Investigating Pluggable Transceivers' Laser Linewidth, Chirp, and Stimulated Brillouin Scattering Effects on Data Transmission in Different Kinds of Optical Fibers

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Abstract

Pluggable transceivers; either small form factor (SFP) that operates up to 2.5Gbps or XFPs that operates at 9.95Gbps, transmitter's laser characteristics are investigated experimentally. The laser linewidth and chirp in addition to stimulated Brillouin scattering (SBS) threshold for different transceivers are measured over many kinds of optical fiber. The measured transceiver's parameters are correlated and used to explain different system performance penalties encountered during data transmission over different kinds of optical fiber. This knowledge is valuable to system engineers as it is not available and not provided by transceivers' vendors. System performance penalties for different kind of fibers with positive and negative accumulative dispersion are measured experimentally at OC-192 and OC-48 modulated signals for different XFPs and SFPs, respectively.

Keywords: laser linewidth, chirp, Stimulated Brillouin Scattering, fiber dispersion, SFP, XFP, optical communication, fiber nonlinearity

1. INTRODUCTION

The demand for increased data and telecommunication services requires enhanced performance of systems in the metro-edge area of the communication network. Such networks require extending the transmission distance and packing more signals into transmission lines. Currently, over 40 signals could be packed in one fiber each having its own wavelength within a narrow span of wavelengths centred around 1550 nm. Each of the many optical signals is transmitted with a spacing of as little as 0.8 nm from its closest neighbour. To keep these laser signals from interfering with each other, signals must be spaced properly and must guarantee adjacent signals from drifting into one another.

This paper explores the possible correlation between transmitter laser linewidth, chirp, and SBS threshold in addition to their effect on data propagation in different dispersion regimes. The system performance is characterized in terms of BER. Discovering possible correlations can help to predict the performance of the transmission system based on the knowledge of the transceiver laser characteristics. Such data can provide valuable information when designing and building optical transmission systems for various applications. Several DWDM XFPs and SFPs with different characteristics from various vendors have been used to conduct tests and collect data. This paper will cover the basic theory of chirp, laser linewidth and Stimulated Brillouin Scattering, set-up used to conduct measurements, discovered correlations which would influence transmission system penalties. Optical heterodyne method was used to measure laser linewidth and chirp was measured by OSA Monocromator with digital communication analyzer (DCA) method. System performance measurements of each transceiver were done over SMF-28 fiber, and three different dispersion compensation fibers.

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2. LASER LINEWIDTH

SFPs are small form pluggable modules that contain laser diode and receiver photodiode circuitries in one unit. Data transmission rates between 125Mbps to 2.5 Gb/s (OC-48) can be achieved with commercial SFPs. Supported distances range from 500 m to 120 km. SFPs use directly modulated lasers to modulate the signal. XFPs are extended small form pluggable devices transmit data at 10 Gb/s and can be used in OC-192 systems. The signal in XFP optical modules is externally modulated compared to SFPs. The linewidth of a laser is the full width at half-maximum (FWHM) of its optical spectrum. More precisely, it is the width of the power spectral density of the emitted electric field that is usually expressed in terms of frequency.

In DWDM systems, signals are packed very close together so transceivers' laser linewidth values must be known within hundreds of picometers. The linewidth should be small enough to ensure adjacent DWDM channels do not overlap. The laser linewidth have an effect on the chromatic dispersion and SBS threshold in optical fiber that ultimately will define the possible transmitting distance. Lasers with narrower linewidth enable longer reach that can be explained as signal transmitted with narrower linewidth laser encounter less of chromatic dispersion [1]. Typical 1550nm DFB laser has a very narrow width which is about 10 MHz, or 0.00008 nm. Due to a very narrow laser spectral width the use of Optical Spectrum Analyzer (OSA) is not suitable to measure its width because of limited resolution of the instrument bandwidth filter [2]. Optical self-heterodyne method maybe used to measure the linewidth of the lasers in the electrical domain.

