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Optical Gaussian pulse source based on spectrum slicing and frequency chirp compression

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ABSTRACT

An external-modulated optical Gaussian pulse generator based on optical filtering and chirp compression is proposed. The scheme works in linear regime using two phase modulators which does not require nonlinear compression and bias control. Theoretical and numerical analysis is first performed to elaborate the working principle and optimize the working condition of the pulse source. Using the analysis as a guideline, nearly chirp-free 25-GHz 3-ps Gaussian pulses are experimentally achieved over C band. The pulse source is further applied in 100-Gbit/s optical time-division multiplexing (OTDM) transmission system and the power penalty for 100-km transmission at a bit error rate (BER) of 10^{-9} is 0.6-dB, which demonstrates that the pulse generator is a simple, robust and practical pulse source for OTDM applications.

1. Introduction

High repetition rate, low duty cycle, wavelength-tunable optical pulse source is the key part for ultra-high capacity optical networks [1–3] and ultra-speed optical signal processing [4–5]. Several schemes have been demonstrated for optical pulse generation, including mode-locked lasers [6], electro-absorption modulators (EAMs) [7], cascaded Mach–Zehnder intensity modulator (MZM) and phase modulator (PM) [8], etc. However, these pulse generators often have the disadvantages of high system cost, unstable operation, large pulsewidth, low extinction ratio (ER), or poor tunability. The two-stage scheme based on optical seed pulse generation followed by pulse compression is a promising way, which has been further reported, such as cascaded PM and MZM followed by nonlinear compression [9], a MZM-based flat comb generator followed by a dispersion-flattened dispersion-decreasing fiber [10], dual-parallel Mach–Zehnder (DPMZM) followed by a Mamyshev reshaper [11,12], phase modulation and chirp compression followed by pulse reshaping [13], etc. However, optical seed pulse generations using EAM, MZM or DPMZM suffer from large insertion loss or bias drift, etc. The performance of the method with the combination of PM and dispersive medium is limited by the observable pulse pedestal [13]. High pumping power is also required in nonlinear compression stage.

In this study, we proposed and demonstrated an optical pulse generator using a pulse carver followed by a linear pulse compressor. The proposed pulse generator is essentially made up of two PMs driven by synchronized sinusoidal waves. Compared with MZM and DPMZM, the pulse carver composed of a PM (PM1) and an optical band-pass filter (OBPF) can not only generate a shorter pulsewidth, but also eliminate the bias control circuits required by the MZM and DPMZM. The subsequent linear pulse compressor consists of another PM (PM2) and a dispersive medium, which can further reduce the duty cycle of the seed pulse. Such a linear pulse compressor is also simpler and more cost-effective than the nonlinear compression. Generally speaking, our scheme provides a very simple, low-cost and robust solution for short optical pulse generation. We investigated the working principle and optimization guidelines of the pulse source by theory and simulation, indicating that the pulse quality can be significantly improved after optimization. Based on the theoretical study and numerical calculation, optical seed pulse with a duty cycle of 21% and a Gaussian shape is experimentally achieved after the pulse carver. Thanks to the low duty cycle of the seed pulse, the frequency chirp induced by PM2 is quasi-linear around the center of the seed pulse. After the dispersion compensation, nearly transform-limited Gaussian pulse with a duty cycle of 7.5% and an ER of 29 dB is experimentally obtained. The 25-GHz pulse source is also tunable over C band and successfully employed in 100-Gbit/s on-off keying (OOK) optical time division multiplexing (OTDM) transmission system.

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2. Working principle

The setup of the proposed optical Gaussian pulse source is shown in the dash box of Fig. 1. The pulse generator is achieved by spectrum slicing and frequency chirp compression. In the first stage, the continuous wave (CW) light is launched into PM1 driven by a sinusoidal radio frequency (RF) signal. The output electric field of PM1 can be expressed as

$$U_1(t) = U_0(t)\exp(-i(\omega_{CW}t + M_1\sin(\omega_0 t))) \tag{1}$$

Where U_0 is the electric field of the CW light; ω_{CW} is the angular frequency of the CW light; ω_0 is the angular frequency of the RF signal; M_1 is the modulation index of the PM1. Eq. 1 also can be written as the sum of Fourier series:

$$U_1(t) = U_0(t)\sum_{n=-\infty}^{+\infty}(-1)^n J_n(M_1)\exp[j(\omega_{CW} + n\omega_o)t] \tag{2}$$

Where J_n is the n-th order Bessel function of the first kind. Although the subscript runs from minus to plus infinity in theory, only the components with small absolute value of n are non-negligible since the modulation index M_1 is limited in practice.

By filtering out part of the spectrum of the modulated light, optical seed pulse can be obtained, which can be expressed in the frequency domain:

$$u_2(\omega) = u_1(\omega)\cdot u_{OBPF}(\omega) \tag{3}$$

Where u_{OBPF} is the response of the OBPF.

