

Fiber transmission characteristics of phase only pulse and its dispersion compensation in high power regime

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Abstract: We investigated fiber transmission characteristics of phase only pulses (POPs) that had constant intensity and pulse-shaped phase waveforms. A 10-ps-wide Gaussian-shaped POP was generated by an optical pulse synthesizer that generates arbitrary waveforms through a frequency-domain modulation. It was transmitted through a standard single mode fiber and a dispersion compensating fiber. The POP was nonlinearity-tolerant due to the constant intensity and, consequently, its initial pulse waveform was successfully regenerated by dispersion compensation even in a high power regime.

Keywords: Photonic signal processing, arrayed-waveguide grating, dispersion compensation, optical pulse, fiber nonlinearity

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

- [1] M. G. Taylor, "Coherent Detection Method Using DSP for Demodulation of Signal and Subsequent Equalization of Propagation Impairments," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 674–676, Feb. 2004.
- [2] S. J. Savory, G. Gavioli, R. I. Killey, and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver," *Optics Express*, vol. 15, no. 5, pp. 2120–2126, March 2007.
- [3] K. Kikuchi, "Phase-diversity homodyne detection of multilevel optical modulation with digital carrier phase estimation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 4, pp. 563–570, July 2006.
- [4] B. P. P. Kuo, P. C. Chui, and K. K. Y. Wong, "Suppression of WDM Signal Crosstalk in Fiber Optical Parametric Amplifier by using RZ-DPSK Modulation Format," *Proc. Optical Fiber Communication Conference 2007*, Anaheim CA, USA, OWB3, March 2007.
- [5] N. Alic, R. M. Jopson, J. Ren, E. Myslivets, R. Jiang, A. H. Gnauck, and S. Radic, "Impairments in deeply-saturated optical parametric amplifiers for amplified- and phase-modulated signals," *Optics Express*, vol. 15, no. 14, pp. 8997–9008, 2007.

- [6] H. Tsuda, Y. Tanaka, T. Shioda, and T. Kurokawa, “Analog and Digital Optical Pulse Synthesizers Using Arrayed-Waveguide Gratings for High-Speed Optical Signal Processing,” *J. Lightw. Technol.*, vol. 26, no. 6, pp. 670–677, 2008.
- [7] A. M. Weiner, “Femtosecond optical pulse shaping and processing,” *Progress Quantum Electronics*, vol. 19, no. 3, pp. 161–237, Jan. 1995.
- [8] K. Kashiwagi, H. Ishizu, and T. Kurokawa, “Fiber Transmission Characteristics of Parabolic Pulses Generated by Optical Pulse Synthesizer,” *Jpn. J. Appl. Phys.*, vol. 50, no. 9, 092501, Sept. 2011.
- [9] W. Qiao, K. Mozawa, K. Kashiwagi, Y. Tanaka, and T. Kurokawa, “Generation of Phase Only Pulses Using Optical Pulse Synthesizer,” *Appl. Phys. Express*, vol. 4, no. 9, 092703, Sept. 2011.

1 Introduction

In recent years, phase and polarization diverse coherent detection in conjunction with digital signal processing (DSP) has attracted a lot of attention because it makes a coherent receiver robust and practical. The DSP-based coherent detection fully recovers both the phase and the magnitude of the complex electrical field of the light signal, allowing compensation of linear impairments including chromatic dispersion and polarization-mode dispersion [1, 2]. Although nonlinear impairments can be compensated using DSPs as long as they are deterministic [3], the perfect compensation of nonlinear impairments is difficult.

Although return-to-zero phase-shift keying (RZ-PSK) formats generally have greater nonlinearity-tolerance than RZ intensity modulation formats [4], such temporal intensity variations of the transmitted signal produce the phase fluctuation due to self-phase modulation (SPM) through the fiber transmission, distorting the signal waveform. One of the ways to avoid the nonlinear impairments is to adopt a constant-intensity modulation format that is nonlinearity-tolerant, for example, NRZ-PSK with differential detection [5].

To suppress the nonlinear effect more perfectly in high-speed transmission, we have proposed phase only pulses (POPs) that possess constant amplitude and pulse-shaped phase waveforms as shown in Fig. 1 (a). The constant amplitude suppresses the nonlinear effect and, consequently, POPs can propagate along fiber with dispersion compensation. It is difficult to generate POPs using a phase modulator because the direct modulation requires broadband electric signals for Gaussian or sech^2 -shaped waveforms with picosecond pulse width. On the contrary, we have developed an optical pulse synthesizer (OPS) [6] that can generate arbitrary optical waveforms based on frequency-domain modulation of optical spectra [7], and generated various kind of optical waveforms including POPs [8, 9].