This technique offers exceptional sensitivity and resolution. It involves mixing an optical signal from a reference laser with an unknown optical signal, then converting the interfered optical signal into the RF frequency spectrum. The main component of the system is stable narrow linewidth reference laser local oscillator (LO). In such system, the reference laser is tuned appropriately to the measured laser and then its optical frequency is fixed during the measurement. This is possible because of the of the wide analysis bandwidth offered by electrical spectrum analyzer (ESA). The reference laser is tuned to the frequency immediately below the average frequency of the studied laser. This creates a heterodyne beat tone between the LO and each of the frequency components in the signal spectrum. Thus, each frequency component is translated to low frequency interference. The ESA display is proportional to the power spectrum of photodetector current which contains product of optical heterodyne mixing as well as direct detection. The line shape of the laser, including any asymmetries, is replicated at low frequency set by optical frequency difference between the two lasers [3]. Because laser noise does not permit to measure linewidth accurately at -3dB level, a Gaussian curve approximation was used to determine linewidth at -3dB level. Each laser was measured three times because of unstable spectrum line shape. Figure 1 displays examples of laser linewidth measurements with a bell curve approximation. On the left an SFP with 307 MHz linewidth and on the right an XFP with 27 MHz linewidth are displayed. Table 1 presents the measured linewidth for different SFP and XFP lasers from different vendors.

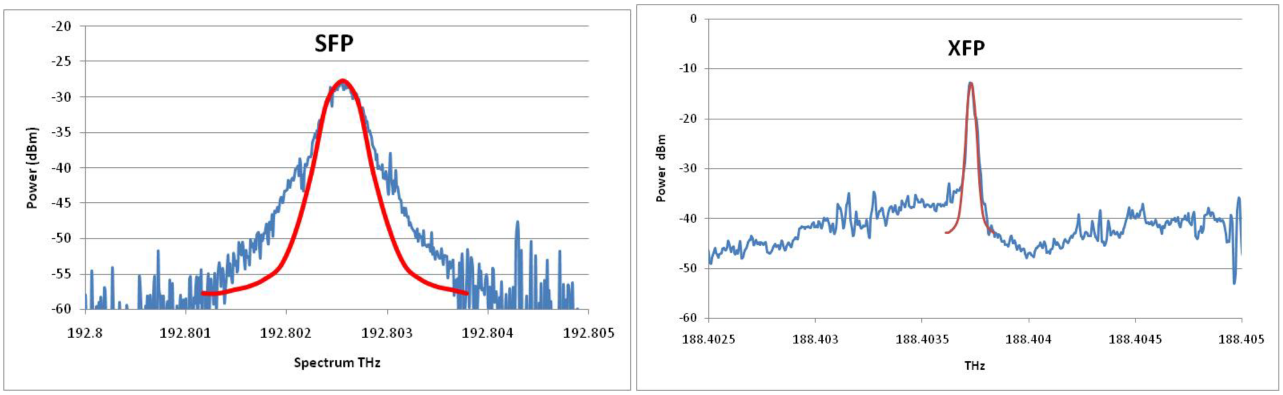

Fig. 1 Laser linewidth measurement of SFP 307 MHz and XFP 27 MHz

Table 1 Laser linewidth measured data.

			Linewidth	
SFP	**Wavelength (nm)**	**MHz**	**MHz**	**MHz**
1	1530.33	3300	3300	3000
2	1559.79	377	91	87
3	1559.794	323	308	125
4	1554.94	444	364	307
5	1548.51	36	40	27
6	1548.51	143	125	118
XFP				
7	1559.794	222	147	167
8	1559.794	56	52	54
9	1591	33	27	25
10	1540.55	-	-	-
11	1542.1	-	-	-
12	1560.6	60	105	95

3. CHIRP

In densely spaced wavelength network such as DWDM (Dense Wave Division Multiplexing), stable low chirp lasers needed to operate at a very precise wavelength. It is important to quantify and understand chirp effects on the transmission characteristics of the optical system. The laser chirp or frequency chirp is the instantaneous frequency change of the emitted laser signal associated with intensity modulation of output power. The chirp is usually viewed as a parasitic effect that originates in the laser's cavity from the variation of carrier density concentration due to driving current modulation. These variations in the laser cavity create a variation in the index of refraction, and therefore a change in the resonant frequency. The chirp has an unwanted effect of linewidth broadening when the laser is modulated. The broadening can happen well beyond the free running optical linewidth. The chirp effect becomes significant when increased linewidth interacts with chromatic dispersion and limits the transmitting distance especially with ultra-high bit rate systems. Since transient chirp accounts for the most of frequency broadening, measurement and analysis of transient chirp will be discussed in this work.

