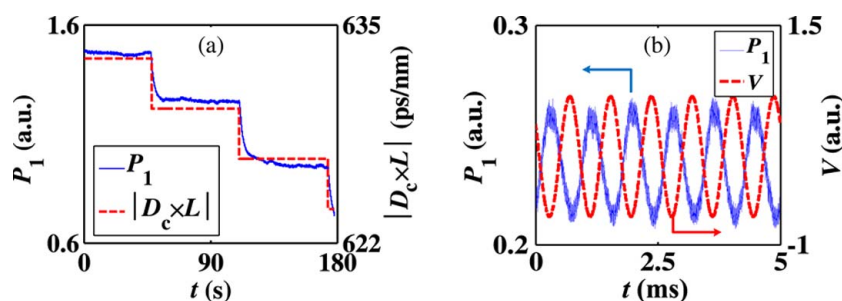


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Yang Lu
Chams Baker
Liang Chen
Xiaoyi Bao



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Yang Lu, Chams Baker, Liang Chen, and Xiaoyi Bao

Department of Physics, University of Ottawa, Ottawa, ON K1N 6N5, Canada

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Abstract: We present a novel approach for real-time chromatic-dispersion (CD) monitoring using a Kerr phase-interrogator. CD induces a differential phase shift between two sinusoidal signals carried by two different wavelengths. A Kerr phase-interrogator converts the differential phase shift into power variation, and CD monitoring is achieved by measurement of the power variation in real time. A CD monitor with a resolution of 0.196 ps/nm is experimentally demonstrated. The high sensitivity and fast response of this CD monitoring approach opens the way for novel sensing applications.

Index Terms: Nonlinear, Kerr effect, fiber non-linear optics, microwave photonics, microwave photonics signal processing.

1. Introduction

Real-time chromatic-dispersion (CD) monitoring is practical for automated CD compensation in high bit-rate and long-distance optical transmission systems [1]. Due to temperature and strain dependence of CD in optical fibers and chirped fiber Bragg gratings [2]–[5], CD monitors can be used for sensing applications. CD monitoring has been achieved using asynchronous amplitude sampling techniques and histogram evaluation approaches [6]–[8] where CD is acquired from statistical properties of the monitored optical signal. Time-consuming signal processing makes these statistical approaches impractical for real-time monitoring. Signal-modulation based approaches have also been used for monitoring CD by measurement of the peak-to-peak values of the amplitude modulated (AM) pilot tones [9]–[11], or the phase difference between the upper and lower sidebands of the AM pilot tones [12]. Signal-modulation approaches require broad-band detector to obtain the AM pilot tones and special electronic circuits such as phase-locked loops for signal processing, leading to complex signal acquisition and bandwidth limitations.

We have recently demonstrated a Kerr phase-interrogator that measures phase-shift between two sinusoidal signals carried by the same laser wavelength using phase-modulation induced by the Kerr effect [13]–[17]. The Kerr phase-interrogator can also measure the phase-shift between sinusoidal signals carried by different laser wavelengths, allowing for differential phase-shift measurement. Because the differential phase-shift is linearly proportional to the CD in the

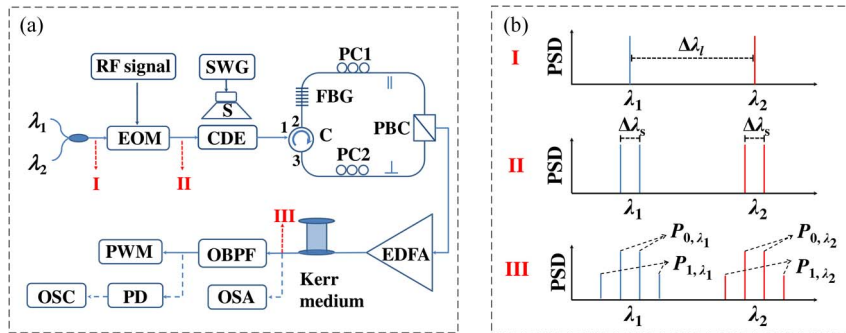


Fig. 1. (a) Schematic of the chromatic dispersion monitoring setup based on a Kerr phase-interrogator. (b) Illustrations of the optical spectra at different points of the setup. EOM: electro-optic modulator; RF: radio frequency; CDE: chromatic-dispersion emulator; SWG: sinusoidal waveform generator; S: speaker; C: circulator; FBG: fiber Bragg grating; PC: polarization controller; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier; OBPF: optical band-pass filter; OSA: optical spectrum analyzer; PWM: power meter; PD: photodiode; OSC: oscilloscope; PSD: power spectral density.

