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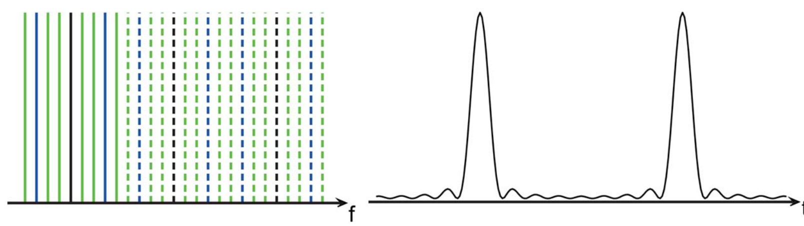

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Flexible Nyquist Pulse Sequence Generation With Variable Bandwidth and Repetition Rate

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Abstract: The rectangular spectrum of sinc-shaped Nyquist pulses enables the encoding of data in a minimum spectral width. Sinc pulses can improve optical sampling devices, could enable the implementation of ideal rectangular microwave photonics filters, and can be used for all-optical signal processing, spectroscopy, and light storage. Recently, the generation of sinc-pulse sequences with extraordinary quality was shown by the utilization of cascaded modulators. However, the line width and repetition rate of the pulses is limited by the modulator bandwidth. Here, we present the nonrestricted generation of flexible Nyquist pulse sequences. Therefore, multiple single lines of a comb generator are extracted with optical filters and subsequently processed by cascaded modulators. In a first proof-of-concept experiment, we achieved almost ideally sinc-shaped Nyquist pulses with a bandwidth of 286 GHz, a pulse width of 3.5 ps, and a duty cycle of 2.2%. However, sinc-shaped Nyquist pulse sequences in the femtosecond range with terahertz bandwidths would be possible with the method.

Index Terms: Modulation, optical communication, pulses, sources.

1. Introduction

Besides high bit rate optical telecommunications [1], sinc pulses could bring benefits to many other fields. The ideal interpolation function for the perfect restoration of band-limited signals from discrete and noisy data corresponds to sinc-shaped pulses, for instance [2]. Thus, optical sampling devices could be substantially improved [3]. Furthermore, sinc pulses could enable the implementation of ideal rectangular microwave photonics filters [4]–[6], they can be used for all-optical signal processing [7], spectroscopy [8] and light storage [9], [10].

These unique advantages lead to a strong research activity in the field of Nyquist pulse transmission and sinc pulse generation. Nyquist pulses can be generated electronically, which can be done by an arbitrary waveform generator for instance [11], [12]. However, conventional generators are very limited regarding sampling rate and processor capacity. Another possibility is the optical filtering of a comb generated by a mode locked laser (MLL) [13]–[15], or the generation by optical parametric amplification [16]. Optical Nyquist pulse generation can generate much shorter pulses than electronics. However, most of the reported methods use complex and costly equipment and due to the optical filter characteristics the generated pulses are not sinc-shaped, making them not usable for many of the above mentioned applications.

Unfortunately, a single sinc pulse is unlimited in time domain and therefore non-causal. However, recently it has been shown that under certain conditions, the periodic summation of unlimited sinc pulses leads to a periodic sinc pulse sequence [17]–[19]

$$\sum_{n=-\infty}^{\infty} \mathrm{sinc}\left(\pi N\Delta f\left(t-\frac{n}{\Delta f}\right)\right) = \frac{\sin(\pi N\Delta f t)}{N\sin(\pi\Delta f t)} \quad \circ\!\!-\!\!\!- \sum_{n=\frac{N-1}{2}}^{\frac{N-1}{2}} \delta(f-n\Delta f) \tag{1}$$

with $n = 1, 2, 3, \ldots$ as an integer number. The Fourier transform ($\circ\!\!-\!\!\!-$) represents a frequency comb with N equally spaced frequency lines ($\delta(f)$) separated by Δf. Thus, an ideal sinc pulse sequence can be simply obtained by a flat, phase-locked frequency comb with narrow lines. The symbol duration T_S of the sinc pulse is defined by the inverse bandwidth of the comb $T_S = 1/(N\Delta f)$ and the repetition rate of the pulses is determined by the frequency spacing between the comb lines $T_R = NT_S = 1/\Delta f$. Such a phase locked frequency comb can be generated via two cascaded Mach-Zehnder modulators (MZM) [17]–[19]. The generated sequence of sinc pulses is almost perfectly shaped. However, this scheme can only provide frequency combs with no more than 3 frequency tones using a single MZM and no more than 9 frequency tones using two MZMs in tandem. Therefore, the overall bandwidth of such a comb is limited due to the frequency range of the modulators. This results in a limited pulse duration and repetition rate of the generated pulses. Additionally, the small number of frequency lines result in a Nyquist pulse with a relatively large duty cycle (9.8%), which is unsuitable in applications such as high-speed orthogonal time division multiplexing [14] and arbitrary waveform generation [20]. Recently, improved flat rectangular frequency comb generation has been proposed by utilizing two cascaded dual-parallel MZM [21]. The number of lines could be increased to 25 and Nyquist pulses with a repetition rate of 200 ps, a full width at half maximum (FWHM) pulse width of 7.32 ps and a duty cycle of 3.66% were generated. However, the method is still limited by the bandwidth of the used modulators.

