

Estimating nonlinear phase shift in a multi-span fiber-optic link using a coherent transceiver

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Abstract: We demonstrate a novel technique to measure the nonlinear phase shifts of multi-span fiber optic links with a polarization-multiplexed coherent transceiver based on cross-phase modulation between two orthogonally polarized subcarrier tones.

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1. Introduction

Kerr effect nonlinearity in optical fiber is known to cause transmission performance degradation in fiber optic communication systems. With the increase of wavelength-division multiplexed (WDM) channels and per-channel data rates, fiber nonlinearity-induced performance penalties become more and more critical in optical network design and operation. With the wide adoption of coherent optical systems and digital signal processing (DSP) in which signals are carried by complex optical fields, the impacts of chromatic dispersion and polarization mode dispersion (PMD) can be compensated by digital filtering. However, it still remains challenging to compensate transmission performance degradation caused by fiber nonlinearities manifested through self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Nonlinear phase shift created on an optical carrier is an important measure of fiber nonlinearity, which depends on signal optical power and the fiber nonlinear parameter. In a fiber system with multiple spans and in-line optical amplifiers, nonlinear phase generated from different fiber spans will add up. The knowledge of nonlinear phase in each amplified fiber span is desirable in optical network design and performance evaluation [1]. The accumulated nonlinear phase between the transmitter (Tx) and the receiver (Rx) can also be useful to estimate the transmission performance [2]. Various techniques have been demonstrated to measure fiber nonlinearities based on the measurements of SPM, XPM or FWM [3-4]. Most of these techniques require specific laboratory setups. Utilizing commercial optical transceivers to interrogate parameters of installed fiber links before data transmission would be beneficial for system engineering, especially in open optical networks [5]. In this paper we present a novel technique to measure the nonlinear phase of multi-span fiber optic links using a commercial polarization-multiplexed (PM) coherent transceiver. The measurement is based on XPM between two orthogonally polarized subcarrier tones emitting from the same Tx. In addition, the measurement can also tell the number of amplified fiber spans, and the chromatic dispersion of each span. While two synchronized transceivers were usually required to perform such XPM based measurements [6], a technique based on a single transceiver would make the optical telemetry much more practical.

2. Operation principle and waveform design

In this work, a PM-coherent optical transceiver (Ciena WaveLogicAi) is used to demonstrate the proposed technique. The Tx is equipped with two in-phase/quadrature (I/Q) electrooptic modulators to perform independent complex field modulation of x - and y -polarized optical carriers emitting from the same tunable laser diode with <100kHz spectral linewidth. The real and imaginary parts of a complex waveform can be designed and applied to each modulator through two digital-to-analog converters (DAC) at 68GS/s sampling rate and driving amplifiers with >34GHz analog bandwidth. For a measurement based on XPM between a pump and a probe, their frequency separation leads to a temporal walk-off between them in the fiber due to the chromatic dispersion, which is essential to provide spatially resolvable nonlinear phase along the fiber. As shown in Fig. 1(b), the central frequencies of the pump and the probe are set at 28GHz and -22GHz, respectively, through subcarrier multiplexing, and thus the pump-probe frequency separation is 50GHz (0.4nm). These subcarrier frequencies are chosen to minimize potential pump-probe crosstalk due to the non-ideal opposite-sideband rejection of I/Q modulation. Gaussian noise in the low frequency region of up to ± 3 GHz is added to maintain stability of modulator controls. The pump and probe optical fields are generated by the two I/Q modulators, and their state-of-polarizations (SOPs) are mutually orthogonal.