Dispersion in optical fiber can be positive or negative depending on the fiber zero dispersion wavelength and the transmitter laser wavelength. In the case of positive dispersion which can be found in standard SMF-28 optical fiber at wavelengths above 1310nm the rising edge of the pulse which has blue-shifted frequency components propagates in the fiber with a higher group velocity and falling edge which has red-shifted frequency components travel slower in the fiber. Such combination causes pulse compression in the frequency domain or pulse broadening in the time domain [4]. Fiber with negative dispersion such that is used in dispersion compensation module (DCM) has the opposite effect on the propagated pulses in fiber with positive dispersion. Rising edge of the pulse propagates slower while the falling edge travels faster. This causes the signal pulses to broaden in the frequency domain, but compress in the time domain.

Chirp as well can be positive or negative. Depending on the combination of the chirp and dispersion type, pulse gets broader or narrower during propagation. In the case of a laser with positive chirp carrying pulses propagating through a positive dispersion medium, positive chirp reinforces the effect of the positive dispersion and broadening of the pulse in the time domain occurs faster. Laser with higher positive chirp and narrower linewidth would suffer larger penalty in such chirp/dispersion transmission combination. In the case of a positively chirped pulse traveling in the negative dispersion medium, chirp suppresses the effect of dispersion compensation, so compression of the pulse width would be lower. Positive chirp would reduce the dispersion compensation effect of DCM modules. On the other hand, negative chirp would helps to compress the pulse in the time domain when applied in the positive dispersion regime which help to keep the pulse width narrower. Therefore, some negative chirp is desired to keep pulses from spreading in a positive dispersion environment. Although in the negative dispersion regime, negative chirp amplify the effect of dispersion compensation, so red component of the pulse will cross over with blue component and broadening of the pulse in the time domain may occur. This would depend on the level of chirp, compensation factor of DCM module and original linewidth of the laser.

Figure 2 shows the set-up block diagram. OSA Monocromator and Digital Communication Analyzer (DCA) method [5] has been used to measure chirp of SFPs and XFPs. Measurements were done with a modulated signal at frequency of 10Gb/s for XFP lasers and at 2.5Gb/s for SFP modules.

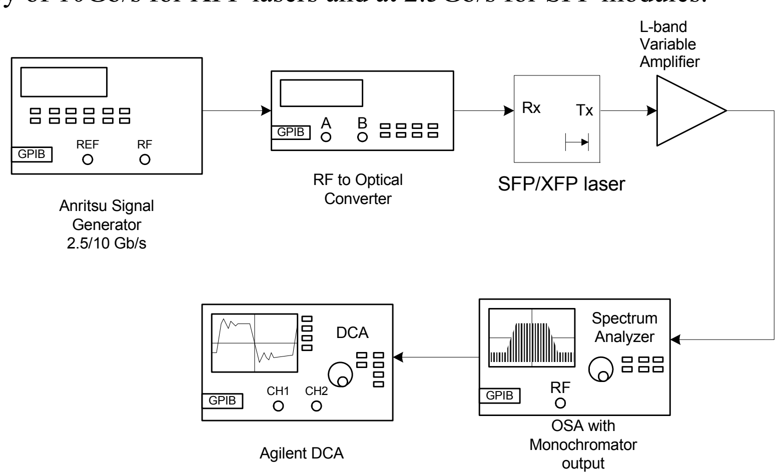

Fig. 2 Chirp measurement set-up block diagram.

Figure 3 displays the measured chirp for one of the used SFPs in this work, the blue line represents measured chirp in GHz and the red line represents signal intensity measured in Watts. Chirp identified by a yellow line represents the peak chirp.

