Novel all-optical dispersion monitoring technique for ultra-high-speed WDM networks

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Abstract. This paper represents a novel all-optical dispersion monitoring technique based on fiber parametric amplifiers (FOPAs). The monitoring method is truly bit-rate transparent because it is enabled by the exponential power transfer function (PTF) provided by the FOPA gain. The slope of the PTF is increased from 2 to 3 by choosing appropriate phase-matching conditions. Due to the steeper PTF the monitoring sensitivity is greatly improved compared to the other PTF-based methods proposed before. The PTF obtained by numerical simulations agrees very well with the experimental results. Numerical simulations are then used to demonstrate that our method can be used to monitor signals in various modulation formats.

1. Introduction

Due to continued growth of the Internet and the introduction of new broadband services, it is expected that individual channel data rates will exceed 100Gb/s in the next 5 years. One of the major limitations to operating at such high data rates will be the amount of chromatic dispersion (CD) introduced \cite{1}. As channel data rates increases, CD tolerance decreases precipitously as the square of the increase in data rate. Due to the severer CD tolerance CD fluctuations caused by seasonal temperature variations and mechanical stress become a serious problem \cite{2}. In addition, in dynamic networks, each channel can experience a different amount of CD whenever the network is reconfigured. Thus the adaptive dispersion compensation technique becomes indispensable \cite{1-5}. However, in order to realize the adaptive dispersion compensation, it is vital to develop a fast and accurate CD monitoring technique \cite{3-5}. By now, a number of monitoring techniques have been proposed, including: RF tone measurement \cite{1}; asynchronous histogram evaluation \cite{3}; self-phase modulation \cite{4} and cascaded four-wave mixing \cite{5,6} in optical fibers. However each of these approaches tends to require either high-speed components (e.g. oscilloscope, photodetector and analog-to-digital converter) or high input power. Recently two-photo absorption in semiconductor detectors is also used in CD monitoring in high-speed, WDM networks \cite{7,8}. In order to overcome the inefficiency associated with the nonlinear TPA process, a microcavity structure is employed. But the signal is only enhanced over a very narrow wavelength range. Thus to monitor different WDM channels mechanical movement components must be used to alter the incident angle of the input signal so that the resonance wavelength can be changed \cite{8}.
In this paper, we proposed a novel all-optical CD monitoring method based on a fiber optical parametric amplifier (FOPA). No fast electronics are needed due to the ultra-fast response time of FWM (<10fs). The pre-amplified signal is used as the pump of the FOPA. The pump and a cw probe wave are input into the FOPA. The accumulated dispersion of the input signal can be measured just by monitoring the average power of the idler wave at the output port of the FOPA using an optical power meter. The slope of the PTF is increased from 2 to 3 by choosing appropriate phase-matching conditions. Due to the steeper PTF the monitoring sensitivity is greatly improved compared to the other PTF-based methods proposed before. The dependence of sensitivity and operational bandwidth on phase matching conditions is analysed. The monitoring bandwidth can be tailored to cover any commonly used WDM bands. Numerical simulations are then used to demonstrate that our method can be used to monitor signals in various modulation formats.

2. Device concept

Because FWM is a quasi-instantaneous effect, the parametric gain actually depends on the instantaneous intensity of the pump. Thus if the signal serves as the pump and is input into the FOPA with a cw probe wave, the FOPA gain can map the CD induced instantaneous power variations of the signal pulse onto the average power of the output idler wave. The PTF, i.e. the gain, for one-pump FOPA can be derived analytically when pump depletion and fiber loss can be neglected and is given by [9].

\[ G = (\gamma P_0 L)^2 \left[ \sinh(gL) / gL \right]^2, \]  

where \( P_0 \) is pump power, \( \gamma \) is the fiber nonlinear coefficient, \( L \) is the fiber length. The output power of the idler wave is \( P_{\text{idler}}(L) = GP_{\text{probe}}(0) \). In Eq. (1) \( g \) is the parametric gain defined as:

\[ g = \sqrt{-\Delta \beta \left( \gamma P_0 + \frac{\Delta \beta}{4} \right)}. \]  

The linear phase mismatch \( \Delta \beta \) is given by

\[ \Delta \beta = \beta_{\text{probe}} + \beta_{\text{idler}} - 2\beta_{\text{pump}}, \]  

where \( \beta_{\text{probe,idler,pump}} \) are the respective propagation constants of the probe, idler and pump. Eqs. (1-2) show that when the condition

\[ -4\gamma P_0 \leq \Delta \beta \leq 0 \]  

is satisfied, \( g \) is real. In this case \( P_{\text{idler}}(L) \) increases exponentially with \( P_0 \) [10-12] and in this way, an exponential PTF can be obtained. For ordinary fibers the effects of the fourth order dispersion can be neglected. Considering up to the third order dispersion and by Taylor expansion around the fiber zero dispersion frequency \( \omega_0 \), \( \Delta \beta \) can be expressed as [10]

\[ \Delta \beta(\omega_p) = \beta_3 (\omega_p - \omega_0)(\omega_p - \omega_{\text{probe}})^2. \]  