The time-domain pump and probe waveforms are shown in Fig. 1(c), which are both repetitive with 1.92 μ s pattern lengths. Each pattern is divided into 5 equal-length sections, each including a band-limited noise, a pump (probe) pulse on the 28GHz (-22GHz) subcarrier, and there is a silent region on each side of the pump (probe) pulse. For the first two sections, pump pulses are short with 250ps FWHM width, while for the last two sections, 10ns wide pump pulses are used as shown on top of Fig. 1(c). No pump pulse is in the middle section, which is used for probe phase

calibration. All probe pulses are 50ns wide, but the amplitude of the 1st probe pulse is 20% higher than the other 4 to indicate the beginning of each pattern at the receiver. The designed pump/probe complex waveforms are linearly translated to the x - and y -polarized complex optical fields through DACs and I/Q modulators, and the optical spectrum at the Tx output is shown in the inset of Fig. 1(a). After propagating through the fiber system under test, a coherent receiver selectively detects the complex optical field of the probe tone, as illustrated in Fig. 1(a), and the optical phase variation within each 50ns-long probe pulse is measured.

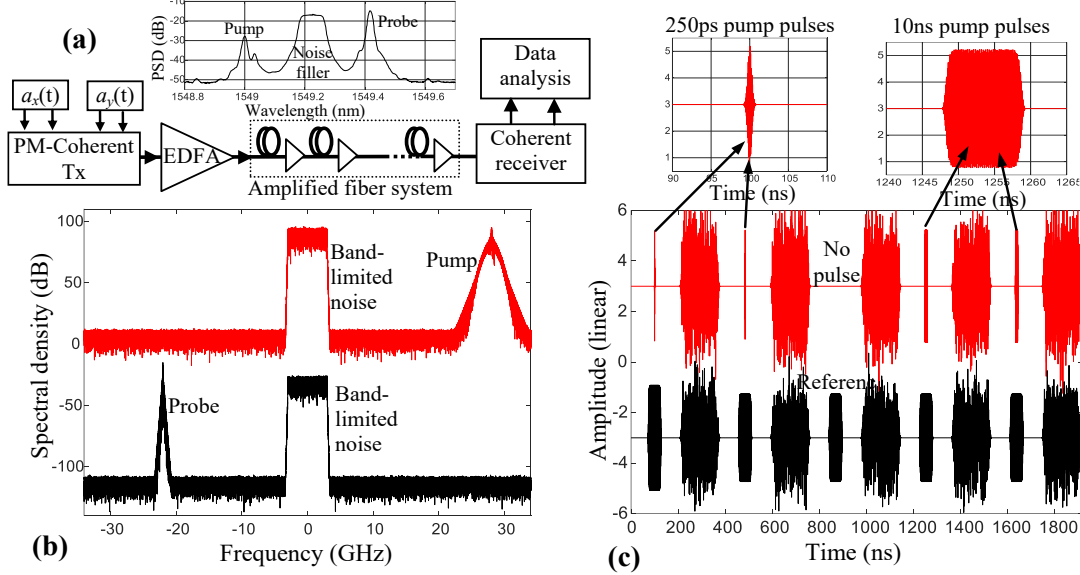


Fig. 1. (a) System setup. Inset: measured Tx optical spectrum. (b) Spectra of pump (red) and probe (black) channels, (c) Time-domain waveforms of pump (red) and probe waveforms, with the detailed shapes of short and long pump pulses shown on the top.

3. Results and discussion

Fig. 2(a) and (b) show the measured nonlinear phase variations of probe pulses caused by the 250ps (a) and 10ns (b) pump pulses, respectively, for different signal average power levels P_{ave} . The phase of the center probe pulse, not overlapping with any pump pulse, is used as the phase reference to minimize the impact of random phase variation due to the laser phase noise. The peak nonlinear phases vs. P_{ave} are shown in Fig. 2(c) corresponding to short (solid circle) and long (open squares) pump pulses (averaged over the flat top region). Solid straight line in Fig. 2(c) shows the calculated nonlinear phase shift based on $\phi_{NL} = (8/9)\gamma P_{pump}(0)L_{eff}$, where $\gamma = 1.19W^{-1}km^{-1}$ is the nonlinear parameter, $L_{eff} = 21.5km$ is the effective nonlinear length of the fiber, and the well-known 8/9 factor is due to the orthogonal SOPs between the pump and the probe which reduces the nonlinear coefficient according to the Manakov-PMD equation [7]. The calculation also included a factor of 2.96 between the input pump pulse peak power $P_{pump}(0)$ and the signal average power P_{ave} based on the designed waveforms shown in Fig. 1(b).

