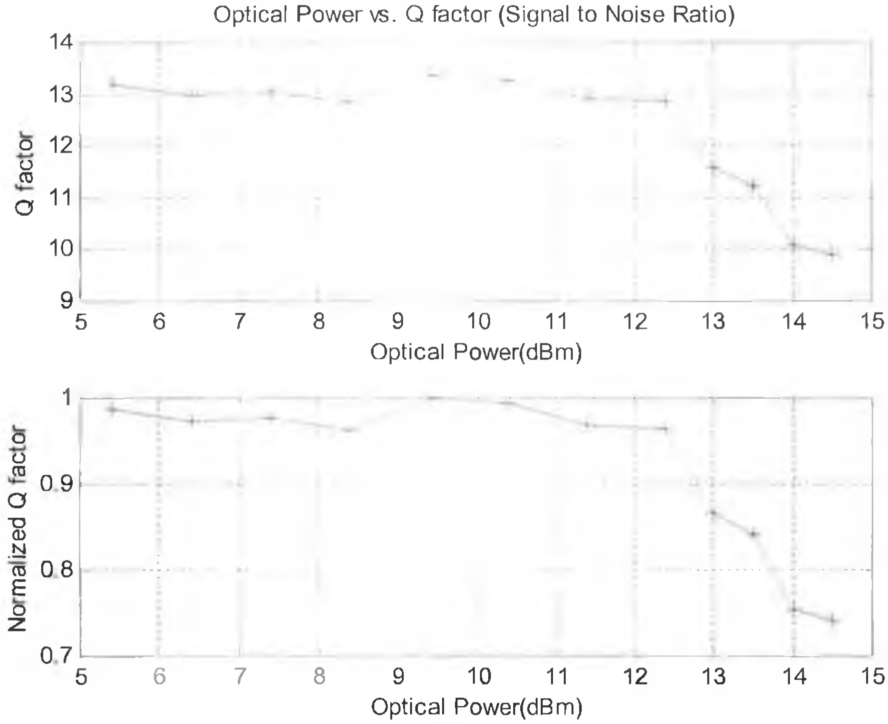

Figure 4. Optical Power vs. Q factor

In this experiment, we change the optical power launched into the fiber reel by changing the pump power of the EDFA (optical amplifier) and read the optical power value from the inline power meter 1. After the signal propagating through the 12.7 km long fiber reel, we adjusted the attenuation of the inline power meter 2 to keep the optical power to be launched into the photodiode 3 dBm constant. For the laser diode, we set the bias current at 60 mA to guarantee that it works in linear area. From the oscilloscope we read the value of signal to noise ratio, which is the same as the Q factor. In Figure 4 we see that the Q factor fall down sharply when the optical power launched into the fiber reel reached 12.5 dBm. Since the degradation of Q factor begins at the SBS threshold, we know that for our experiment set-up, the SBS threshold is about 12.5 dBm.

4.2 Fading Effect Without any Filter

In order to investigate the fading effect and the SBS effect simultaneously, we set up the experiment without any Bragg grating in the system and change the pump power of the EDFA to keep the optical power launched into the fiber reel 12.5 dBm (shown on the inline power meter 1). At the receiver, we adjusted the attenuation of the inline power meter 2 to keep the optical power launched into the photodiode 0 dBm.

From experiments, we found that, when the fiber reel is as long as 25 km, the fading effect is the most serious. Hence we connected two fiber reels of 12670m together to get the fiber length at around 25 km.

In order to measure the optical spectrum, an Optical Spectrum Analyser (Anritsu MS 9717A) is employed just before the photodiode (see Figure 2). The result is displayed in Figure 5.

