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Chromatic Dispersion Monitoring Method Based on Semiconductor Optical Amplifier Spectral Shift Effect in 40 Gb/s Optical Communication Systems

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1. Introduction

The optical signals degrade as travel down the optical link due to the optical fiber properties such as chromatic dispersion, polarization mode dispersion, polarization dependent loss, polarization dependent gain and various fiber nonlinear effects, which are considered as limitations in the high-speed, lang-haul fiber communication systems. Where chromatic dispersion causes different wavelengths to travel at different group velocities in single-mode transmission fiber and it has become a major source of transmission degradation due to the continuing increase of the bit rate and distance in high-speed long-distance optical communication systems (Kaminow et al., 2008). In the long-haul optical fiber communication systems or optical fiber communication networks, the accumulated chromatic dispersion is managed by creating a dispersion "map", in which the designer of a transmission optical fiber link alternates elements that produce positive and the negative chromatic dispersion. In this dispersion "map", the dispersion has some nonzero value at each point along the optical fiber link, the degradations, from nonlinear effects such as four-wave-mixing (FWM) and cross phase modulation (XPM), are effectively eliminated, but the total accumulated dispersion is near to zero at the end of the optical fiber link (Kaminow & Li, 2002). It seems that there need not other dispersion compensation techniques any more. Unfortunately, chromatic dispersion changes with dynamic optical fiber network reconfiguration and variation with environmental conditions such as temperature in practice (Agrawal, 2002). This dynamical action causes dynamical residual chromatic dispersion in a dynamical fiber link. In addition, signal tolerance to accumulated chromatic dispersion diminishes as the square of the bit rate. Therefore, 40Gbit/s signals are 16 times more sensitive to chromatic dispersion than 10Gbit/s signals. The signal tolerance to chromatic dispersion is restricted about 50ps/nm in single channel speed 40Gbit/s fiber communication systems, so there requires more carefully chromatic dispersion management. The residual chromatic dispersion of a dynamical fiber link can easily extend the tolerance in those high speed fiber communication systems, they need more precise and dynamical monitoring and compensation methods (Pan, 2003).

Many novel and effective dispersion compensation methods have been proposed (Kaminow & Li, 2002) (Pan, 2003), and they are included, dispersion compensating fibers, linear-chirped fiber Bragg gratings etc., for fixed dispersion compensation. The dispersion compensating fibers have negative dispersion, which can compress the extended signal pulses due to the

positive dispersion of the single-mode transmission fibers. These dispersion compensating fibers can be made by conventional optical fiber fabrication technics and can also be made by photonic crystals — a novel new optoelectronic technology (Sukhoivanov et al, 2009), called microstructured fibers or photonic crystal fibers with many periodic-arrayed air-holes and one or many defects in the fiber cross section (Bjarklev et al, 2003). Due to the complicated cross section structure, many excellent optical properties can be obtained by careful selecting the photonic crystal fiber structure parameters, such as photonic crystal fibers with large negative dispersion can be achieved. (Chen et al., 2010) Optical fiber Bragg gratings with linear-chirp have emerged as powerful tools for chromatic dispersion compensation because of their potential for low loss, small footprint, and low optical nonlinearities (Sukhoivanov et al, 2009). Fiber Bragg gratings are section of single-mode fiber in which the refractive index of the core is modulated in a periodic fashion as a function of the spatial coordinate along the length of the optical single-mode fiber (Kashyap et al, 2009). In chirped fiber gratings, the Bragg matching condition for different positions along the grating length, thus the different wavelength is reflected at different position. As a result, the extending signal pulses can be compressed by careful tailing the chirp profile of the fiber gratings (Kaminow & Li, 2002). Fiber Bragg gratings, achieved by sampled fabricating techniques, can be used for chromatic dispersion compensation in multichannel optical communication systems, such as wavelength division multiplexing (WDM) fiber communication system (Ibsen et al., 1998). And those with nonlinear chirped profiles can be used to achieve dynamical compensation in optical fiber communication systems with variable and unpredictable residual chromatic dispersion. When using a nonlinear chirp profile, the chromatic dispersion can be tuned by simply stretching the grating or heating the grating with heat-conduction coatings because of the sensitiveness of the reflection spectrum and group delay with grating structure, stress and temperature (Sun et al., 2006). Based on a thermally tunable nonlinear chirped fiber grating, we have achieved a tunable chromatic dispersion compensation system for optical fiber communication system with single channel speed 40Gbit/s and carrier suppressed return to zero (CSRZ) modulation format (Chen et al., 2007). The fiber grating is covered with uniform thin metal electric-conducting film which can add voltage to heat up. when the fiber grating is added voltage and has current in the electric-conducting film, the fiber grating is heated and then the temperature is changed, the reflection spectrum and group delay is also changed. We can control the group delay at certain wavelength by control the voltage added in the film-covered optical fiber grating. In our system, the measured chromatic dispersion can be varied from -60ps/nm to -260ps/nm for wavelength 1553.40nm.

