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Multicolor optical Nyquist pulse generation based on self-phase modulation without line-by-line control

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Multicolor optical Nyquist pulse generation based on self-phase modulation without line-by-line control is proposed and experimental demonstrated. By 1.4-ps nearly chirp-free optical Gaussian pulse pumping of a high nonlinearity fiber, a 25-GHz spacing, flat-topped supercontinuum (SC) over 17.8 nm within 3.6 dB power variation at a modest pump power of 21.8 dBm is performed. As the phase of the central 90 tones is almost linear to the wavelength after dispersion compensation, spatial light modulator placed after SC for precise line-by-line control both of amplitude and phase can be replaced by conventional optical band-pass filter (OBPF). With an array of quasi-rectangular OBPFs, nearly transform-limited optical Nyquist pulses with a duty cycle of 5.5% on 4 wavelengths are achieved simultaneously.

1. Introduction

The demand for the total capacity of optical networks exhibits a significant increasing trend with the rapid development of network applications. At the same time, there is also a strong requirement for the growth of single-wavelength bit rate. Terabits-per-second optical communications have been achieved with optical time-division multiplexing (OTDM) method [1,2]. In OTDM system, low bit-rate signals at the same wavelength are multiplexed in time to perform a high bit-rate signal stream [3]. The record high single-wavelength bit rate has been demonstrated up to 10 Tbit/s, which is based on 1.28 Tbaud symbol rate using polarization multiplexing and 16-ary quadrature amplitude modulation (16-QAM) [4]. Besides enhancing the capacity, OTDM is also a promising way to reduce the transmission cost per bit and a long-term approach for speed upgrade by overcoming the electronic speed bottleneck. However, ultra-short Gaussian-shaped or sech-shaped optical pulse is traditionally used in OTDM system. The corresponding spectrum spreads over a large bandwidth, which results in a relatively low spectral efficiency [5,6].

Recently, Nyquist optical time-division multiplexing (N-OTDM) is proposed and demonstrated [7]. Compared with traditional OTDM system, optical Nyquist pulse with a sinc-like temporal waveform and a rectangular or raised-cosine spectral profile is used instead of the Gaussian-shaped or sech-shaped pulse [8]. With the same pulsewidth, the bandwidth of the Nyquist pulse is significantly reduced, which has the advantages of improving the tolerance to nonlinear impairments, inter-symbol interference (ISI), chromatic dispersion (CD) and polarization mode dispersion (PMD) [9,10]. Based on these advantages, error-free 2.56 Tbit/s N-OTDM signal using differential phase shift keying (DPSK) and polarization multiplexing over 100-km transmission has been achieved [11]. Thanks to the rectangular spectrum of Nyquist pulse, N-OTDM also can be combined with Nyquist wavelength-division multiplexing (Nyquist-WDM), which is capable of enhancing the system capacity and spectral efficiency [12].

Numerical and experimental investigations on different aspects of N-OTDM system, such as pulse generation, multiplexing, transmission, demultiplexing and modulation formats, have been reported [13–16]. Among those, optical Nyquist pulse generator is the key of N-OTDM system. Nyquist pulse generation has been demonstrated in several schemes, including electrical Nyquist filtering [17], optical parametric amplification [18], cascaded electro-optic modulators [19–22], and temporal pulse-shaping [23]. Schemes based on digital signal processing (DSP) in electrical domain is restricted by the limited electronic bandwidth and high system complexity, which make it difficult to obtain Nyquist pulse of high repetition rate and low duty cycle. The method using optical parametric amplification is limited by the saturation power of the radio frequency (RF) driver and the power rating of phase modulator (PM). Cascaded electro-optic intensity modulators, such as Mach–Zehnder modulator (MZM) [19,20] or dual-parallel Mach–Zehnder (DPMZM) [21,22], can generate high-quality optical Nyquist pulse. However, this scheme can only provide limited number of comb lines even with two cascaded modulators, which results in a relatively large pulsewidth. In our previous work, a

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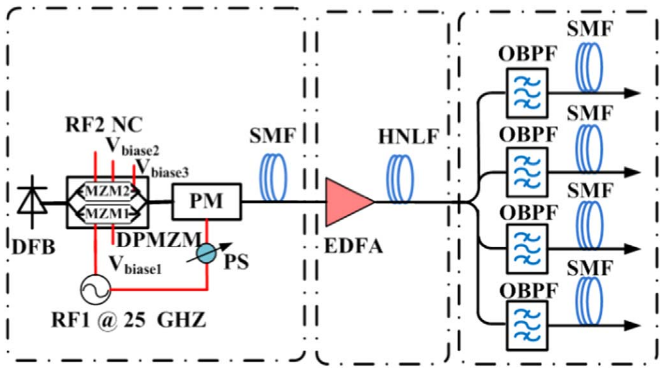

Fig. 1. Experimental setup of the proposed multicolor optical Nyquist pulse generator.

