Highly tunable method to generate sinc-shaped Nyquist pulses from a rectangular frequency comb

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Abstract: A method to produce highly-stable optical sinc-shaped pulses is proposed based on the generation of a rectangular-spectrum frequency comb. Nyquist pulses with <1% power distortion, 82-fs jitter and more than 40 dB SNR are achieved.

OCIS codes: (060.4510) Optical communications; (060.4080) Modulation; (320.5550) Pulses.

1. Introduction

The demand for higher capacity optical fiber networks is on the rise. Limitations of viable alternatives to expand the bandwidth of optical telecommunications beyond the constraints imposed by erbium-doped fiber amplifiers (EDFAs) has funneled recent research efforts towards increasing the spectral efficiency of transmitted signals. Besides multiplying the number of transmitted bits per symbol with multi-level phase and/or amplitude modulation schemes in coherent transmission systems, efforts are underway to contain the transmitted signal spectrum within a band-width that is as close as possible to the symbol rate, which is the lower bound dictated by the Nyquist theorem [1]. Such a trend is observed in recent demonstrations of Nyquist-WDM transmissions [2], where the baseband signal is digitally processed so as to achieve a rectangular spectrum. An all-optical counterpart, in which the optical symbol pulse transporting data has a sinc temporal shape and a rectangular spectrum, would pave the way for the growth of the data throughput by efficiently aggregating data in both time and frequency domains. In addition, for applications such as all-optical sampling or optical analog-to-digital conversion (ADC), the possibility to use optical Nyquist-limited pulses for data sampling could ease bandwidth constraints and improve performances [3].

All-optical techniques to generate Nyquist pulses that have been reported either use parametric amplification [4] or a spatial light modulator together with mode-locked lasers [5]. Besides the high complexity of the proposed methods, these techniques fail to generate ideal sinc pulses, leading to non-rectangular spectrum and hence to inefficient use of the spectral bandwidth.

In this paper, a method to produce perfect optical Nyquist pulses is proposed based on the generation of a phase-locked frequency comb with an ideal rectangular spectral shape. We demonstrate the effectiveness and flexibility of the method using two cascaded electro-optic intensity modulators (EOMs), achieving sinc-shaped Nyquist pulses with variable width down to 8.9 ps, low jitter and high signal-to-noise ratio (SNR >40 dB).

2. Theory and principle of the proposed method

The method proposed in this paper is based on the direct generation of a flat frequency comb containing equally-spaced and phase-locked spectral lines. This comb corresponds to a train of sinc pulses in the time domain. While the pulse period is given by the frequency spacing between adjacent lines, the pulse duration is defined by the bandwidth of the frequency comb. If every spectral component of a flat frequency comb (with N lines, frequency spacing Δf and similar phase ϕ around the carrier frequency f_0) is represented by $\exp(2i\pi(f_0 + n\Delta f)t + i\phi)$, for $n = -(N-1)/2, \ldots, (N-1)/2$, the field of such a comb can be expressed in the time domain as:

$$E(t) = \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} e^{2i\pi(f_0+n\Delta f)t+i\phi} = e^{2i\pi f_0 t+i\phi} \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} e^{2i\pi n\Delta f t} = \frac{\sin(\pi N\Delta f t)}{\sin(\pi\Delta f t)} e^{2i\pi f_0 t+i\phi} \tag{1}$$

The intensity of the generated pulses can be represented by $I(t) = |E(t)|^2 = \sin^2(\pi N\Delta f t)/\sin^2(\pi\Delta f t)$, while the period of pulse train is $T = 1/\Delta f$ and the zero-crossing pulse duration is $\tau = 2T/N = 2/N\Delta f$.

The method here proposed is based on the possibility to generate 2 or 3 spectral lines, with high suppression of higher-order sidebands, using electro-optic intensity modulators [6]. This way, a frequency comb can be produced by simply cascading EOMs with appropriate bias and RF voltages. Depending on the number of frequency lines that each EOM generates, it is possible to have an odd or even number of spectral lines in the generated comb. For instance, if two EOMs are used, one driven at a frequency f and the other at $3f$ without any carrier suppression, a comb with 9 spectral lines and frequency spacing f covering the optical bandwidth of $9f$ can be generated. In particular, the output field of an intensity EOM with normalized bias voltage $\epsilon = \frac{V_B}{V_\pi}$, and RF signal $\alpha = \frac{v_s}{V_\pi}$ is [6]:

$$E(t) = \sum_{k=-\infty}^{+\infty} (-1)^k (\cos(\pi\epsilon) J_{2k}(\pi\alpha)\cos(\omega_0 t + 2k\omega_s t) + \sin(\pi\epsilon) J_{2k-1}(\pi\alpha)\cos(\omega_0 t + (2k-1)\omega_s t)) \quad (2)$$

where V_π is the half-wave voltage of the EOM and J_k is the Bessel function of the first kind. In order to achieve a flat frequency comb, it is necessary that every EOM produces lines with the same amplitude. To achieve this condition, the bias voltage V_B and the modulating RF signal v_s applied to every EOM must satisfy the following equation:

$$V_B = \frac{V_\pi}{\pi} \tan^{-1}\left\{ -J_0\left(\pi \frac{v_s}{V_\pi}\right) \Big/ J_1\left(\pi \frac{v_s}{V_\pi}\right) \right\} \quad (3)$$

On the other hand, in order to produce a rectangular-shaped comb, the higher-order modulation components have to be strongly suppressed. This can be achieved by adjusting the RF signal. As shown in Fig. 1, a suppression of more than 20 dB (with respect to the carrier and first-order sidebands) can be achieved for the second (and higher) order modulations by decreasing the modulating signal below $0.25V_\pi$.