propagation path of the two sinusoidal signals, the Kerr phase-interrogator can monitor CD variations allowing for novel sensing applications. In comparison with existing approaches, CD monitoring is achieved by a mere power measurement at the output of the Kerr phase-interrogator without additional signal-processing allowing for measurement of fast CD variations and, consequently, real-time CD monitoring.

In this paper, we propose and experimentally demonstrate a novel approach for real-time CD monitoring by a differential phase-shift method using a Kerr phase-interrogator. A Kerr phase-interrogator setup is configured for real-time CD monitoring by utilization of two orthogonally-polarized sinusoidal optical signals that are carried by two different laser wavelengths. Phase-modulation induced by the Kerr effect on the sinusoidal optical signals is theoretically analyzed showing that the power of the generated first-order sideband varies sinusoidally with CD. Real-time CD monitoring by measurement of the power of the first-order sideband is experimentally demonstrated.

2. Experimental Setup

Fig. 1(a) shows the Kerr phase-interrogator configured for CD monitoring. Two continuous-wave lasers (Agilent 81980A) operating at wavelengths λ_1 and λ_2 are amplitude-modulated by an electro-optic modulator (EO-Space) and a sinusoidal electrical signal generator (HP 83752A) at a radio frequency (RF) f_m . The outputs of the modulator are two sinusoidal optical signals oscillating at a frequency $f_s = 2f_m$. The optical spectrum for each sinusoidal optical signal consists of two distinct peaks separated by $\Delta\lambda_s = (\lambda_1^2/c)f_s \approx (\lambda_2^2/c)f_s$ with c being speed of light in vacuum, as illustrated in Fig. 1(b). The modulated signals then propagate through a tunable CD emulator (TDC-109181917) that induces an accumulated CD equivalent to $D_c \times L = t_d/\Delta\lambda_l$, where D_c is the CD parameter; L is the propagation distance; $t_d = t_2 - t_1$ is the group delay difference of two sinusoidal signals induced by CD emulator, with t_j being the group-delay accumulated by the sinusoidal signal carried by the laser carrier at λ_j ; and $\Delta\lambda_l = \lambda_2 - \lambda_1$ is the laser carrier separation. The sinusoidal optical signals are separated using a fiber Bragg grating and a circulator, and then recombined using a fiber-coupled polarization beam combiner to obtain two orthogonally polarized sinusoidal optical signals. Two polarization controllers, i.e., PC1 and PC2, ensure the powers of the parallel and perpendicular components of the combined signal are maximum and equal. The combined signal is amplified by an Erbium-doped fiber amplifier (Amomics AEDFA-33-B-FA) and then launched into a Kerr medium composed of a dispersion-shifted fiber (DSF) with a zero dispersion wavelength at $\lambda = 1552$ nm, a length $L_{Kerr} = 2.27$ km and waveguide nonlinearity $\gamma = 2.28$ W⁻¹/km.

The amplitude of the sinusoidal optical signal carried by λ_j at the input of the Kerr medium is given by

$$A_j = \sqrt{\frac{P_p}{2}} \cos[\pi f_s(t - t_j)] \quad (1)$$

where P_p is the total peak power of the combined signal. Neglecting CD effects in the Kerr medium, the evolution of the sinusoidal optical signals in a non-birefringent fiber is governed by the coupled nonlinear Schrodinger equations [18]

$$\frac{dA_{1m}}{dz} = i\gamma_1 \left(|A_{1m}|^2 + 2|A_{2m}|^2 + |A_{1n}|^2 + |A_{2n}|^2 \right) A_{1m} \quad (2)$$

$$\frac{dA_{2n}}{dz} = i\gamma_2 \left(|A_{2n}|^2 + 2|A_{1n}|^2 + |A_{2m}|^2 + |A_{1m}|^2 \right) A_{2n} \quad (3)$$