In this study, we experimentally investigate the fiber transmission characteristics of POPs. We generated a Gaussian-shaped POP using the OPS and transmitted it through a standard single mode fiber (SMF), and subsequently a dispersion compensating fiber (DCF). The POP was nonlinearity-tolerant

and, consequently, the initial pulse waveform was successfully regenerated by the DCF even in a high power regime.

2 Generation of phase only pulse using optical pulse synthesizer

The electric fields of POPs with a data signal phase are defined as:

$$u(t) = \exp[i(\phi_P(t) + \omega_0 t + \phi_s(t))], \quad (1)$$

where $\phi_P(t)$ is a temporal phase change and $\phi_s(t)$ is the data signal phase. The phase change of a Gaussian-shaped POP with a phase amplitude of ϕ_a and a pulse width of T can be expressed as

$$\phi_P(t) = \phi_a \exp \left\{ - \left[\frac{2\sqrt{\ln(2)}t}{T} \right]^2 \right\}. \quad (2)$$

We generated a Gaussian-shaped POP whose phase amplitude ϕ_a was $\pi/2$ and a pulse width of 10 ps using an OPS. An experimental setup for the POP

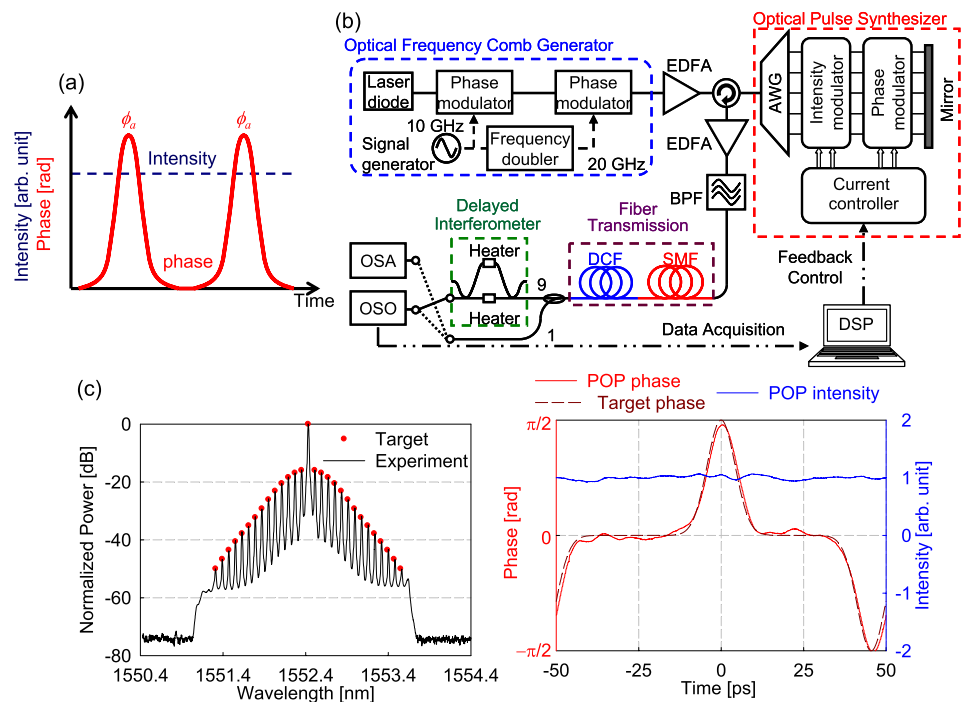


Fig. 1. (a) Schematic drawing of phase only pulse. (b) Experimental setup for phase only pulse generation and fiber transmission. EDFA: erbium-doped fiber amplifier, BPF: band pass filter, SMF: single mode fiber, DCF: dispersion compensation fiber, AWG: arrayed-waveguide grating, OSA: optical spectrum analyzer, OSO: optical sampling oscilloscope, DSP: digital signal processor. (c) Generated Gaussian-shaped phase only pulse with a $\pi/2$ phase amplitude and a 10 ps pulse width: spectrum (left), and phase and intensity waveforms (right).