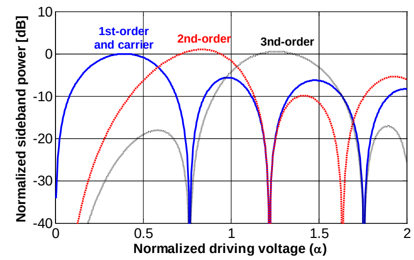

Fig. 1. Power of the lower-order sidebands vs the normalized RF voltage (equalized case)

3. Experimental setup

Fig. 2 shows the experimental setup, in which the light from an external cavity laser (ECL) at 1550 nm is launched into two cascaded Mach-Zehnder modulators (MZMs). Note that, the microwave generators have been synchronized using a common time base, while the relative phase among them has been carefully adjusted, leading in this way to almost-ideal and symmetric sinc-shaped Nyquist pulses. A semiconductor optical amplifier (SOA) and an EDFA have been used, together with two tunable optical filters (TOF), to measure the pulses on a 500-GHz optical sampling oscilloscope, which requires a minimum average power of 0 dBm for reliable jitter and SNR measurements. Note that the optical filters are used only to reduce amplified spontaneous emission (ASE) noise generated in the optical amplifiers and are not required for spectral shaping as typically employed in other methods generating Nyquist pulses. An optical spectrum analyzer (OSA) with a resolution bandwidth of 0.01 nm is used to measure the spectrum of the generated phase-locked, rectangular-shaped frequency combs.

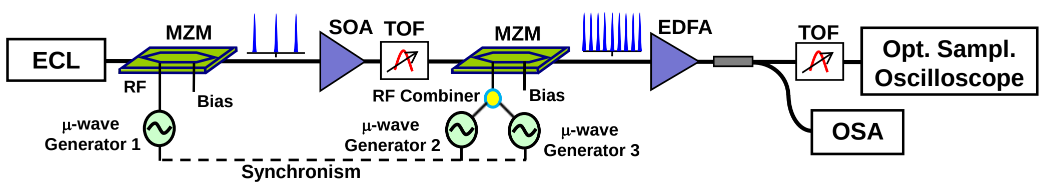

Fig. 2. Experimental setup for ideal and higly-stable Nyquist pulse generation based on a rectangular frequency comb.

4. Experimental results and discussion

In order to verify the flexibility of the proposed method, frequency combs with different bandwidth and number of spectral components have been generated. First, modulating the first and second EOM with RF signals at 30 GHz and 10 GHz, respectively, a comb with $N = 9$ spectral components separated by $\Delta f = 10$ GHz, and expanding over a bandwidth of 90 GHz, has been generated, as shown in Fig. 3(a). The spectral separation Δf and the bandwidth of the comb can be easily modified by changing the frequency of the modulating signals. Furthermore, in order to increase the number of lines of the comb, the second EOM has been driven by two RF signals combined in the

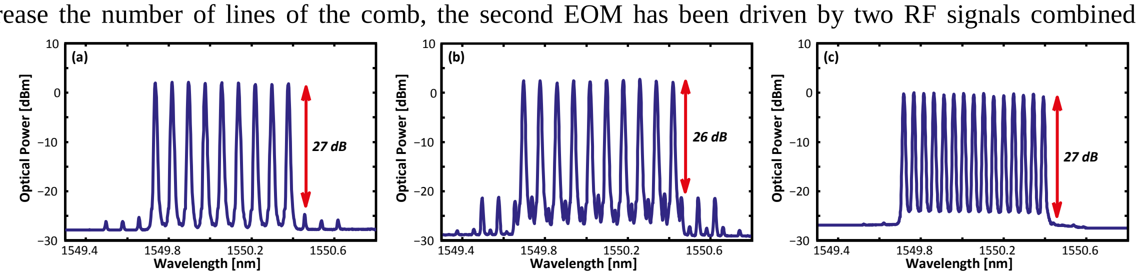

Fig. 3. Higly tunable generation of almost-ideal rectangular-shaped frequency combs using two cascaded intensity modulators. (a) Frequency comb with $N = 9$ spectral lines, spectral separation $\Delta f = 10$ GHz and bandwidth of 90 GHz. (b) Frequency comb with $N = 10$, $\Delta f = 10$ GHz and bandwidth of 100 GHz. (c) Frequency comb with $N = 15$, $\Delta f = 6$ GHz and bandwidth of 90 GHz.