In order to obtain a chirp-free Gaussian optical pulse train, the envelope of the optical spectrum should be Gaussian and the phase should be linear to the frequency offset to the center frequency. In our scheme, the optical filtering is performed at either the blue or the red edge of the phase modulated spectrum. Take the blue edge as an example, if the components with the subscripts of $-N-m$, $-N-m+1$… -N-1 (N and m are integers) in Eq. (2) are selected, their amplitude envelope can be made close to the raising edge of a Gaussian function. The trailing edge of the Gaussian spectrum can be guaranteed by using an OBPF with a Gaussian spectral trailing edge. In this way, a near-Gaussian spectral profile can be obtained. Notice that in Eq. (2) all the components have the same phase of zero, thus chirp-free pulse can be obtained.

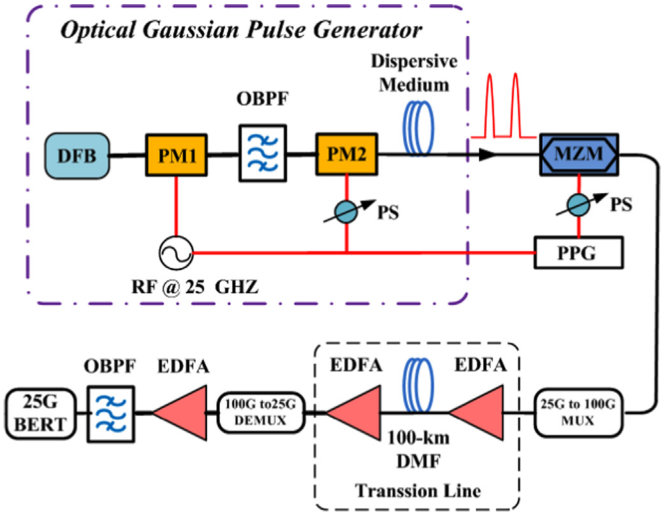

Fig. 1. Experimental configuration for 100-Gbit/s OOK OTDM transmission system. The proposed optical Gaussian pulse generator is shown in the dash box. PPG: Pulse pattern generator; BERT: Bit error rate tester.

In the second stage, the optical seed pulse is sent into another PM (PM2). The output electric field of PM2 can be expressed as

$$U_3(\mathrm{t}) = U_2(t)\exp(-iM_2\sin(\omega_0 t + \varphi)) \tag{4}$$

where M_2 is the modulation index of the PM2; φ is the relative phase between the RF signals applied to the two PMs. The instantaneous angular frequency of the signal after phase modulation can be expressed as:

$$\omega_{inst} = \frac{d(\omega_{CW}t + M_2\sin(\omega_0 t))}{dt} = \omega_{CW} + M_2\omega_0\cos(\omega_0 t) \tag{5}$$

After the PM2, the spectrum of the seed pulse is further broadened and a periodic sinusoidal distribution of the instantaneous frequency is introduced again. By adjusting the electrical phase shifter (PS), the induced frequency chirp around the center of the seed pulse can be quasi-linear.

A single mode fiber (SMF) can be used as a dispersive medium after PM2 to compensate the quasi-linear up-chirp. The medium should be a dispersion compensating fiber (DCF) as the down-chirp part is around the center of the pulse. The output of SMF can be expressed in the frequency domain:

$$u_4(\omega) = u_3(\omega)\exp\left[\frac{j}{2}\beta_2 z\omega^2\right] \tag{6}$$

Where β_2 and z represent the second-order dispersion and the length of the SMF, respectively. When the maximum value of up-chirp is completely compensated by the SMF-induced dispersion, the optimum linear chirp compression is achieved. The optimum length of the SMF L satisfies the following equation:

$$\beta_2 L = \frac{1}{M_2\omega_0} \tag{7}$$

3. Numerical calculation and discussion

Using the theoretical analysis as a guideline, we investigated the performance of the proposed pulse source with numerical calculation. In our simulation, the central wavelength of the CW light is 1546.1 nm, the modulation index of PM1 is 0.9π and the repetition rate is 25 GHz. 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 spectrum of the CW light is significantly broadened by the phase modulation, which is shown in Fig. 2(b). Fig. 2(c) and (d) show the spectrum and waveform of the pulse after spectrum slicing, respectively. By adjusting the central wavelength and bandwidth of the OBPF, optical seed pulse with a full width at half maximum (FWHM) of 8.4 ps (correspond to a duty cycle of 21%) is achieved, which is well fitted to a Gaussian function. Here, the central wavelength of the 1.1-nm cascaded OBPFs is located at 1544.3 nm with an offset of 1.8 nm to the original central wavelength on the blue side.

It is noticed that the 3-dB bandwidth and the central wavelength of the OBPF are critical to optimize the seed pulse in the first stage. Fig. 3(a)–(c) show the root-mean-square (RMS) width of the seed pulse as functions of the bandwidth and the central wavelength of the OBPF. In order to further extend the above-discussed special case with a modulation index of 0.9π, the modulation index is set as 2π, 3π, and 4π, respectively. As indicated by Fig. 3, there exist an optimal set of filter parameters to obtain a shortest pulse, and the optimized RMS pulsewidth of the seed pulse can be significantly reduced by increasing the modulation index of PM1. The optimum bandwidth and the central wavelength of the OBPF are correspondingly increased.

Return to the special case of 0.9π, the 8.4-ps optical seed pulse