generation and transmission through fibers is shown in Fig. 1 (b). An optical frequency comb with 10 GHz spacing and 320 GHz bandwidth was generated by modulating single frequency light at the wavelength of 1552.6 nm using two LiNbO₃ phase modulators, which were driven by 10 and 20 GHz signals. It was amplified and subsequently input to the OPS. Its power spectrum was adjusted to a target spectrum using intensity modulators in the OPS. The OPS contained an arrayed waveguide grating to separate each frequency components into different waveguide and intensity and phase modulators in each waveguides to independently and parallelly manipulate each frequency components for the frequency-domain modulation. They are integrated on a single chip fabricated by silica-based planar waveguide technology. The AWG had 30 output channels with 10 GHz spacing. The target spectrum was calculated by Fourier transform of the POP. The power spectrum was adjusted by controlling driving signal to the intensity modulators referring the output power spectrum from the OPS. The phase spectrum was adjusted by genetic-algorithm-based feedback control of the phase modulators so as to minimize the differences between the target and measured waveforms. To measure the phase waveform, the temporal phase changes were converted to the amplitude change using a delayed interferometer. It was retrieved from the four waveforms with four different phase difference of the two arms in the interferometer. The interferometer had two arms with a relative delay time of 45.6 ps, which was almost half of the pulse interval (100 ps). By measuring the delayed interferometer output waveforms, the phase waveforms $\phi_P(t)$ were calculated.

Fig. 1 (c) shows the amplitude and the phase waveforms of the POP and its spectrum. The intensity kept constant in the entire repetitive duration of 100 ps, and the phase waveform well matched with the target waveform. The retrieved phase waveform had inverted delayed replica at 45.6 ps because the phase waveforms were retrieved from the output waveforms from the delayed interferometer. The generated POP had 10.4 ps phase pulse width with the Gaussian waveform and almost constant intensity waveform. In the followings, we only discuss about the POP with positive phase change, not inverted delayed replica.

3 Fiber transmission characteristics of phase only pulse

The generated POP shown in Fig. 1 (c) was amplified up to 20 dBm average power and transmitted through a 1.3-km-long standard SMF whose propagation loss, dispersion and nonlinear coefficient were 0.2 dB/km, 16.9 ps/(nm·km), and 1.1/(W·km) at 1550 nm wavelength range, respectively. Fig. 2 (a) shows a measured POP pulse width change along a fiber transmission and a simulation result. The initial POPs have a Gaussian waveform with a $\pi/2$ phase amplitude, a pulse width of 10 ps, and average powers of 20 dBm. We used split step Fourier method to simulate the pulse propagation along the fiber. The measured pulse width at the SMF output matched with the simulation result.