The schematic common chromatic dispersion compensation system is shown in Fig.1. It is mainly consisted by a chromatic dispersion compensation module, a chromatic dispersion monitoring module and an optical fiber coupler, as shown in Fig.1. The optical signal with accumulated residual chromatic dispersion from optical fiber link is firstly sent into the chromatic dispersion compensation module. After compensating, the optical signal is sent into the optical fiber link again, and some power of the compensated optical signal is separated from the optical fiber link by the optical fiber coupler after the chromatic dispersion compensation module and is sent into the chromatic dispersion monitoring module, which includes an optical receiver, some electrical signal processing modules and relevant computer algorithms. This chromatic dispersion monitoring module can generates an electrical control signal for the chromatic dispersion compensation module according to one or certain parameters of the input optical signal. The one or certain parameters are relating to the accumulated residual chromatic dispersion of the fiber communication system links
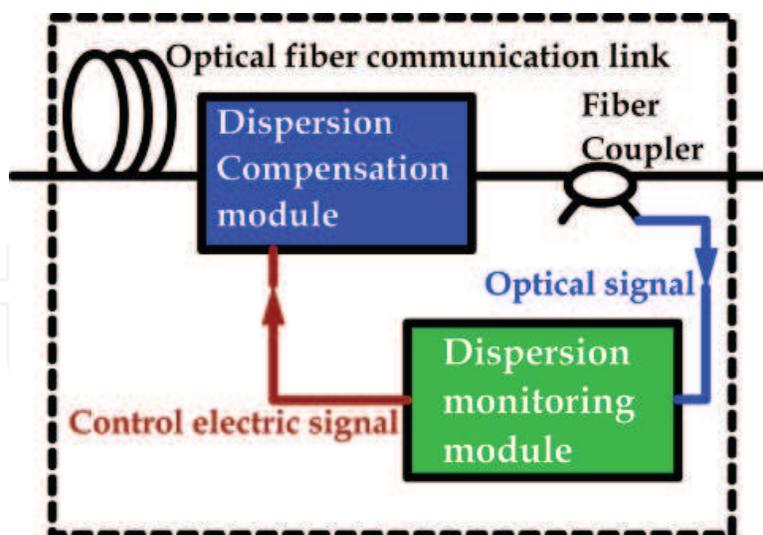
Fig. 1. Dispersion compensation system. The blue solid line denotes optical signal withdraw from optical fiber link after dispersion compensation and the red that denotes electric control signal come from dispersion monitoring module.

(Kaminow & Li, 2002) (Pan, 2003) (Hong, 2002).

Dynamical chromatic dispersion management has become a critical issue for high-bit-rate transmission systems, especially for systems with speeds beyond 10Gbit/s, and reconfigurable optical networks, because the accumulated chromatic dispersion can easily go beyond the optical communication systems' tolerance. Chromatic dispersion management, in high speed optical communication systems, is very difficult and needs effective high speed response chromatic dispersion monitoring methods, as shown in Fig.1. The range and precision of the monitoring methods decide the range and precision of the chromatic dispersion compensation systems (Seyed Mohammad Reza Motaghian Nezam, 2004). Previous works on chromatic dispersion monitoring have resulted in the development of numerous approaches, such as detecting the intensity modulating from phase modulation (Ji et al., 2004), modulating the frequency of the transmitted data signal and monitoring the clock deviation (Pan et al., 2001), inserting in-band subcarriers in the transmitter and monitoring their radio frequency tones (Ning et al., 2006) (Luo et al., 2006), adding an amplitude modulated double sideband subcarrier to the signal and measuring the phase delay between two subcarrier tones (Wang et al., 2006), extracting the clock component and measuring its radio frequency (RF) power (Inui et al., 2002), extracting two single sideband sideband components of the data signal and detecting their phase difference (Hirano et al., 2002), employing nonlinear optical detection (Wielandy et al., 2004) (Li et al., 2004), measuring the chromatic dispersion induced distortion using a peak detector (Ihara et al., 1999), and so on. In practice, both chromatic dispersion and polarization mode dispersion are all influent the performance of the high-speed optical fiber communication systems, and effective simultaneous monitoring methods for chromatic chromatic dispersion and polarization mode dispersion are necessary. We developed a novel and effective method to monitor chromatic dispersion and polarization mode dispersion simultaneously using two polarization-modulation pilot tones with different frequencies (Chen et al., 2007). It has been demonstrated that radio frequency (RF) output power increase with group velocity delay (GVD) and differential group delay (DGD) and the power radio of the two pilot tones increases with GVD and decreases with DGD, thus chromatic dispersion and polarization

mode dispersion can be distinguished and monitored simultaneously. This is an effective monitoring method in high-speed optical fiber communication systems.

In this chapter, we demonstrate an other novel in-line dynamical monitoring methods for chromatic dispersion based on the spectral shift effect of a semiconductor optical amplifier (Chen et al., 2007). This spectral shift effect is result of the self phase modulation effect in the semiconductor amplifier. Due to large nonlinearites of semiconductor optical amplifiers, the spectral shift effect is enhanced, and this effect is impacted by the residual chromatic dispersion of the optical fiber link, which is optical signal transmitted. Using an optical filter — a fiber grating, we can obtain the variational power of the spectrum of the optical signals, and then we can achieve the dynamical chromatic dispersion monitoring in line for a high speed optical fiber communication system.

