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Performance optimization of ultra-short optical pulse generation based on Mamyshev reshaping and its application in 100-Gb/s and 200-Gb/s optical time-division multiplexing

Dong Wang, Li Huo *, Qiang Wang, Caiyun Lou

Tsinghua National Laboratory for Information Science and Technology, and State Key Laboratory of Integrated Optoelectronics, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

A robust, cost-effective external-modulated ultra-short pulse generator based on chirp compression and Mamyshev reshaper is simulated numerically and demonstrated experimentally. We investigated the quality of the pulse with numerical calculation, demonstrating that the pulsewidth and pulse pedestal can be significantly improved after optimization. The role of out-of-band suppression ratio of the optical filter in reducing the pulse pedestal is explained. Using the numerical analysis as a guideline, 25-GHz 1.9-ps pedestal-free nearly transform-limited optical pulse with an extinction ratio of 29 dB and a root-mean square timing jitter of 120 fs (100 Hz to 10 MHz) is experimentally generated. The pulse source is then successfully applied in 100-Gb/s and 200-Gb/s optical time-division multiplexing (OTDM) system with 100-km transmission, which is a strong proof that such pulse generator is a simple, practical, low-cost, power efficient solution for OTDM applications.

1. Introduction

With the increasing demands on the total transmission capacity of optical networks, there is also a requirement to increase the single-channel data rate accordingly to lower the per-bit transmission cost and simplify the network management. Optical time-division multiplexing (OTDM) holds the promise of supporting a long-term speed upgrade in the future. The key to implement OTDM is a high repetition rate, ultra-short optical pulse source [1]. In OTDM, the pulsewidth should be short enough to accommodate more sub-channels, the extinction ratio should be high enough to suppress the inter-channel crosstalk, and the noise should be low to reduce the bit error rate (BER). These requirements rule out many existing schemes for ultra-short pulse generation. Mode-locked lasers (MLL's) based on fiber [2], semiconductor [3] and erbium-doped glass [4] are generally used in OTDM experimental demonstrations due to their high performance. However, their stability, easiness for tuning still need to be improved and the cost needs to be reduced. Modulator-based ultra-short pulse generators are practical solutions for future industrial applications. These schemes may consist one or more modulators, driven by radio-frequency (RF) sinusoidal signal and/or its harmonics, with or without subsequent nonlinear compression stages [5–9]. The open-loop structures of such schemes provide the robust and wavelength-transparent operation, and the mature technologies of modulators and RF drivers support the low cost. Terabit/s OTDM systems have been achieved based on these ultra-short optical pulse generators [10–12].

In order to further reduce the loss induced by modulators for a higher optical signal-to-noise ratio (OSNR), we advocated an extremely simple by effective pulse generator made of a phase modulator (PM), a piece of dispersive fiber and a subsequent Mamyshev reshaper. Igarashi demonstrated 2-ps ultra-short pulse generation at 10 GHz with similar configuration [13]. We proved by theory and experiment that it is much easier to generate ultra-short pulses at higher speed (such as 25 GHz and 40 GHz) with this scheme by using moderate and even low RF driving power and the optical power for nonlinear compression [14]. However, the optimization for the working conditions of the short pulse source has not been presented. The performance of the pulse source has yet to be verified with transmission test to demonstrate whether the pulse generator can be practically used in ultra-speed OTDM transmission system.

In this paper, the quality of the pulse generated by the PM and Mamyshev reshaper is characterized with numerical model. We investigated how the pulsewidth and peak-to-pedestal ratio (PPR) change with experimental parameters. It is shown that a high out-of-band suppression ratio of the optical filter is essential to obtain

* Corresponding author.
E-mail address: lhuo@mail.tsinghua.edu.cn (L. Huo).

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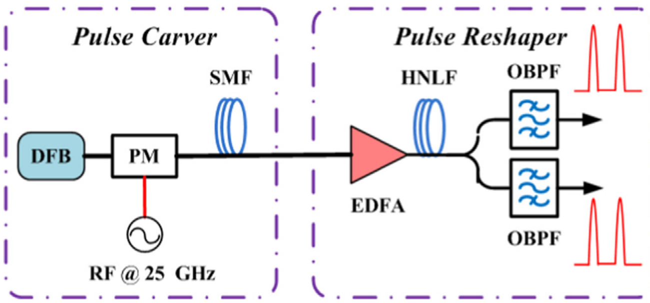

Fig. 1. Schematic of the proposed dual-wavelength optical pulse generator.

a short pulse with high PPR which is very important for OTDM pulse source. The numerical study reveals the potential of such pulse generation scheme and provides guidelines to optimize the pulse quality. Based on the numerical results, a nearly transform-limited 25-GHz pulse train is experimentally obtained with 1.9-ps full-width at half-maximum (FWHM) pulsewidth, 29-dB extinction ratio (ER), 33-dB OSNR, and 120-fs root-mean square (RMS) timing jitter. It is noted that the RMS timing jitter of RF source is 95 fs and the RMS timing jitter induced by Mamyshev reshaper is less than 73 fs. The pulse source is also wavelength tunable, emitting ~2 ps optical pulses with the time bandwidth products (TBPs) between 0.444 and 0.477, which are very close to the transform limited TBP of 0.441 (for Gaussian pulse). Furthermore, the pulse source is successfully applied to 100-Gb/s and 200-Gb/s 100-km OTDM system for the first time, demonstrating that the pulse generator can be practically used in ultra-speed OTDM transmission system.