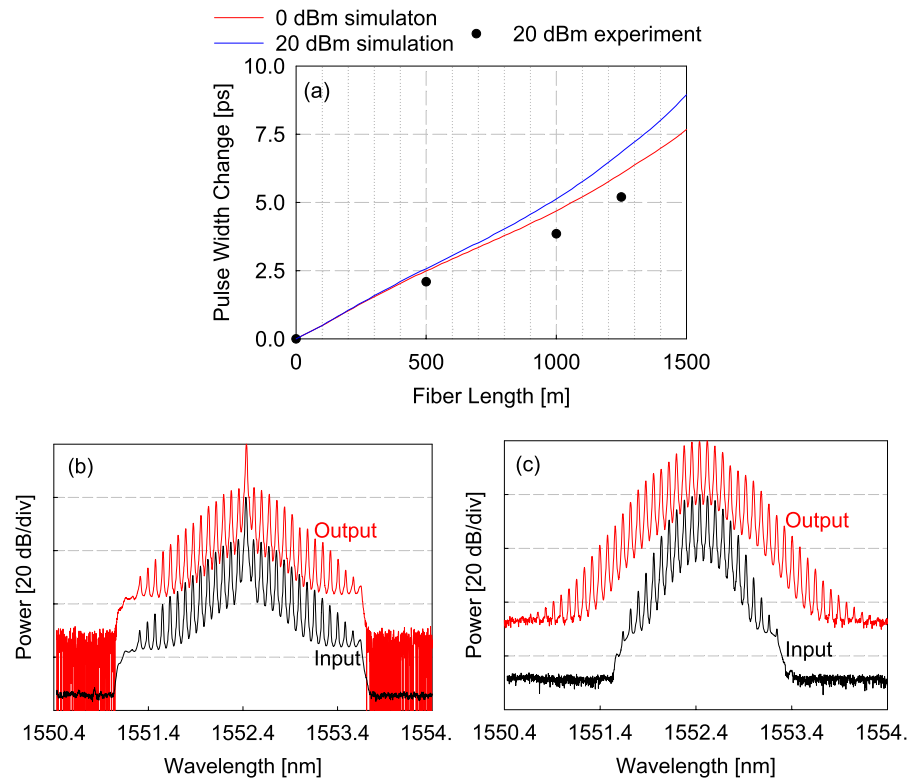


Fig. 2. (a) Experimental and simulation results of pulse width change of phase only pulses along single mode fiber transmission. Optical spectra of Gaussian-shaped (b) phase only pulse and (c) conventional amplitude pulse with a 10 ps duration and a 20 dBm average power at the input and the output of the 1.3-km-long single mode fiber.

Fig. 2 (b) shows the spectrum of the POP at the input and the output of the SMF. The spectrum of the POP with 20 dBm average power did not exhibit any broadening. On the contrary, the spectrum of the Gaussian-shaped amplitude pulse exhibited large broadening by the SPM after the SMF transmission as shown in Fig. 2 (c). The spectral broadening by the SPM prevents regeneration of the initial pulse waveform by dispersion compensation. The nonlinear effect suppression indicates that the POP can be regenerated by the dispersion compensation even in the high power regime as high as 20 dBm average power.

After the POP with 20 dBm average power was transmitted through the 1.3-km-long SMF, it was launched into the DCF which had opposite sign of total dispersion of the SMF. The DCF had a dispersion of $-119.0 \text{ ps}/(\text{nm}\cdot\text{km})$, a length of 195 m and total dispersion of $-23.2 \text{ ps}/\text{nm}$, respectively. Fig. 3 (a), (b) shows the phase and the intensity waveform change of the POP along the fiber transmission. The dispersion of the SMF distorted the phase and the intensity waveforms. The initial phase pulse width of 10.4 ps broadened to 16.0 ps after the transmission through the SMF. After the DCF, the phase waveform distortion was compensated and the duration was compressed to 10.1 ps. The large variation of the inten-

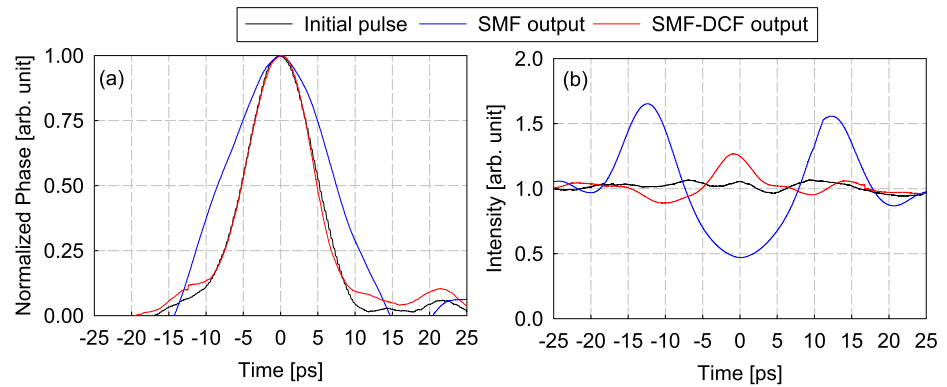


Fig. 3. Waveforms before and after the fiber transmission, and after dispersion compensation of the POP. SMF: length: 1.3 km, dispersion: 16.9 ps/(nm·km), total dispersion 22.0 ps/nm, DCF: length: 195 m, dispersion: −119.0 ps/(nm·km), total dispersion −23.2 ps/nm: (a) phase waveform, (b) intensity waveform.

sity waveform was also reduced although the intensity waveform had a little residual variation. The residual variation was mainly due to the remaining dispersion which was not fully compensated by the DCF.

4 Conclusion

In summary, we generated a Gaussian-shaped POP with a $\pi/2$ phase amplitude using an OPS and experimentally investigated the transmission characteristics through fibers. The Gaussian-shaped POP with a 10 ps pulse duration was transmitted through a SMF. Due to the constant amplitude, the POP experienced little nonlinear effect even in the high power regime as high as 20 dBm average power whereas an intensity pulse with the same pulse duration experienced the nonlinear spectral broadening. Finally, the initial phase waveform was successfully regenerated by the dispersion compensation even in the high power regime. It is confirmed that the POPs with constant intensities have potential for giving the nonlinearity-tolerant modulation format for coherent communication systems.

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