2. Monitoring principle based on semiconductor optical amplifiers

In the past two decades, optical communication has changed the we communicate. It is a revolution that has fundamentally transformed the core of telecommunications, its basic science, its enabling technology, and its industry. The optical networking technology represents a revolution inside the optical optical communications revolution and it allows the letter to continue its exponential growth. Optical networking represents the next advance in optical communication technology. Semiconductor optical amplifier is a kind of key devices for all-optical networks (Dutta & Wang, 2006). The advances in research and many technological innovations have led to superior designs of semiconductor optical amplifiers. Semiconductor optical amplifiers are suitable for integration and can be used as signal amplification and functional devices, such as optical demultiplexing, wavelength conversion, and optical logic elements make them attractive for all-optical network and optical time division multiplexed systems (Kaminow & Li, 2002) (Kaminow et al, 2008).

The theory of pulse propagation in semiconductors is well known (Shimada et al, 1994). The semiconductor optical amplifiers are treated as a two-level system. When the carrier's intra-band relaxation time τ_{in} in the conduction band is induced, solving the problem become complex. Fortunately, the intra-band relaxation time τ_{in} is generally about 0.1 ps in semiconductor devices. It is supposed that the pulse width of input optical signals $\tau_p \geq 1.0 ps$, solving this problem will become very simple. It is to said that the condition $\tau_p \gg \tau_{in}$ is always satisfied. In our research, this condition is easily satisfied. At the same time, given that the semiconductor optical amplifier cavity is very short, and the dispersion of the waveguide in the semiconductor optical amplifier can be neglected, and the we can obtained the equations that described transmission actions of the input pulses in semiconductor optical amplifiers as follows:

$$\frac{\partial P(z,\tau)}{\partial t} = (g(z,\tau) - \alpha_{int}) \cdot P(z,\tau), \tag{1}$$

$$\frac{\partial \phi(z,\tau)}{\partial z} = -\frac{1}{2}\alpha_{LEF} \cdot g(z,\tau), \tag{2}$$

$$\frac{\partial g(z,\tau)}{\partial \tau} = \frac{g_0 - g(z,\tau)}{\tau_c} - \frac{g(z,\tau) \cdot P(z,\tau)}{E_{sat}}, \tag{3}$$

where $P(z,\tau)$ and $\phi(z,\tau)$ denote instantaneous power and phase respectively, $g(z,\tau)$ is the saturation gain parameter, α_{int} is the loss coefficient of the semiconductor optical amplifier cavity, g_0 denotes the small signal gain, α_{LEF} is the line-width enhancement

factor, $\tau = t - z/v_g$, v_g is the group velocity of light, and E_{sat} is the saturation of the semiconductor optical amplifier. Equation (2) describes the self-phase modulation (SPM) of the semiconductor optical amplifier. Our chromatic dispersion monitoring method is based on this nonlinear effect.
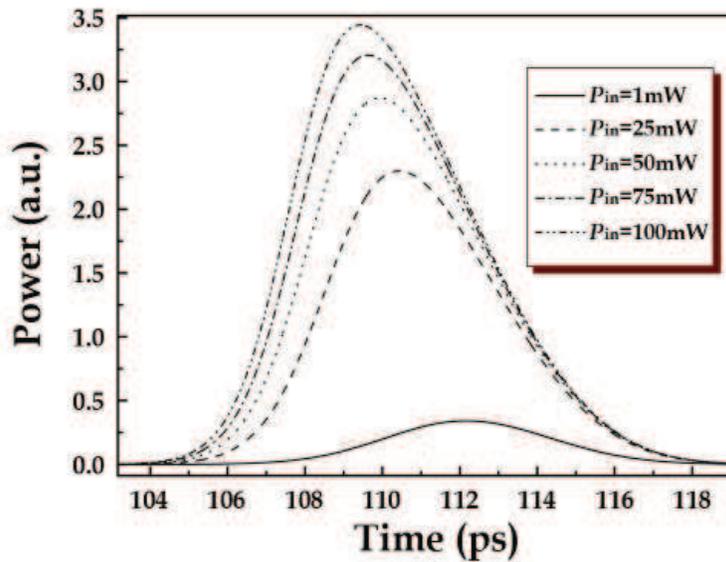
(a) Waveforms of the amplified Gauss pulses with different peak power.
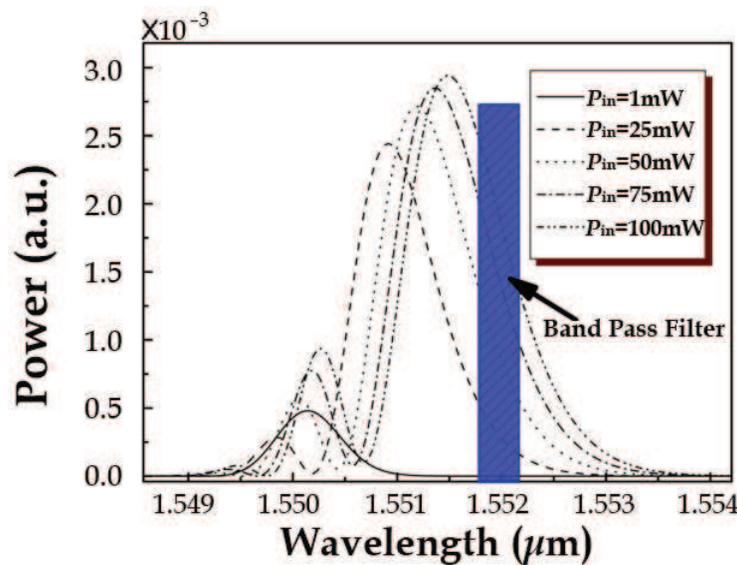
(b) Spectra of the amplified Gauss pulses with different peak power.

