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# Improved all optical chromatic dispersion monitoring method for WDM systems

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ABSTRACT

In this paper we propose an improved all optical chromatic dispersion (CD) monitoring method applicable to wavelength division multiplexing (WDM) systems with intensity or phase modulation format. This method can operate over a much larger bandwidth and CD monitoring range and is insensitive to optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD). These improvements are achieved by utilizing a wavelength tunable laser as the probe to maintain the appropriate phase-matching condition and a loop-back controlled tunable CD compensator to discriminate CD distortions from PMD and OSNR influences. Numerical simulations show that by this method the operational bandwidth and CD monitoring range can be expanded to cover C + L bands and ±1600 ps/nm, respectively, for different modulation formats and the sensitivity is higher than the other methods proposed before.


## 1. Introduction

In high speed dynamic optical transmission systems, residual CD must be monitored to realize adaptive CD compensation due to the reduced CD tolerance of high speed signals [1]. All-optical chromatic dispersion monitors based on ultra-fast nonlinear effects are attractive because they can be used to monitor the CD distortions in a modulation format and bit rate transparent fashion 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 has been proposed [2–9]. 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 be not feasible or convenient to use in practical applications. For the methods based on power transfer function (PTF) provided by nonlinear effects [6–9], such as two-photon absorption (TPA) and four-wave mixing (FWM), 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. But their sensitivity is relatively low and only applicable to 33% RZ signals because of the lowly nonlinear PTF [6–9]. Other important issues for the all optical monitors include how to be insensitive to PMD and OSNR influence and how to expand the CD monitoring range beyond the limitation of Talbot effects (for 40 Gb/s 33% RZ signals the monitoring range is about 39 ps/nm) [6].

In our previous work, we proposed a method to enhance the monitoring sensitivity by utilizing the exponential PTF provided by phase-matched FWM in highly nonlinear optical fibers (HNLFs) [10]. The sensitivity improvement is important for highly accurate dispersion compensation and makes the method effective for signals with high duty cycles. However, it is still sensitive to PMD and OSNR and the operational bandwidth is limited to about 10 nm because the signal wavelength change may destroy the phase matching condition required [10]. In this paper we propose an improved monitoring method that can operate over a much larger CD range and bandwidth, and meanwhile is insensitive to OSNR and PMD.

## 2. Method to expand the operational band

The setup of the system is shown in Fig. 1. The signal to be monitored ($\omega_s$) is amplified and launched into the HNLF with a continuous probe wave $\omega_{pb}$. 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]

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

with $g^2 = -\Delta\beta(\Delta\beta/4 + \gamma P_s)$, where $\gamma$, $L$ and $\Delta\beta$ are the nonlinear coefficient, fiber length and linear phase mismatch. $P_{s,pb}$ are the input power of the signal and probe wave. As demonstrated in our previous work, the CD information of the input signal is mapped onto the

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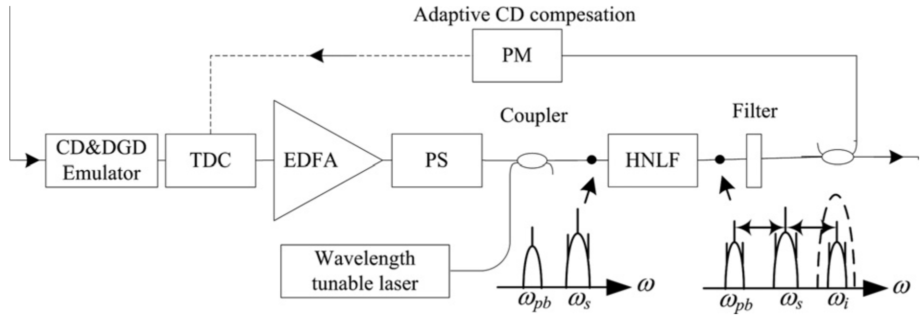


**Fig. 1.** System setup. EDFA: Erbium-Doped Fiber Amplifier, PS: Polarization Scrambler, PM: Power Meter. DGD: Differential Group Delay.

average idler power by the PTF and the monitoring sensitivity depends on the slope of the PTF [10]. An exponential PTF and very high sensitivity can be obtained when the following phase matching condition is satisfied [10,11],

$$-4\gamma P_s \leqslant \Delta\beta \leqslant 0 \tag{2}$$

Considering up to the third order dispersion $\Delta\beta$ can be written as

$$\Delta\beta = \beta_3(\omega_s - \omega_0)(\omega_s - \omega_{pb})^2 \tag{3}$$

here $\beta_3$ is the third order dispersion coefficient at fiber zero dispersion frequency $\omega_0$. In WDM systems the input signal wavelength changes, thus may destroy the required phase-matching conditions given by Eqs. (2) and (3). To expand the operational bandwidth one can keep $\Delta\beta$ unchanged by tuning $\omega_{pb}$ as follows:

$$\omega_{pb} = \omega_s \pm \sqrt{\frac{\Delta\beta}{\beta_3(\omega_s - \omega_0)}} \tag{4}$$

here we set $\Delta\beta = -3.95 \times 10^{-3}\ \mathrm{m}^{-1}$. The other chosen parameters are listed in Table 1. To keep $\Delta\beta$ unchanged, the change of $\lambda_{pb}$ against $\lambda_s$ is shown in Fig. 2a. The PTF obtained with $\lambda_s$ = 1536.5 nm and $\lambda_{pb}$ = 1541.6 nm is shown in Fig. 2b. The PTF has a slope of about 4.6 which means $P_i \propto P_s^{4.6}$. The analytical and numerical results agree well with each other except at very high powers. The roll-off at high power is due to gain saturation which is not considered in the analytical model.