2. Working principle

Fig. 1 shows the schematic of the proposed dual-wavelength optical pulse generator. The pulse source consists of a pulse carver and a pulse reshaper. In the first stage, the continuous wave (CW) light is launched into a PM driven by a sinusoidal RF signal. The output electric field of the PM can be expressed as

$$E_{out}(t) = E_{in}(t)\exp[iM_{depth}\sin(2\pi f_m t)] \quad (1)$$

where E_{in} is the electric field of the CW light; f_m is the frequency of the RF signal; M_{depth} is the modulation depth of the PM, which is defined by

$$M_{depth} = \frac{V_m}{V_\pi}\pi \quad (2)$$

where V_m is the amplitude of the RF signal and V_π is the half-wave voltage of the PM. As shown in Fig. 2(a), periodic sinusoidal distribution of the instantaneous frequency is impressed on the incident CW light after the phase modulation. The following single-mode-fiber (SMF) is used as a group dispersive medium to compensate the linear up-chirp induced by the PM. The propagation of the modulated light in the SMF can be described by the nonlinear Schrödinger equation

$$\frac{\partial E}{\partial Z} + \frac{\alpha}{2}E + \frac{i\beta_2}{2}\frac{\partial^2 E}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 E}{\partial T^3} = i\gamma|E|^2 E \quad (3)$$

where E is the slowly varying pulse envelop; β_2 and β_3 are the dispersion parameter; γ is the nonlinear parameter; α is the loss of the SMF. In the simulation, the central wavelength of the CW light is 1543.7 nm, the modulation index of the PM is π, the repetition rate is 25 GHz and the accumulated dispersion in SMF is 13.6 ps/nm. Fig. 2(b) shows that optical seed pulse with large pedestal is obtained at the end of SMF. In the SMF, the nonlinear term can be neglected, but it must be taken into account in the subsequent Mamyshev reshaper.

It is noticed that the modulation depth of the PM and the accumulated dispersion in SMF are critical to optimize the seed pulse in the first stage. Fig. 3(a) and (b) shows the RMS pulsewidth and the PPR of the seed pulse as functions of the modulation depth M_{depth} of the PM and the total amount of dispersion D of the SMF. For the pulsewidth, there is an optimal D for each fixed M_{depth}, roughly corresponding to the case where the linear chirp introduced by M_{depth} is exactly compensated by D. The PPR plot follows the same tendency with some offset to the RMS pulsewidth plot. When the modulation index is π and the accumulated dispersion is 13.6 ps/nm, the RMS width and the PPR of the seed pulse are 7.8 ps and 9.3 dB, respectively.

In the second stage, the seed pulse is amplified by an Erbium-doped optical fiber amplifier (EDFA) with a modest output power and sent into a highly nonlinear fiber (HNLF). The spectrum of seed pulse is significantly broadened by the self-phase modulation (SPM) effect in the HNLF. By filtering out part of the broadened spectrum on either the blue side or red side to the original center wavelength, the pedestal can be eliminated and the PPR can be improved as the new frequency components are mainly generated by the SPM on the edges of the seed pulse. The pulsewidth also can be further decreased when the filtered spectrum is broader than that of the seed pulse. The FWHM pulsewidth and PPR of the reshaped pulse, two major parameters of interest in OTDM application, vary with the maximum nonlinear phase shift Φ_{max} in HNLF and the parameters of the optical band-pass filter (OBPF). Fig. 4(a) and (b) shows the influence of the 3-dB bandwidth and

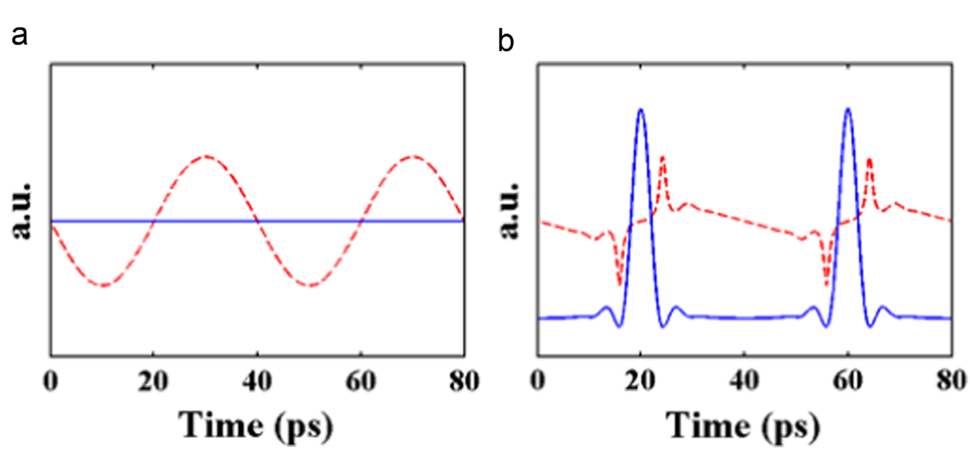

Fig. 2. Simulation results: temporal amplitude (solid line) and chirp (dash line) of the optical pulse after (a) PM and (b) SMF, respectively.