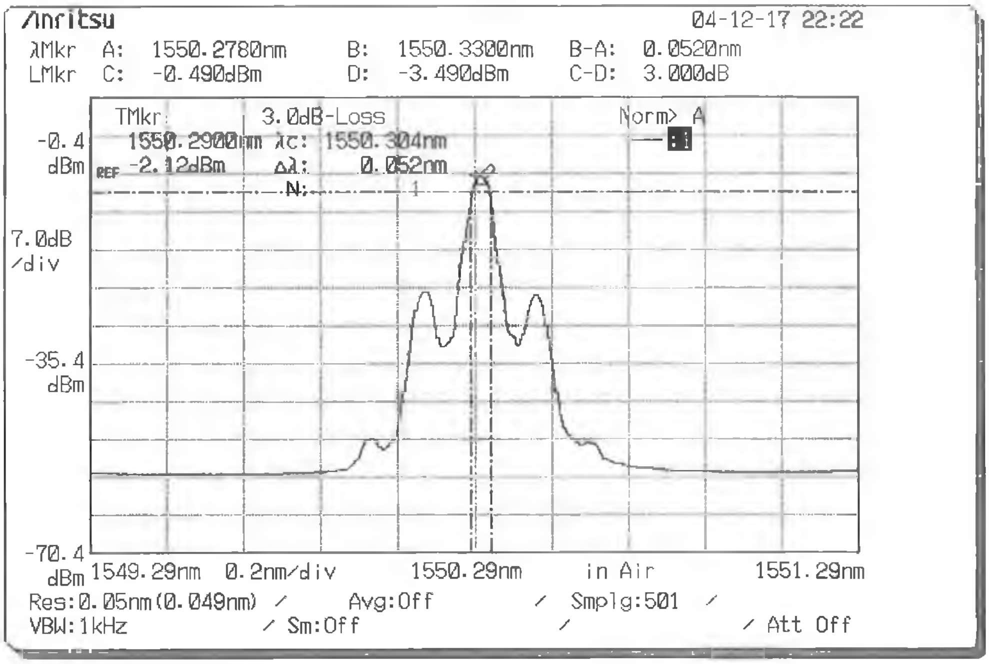

Figure 5. The optical spectrum just before the photodiode

The optical spectrum is shown as Double Side Band signal (DSB), which causes signal fading as we have mentioned before. In this case, the phase difference between the two side bands is around π, which induces the cancel out of the signals. As for this experiment, the eye-diagram shown from the oscilloscope is displayed in figure 6, which verifies our prediction of closed eyes very well. In additional, because of the influence of SBS, even when the eye is closed, severe noise is also clearly shown on the eye-diagram.

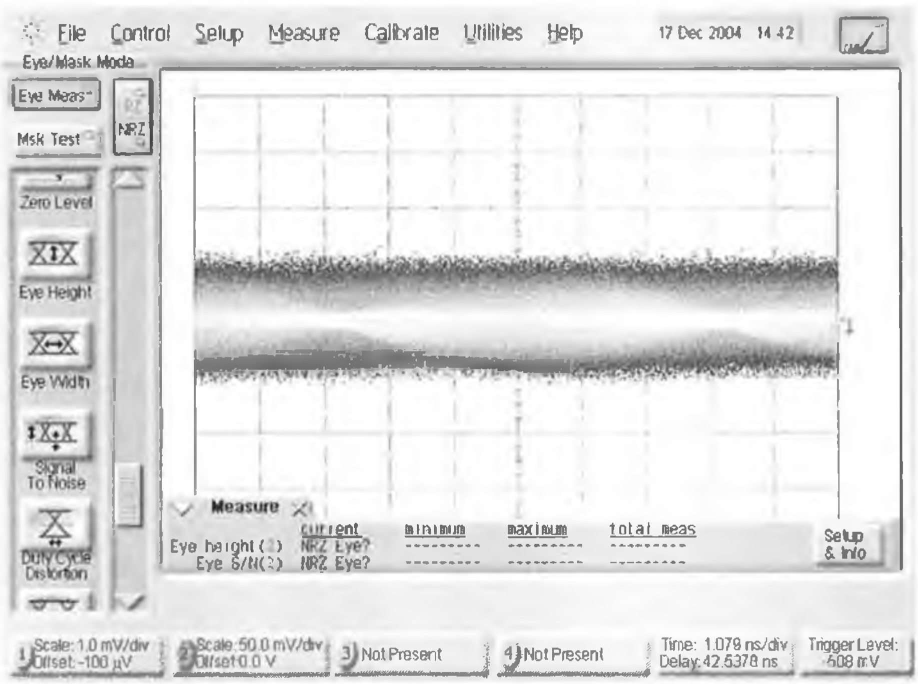

Figure 6. The eye-diagram of the DSB signal shown on the oscilloscope

4.3 The System with Post-filtering

In order to measure the effect of the post-filtering, we posit the Bragg grating at the position "C" of Figure 2. The optical power launched into the 25 km fiber reel is kept at 12.5 dBm and the optical power launched into the photodiode is still been kept at 0 dBm as before.

By using the Optical Spectrum Analyser to measure the optical spectrum just before the photodiode, we got figure 7.