Here \( \omega_p \) and \( \omega_{\text{probe}} \) are the pump and probe frequencies, respectively. Noting that \( \beta_3 > 0 \) in telecommunication bands for most optical fibers, to get the exponential gain, it is required that \( \omega_p \leq \omega_0 \) and \( P_0 \geq P_{\text{min}} = -\Delta \beta / 4\gamma [10]. \) The monitoring bandwidth depends on the allowable tuning range of the pump over which exponential gain can sustain. A detailed analysis represented before by us shows that when \( \omega_{\text{probe}} = \omega_0 - 3(\gamma P_0 / \beta_3)^{1/3} \), the monitoring bandwidth can reach its maximum \( \Delta \omega_{\text{pump}}^{\text{max}} = 4(\gamma P_0 / \beta_3)^{1/3} \) for a given pump power \( P_0 \) and the operational band can be tailored by selecting fibers with appropriate \( \omega_0 \) [11]. So the operational band of the monitor can be tailored according to the wavelength plan of the WDM system.
3. Monitoring results

The monitoring is enabled by the nonlinear PTF of the FOPA. Once the PTF is obtained, the pulse shape can be mapped from the signal onto the idler wave by the PTF [6]. So we first use numerical simulations to calculate the PTF of the FOPA and compare it to the experimental results reported by [13,14] in order to validate the simulation results. The parameters used in the calculation and experiments are listed in Table.1. The setup of the experiment is showed in Fig.1. Fig.2 shows the PTFs for FOPA1 and FOPA2. For FOPA1, \( \Delta \beta = 1.98 \times 10^{-4} \text{m}^{-1} \), thus \( \Delta \beta \leq -4 \gamma P_0 \) for \( 2.5 \text{mW} \leq P_0 \leq 5 \text{mW} \). While for FOPA2 \( \Delta \beta = -4e^{-3} \), thus \( -4 \gamma P_0 \leq \Delta \beta \leq 0 \) for \( 100 \text{mW} \leq P_0 \leq 200 \text{mW} \). As we can see in Fig.2 (a) and (b) with the appropriate phase-matching conditions the slope is increased from 2 to 3. The results obtained by numerical simulations agree very well with the experimental results. Fig.3 shows the monitoring results utilized FOPA2. The output power of the idler wave is scaled by the one at CD=0ps/nm. As we can see it changes by about 5.9, 1.35, 0.39 and 4.6dB within the monitoring range for 33% RZ, CSRZ, NRZ and 33% RZ-DPSK signals. For comparison the quadratic PTF-based monitor relying on two photon absorption (TPA) has only 3.1, 0.45 and 0.088dB output dynamic range for 33% RZ, CSRZ and NRZ signals [7], while the quadratic PTF-based monitor relying on cascaded FWM has only 1.8dB dynamic range for a 40Gb/s RZ signals.

![Configuration of the monitor](image)

**Table 1** Parameters used in calculation and experiments

|       | \( \lambda_d \)  | \( \lambda_{probe} \) | \( \lambda_0 \) | \( S \) | \( \gamma \) | \( L \) | \( \alpha \) | \( P_0 \) |
|-------|-----------------|----------------------|----------------|-------|----------|------|----------|--------|
| FOPA1 | 1559            | 1560.6               | 1557           | 0.06  | 2.1      | 17.5 | 0.21     | 2.5~5  |
| FOPA2 | 1534.6          | 1545                 | 1534           | 0.05  | 9.9      | 0.72 | 0.6      | 100~200|

![Comparison between experimental](image)

Fig.2 Comparison between experimental (circles) and calculated transfer functions of the idler wave power versus pump power for FOPA1 (a) and FOPA2 (b). The calculation was carried out analytically (dashed lines) and numerically (solid lines).
Fig. 3 Monitoring results utilizing FOPA2. (a): the modulation formats are 33% RZ (red) and 33% RZ-DPSK (blue). (b): the modulation formats are CSRZ (red) and NRZ (blue).

Thus, the sensitivity and output dynamic range of the monitor are greatly improved compared to those PTF-based monitors proposed before. Due to the Talbot effect the signal pulse will reconstruct after the residual CD exceeds the Talbot period [7], for this reason the monitoring ranges are limited. For RZ, RZ-DPSK and NRZ signals the range is about 40ps/nm. While for CSRZ signals the range is about 30ps/nm. This underlying periodicity is fundamental to the data sequence itself, it is not a unique feature of the nonlinear monitor and will also manifest itself in many other dispersion-monitoring schemes such as RF spectral analysis [1,6,7]. Finally it is noteworthy that average input power required is actually about 50mW because $P_0$ is the peak power of the signal pulse. So the monitor based on the FOPA can work in a low power consumption mode because the FOPA gain can be very small (-10~10dB).

4. Conclusions

This paper presents a novel method to monitor CD in high-speed WDM networks. The method utilizes the fast response time and the broad bandwidth of FWM process. By choosing appropriate phase matching conditions the sensitivity of the monitor is greatly improved compared the other PTF-based methods proposed before. No fast electronics are needed and the required operational power is low. This monitor is very suitable for future ultra-high speed and reconfigurable WDM networks.

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