Fig. 2. Waveforms and corresponding spectra of the amplified Gauss pulses with different peak power after amplified by the semiconductor optical amplifier.

Without loss of generality, we show the principle of the chromatic dispersion monitoring methods using Gauss profile pulses due to their simplicity, although the optical pulses with the carrier suppressed return to zero modulation format cannot be approximated by Gauss profile pluses. Firstly, we study the influence on the shape and spectrum of input signal

pulses in a semiconductor optical amplifier in theory. In our study, the small signal gain g_0 is 30dB, and the spontaneous carrier lifetime τ_c is 140ps. The line-width enhancement factor α_{LEF} is decided by the peaks of input signal pulses, and its typical values for semiconductor lasers and semiconductor optical amplifiers are in the range between 3 to 8 (Shimada et al, 1994). Let $\alpha_{LEF} = 5$ in our research. The input Gauss profile pulses can be written as:

$$A_{in}(\tau) = \sqrt{P_{in}}exp\Big(-\frac{1+iC}{2}\Big(\frac{\tau}{\tau_0}\Big)^{2m}\Big), \tag{4}$$

where P_{in} and C denote peak power and chirp parameter of the input signal pulses, respectively, m is the pulse amplitude. In order to further simplify this problem, we suppose the chirp paraments of the input signal pulses to be $C = 1$ and Gauss function of the order $m = 1$. In our theoretical system, the wavelength of the carrier light wave is 1550nm, the pulse width equals 0.2 bit period, and the single-channel speed of the optical communication system is 40Gbit/s. The numerical simulating software is Optisystem 6.0 from OptiWave$^{\circledR}$ Inc. of Canada.

The waveform shapes and spectra curves of the transmitted pulses with different peak powers, after amplified by the semiconductor optical amplifier, are shown in Fig. 2. Figure 2(a) shows the waveform shapes and Figure 2(b) shows corresponding spectra curves of the amplified transmitted optical signal pulses with Gauss profile. In Figure 2(b), the blue shadowed part indicates the filter band of the band-pass optical filter, which can select corresponding frequencies' power to be detected in our chromatic dispersion monitoring method, which will be demonstrated in detail in the following parts of this chapter. From this figure, we can conclude that the amplified Gauss pulses lose their symmetry with increasing of the input light pulse peak power, the leading edge is more sharper compared with the trailing edge. This is because the leading edge experiences more larger gain than that of the trailing edge. The spectrum of the amplified optical signals develops a structure with multi-peaks, with the dominant spectral peak shifting to the long wavelength side (red shift) as the input pulse peak power increases. The physical mechanism behind the spectral shift and distortion is the self phase modulation, which occurs as a result of index nonlinearities induced by gain saturation effect.

Our dynamical chromatic dispersion monitoring method is based on the spectral effect resulted from self phase modulation effect of the semiconductor optical amplifier, as mentioned previously. As an optical signal pulses transmitting in an optical fiber link with chromatic dispersion, the peak power of the optical signal pulses are influenced by the chromatic dispersion. Because the self phase modulation is related to the peak power of the input pulses, the peak power decides the spectral shift effect. As shown in Figure 2(b), we can use a band-pass optical filter to obtain the corresponding frequencies' power and use it to accomplish online dynamical chromatic dispersion monitoring, because the power depends on chromatical dispersion of optical communication fiber links sensitively.

3. Experimental System

Figure 3 shows our dynamical chromatic dispersion monitoring system. The optical carrier comes from the continuous wave (CW) laser with center wavelength 1553.40nm and is sent into a 40Gbit/s pseudo random binary sequence (PRBS) system with suppressed return to zero modulation format is shown in Figure 4. As shown in this figure, the optical carrier frequency — 1553.40nm, is wholly suppressed, the frequency difference of the two first-order

harmonic wave peaks is 40GHz, and the frequency difference is also 40GHz between the high-order (order>1) harmonic waves and the neighboring lower-order harmonic waves.
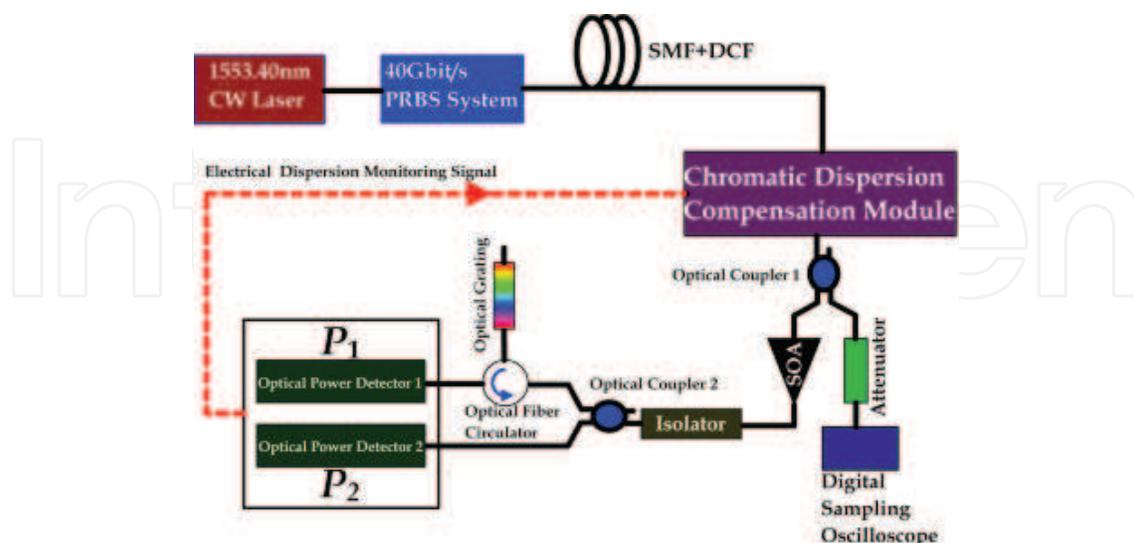