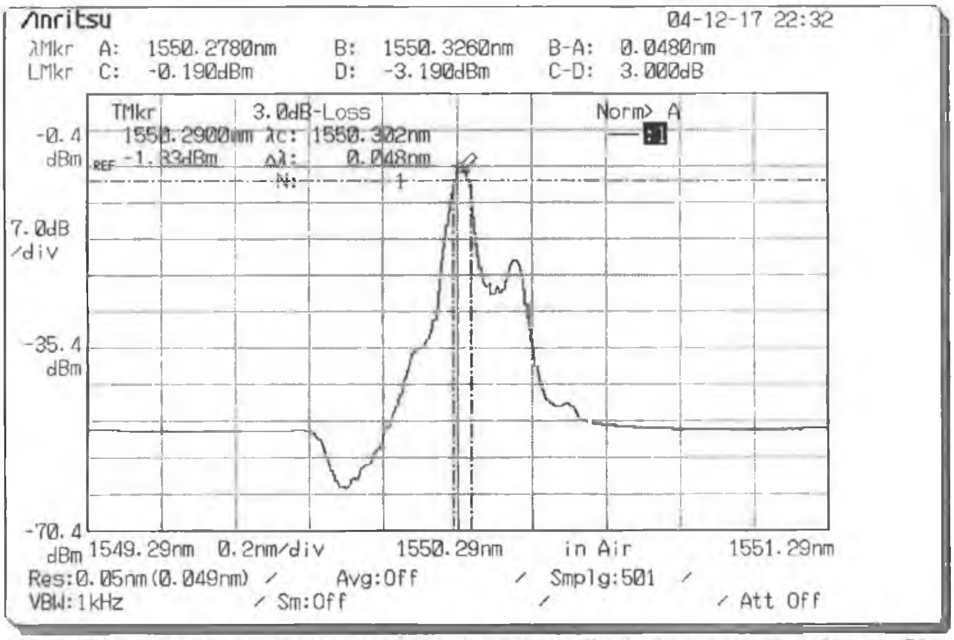

Figure 7. The optical spectrum before the photodiode in the case of post-filtering

Figure 7 shows not only the depression of one side band, but also the SBS effect at about the 11GHz distance from the optical central carrier. We can get it from the form of the fluctuation curve between the carrier and the remaining sideband. The carrier fluctuates because of the effect of SBS, which is not shown in this spectrum, but can be realized if we investigate the inline power meter 2. Since the down-converted signal is the beat result between the fluctuated carrier and the side band, severe noise is induced into the signal and the eye in this case is as follows in figure 8.

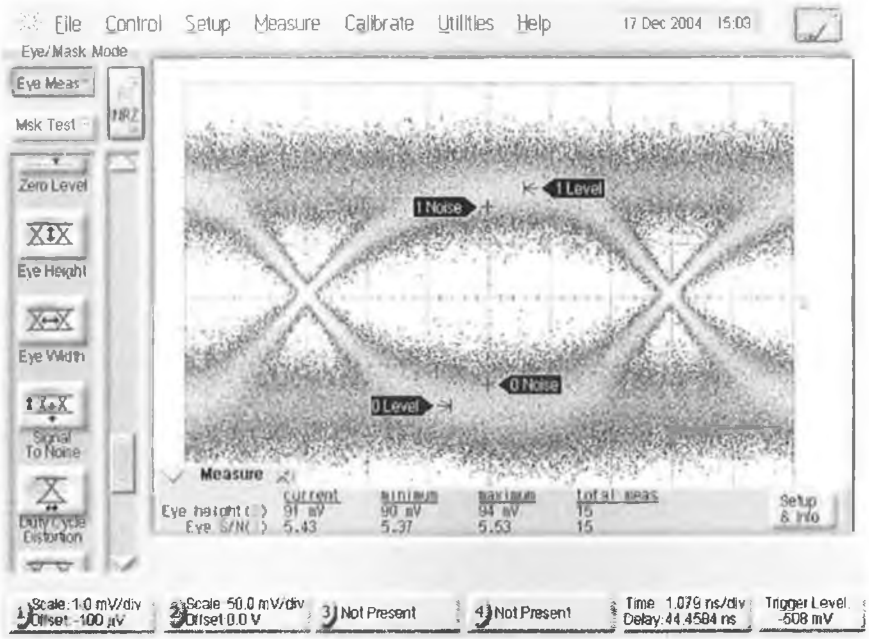

Figure 8. The eye-diagram of the post-filtering system

4.4 The System with Pre-filtering

At last, in order to measure the effect of pre-filtering, we posit the Bragg grating at the position "A" in Figure 2. Although the optical power before the Bragg grating is still 12.5 dBm, after passing through the Bragg grating, the inline power meter 1 show that the optical power launched into the fiber reel is only 7.0 dBm. As before, we adjust the attenuator value of the inline power meter 2 to make sure the optical power to be launched into the photodiode kept at 0 dBm. The same as before, we examine the optical spectrum before the photodiode, which is manifested in Figure 9.