**Table 1**
Monitor parameters.

| $L$ (km) | $S$ (ps/nm$^2$/km) | $\alpha$ (dB/km) | $\gamma$ (W$^{-1}$/km) | $\lambda_0$ (nm) |
|---|---|---|---|---|
| 1.5 | 0.0771 | 0.6 | 9.9 | 1534.0 |

To demonstrate the effectiveness of method for different modulation formats, 40-G Baud/s pseudorandom binary sequence (PRBS) 33% RZ OOK and 33% RZ DQPSK WDM signals are used as the input signals. The simulation results are obtained by VPI Transmission Maker 8.6 based on nonlinear Schrödinger equation and split-step Fourier method. An optical filter with 1 nm bandwidth is used to extract the idler wave. It is noted that the theoretical ratios between the peak power and average power are 5.7 and 2.9 for 33% RZ and 33% RZ DQPSK signals. Thus the average input signal powers are set at 26 mW and 52 mW, respectively to ensure the exponential PTF takes effect. Note that from (2) the exponential PTF begins to act when the pulse peak power is above 100 mW.

The monitoring results are shown in Figs. 3 and 4. The output contrast keeps above 10 dB over the whole C + L bands. The operational bandwidth and sensitivity are much larger than those of the CD monitors proposed before [6–10]. It is noteworthy that when $\lambda_s$ approaches $\lambda_0$ = 1534 nm the exponential PTF becomes a quadratic one, i.e. $PTF = (\gamma P_s L)^2$ [10], resulting in a small output contrast near 1534 nm. The fluctuation of the contrast within the C + L band is caused by the self-phase modulation (SPM) of the signal. As we know SPM causes spectrum broadening and the broadening is proportional to the pulse peak power which is dependent on the residual CD. This effect has been used for CD monitoring before [12]. So when $\lambda_s$ is tuned toward 1620 nm ($\Delta\lambda$ becomes smaller and $|\lambda_s - \lambda_i|$ also becomes smaller, see Fig. 2), a part of the SPM broaden spectrum begins to fall into the pass band of the filter and is measured with the idler, thus enhancing the output contrast to some extent. But when $\lambda_s$ approaches 1620 nm ($\Delta\lambda$ approaches zero, see Fig. 2), the signal overlaps with the idler wave. So the contrast becomes

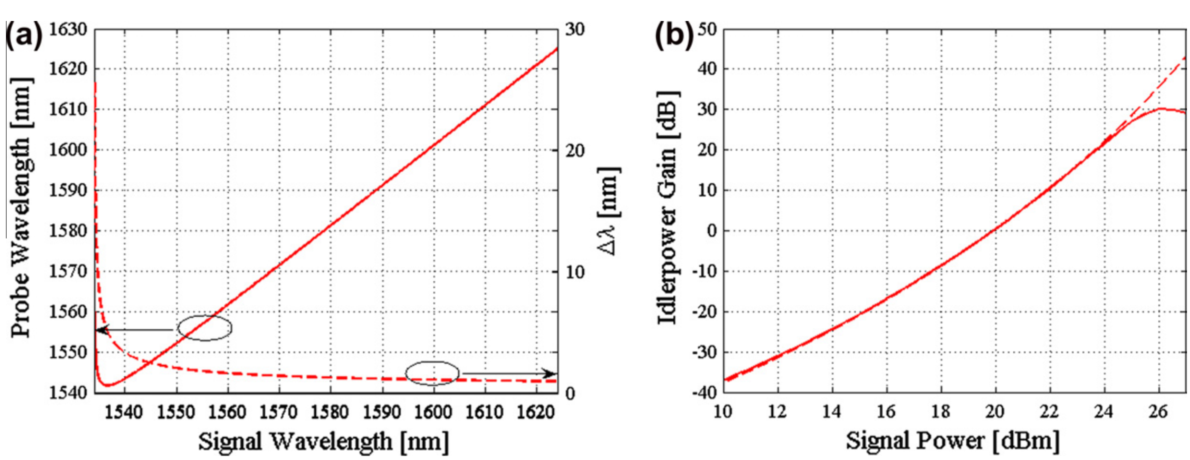


**Fig. 2.** (a) Variation of probe wavelength against the input signal wavelength and (b) nonlinear power transfer function of the monitor.