Fig. 3. Experimental system of dispersion monitoring based on semiconductor optical dispersion spectral shift effect.

Output optical signals from the pseudo random binary sequence system are transmitted into an optical fiber link that consists of some single-mode fibers with positive chromatic dispersion and some conventional dispersion compensation fibers with negative chromatic dispersion. In order to simulate the dynamical residual chromatic dispersion of a dynamical fiber links, we can obtain different chromatic dispersion values for the experiment by changing the length of single-mode fibers and that of the dispersion compensation fibers. The optical signals are then transmitted in to a dynamical chromatic dispersion compensation module, which can compensate the remnant chromatic dispersion using the monitoring signal from our proposed chromatic dispersion monitoring method. This dispersion compensation module is based on a thermally tunable optical fiber grating (Sun et al., 2006) (Chen et al., 2007). Output from compensation system, the optical signal stream is sent to an optical fiber coupler and is split into two signal streams with different optical power, the optical power ratio of the two signal streams is 20:80. One signal stream with large optical power is received by a digital sampling, oscilloscope after an attenuator. The other signal stream with small optical power is more further split into other two signal streams with the same optical power after going through a semiconductor optical amplifier and an isolator by a 3dB optical fiber coupler. one is received by an optical detector at an obtained optical power P_2 ; another is received by other optical detector at an obtained optical power P_1 after an optical fiber circulator and an optical fiber grating that can reflect parts of the spectrum denoted by part I, part II and part III, as shown in Figure 4. The semiconductor optical amplifier is a product of the Center for Integrated Photonics® (CIP) Ltd. of the United Kingdom. The product type is SOA-NL-OEC-1500.

If we only used the optical power P_1 to monitor the chromatic dispersion of the optical fiber communication links, it is influenced easily by the optical power fluctuation in the optical fiber communication system links. In order to avoid this influence, in our dynamical chromatic dispersion monitoring method, we use the radio (P_1/P_2) of the obtained optical power P_1 to the obtained optical power P_2 to monitor the remnant chromatic dispersion of a high speed

optical fiber communication system, because the optical power radio is independent of the optical power variety in the optical fiber communication system links.