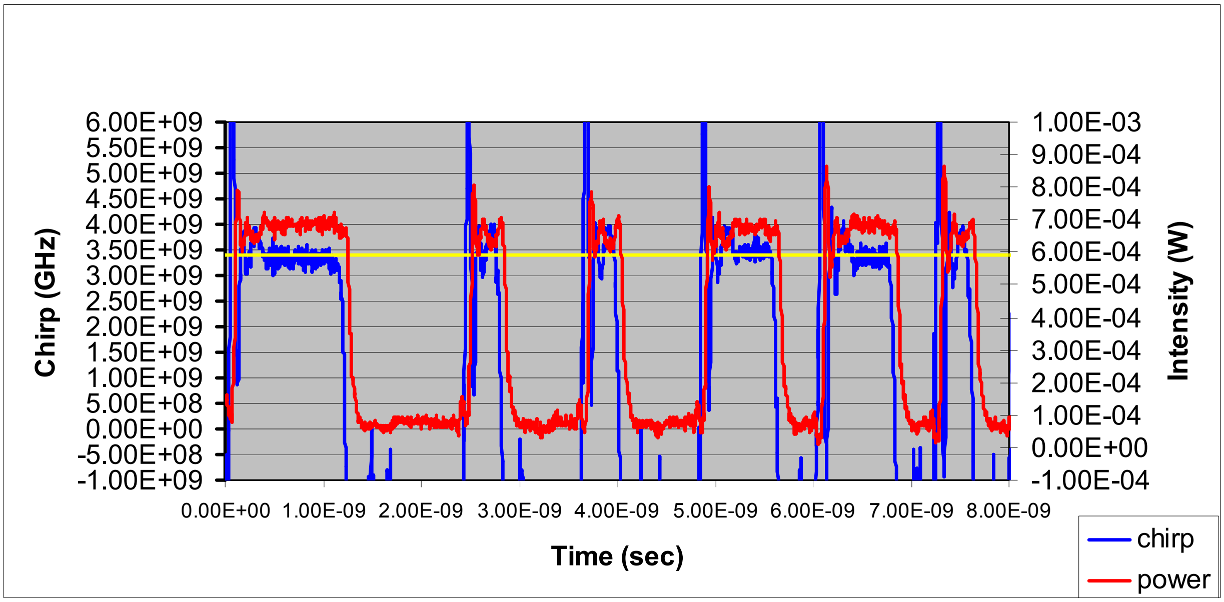

Fig. 3 Measured chirp of commercial SFP.

Table 2 Measured laser chirp for different commercial SFPs and XFPs.

SFP	Wavelength (nm)	Chirp GHz
1	1530.33	4.8
2	1559.79	2
3	1559.794	3.4
4	1554.94	2.2
5	1548.51	2.2
6	1548.51	2.3
XFP		
7	1559.794	0.4
8	1559.794	0.4
9	1591	0.7
10	1540.55	-
11	1542.1	-
12	1560.6	0.8

It is apparent in table 2 that SFP lasers have greater chirp than XFP lasers which could be related to the mechanism of modulating the laser in SFPs and XFPs. SFP laser is directly modulated while XFP laser is externally modulated. Internal modulation creates much more laser chirp.

4. STIMULATED BRILLOUIN SCATTERING

SBS nonlinear effect causes power depletion in fiber optic communication systems which results in performance penalties that limits transmission reach. The SBS effect commences at a threshold related to fiber physical characteristics and laser linewidth. At this threshold, signal transmitted power through the fiber cannot be increased because all the additional power scatters backward in the fiber and does not reach the receiver. SBS threshold essentially determines the maximum power that can be launched into the fiber without power penalties and without decreasing the signal to noise ratio (SNR). The SBS is a nonlinear optical effect resulting from a deviation of the optical wave on the density modulation or acoustic wave in the material [6]. In regions of high optical power density, the material itself becomes denser and the light scatters at those density variations creating backward traveling down shifted or Stokes shifted wave. When an optical field has high intensity, it interferes with the scattered optical field. The superposition of propagating and scattered Stokes waves generates an acoustic wave as illustrated in Figure 4. The wave vector of the acoustic field is related to phonon dispersion by

$$\Omega_B = |q|\upsilon_A \approx 2\upsilon_A |k_p| \sin\left(\frac{\theta}{2}\right), \qquad (1)$$

since in a single mode fiber $\theta = 0$ and π, the Brillouin frequency shift expressed by