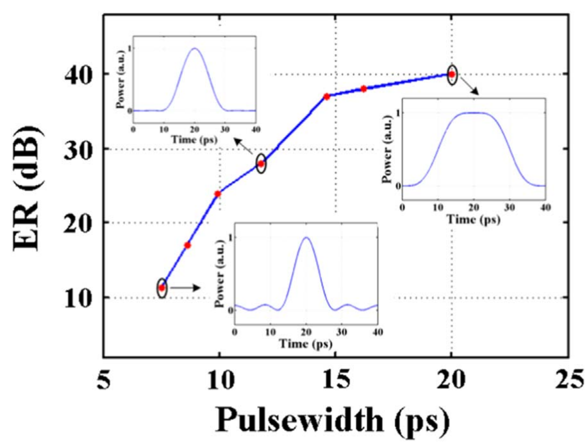

Fig. 2. Simulation results: the ERs of the seed pulses with different pulsewidths.

flexible method for ultra-short optical Nyquist pulse generation over the C-band is demonstrated based on a time lens with subsequent optical filtering [24]. However, the pulsewidth of the optical Nyquist pulse is still limited by the modulation index of the PM. Supercontinuum (SC) generation based on ultra-short optical pulse pumping of a high nonlinearity fiber (HNLF) is an effective method to broaden the bandwidth [25]. Usually, ultra-short optical Nyquist pulse with rectangular-shaped spectrum and linear phase distribution can be obtained by pulse shaping, in which a spatial light modulator (SLM) is placed after the SC [7,23]. However, the spectrum of the SC should be precisely reshaped line-by-line both in amplitude and in phase, which incurs complex operation and severe optical signal-to-noise ratio (OSNR) degradation.

In this study, we propose and experimental demonstrate a multicolor optical Nyquist pulse generator based on ultra-short optical Gaussian pulse pumping of a HNLF where line-by-line control is not necessary. First, a relatively simple but effective ultra-short pulse generator made of cascaded DPMZM, PM and dispersive fiber is proposed and demonstrated which is capable of delivering 25-GHz, 1.4-ps Gaussian seed pulse. Second, we launch the seed pulse into a HNLF to broaden the spectrum by self-phase modulation (SPM). The launched power and the wavelength of the seed pulse are controlled not to incur wave-breaking, but are still able to generate a wide enough, flat-topped SC. The phase of the frequency lines in such SC is almost linear with frequency. Finally, an array of optical band-pass filters (OBPFs) followed by segments of single-mode fiber (SMF) are used to obtain multicolor Nyquist pulses simultaneously. Experimentally, a Gaussian-shaped optical seed pulse with a duty cycle of 3.5% and a time bandwidth product (TBP) of 0.457 is obtained. When pumping a HNLF with the nearly transform-limited Gaussian-shaped optical pulse, 90-tones flat-topped SC of 25-GHz frequency spacing within 3.6 dB power variation is achieved with a modest total pump power of 21.8 dBm. With the subsequent OBPFs, nearly chirp-free optical Nyquist pulses with a duty cycle of 5.5% on 4 wavelengths are achieved simultaneously.

2. Working principle and numerical analysis

An ideal optical Nyquist pulse has a rectangular-shaped envelope and linear phase in the spectral domain. These requirements are difficult to be satisfied when the bandwidth of the pulse is large. When an ultra-short transform-limited Gaussian pulse is launched into a HNLF, as we will show in the following simulations, a nearly flat-topped SC can be achieved because of SPM effect. The wavelength of the pulse should be set away from the zero dispersion wavelength of the HNLF and the optical power should be limited without initiating wave-breaking. Moreover, it is found that the phase of the central lines of SC could be well fitted to a linear curve after a following dispersive fiber. With these principles, we propose a simple method for ultra-short multicolor optical Nyquist pulse generation with the configuration shown in Fig. 1.

The pulse source consists of three stages: an ultra-short chirp-free Gaussian-shaped seed pulse generation stage, a SPM-based SC generation stage and a multicolor Nyquist pulse generation stage. In the first stage, the Gaussian seed pulse is obtained by pulse carving and frequency chirp compression. Although this can be done by actively mode-locked lasers [2], we design the current scheme with the purposes of reducing the cost of the pulse source

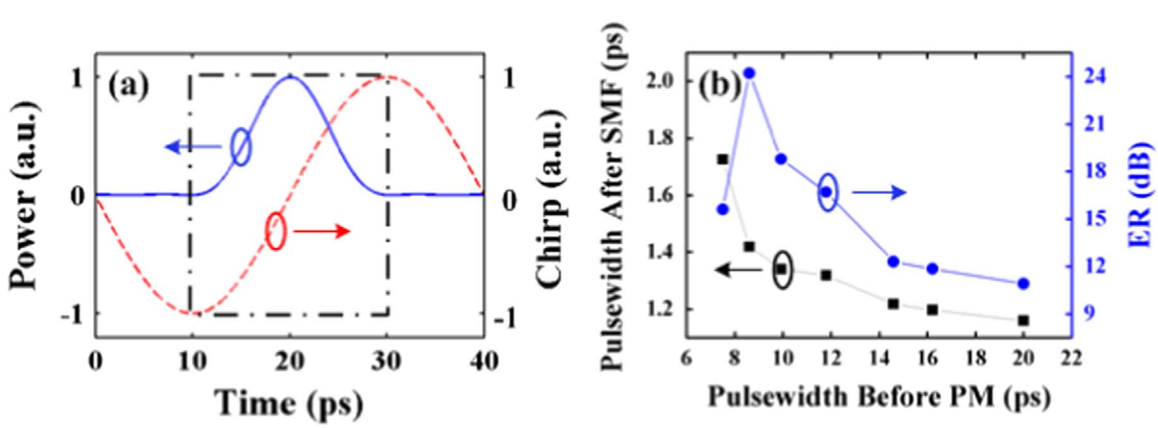

Fig. 3. Simulation results: (a) PM-induced sinusoidal chirp (dash line) and waveform of the pulse after DPMZM (solid line); (b) the pulsewidth (squares) and the ER (dots) of the compressed pulse at the end of the SMF as a function of the pulsewidth of the seed pulse before the PM.