As mentioned previously, similar to the optical spectrum of Gauss profile pulses shown in Figure 2(b), the peak of the amplified output optical spectrum will shift toward the more longer wavelength side as the peak power of input pulses increases, as shown in Figure 5. The amplified output optical spectrum symmetry is lost. The optical power of the long wavelength side is higher than that of the short wavelength side.
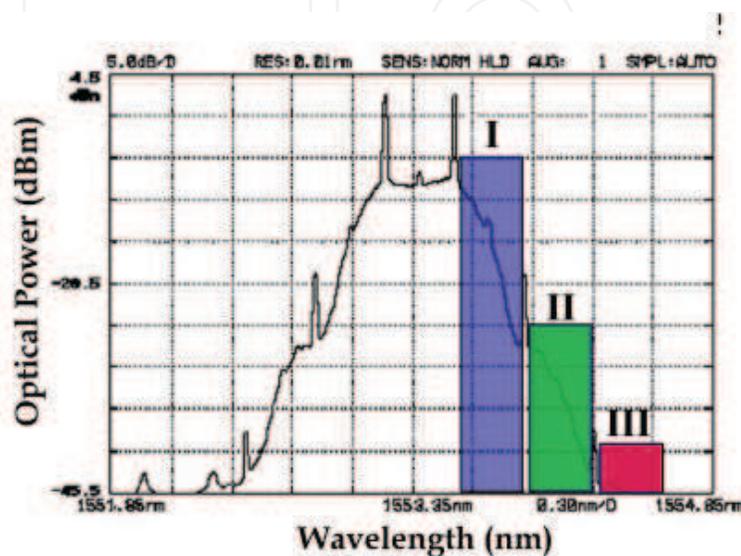
Fig. 4. Back to back spectrum of optical signals in high speed optical communication system with 40Gbit/s single-channel speed.
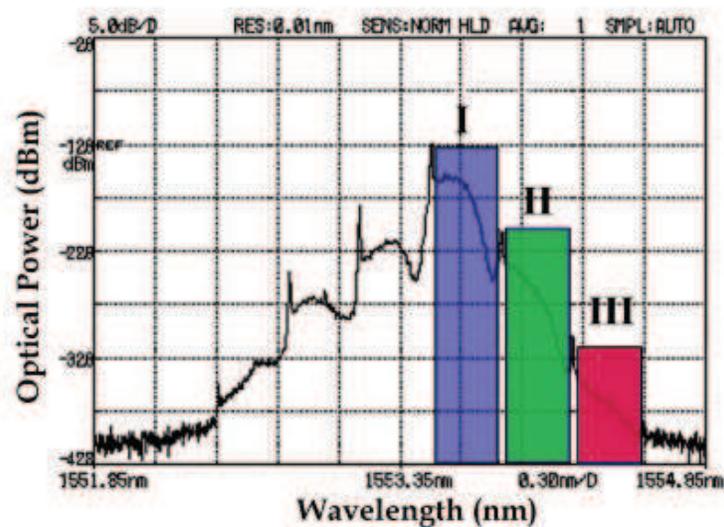
Fig. 5. Spectrum of output optical signals after amplified by the semiconductor optical amplifier in high speed optical communication system with 40Gbit/s single-channel speed.
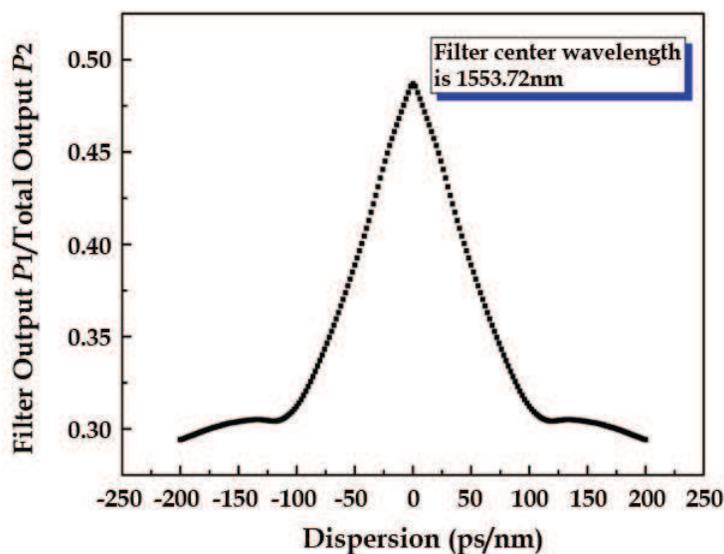
(a) Monitoring curve using optical fiber grating filter with center
wavelength 1553.72nm
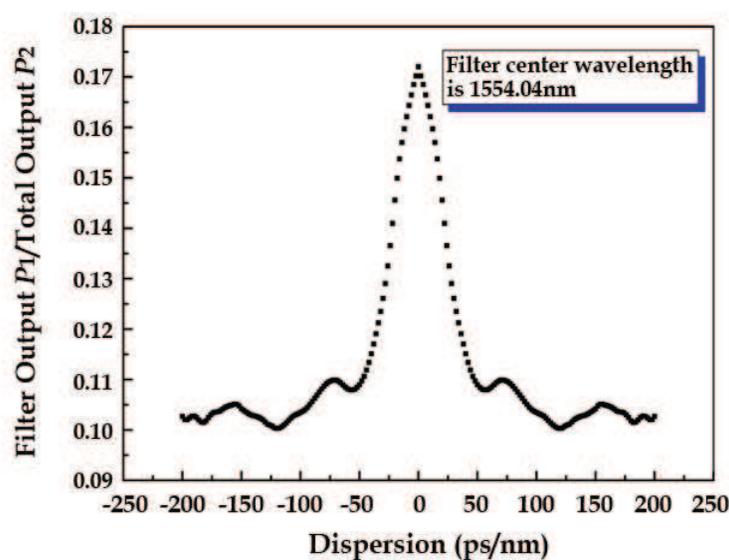
(b) Monitoring curve using optical fiber grating filter with center
wavelength 1554.04nm

Fig. 6. Dispersion monitoring curves using optical fiber grating filter with center
wavelengthes 1553.72nm and 1554.04nm, respectively.

To obtain an optimal chromatic dispersion monitoring signal, one needs to filter part of the
output amplified spectrum to detect the optical power of spectral shift components. However,
because the distribution of the spectral shift resulting from self phase modulation effect spans
a wide frequency range, it needs an optimal scheme of the filter that can output the power
of spectral shift components for chromatic dispersion monitoring. As shown in Figure 4, the
power of each separate harmonic wave peak is higher than the shift frequencies' power due
to the frequency shift effect. Thus, the separate harmonic wave peaks should be excluded
from the filter pass-band. The short wavelength spectrum side is not suited for chromatic

dispersion monitoring due to its multi-peaks structure, as shown previously. We divide the spectrum of the long wavelength side into three parts, (part I, part II and part III masked by three colored shadows, as shown in Figure 4 and 5) with frequency ranges 20-60 GHz, 60-100 GHz and 100-140GHz offset from center frequency (the wavelength is 1553.40 nm) of the optical spectrum, respectively. The spectral range part III beyond the wavelengths of part II is ignored due to low optical power.