$$\nu_B = 2n\upsilon_A / \lambda_p \qquad (2)$$

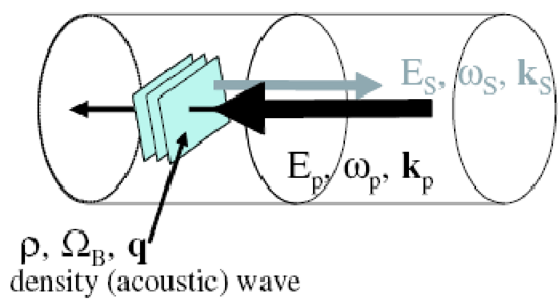

Fig. 4 The SBS process in the optical fiber, where $\omega_{p,S}$ and $k_{p,S}$ are the optical frequencies and wave vectors of the pump and Stokes shifted fields, Ω_B is a Brillouin frequency, ρ is density of the acoustic wave and q is the wave vector.

An acoustic wave in pure silica travels at 5.96km/s [7] with index of refraction n=1.44 at wavelength 1550nm corresponding frequency shift of ~9-12GHz. The acoustic wave moves in forward direction producing intensity modulation which in turn translates into density variations of the material. When an incoming light starts to feed the acoustic wave with more energy, the scattering increases exponentially and SBS threshold is reached. At that point, the incoming light creates an amplification of scattered light leading to stimulated phenomenon. Because the SBS depends on the intensity of the pump wave, knowledge of the laser linewidth should help to predict the possible SBS threshold. Since optical power density can be described as the optical power per optical frequency (or wavelength) interval, lasers with narrow linewidth would create higher power density regions in the core of the fiber. That is an important consideration that has to be taken into account when choosing a laser for a particular application. The laser linewidth characteristics could influence the maximum launch power and eventually the reach of the communication system.

SBS threshold for SFPs and XFPs were measured when they are modulated and when operated in CW mode. In the case of modulation, a modulated signal was sent to the receiver of the SFP/XFP device and the corresponding electrical signal was looped back to its transmitter. As shown in Figure 5, the signal that was launched into the fiber was amplified up to 20dBm by a variable gain EDFA. Signal then travelled through an isolator to prevent any back reflection to EDFA. A 3dB coupler split the power to the 25km fiber spool path and to the power meter path which is used to measure launched power into the fiber. Part of the light travelling through the fiber spool when experience SBS would travel backward onto the 3dB coupler. Isolators are placed in the setup to eliminate any back reflection. The power meter placed after the fiber spool measures transmitted power. The backward reflected light is measured by the lower left power meter.

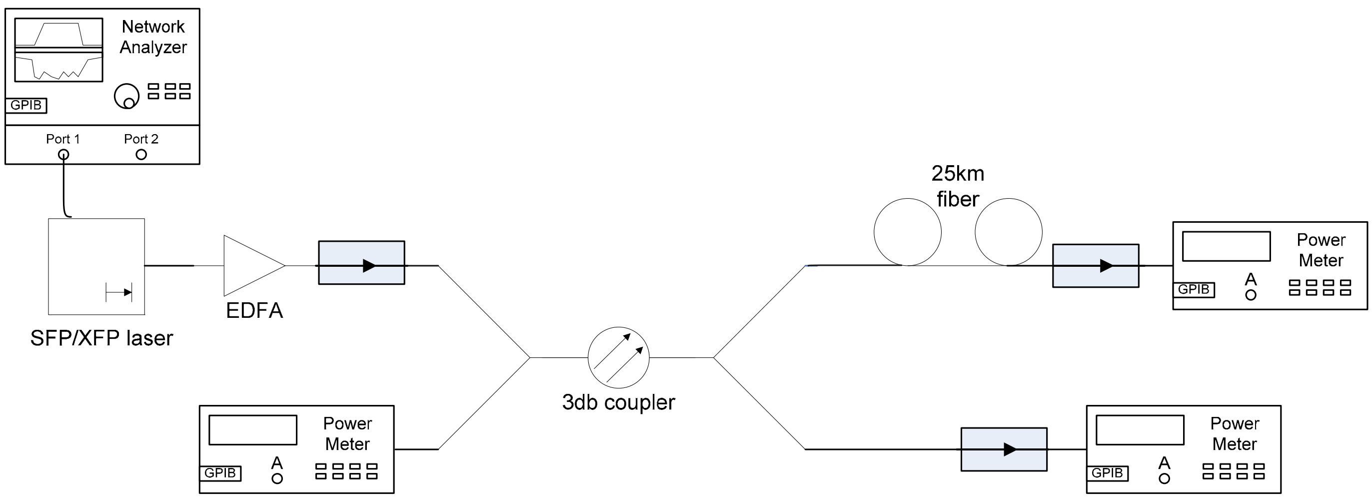

Fig. 5 SBS measurement set-up block diagram.

