Optics Communications 309 (2013) 180–186

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Format transparent, wide range and independent dispersion monitoring method based on four-wave mixing

Sheng Cui [a,b,c], Sheng He [a,b,c], Simin Sun [a,b,c], Changjian Ke [a,b,c,*], Deming Liu [a,b,c]

[a] School of Optical and Electronic Information, Huazhong University of Science and Technology, Hubei, China
[b] National Engineering Laboratory for Next Generation Internet Access System, Wuhan, Hubei, China
[c] Wuhan National Laboratory for Optoelectronics, Wuhan, Hubei, China

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form
6 July 2013
Accepted 8 July 2013
Available online 19 July 2013

Keywords:
Fiber optics communications
Chromatic dispersion monitoring
Four-wave mixing
Power transfer function
Tunable dispersion compensator

ABSTRACT

In this paper we propose an improved all optical chromatic dispersion (CD) monitoring method based on highly nonlinear power transfer function (PTF) provided by four-wave mixing (FWM) in highly nonlinear fibers (HNLFs). This method can be applied for various modulation formats, including on–off keying and advanced multi-level modulation formats, without necessitating any changes of the hardware or software. Furthermore, it can expand the CD monitoring range beyond the limitation of Talbot effects and is insensitive to optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD). These improvements are achieved by optimizing the profile of the PTF curve and utilizing a sweeping tunable dispersion compensator (TDC) in combination with an extremely simple digital signal processing (DSP) to find the zero residual dispersion point. Numerical simulations are then used to demonstrate the effectiveness of this method.

1. Introduction

In high speed optical transmission systems CD is an indispensible signal quality parameter to be monitored [1]. All-optical chromatic dispersion monitors based on ultra-fast nonlinear effects are attractive because they can accommodate different modulation formats and bit rates and are relatively simple, thus cost-effective to be deployed at optical nodes without coherent receivers [1–9]. By now, many all-optical CD monitors have been proposed [2–10]. For the all-optical monitors utilizing nonlinear effects to map the CD information onto the optical spectrum, prior knowledge of the input signal spectrum and delicate spectrum analysis of the output signal are required [2–5], which may not be feasible or convenient for practical applications. For the methods based on nonlinear power transfer function (PTF) provided by nonlinear effects [6–9], such as two-photon absorption (TPA) in semiconductor detectors and cascaded FWM in parametric amplifiers, the CD information of the input signal is mapped onto the output average optical power; thus, only a simple slow optical detector is required for the measurement. However, their sensitivity is low and only applicable to 33% RZ signals with high OSNR because of the lowly nonlinear quadratic PTFs obtained [6–9]. Recently, we proposed a method to obtain a highly nonlinear PTF by single stage FWM with phase-matching condition optimized [10]. By this method the sensitivity is greatly enhanced, while the required input power is reduced. The sensitivity enhancement is important for highly accurate dispersion compensation and makes the method effective for signals with different duty cycles and low OSNR. However, it is still sensitive to PMD and OSNR and the CD monitoring range is also limited by the temporal Talbot effects as previous all-optical CD monitors (for 40 Gb/s 33% RZ signals the monitoring range is about 39 ps/nm) [6,10]. Furthermore, with the application of advanced multi-level modulation formats [11], it is desirous for the monitors to accommodate such signals.

In this paper we propose an improved monitoring method which can be applied for various modulation formats, including on–off keying (OOK) and advanced multi-level modulation formats, in a truly format-transparent fashion. No changes of the hardware or software are needed during the operation. Furthermore, it can expand the CD monitoring range beyond the limitation of Talbot effects and is insensitive to optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD). These improvements are achieved by optimizing the profile of the PTF curve and utilizing a sweeping tunable dispersion compensator (TDC) in combination with extremely simple digital signal processing (DSP) to find the zero residual dispersion point. The operating principles are introduced in Section 2. In Section 3 numerical simulations are used to demonstrate the accuracy and robustness of the method.