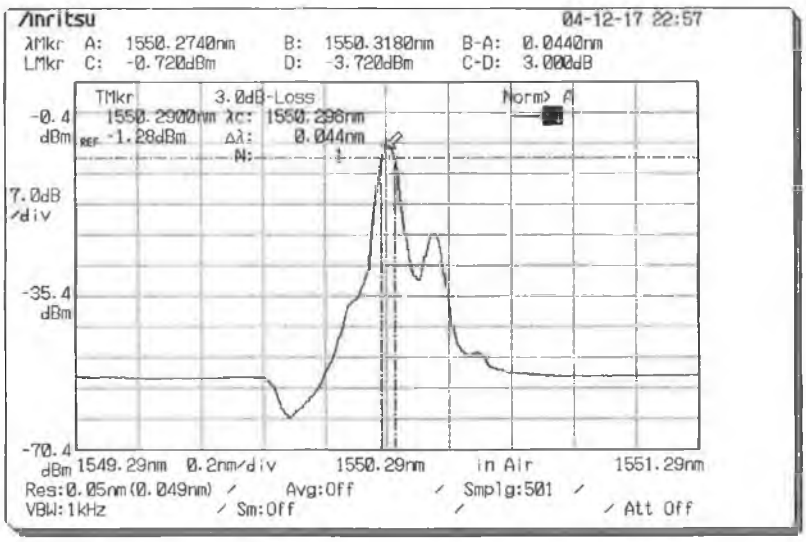

Figure 9. The optical spectrum in front of the photodiode in case of pre-filtering

Since the optical power launched into the optical fiber is lower than the SBS threshold, the optical spectrum shows smooth between the carrier and the sideband,

and we successfully avoid the effect of SBS. In this case, we get a clear and clean eye-diagram shown in figure 10.

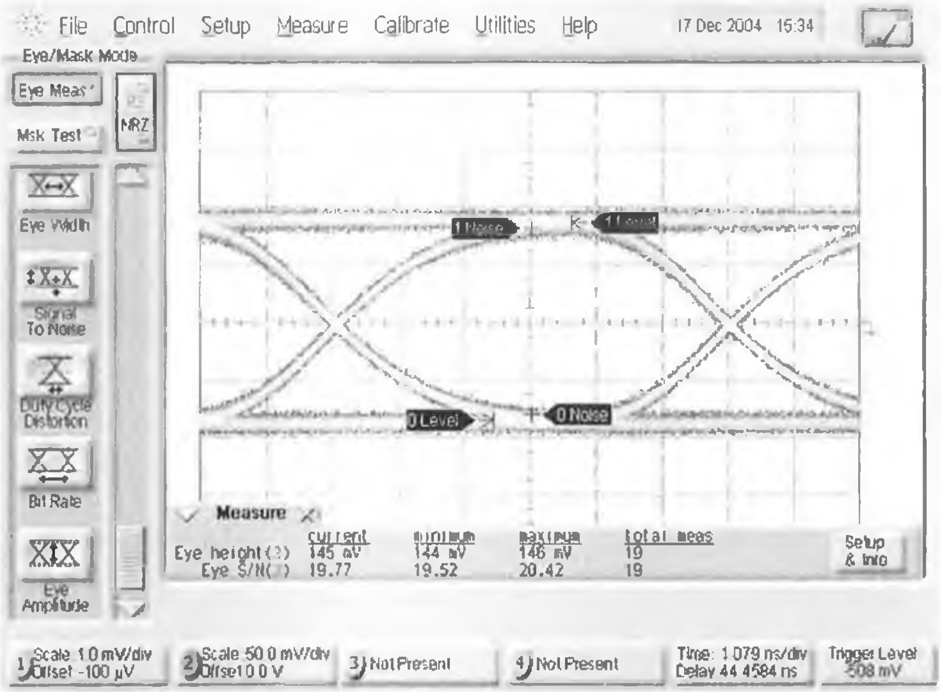

Figure 10. The eye-diagram of the pre-filtering system

Conclusion

In this paper, we investigate the possibility of performing SSB filtering to simultaneously overcome the effects of dispersion and SBS in the transmission fibre. The system performance is verified for SSB pre-filtering and compared with the case where the filtration is performed at the receiver. Our experiments showed that the pre-filtering method could not only get the SSB transmission signal, but also avoid the effect of SSB, which is benefit for the quality of the received signals of the systems.

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