Figure 5 illustrates the measured transmitted and reflected power in dBm for two SFPs operating in CW mode. Figure 5.a presents a case with a low SBS threshold below 10dBm while Figure 5.b shows high SBS threshold of about 17dBm

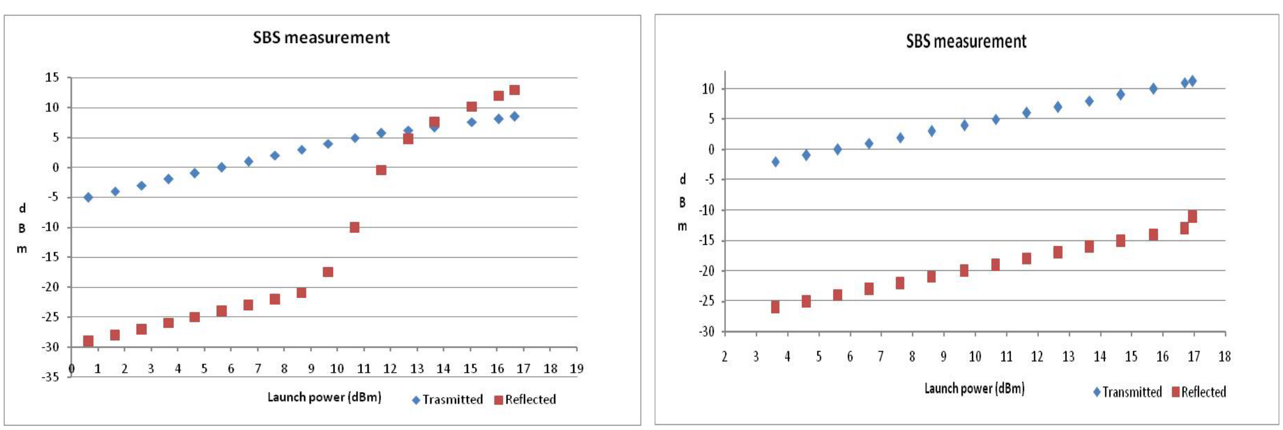

Fig. 5 (a) low SBS threshold SFP. (b) high SBS threshold SFP

Table 3 Measured SFPs/XFPs SBS threshold.

SFP	Wavelength (nm)	Un-modulated dBm	Modulated dBm
1	1530.33	>16	>16
2	1559.79	13.6	>16
3	1559.794	15.6	>16
4	1554.94	16.9	>16
5	1548.51	9.6	>16
6	1548.51	12.6	>16
XFP			
7	1559.794	>16	>16
8	1559.794	11.35	11.35
9	1591	>16	>16
10	1540.55	13.5	13.5
11	1542.1	12.4	12.4
12	1560.6	13.95	13.95

It is clear in Table 3 that modulation affects SBS threshold level for both SFPs and XFPs. SFP lasers are internally modulated and have much higher SBS thresholds. Internal modulation broadens the linewidth significantly and increasing the SBS threshold level well beyond 16dBm. Practical communication transmission systems that use SFPs could use higher launch power levels. XFP lasers are externally modulated and it is clear that modulation has no effect on the SBS threshold as shown in table 3.