* Corresponding author at: Huazhong University of Science and Technology, School of Optical and Electronic Information, Luoyu Road 1037, Wuhan, Hubei, China. Tel.: +86 027 87559189x3094; fax: +86 027 87556188.
E-mail address: cjke@hust.edu.cn (C. Ke).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.07.011

2. Operating principles

The setup of the monitor is shown in Fig. 1. The signal to be monitored (ω_s) is amplified and launched into the HNLF with a continuous probe wave ω_{pb}. A new idler wave at $\omega_i = 2\omega_s - \omega_{pb}$ is generated from the FWM in the HNLF. In the undepleted condition the output power of the idler wave P_i is given by [10]

$$P_i = P_{pb} PTF(P_s) = P_{pb}(\gamma P_s L)^2[\sinh(gL)/gL]^2, \tag{1}$$

with $g^2 = -\Delta\beta(\Delta\beta/4 + \gamma P_s)$, where γ, L and $\Delta\beta$ are the nonlinear coefficient, fiber length and linear phase mismatch, respectively. $P_{s,pb}$ is the input power of the signal and probe waves. As demonstrated in our previous work, the CD information of the input signal is mapped onto the average idler power by the PTF and the sensitivity is proportional to the slope (S_{PTF}) of the PTF. A PTF with a larger S_{PTF} can be obtained when $\Delta\beta < 0$ and the phase matching condition as follows is satisfied [10]

$$P_s > P_s^\pi = P_s^0 - \frac{\pi^2}{\gamma L^2 |\Delta\beta|}, \tag{2}$$

where $P_s^0 = |\Delta\beta|/(4\gamma)$. Eq. (2) indicates that P_s^π is proportional to $|\Delta\beta|$ and may be positive or negative for different ranges of $|\Delta\beta|$, while the corresponding PTF also takes on different types of profiles, as shown in Fig. 2 and summarized in Table 1. When $|\Delta\beta| > 2\pi/L$, $P_s^\pi > 0$ and as we can see there is an obvious concave point at P_s^π dividing the PTF into two distinct sections with different slopes.

In the section below, P_s^π, $S_{PTF} \approx 2$ because when in the low power region PTF$\propto(\gamma P_s L)^2$, noting that the PTF is drawn on a log–log plot. While the section above P_s^π has a much higher S_{PTF} it was demonstrated in our previous work that a much higher monitoring sensitive can be obtained regarding to OOK signals in this section [10]. When $0 < |\Delta\beta| < 2\pi/L$, $P_s^\pi < 0$ and the PTF has a smooth profile with increasing slope. When $\Delta\beta = 0$, PTF $= (\gamma P_s L)^2$ and $S_{PTF} = 2$. The numerical results agree very well with the analytical ones using Eq. (1), except the deviations at P_s^π and the high power region because the fiber loss induced suppression of destructive interference and gain saturation is not considered in the analytical model [10].

We stress that FWM is a quasi-instantaneous effect [12]; thus, $P_{s,i}$ in Eqs. (1) and (2) refers to the instantaneous pulse power. For OOK formats the signal pulses have only one peak power level while for multi-level advanced modulation formats like m-ary quadrature amplitude modulation (mQAM) the signal pulses have multiple peak power levels. For example, the 16QAM signals have three levels of peak power and the ratio is 1:5:9, as shown in Fig. 3. The ratio between the lowest and the highest levels is 9.5 dB and after taking the CD into account the peak power variations may be even larger. Although the PTF with $P_s^\pi > 0$ has a larger S_{PTF}, the dynamic range is relatively smaller because of the uncontinuous profile and power saturation in high power regions, as seen in Fig. 2. Thus, the PTF with a smooth profile and wide dynamic range is more desirous to accommodate such signals because a relative large S_{PTF} can be maintained with the whole range.