where γ_j is the waveguide nonlinearity at λ_j , $m = x, y$ and $n = x, y$ with $m \neq n$, x and y represent two orthogonal polarization states. Setting $A_{1y} = A_{2x} = 0$ and $\gamma_1 = \gamma_2 = \gamma$ leads to $A_{1x} = A_1$, $A_{2y} = A_2$, and (2) and (3) reduce to

$$\frac{dA_j}{dz} = i\gamma \left(|A_1|^2 + |A_2|^2 \right) A_j \quad (4)$$

with $j = 1, 2$, which has a solution $A_j(L_{Kerr}) = A_j(0)\exp(i\phi_{NL})$, where

$$\phi_{NL} = \frac{P_p \gamma L_{Kerr}}{2} \left\{ \cos^2[\pi f_s(t - t_1)] + \cos^2[\pi f_s(t - t_2)] \right\}. \quad (5)$$

The phase modulation induced by ϕ_{NL} leads to the formation of distinct sidebands P_k with $k = 1, 2$, [13], [14], as illustrated in Fig. 1(b). The ratio of P_1 to P_0 is derived analytically as described in [14] to obtain

$$\frac{P_1}{P_0} = \frac{J_1^2 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] + J_2^2 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] \pm 2\sin(\phi) J_1 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] J_2 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right]}{J_0^2 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] + J_1^2 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] \pm 2\sin(\phi) J_0 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right] J_1 \left[\frac{\phi_{SPM}}{2} \cos(\phi) \right]} \quad (6)$$

where the positive and negative signs refer to A_1 and A_2 , respectively, $\phi_{SPM} = P_p \gamma L_{Kerr}$, $\phi = \pi f_s t_d + \phi_0$ with ϕ_0 being a constant, and $t_d = D_c \Delta \lambda_l L$. For $\phi_{SPM} < 0.5$, (6) reduces to

$$P_1 = P_1^{max} \cos^2(\pi f_s D_c \Delta \lambda_l L + \phi_0) \quad (7)$$

where P_1^{max} is the maximum value of P_1 [14].

3. Experimental Results

The operating wavelengths of the lasers are set to $\lambda_1 = 1550.05$ nm and $\lambda_2 = 1550.91$ nm, and the modulation frequency is set to $f_m = 9$ GHz. The accumulated CD is varied from -617 ps/nm to -641 ps/nm in steps of 6 ps/nm and the spectrum of the signal at the output of the Kerr medium is measured by an optical spectrum analyzer (Yokogawa AQ6370C). Fig. 2(a) presents the evolution of the measured spectra at the output of Kerr medium as the accumulated CD is varied and Fig. 2(b) presents a magnified image of the generated first-order sideband. The first-order sideband is extracted by a band-pass filter (TeraXion TFC) with a 3 dB bandwidth of 3 GHz, and a power meter (Agilent/HP 81536A) is used to measure P_1 as the accumulated CD is varied. Fig. 2(c) presents the measured values of normalized power P_1/P_1^{max} as the accumulated CD is varied between -644 ps/nm and -584 ps/nm, in steps of 3 ps/nm. The normalized power calculated using (7), showing close agreement with experimental values, is also presented in Fig. 2(c).

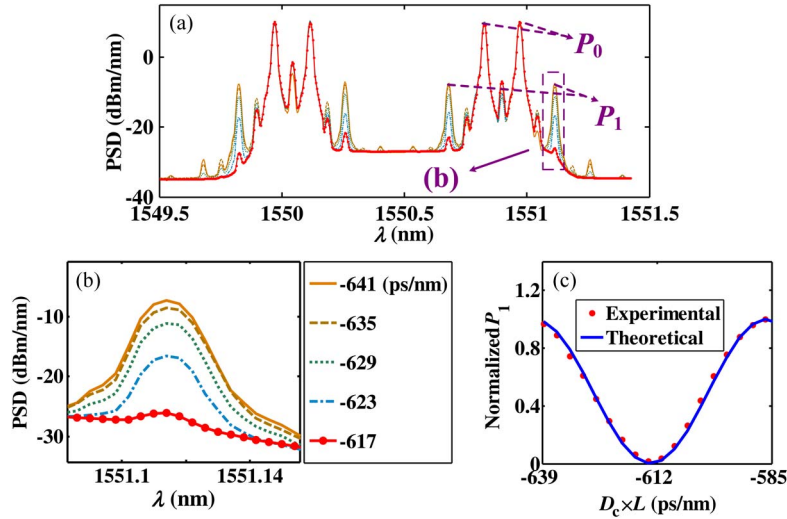


Fig. 2. (a) Measured spectra at the output of the Kerr medium and (b) a magnified image of the first-order sideband. (c) Experimentally measured and theoretically calculated values of normalized power P_1/P_1^{max} as a function of the accumulated CD.