It can be observed that lasers with a narrower linewidth generally have lower threshold level than the ones with a wider linewidth. So there is a dilemma about linewidth required for SBS threshold and linewidth required for dispersion. Lasers with narrow linewidth would have lower dispersion penalty but are more prone to lower SBS threshold. The following equations display the relationship of linewidth and Brillouin gain. The Brillouin-gain spectrum usually has Lorentzian spectral profile given by

$$g_B(\nu) = \frac{(\Delta\nu_B)^2}{(\nu-\nu_B)^2+(\Delta\nu_B/2)^2}\, g_B(\nu_B)\,, \tag{3}$$

where $\Delta\nu_B$ is the full width at half maximum of Brillouin spectrum, $g_B(\nu_B)$ is the Brillouin gain coefficient. If the pump has Lorentzian spectral profile of width (FWHM) $\Delta\nu_p$, the peak Brillouin gain is given by

$$\tilde{g} = \frac{\Delta\nu_B}{\Delta\nu_B+\Delta\nu_p} g_B(\nu_B), \tag{4}$$

Such communication system impairment can be reduced by increasing SBS threshold level through phase modulation and bias dithering of the laser sources. Because of that dispersion tolerance and system penalties could be affected which may set a limit on such approaches.

5. SYSTEM MEASUREMENTS

System performance is characterized by bit error rate (BER) measurement of data transmitted over different kinds of optical fibers. Each laser under modulation (XFP – 10 Gb/s signal, SFP – 2.5Gb/s signal) has been tested with SMF-28 single mode fiber (SMF) of 100km, 90km and 85km length depending on the laser wavelength. The block diagram of the measurement set-up is shown in Figure 6. A 2-way cross connection was established between two SFPs/XFPs in the setup, one is interacting with BER test set and the other one is the devise under the test (DUT). Variable attenuator controls the power level received to SFP/XFP. The length of the fiber used depends on the wavelength of the laser, because wavelength will determine the dispersion factor. Different lengths had to be used to simulate similar dispersion of all the lasers to create similar conditions for the BER test. It is known that dispersion in SMF-28 fiber at 1540nm is about 16ps/km-/nm, 17ps/km/nm at 1560nm wavelength and 19ps/km/nm at 1590nm wavelength [8]. Based on dispersion, fiber length of 100km, 90km and 85km for lasers at 1540nm, 1560nm and 1590nm were used respectively. Then all the lasers for different SFPs/XFPs were tested over Dispersion Compensation Modules (DCM). DCM-40, DCM-60 and DCM-80 modules compensate for 800ps/nm, 1200ps/nm and 1600ps/nm respectively.

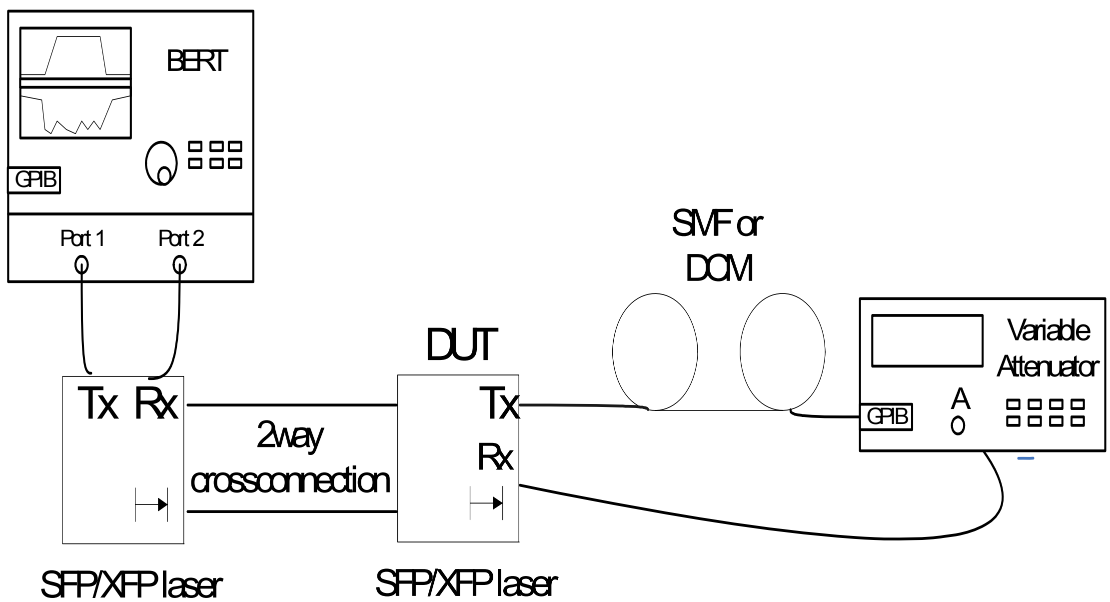

Fig. 6 System measurement set-up block diagram.