Fig. 3(a–c) shows the variations of the idler power against CD for OOK signals with different duty cycles (33%, 66% and 100%) when the PTF with $S_{PTF} = 5.5$ is employed. To demonstrate the performance that can be achieved by the methods proposed before results obtained by the quadratic PTF ($S_{PTF} \approx 2$) is also shown [6–9]. The output power is scaled by the value at 0 ps/nm. As we can see, there is always an obvious symmetric center at 0 ps/nm because for ideal signal pulses the peak power change is the same for opposite-signed CD. Furthermore, using the smooth PTF with $S_{PTF} \sim 5.5$, the monitoring sensitivity is greatly improved. As we can see from Fig. 2(a), for 33% RZ signals the scaled idler power changes from 0 to -11 dB for $0 \sim \pm 40$ ps/nm CD. The sensitivity and dynamic range is around 0.25 dB/(ps/nm) and 11 dB near the symmetric center at 0 ps/nm. While with quadratic PTF the sensitivity and dynamic range is around 0.075 dB/(ps/nm) and 3 dB. This improvement is important because it makes the symmetric center at 0 ps/nm more prominent and identifiable, even

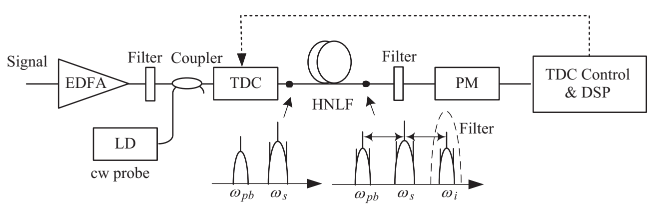

Fig. 1. Setup of the monitor. EDFA: Erbium-doped fiber amplifier, TDC: tunable dispersion compensator, PM: power meter, LD: laser diode.

Table 1
Types of PTFs.

$\Delta\beta$	PTF slope (in dB/dB scale)
$\|\Delta\beta\| > 2\pi/L$	$P_s^\pi > 0$, two sections with different slopes
$0 < \|\Delta\beta\| < 2\pi/L$	$P_s^\pi < 0$, smooth profile with increasing slope
$\Delta\beta = 0$ or $P_s \ll \|\Delta\beta\|/4\gamma$	Constant slope of 2

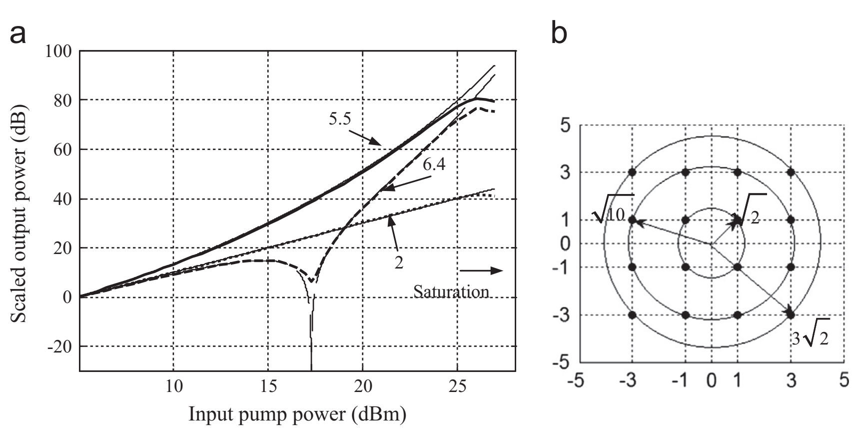

Fig. 2. (a) PTFs under different $\Delta\beta$ obtained by analytical (thin line) and numerical methods (thick line). $2\pi/L$ is set at 4.5×10^{-3} and $|\Delta\beta|$ is set at 0 (dotted line), 4×10^{-3} (solid line) and 5×10^{-3} (dashed line) respectively. The corresponding slopes are 2, 5.5 and 6.4. The data is scaled by the first value on the left. (b) The constellation of the 16QAM signals. Note that the power ratio is the square of the amplitude ratio.