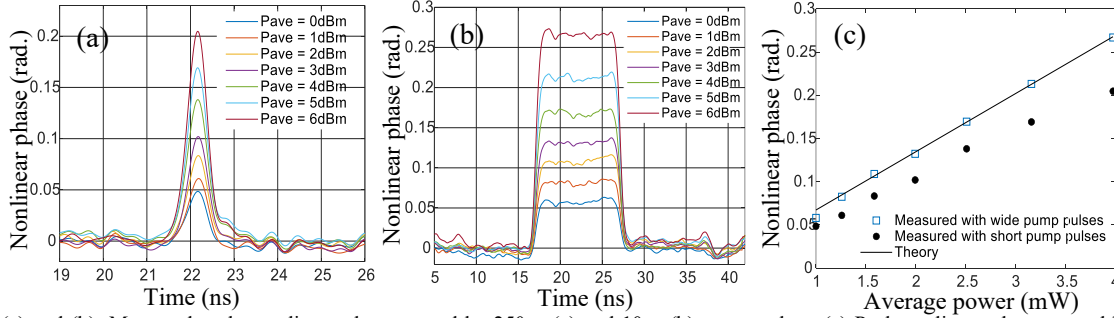


Fig. 2(a) and (b): Measured probe nonlinear phase caused by 250ps (a) and 10ns (b) pump pulses. (c) Peak nonlinear phase caused by 250ps (solid circles) and 10ns (squares) pump pulse as the function of the average signal optical power. Solid line: Theoretical prediction.

Fig. 2(c) indicates that the measured peak nonlinear phase caused by broad pump pulses can accurately predict ϕ_{NL} . But the peak nonlinear phase corresponding to a short pump pulse is not accurate enough to tell fiber nonlinearity; instead the integration of the pulse area shown in Fig. 2(a) should be used in that case [6]. However, short pump pulses can be helpful to estimate relative signal power levels of different fiber spans and chromatic dispersion of each span in a multi-span system, as will be discussed in the following.