DCM modules are made of dispersion compensating fiber, so in the 1550nm region it has negative dispersion, oppose to the positive dispersion in SMF fibers. Penalties for each type of fiber were measured against BER of back-to-back (BB) case. Figure 7 shows system measurements for one of commercially available XFPs. Table 4 presents a summary of all measurements including linewidth, chirp and SBS threshold. Some cells that do not have values couldn't be measured.

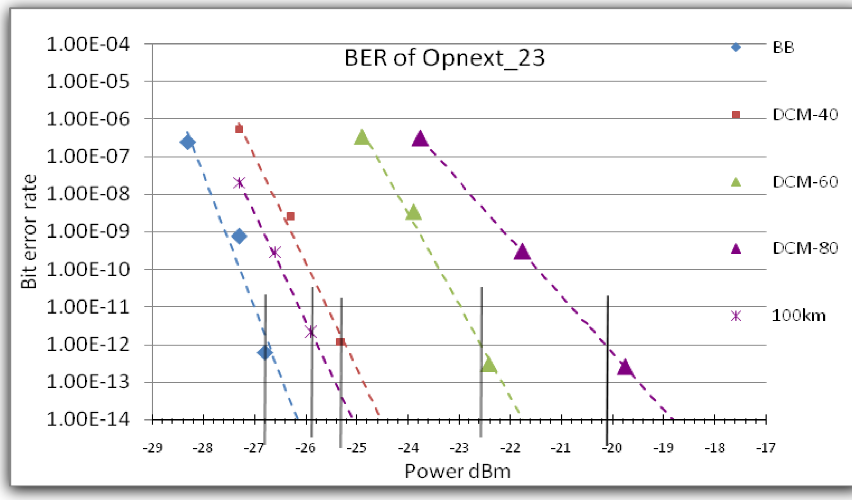

Fig. 7 BER measurements of XFP

Table 4 Summary of BER penalties over different fibers, laser linewidth, SBS threshold and chirp measured data for different commercial SFP and XFP lasers

SFP		SBS	threshold	Linewidth	Chirp		BER	Penalties	
	Wavelength	Un-modulated	Modulated			DCM-40	DCM-60	DCM-80	SMF-28
	nm	dBm	dBm	MHz	GHz	dB	dB	dB	dB
1	1530.33	>16	>16	3000	4.8	0.3	0.5	2	-0.65
2	1559.79	13.6	>16	87	2	-	-	-	-
3	1559.794	15.6	>16	125	3.4	3	2.5	-0.65	-0.8
4	1554.94	16.9	>16	307	2.3	-0.1	-0.2	-0.45	-0.75
5	1548.51	9.6	>16	27	2.2	0.7	-0.15	0.45	-2.1
6	1548.51	12.6	>16	118	2.3	0.85	0.4	1.45	0.3
XFP									
7	1559.794	>16	>16	167	0.4	-0.9	-2.3	-	-0.05
8	1559.794	11.35	11.35	54	0.4	-0.9	-1.7	-13.7	-1.1
9	1591	>16	>16	25	0.7	-2.65	-	-	-1.4
10	1540.55	13.5	13.5	-	-	-0.9	-2.35	-5.4	-1.6
11	1542.1	12.4	12.4	-	-	-1.45	-4.1	-6.5	-0.9
12	1560.6	13.95	13.95	95	0.8	-0.7	-3.3	-	-1.1

6. CONCLUSION

Different SFP/XFP laser parameters were investigated and correlated in optical communication systems. These parameters are laser linewidth, chirp, SBS threshold and dispersion tolerance. SBS threshold and system dispersion tolerance depends on modulated laser linewidth. It is apparent that narrower linewidth results in a lower SBS threshold while causes less pulse dispersion. Lower SBS threshold results in shorter transmitted distance, while lower dispersion result in longer transmission. SFP laser is directly modulated and have wider linewidth which results in higher SBS thresholds. While XFP laser are externally modulated and usually have lower SBS threshold. Directly modulated SFP produce larger chirp compared to externally modulated XFPs. Chirp affect pulses propagation as it interacts with pulses frequency content. It is important to characterize laser chirp as it affect transmission systems.

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