It will be proved that the more narrow the band filter used, the more chromatic dispersion monitoring precision can be achieved in our method, but the output power will be too low to detect and can fail more easily due to the noise of the photoelectric diodes and optical amplifiers. In our method, the 3dB reflective band of the optical grating is 20 GHz; thus, we can obtain enough optical power to monitor chromatic dispersion and exclude the harmonic wave peaks from the pass band of the filter by careful choosing the filter center wavelength.

In order to obtain preferable monitoring conditions, we use two optical fiber gratings filters with center wavelengths of 1553.72nm and 1554.04nm respectively for our analysis and discussion. The 3dB reflective bands of the two optical fiber grating filters are all 20GHz, i.e. their reflective bands are all 0.16nm. The reflective band of the optical fiber grating filter with center wavelength 1553.72nm is stood in part I and other is located in part II, as shown in Figure 4 and Figure 5.
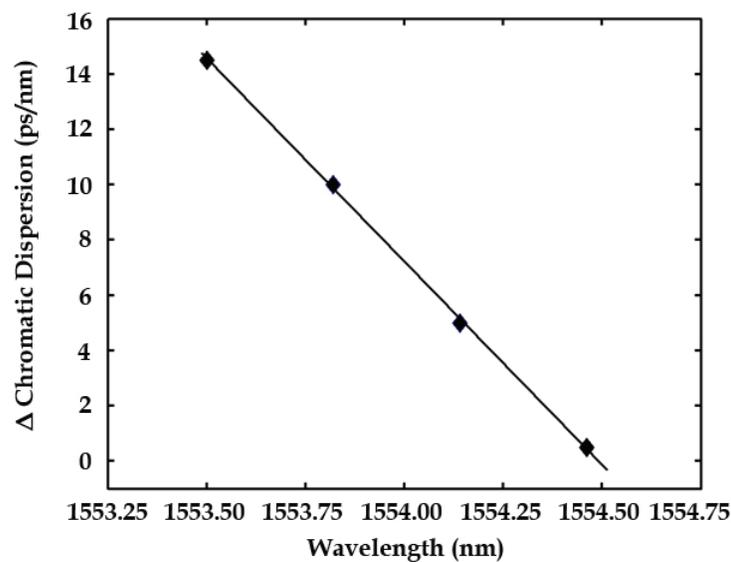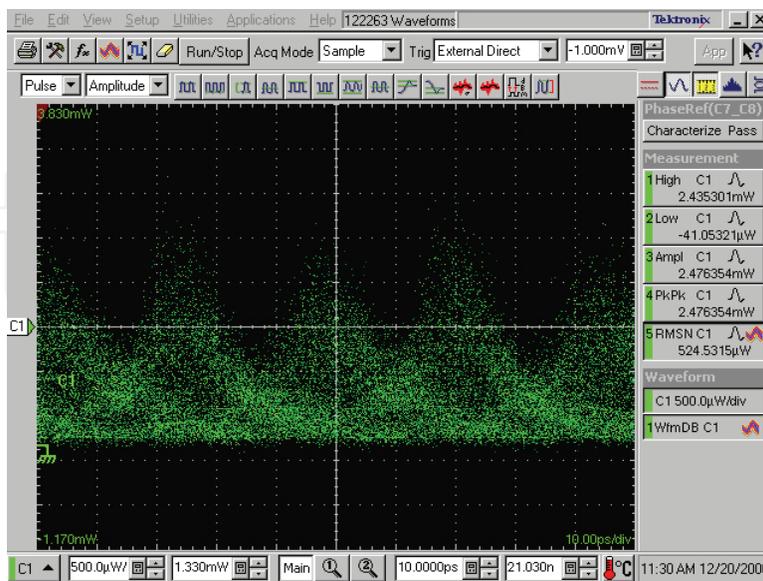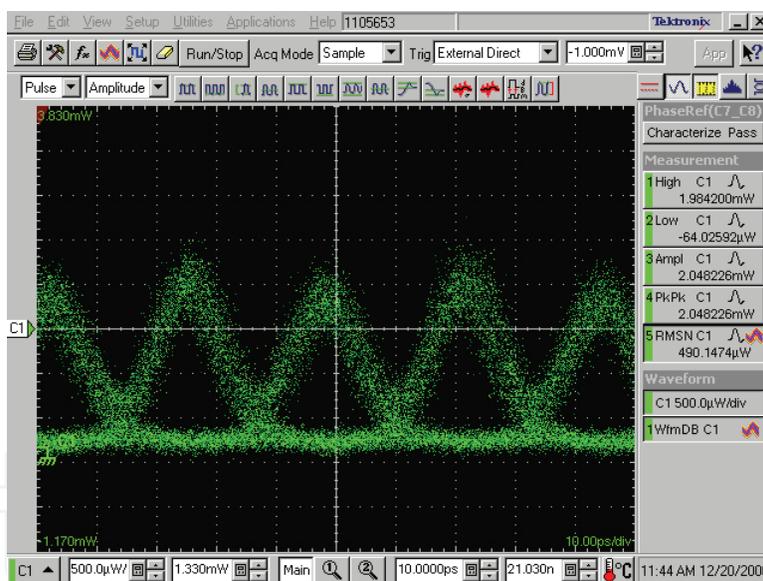

Fig. 7. Dependence of the chromatic dispersion monitoring precision on the filter center wavelength without the influence of the power of the signal peaks.