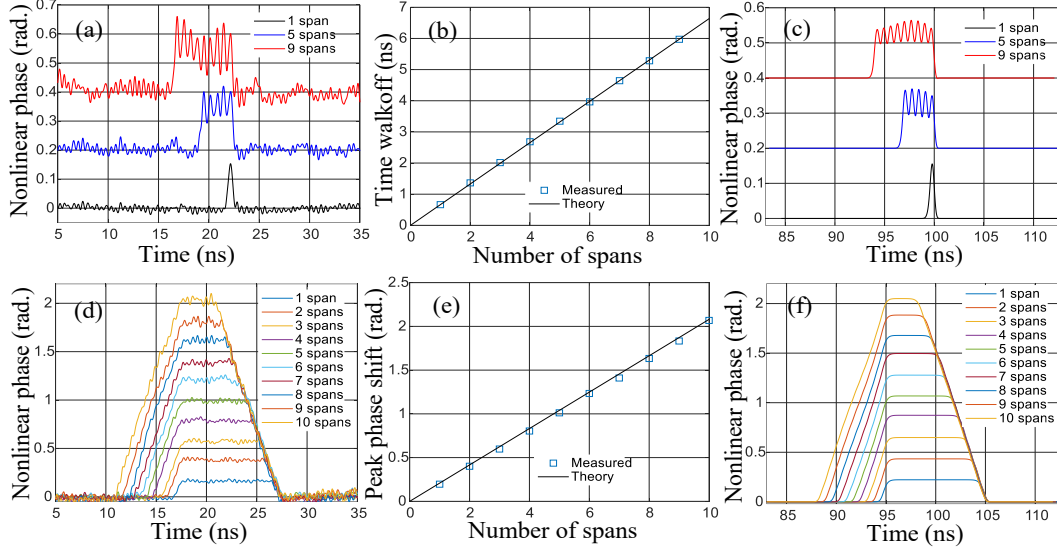


Fig. 3(a) measured nonlinear phase caused by 250ps pump pulses for systems with 1, 5, and 9 spans. 0.2 rad. is added to separate between these curves for clear display. (b) Measured (squares) and calculated (solid line) time walk-off of nonlinear phase peaks shown in (a) versus the number of fiber spans. (c) Simulated nonlinear phase caused by 250ps pump pulses, (d) measured nonlinear phase caused by 10ns pump pulses for systems with 1 to 10 spans, (e) Measured (squares) and calculated (solid line) peak nonlinear phase in (d) versus the number of spans, and (f) Simulated nonlinear phase shift caused by 10ns pump pulses.

In order to demonstrate the application of the proposed technique in multi-span fiber systems, we insert the 101km SMF inside a re-circulating loop, and the equivalent number of amplified fiber spans can be chosen by counting the number of circulations in the loop [4]. Fig. 3(a) shows the measured nonlinear phase caused by 250ps pump pulses for 1, 5, and 9 fiber spans (0.2 rad. is added to adjacent curves for better display). With the fiber dispersion parameter at the signal wavelength $D = 16.1\text{ps/nm/km}$, fiber length $L = 101\text{km}$, and pump/probe wavelength separation $\Delta\lambda = 0.4\text{nm}$, there should be $D\Delta\lambda L = 664\text{ps}$ walk-off between the pump and the probe after each fiber span. Thus, each peak in the nonlinear phase curve in Fig. 3(a) represents an amplified fiber span, and the delays of these peaks versus the number of fiber spans are shown on Fig. 3(b), where the solid line shows the theoretical prediction. Fig. 3(d) shows nonlinear phase caused by 10ns pump pulses for 1-10 fiber spans. Again due to fiber dispersion, after each span the added nonlinear phase is shifted by 664ps, so that the pulse width is narrowed by the same amount. As long as the pump pulse width is larger than the walk-off caused by the accumulated fiber dispersion, the measured nonlinear phase curve shown in Fig. 3(d) always has a flat top. Averaging the flat top provides the peak nonlinear phase versus the number of fiber spans as shown in Fig. 3(e). The solid line in Fig. 3(e) is obtained with $\varphi_{NL} = N(8/9)\gamma P_{pump}(0)L_{eff}$, where N is the number of spans, and an average signal power $P_{pump}(0) = 3\text{mW}$ is used at the input of each fiber span for these measurements. Fig. 3(c) and (f) show results of numerical simulations of XPM on the probe caused by 250ps (c) and 10ns (f) pump pulses, respectively, based on the split-step Fourier method, and the same parameters of the fiber used in the experiments. The measured and simulated results indicate that XPM measurements based on broad pump pulses can accurately predict the accumulated nonlinear phase along the fiber link. Whereas short pump pulses can help identifying the number of fiber spans, dispersion of each span, and distribution of nonlinear phase among different fiber spans. Note that each curve in Figs. 2(a-b), and 3 (a), (d) was obtained by averaged over 20 equal patterns. Increase the number of averages will help further improving measurement accuracy, especially for short pump pulses.

4. Conclusion

In conclusion, we have demonstrated a novel technique to measure the nonlinear phase shift of multi-span fiber optic links with a polarization-multiplexed coherent transceiver. The measurement is based on XPM between two orthogonally polarized subcarrier tones used as the pump and the probe. While relatively wide pump pulses can produce accurate measure of the accumulated nonlinear phase along the fiber system, short pump pulses can be useful to identify the number of amplified fiber spans and chromatic dispersion of each span in the fiber link.

5. References

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