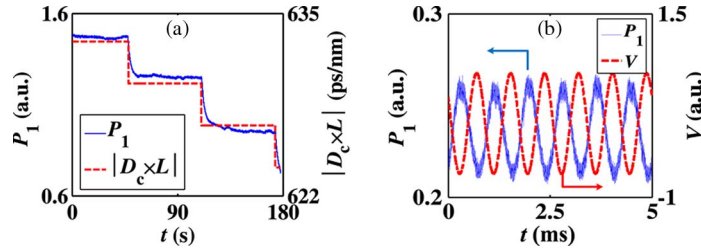


Fig. 3. (a) Measured trace of P_1 as a function of time as $|D_c \times L|$ decreases in steps of 3 ps/nm every minute. (b) Measured trace of P_1 as a function of time showing the vibration induced variation in $|D_c \times L|$.

The power-meter is replaced by a photodiode that is connected to an electrical oscilloscope (Agilent DSO81204B) to record the real-time value of P_1 as the accumulated CD is varied. The accumulated CD is varied by a step of 3 ps/nm every minute in the range between -633 ps/nm and -624 ps/nm where P_1 has quasi-linear dependence on the accumulated CD. Fig. 3(a) presents the measured trace of P_1 as a function of time showing correspondence between P_1 and the accumulated CD, as well as power fluctuation in the measured trace arises from the CD-fluctuation from the emulator.

A speaker is placed on top of the CD emulator and is driven with a sinusoidal waveform generator at a frequency of 1.2 kHz. The acoustic wave from the speaker induces mechanical vibrations in the chirped fiber Bragg grating of the CD emulator leading to periodic variation of the accumulated CD. Real-time variation of the accumulated CD is monitored by measurement of the sideband power $P_1(t)$. Fig. 3(b) presents the measured trace of $P_1(t)$ with a trace of the voltage that is used to drive the speaker showing correlation between these two signals.

4. Discussion

The resolution of proposed CD monitor is determined by the minimum resolvable differential phase-shift $\alpha = \pi f_s D_c \Delta \lambda_l L$. Differentiation of (7) leads to $|\delta \phi \sin(2\phi)| = |\delta P_1 / P_1^{max}|$, where $\delta \phi$ and δP_1 represent fluctuations of phase-shift and power, respectively. Around the quadrature points at $\phi = \pi/4 + m\pi/2$ where m is an integer, the phase fluctuation is given by $|\delta \phi| = |\delta P_1 / P_1^{max}|$. The minimum resolvable differential phase-shift $\alpha = \max\{|\delta \phi|\}$ can be verified experimentally

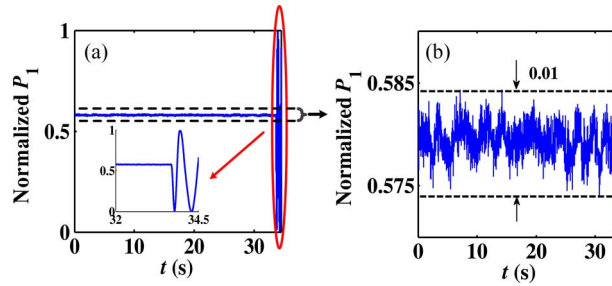


Fig. 4. (a) Measured trace of P_1/P_1^{max} as a function of time with an inset showing the full power swing that results from changing $|D_c \times L|$ by 100 ps/nm. (b) Magnified image showing the fluctuation of the normalized power when $|D_c \times L|$ is unchanged.

from the power fluctuations $|\delta P_1/P_1^{max}|$. Fig. 4(a) presents a measured trace of normalized P_1 as a function of time where the accumulated CD is fixed at -628 ps/nm over a duration of 33 s and then is changed abruptly by 100 ps/nm. Fig. 4(b) presents a magnified image of the measured trace showing that $|\delta P_1/P_1^{max}| < 0.01$ leading to $\alpha = 0.01$ rad around quadrature points. Using $f_s = 18$ GHz, $\Delta\lambda_l = 0.9$ nm, and $\alpha = 0.01$ rad leads to a CD monitor resolution of 0.196 ps/nm.