Figure 6 shows the chromatic dispersion curves in high speed optical fiber communication system with a single-channel speed of 40Gbit/s and suppressed return to zero (CSRZ) modulation format using the two optical fiber grating filters, which have mentioned above. Using the optical fiber grating filter with center wavelength 1553.72nm, the chromatic dispersion monitoring range is ±120ps/nm and the monitoring precision is about 10ps/nm, as shown in Figure 6(a). However, using the optical fiber grating filter with center wavelength 1554.04nm, the chromatic dispersion monitoring range is ±60ps/nm and the monitoring precision is higher than 5ps/nm, as shown in Figure 6(b). It can conclude that we can achieve more smaller chromatic dispersion monitoring range and more higher monitoring precision if we used an optical fiber grating filter with center wavelength located in part III of the

suppressed return to zero modulation format signals' spectrum curve, as shown in Figure 4 and 5.

(a) Signal eye diagram of before chromatic dispersion compensation.

(b) Signal eye diagram of afert chromatic dispersion compensation.

Fig. 8. Signal eye diagrams tested by Tektronix$^{®}$ TDS8200 digital sampling oscilloscope of before and after chromatic dispersion compensation.

Figure 7 shows the dependence of the chromatic dispersion monitoring precision on the optical fiber grating filter center wavelength without the influence of the power peaks of the signals, because these peaks are excluded out of the pass band of the optical fiber grating filter by careful choosing the filter center wavelength. We concluded that the longer the center wavelength of the optical fiber grating filter used, the more chromatic dispersion monitoring precision can be achieved. In practice, we must choose an optimal optical fiber grating filter

to obtain the optimal monitoring range and optimal monitoring precision for the dynamical chromatic dispersion in high-speed optical fiber communication systems. For a high speed optical communication system with a single-channel speed of 40 Gbit/s and suppressed return to zero modulation format, in the chromatic disoersion monitoring system, the best filter with a center wavelength of 1554.04 nm can be selected.

The eye diagrams of the optical fiber communication system with remnant chromatic dispersion of 60 ps/nm, before and after chromatic dispersion compensation, are shown in Figure 8. These eye diagrams were obtained by a Tektronix$^{®}$ TDS8200 digital sampling oscilloscope. Figure 8(a) is an eye diagram before chromatic dispersion compensation, and Figure 8(b) is a corresponding eye diagram after chromatic dispersion compensation. It can be concluded that our dynamical dispersion monitoring method, based on semiconductor optical amplifier spectral shift effect, is preferable for a high speed optical fiber communication system with a single-channel speed of 40 Gbit/s and suppressed return to zero modulation format.

4. Conclusion and Discussion

We demonstrated a dynamical chromatic dispersion monitoring method for high speed optical fiber communication systems. This method is based on the spectral shift resulting from self phase modulation of semiconductor optical amplifier. The more longer the wavelength components used for chromatic dispersion monitoring, the more monitoring precision of this method can be achieved, but the monitoring range becomes small simultaneously. Thus, in practice we must carefully consider the chromatic dispersion monitoring range and monitoring precision at the same time. This can be achieved by choosing an optimal optical fiber grating filter. For a high speed optical fiber communication system with a single channel speed of 40Gbit/s and suppressed return to zero format modulation, we use the optical fiber grating, with center wavelength and band width of 1554.04 nm and 20GHz respectively, as the optical filter. The chromatic dispersion monitoring range is $\pm$ 60 ps/nm and the chromatic dispersion monitoring precision is higher than 5 ps/nm in our method. Therefore, this technique is promising for use in remnant chromatic dispersion online monitoring in 40Gbit/s optical communication systems. In addition, it can be used for other high speed optical fiber communication systems by minimized modification.

5. Acknowledgments

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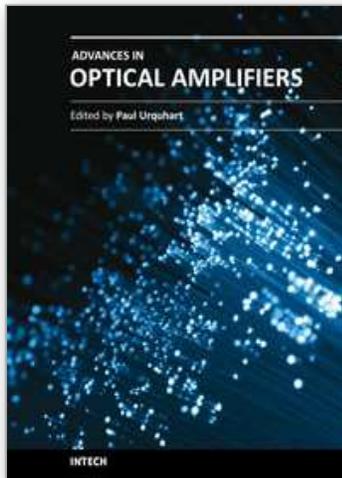
Advances in Optical Amplifiers

Edited by Prof. Paul Urquhart

Optical amplifiers play a central role in all categories of fibre communications systems and networks. By compensating for the losses exerted by the transmission medium and the components through which the signals pass, they reduce the need for expensive and slow optical-electrical-optical conversion. The photonic gain media, which are normally based on glass- or semiconductor-based waveguides, can amplify many high speed wavelength division multiplexed channels simultaneously. Recent research has also concentrated on wavelength conversion, switching, demultiplexing in the time domain and other enhanced functions. Advances in Optical Amplifiers presents up to date results on amplifier performance, along with explanations of their relevance, from leading researchers in the field. Its chapters cover amplifiers based on rare earth doped fibres and waveguides, stimulated Raman scattering, nonlinear parametric processes and semiconductor media. Wavelength conversion and other enhanced signal processing functions are also considered in depth. This book is targeted at research, development and design engineers from teams in manufacturing industry, academia and telecommunications service operators.

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