Here we show and discuss a method to overcome the limitations given by the two modulators. In principle, the method is based on the allocation of multiple phase locked carriers. These are obtained by extraction from a frequency comb, provided by a frequency comb generator and a subsequent modulation with cascaded modulators. Several extraction methods as well as frequency comb sources are compared in terms of their suitability. Within a first proof of concept experiment different pulse widths from 3.5 ps to 8.75 ps, repetition rates from 52.5 ps to 157 ps and accordingly duty cycles of 2.2% up to 16.6% could be achieved with the proposed method. In principle, this method offers the possibility to generate almost ideal sinc-shaped Nyquist pulse sequences, in the time domain, with flexible pulse widths and repetition rate.

2. Theory

The schematic setup for the Nyquist pulse sequence generation can be seen in Fig. 1(a). The light of a single, narrow line width laser source is processed via two cascaded MZM [17]–[19]. This results in a frequency comb with flexible bandwidth and spacing, shown with solid lines in Fig. 1(b). However the maximum achievable bandwidth is limited by the modulators itself. The maximum bandwidth can be achieved if the carrier of the first modulator is suppressed. If at least one of the modulators can be driven with a maximum frequency of $f_1 = 40$ GHz, the second modulator has to be driven with $f_2 = 2/3f_1$ and the maximum bandwidth is 160 GHz, corresponding to 6 ps pulses. In order to enhance the bandwidth of the frequency comb and the possibilities for the Nyquist pulse generation, multiple carrier frequencies are needed as a source for the two modulators. If they have a fixed frequency spacing $\Delta f_c = 3f_1 = 9f_2$, multiple adjacent combs are generated, shown with the dashed lines in Fig. 1(b). However, in order to generate sinc-shaped Nyquist pulse sequences, the different sources need to be phase locked to each other and to the RF generators driving the modulators. Additionally, the frequency difference between them must be stable or can be measured in order to adapt f_1 and f_2.

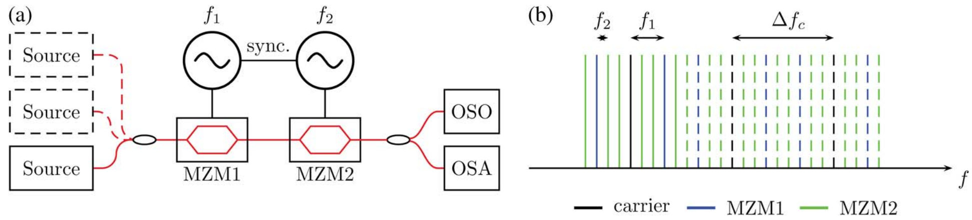

Fig. 1. (a) Principle setup for ideally sinc-shaped Nyquist pulse sequences by cascaded modulation. (b) Generated frequency combs with one carrier (solid) and multiple carriers (dashed). The time domain representation of the comb is the sinc-shaped Nyquist pulse sequence.

Sources that generate a large number of equidistant phase locked frequencies are mode-locked lasers (MLL). They are capable of producing an octave-spanning optical spectrum, which retains the mode structure and phase locking properties of the original seed pulse. In principle, this is a large frequency comb with an uneven power distribution. Solid-state bulk lasers, based on ion-doped crystals or glasses, are today the dominant type of mode-locked lasers. For potentially cheap setups fiber lasers can also be mode-locked. Conventional fiber based mode locked fs-lasers have repetition rates in the range of 100 MHz. Other possibilities to generate large, octave spanning frequency combs are cascaded four wave mixing [22] and monolithic microring resonators [23] with repetition rates of 220 GHz and 100 GHz, respectively. A compact comb generator is a Fabry-Perot Electro-Optic (FP-EO) modulator [24]. This device can generate ultra precise optical combs/pulses with low phase noise and low timing jitter. Due to the specific cavity, the phases of the different frequencies are locked. They are capable of generating combs with a span of more than 10 THz and have a flatness of 7 dB. However, the modulation frequency for these devices, as well as the wavelength of the laser source needs to fit the cavity length or resonance. Typical values for the frequency spacing for such devices are 25 GHz.