electrical domain, as shown in Fig. 2; this way, 5 spectral lines, corresponding to four first-order sidebands and carrier, can be obtained from each line generated by the first EOM. Thus, using the first modulator in carrier-suppressed mode, a frequency comb with $N = 10$ spectral lines has been produced. In particular, driving the first EOM at 25 GHz, and combining two RF signals at 10 GHz and 20 GHz, respectively, to drive the second EOM, a comb with $\Delta f = 10$ GHz and 100 GHz bandwidth has been obtained, as reported in Fig. 3(b). By simply equalizing the power of the carrier with the first-order sidebands (generated at 30 GHz) in the first EOM according to Eq. (3), and by changing the frequency of both RF signals driving the second EOM to 6 GHz and 12 GHz, a comb with $N = 15$, $\Delta f = 6$ GHz, and bandwidth of 90 GHz has been generated, as shown in Fig. 3(c). It is possible to observe that all frequency combs show a flat spectrum (with a maximum power variation among components of about 0.2 dB) and a high suppression of out-of-band components (more than 26 dB suppression in all cases).

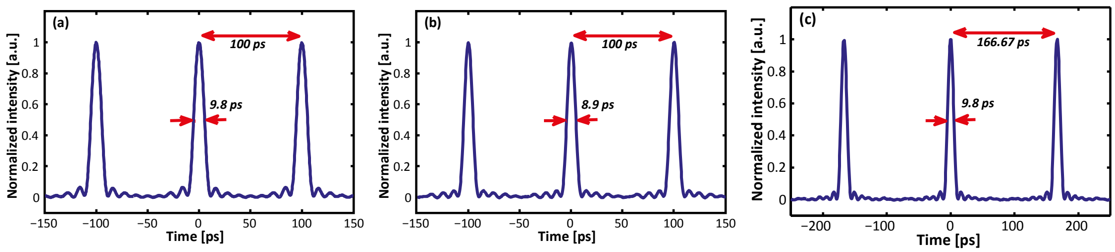

Fig. 4. Higly tunable generation of almost-ideal sinc-shaped Nyquist pulses resulting from the frequency combs shown in Fig. 3. (a) Sinc pulses with 9.8 ps FWHM duration and repetition period of 100 ps. (b) Sinc pulses with 8.9 ps FWHM duration and repetition period of 100 ps. (c) Sinc pulses with 9.8 ps FWHM duration and repetition period of 166.67 ps.

The time-domain measurements corresponding to the spectra reported in Fig. 3 are shown in Fig. 4. In particular, Fig. 4(a) shows a train of sinc pulses obtained from the frequency comb shown in Fig. 3(a). The full-width at half-maximum (FWHM) of 9.8 ps and the period of $T = 100$ ps are given by the full bandwidth of 90 GHz and the component spectral separation $\Delta f = 10$ GHz, respectively. Fig. 4(b) shows the sinc-shaped Nyquist pulses resulting from the spectrum reported in Fig 3(b). In this case, the use of an additional frequency component, leading to a bandwidth of 100 GHz, has reduced the sinc pulse duration down to 8.9 ps (FWHM), maintaining the period of 100 ps, in accordance to the unchanged frequency spacing $\Delta f = 10$ GHz. Finally, Fig. 4(c) shows how the repetition period changed up to 166.67 ps due to the reduced frequency spacing $\Delta f = 6$ GHz reported in Fig. 3(c); the FWHM pulse duration has been maintained in 9.8 ps as in the first case.

The quality and stability of the generated sinc-shaped Nyquist pulses have been evaluated in terms of jitter and SNR. Fig. 5 shows a color-grade plot for pulses with 9.8 ps (FWHM) and repetition period of 100 ps, indicating an rms jitter of 82 fs (equivalent to 0.82% of the FWHM) and more than 40 dB SNR. A power difference below 1% between theoretical and experimental pulses has been verified by comparing measured pulses with the pulse intensity obtained from the field described in Eq. (1).

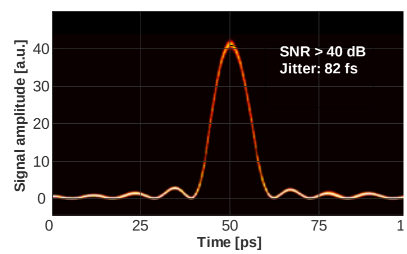

Fig. 5. Color-grade figure of the generated 9.8 ps (FWHM) sinc-shaped Nyquist pulses and repetition period of 100 ps.

5. Conclusion

In conclusion, a method to generate close-to-perfect, low-noise and highly-stable sinc pulses has been proposed using cascaded intensity modulators with a proper bias and modulating voltage adjustment. Experimental results demonstrate the high flexibility of the method to modify the pulse parameters thanks to the possibility to easily change the bandwidth of the frequency comb, the number of spectral components, and the frequency separation among them. Generated sinc-shaped Nyquist pulses can be straightforwardly combined with higher-order modulation formats to increase data transmission rates in telecommunications systems.

6. References

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