Fluctuations of P_1 are induced by the noise in the peak power P_p of the combined sinusoidal optical signal at the input of the Kerr medium. The peak power noise arises from the intensity-noise of the laser and the amplified spontaneous-emission noise of the EDFA. Peak power noise also arises from external mechanical and thermal disturbances that cause birefringence variation in the monitored device which induce polarization variation on sinusoidal optical signals before PBC. The noise of P_p induces variations to $\phi_{SPM} = P_p\gamma L_{Kerr}$ and $P_0 \approx P_p/4$ which, according to (6), lead to fluctuations in the power of the first-order sideband δP_1 . Shot-noise and dark-current noise of the photo-detector further increase the magnitude of δP_1 . The resulting δP_1 leads to phase fluctuations $|\delta\phi| = |\delta P_1/P_1^{max}|$, which limit the minimum resolvable differential phase-shift α , and consequently, limit the finesse of the achievable resolution. The magnitude of δP_1 can be reduced by utilization of a laser with low intensity-noise, a highly nonlinear Kerr-medium to eliminate the need for the EDFA, and a low noise photo-detector. Furthermore, external disturbances that cause polarization variation are relatively slow and their contribution to δP_1 can be eliminated by using a feedback control-system that corrects the polarization of the sinusoidal optical signals before the PBC.

The dynamic-range $\{D_c \times L\}_{DR}$ is not limited by the equipment that comprise the CD monitor. In practice, a value of P_1 corresponds to multiple values of the accumulated CD due to the sinusoidal variation of P_1 with $D_c \times L$. To avoid post-measurement signal processing and obtain a one-to-one correspondence between P_1 and $D_c \times L$, the dynamic-range $\{D_c \times L\}_{DR}$ is restricted within the quasi-linear range over which P_1 varies from $0.2P_{max}$ to $0.8P_{max}$ around the quadrature points [17]. Fig. 2(c) shows that $P_1 = 0.2P_{max}$ at $D_c \times L = -621.0$ ps/nm and $P_1 = 0.8P_{max}$ at $D_c \times L = -633.5$ ps/nm leading to $\{D_c \times L\}_{DR} = 12.5$ ps/nm. The value of $\{D_c \times L\}_{DR}$ is estimated from (7) to be $\{D_c \times L\}_{DR} \approx 1/4f_s\Delta\lambda_l$. Using $f_s = 18$ GHz and $\Delta\lambda_l = 0.9$ nm leads to $\{D_c \times L\}_{DR} = 15.4$ ps/nm, which is in close agreement with the measured value.

Derivation of (7) utilizes the assumption that CD is negligible in the Kerr medium. This assumption is valid when the group-delay difference $|\Delta t| = |D_{c,Kerr}|L_{Kerr}\Delta\lambda_l$ that is induced by the CD of the Kerr medium is negligible in comparison to the period of the sinusoidal optical signal $T_s = 1/f_s$. For our experiment, the CD parameter of the DSF that comprises the Kerr medium is $D_{c,Kerr} \approx -0.04$ ps/nm-km at λ_1 and λ_2 , as measured in [16], $L_{Kerr} = 2.27$ km, and $\Delta\lambda_l = 0.9$ nm, leading to $|\Delta t| = 0.082$ ps, which is much smaller than $T_s = 55.56$ ps.

5. Conclusion

We present a novel approach for real-time CD monitoring by utilizing a Kerr phase-interrogator. CD induced group-delay difference of two sinusoidal optical signals carried by two different

wavelengths is converted to power variation by a Kerr phase-interrogator. Monitoring of CD at a resolution of 0.196 ps/nm is experimentally demonstrated. High-resolution real-time CD monitoring opens ways for novel sensing applications, as will be presented in future work.

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