If an optical filter with a rectangular bandwidth is used to filter out a part of the comb spectrum from these devices, the result would be a sinc pulse sequence. However, an ideal rectangular optical filter does not exist. A very promising source for the generation of sinc-pulses with a broad bandwidth are fs-fiber lasers, since they are easy to handle, offer bandwidths in the THz-range, are cost-effective and have a small footprint. The repetition rate depends on the resonator length and is typically in the range of 100 MHz. Conventional optical filters like a wave shaper (WS), for instance, have a minimum 3-dB bandwidth of 10 GHz, the 6-dB bandwidth is 15 GHz and the 10-dB bandwidth is 25 GHz. Thus, due to the non-rectangular spectrum, the generated pulses would not be sinc-shaped. Additionally, the repetition rate of the generated sinc pulses would be pre-defined by the repetition rate of the initial comb source, which shows no or a very limited tuning range. With our method very low and tunable repetition rates which would not be available with other sources are possible. Additionally, the different spectral powers of the lines in the initial comb would result in significant distortions of the generated sinc pulses. Thus, here we extract single lines out of the initial frequency comb and use them as equidistant, locked sources for the two cascaded modulators.

For the separation of multiple lines, narrow band optical filters need to be utilized. Depending on the frequency comb source, they need to have different requirements. Conventional tunable grating based filters, e.g., fiber Bragg gratings, achieve bandwidths down to 10 GHz with a tuning range over 10 nm or 1.27 THz, respectively. For the extraction of multiple lines the same amount of Bragg gratings is necessary. A special type of filter is a WS. It can be operated over a large frequency range and can be programmed individually with a bandwidth down to 10 GHz. The advantage of the wave shaper is that multiple filters with a different attenuation can be programmed at once. Therefore multiple lines can be extracted from the initial comb with only one device and the power of the lines can be adjusted simultaneously. However, the bandwidths of these type of filters are too large for the extraction of multiple modes out of a fs-fiber laser or other typical MLL with a repetition rate of around 100 MHz. The filter bandwidth needs to be equal to or less than the frequency spacing of the comb. Thus, conventional optical filters

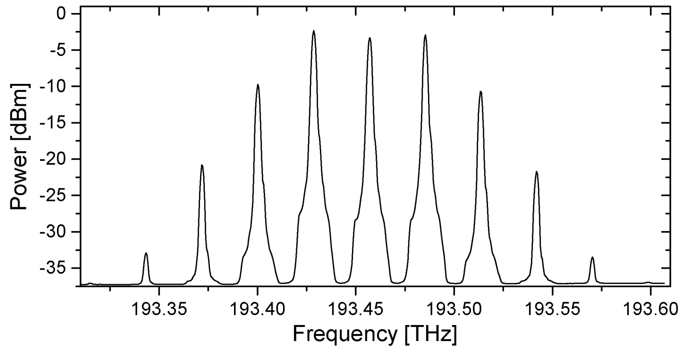

Fig. 2. Initial frequency comb generated by the FP-EO modulator. The frequency spacing is 28.56 GHz.

cannot be used for fiber fs-lasers, for instance, but they would be perfectly suited for the frequency extraction in combination with a FP-EO comb generator.

For the extraction of frequencies out of a frequency comb produced by a fiber fs-laser the nonlinear effect of stimulated Brillouin scattering (SBS) [25], [26] can be utilized. With moderate pump powers in the mW region and standard single mode fibers (SSMF), SBS gain bandwidths of 20 MHz are possible. By using techniques for the bandwidth reduction of SBS, this bandwidth can be even decreased down to 3 MHz [27]–[29]. With this narrow bandwidth, it is possible to filter out and amplify multiple lines of a frequency comb as long as the frequency spacing of the comb is above the SBS bandwidth. In order to suppress the unwanted modes of the spectrum, the polarization pulling assisted SBS gain process can be used to form a sharper filter [30]–[32]. Differences within the amplitude of the extracted comb lines can be compensated with different pump powers and therefore different gains. However, contrary to methods where just a flat, rectangular frequency comb is produced, for the Nyquist pulse generation all comb lines have to have the same or a linear dependent phase. Thus, the repetition rate of the laser must be locked and adjusted to all following elements.

In general, the maximum achievable bandwidth and therefore the minimum pulse width is restricted by the frequency comb source itself, which for the used fs-fiber laser is around 10 THz. However, via the utilization of nonlinear mixing processes the overall bandwidth of the source can reach up to 30 THz. However, the nonlinearity of the setting of the operating point of the used modulators limits the maximum achievable bandwidth. Finally, the number and tunability of the pump lasers might be a limiting factor, since it increases directly with the number of initially extracted lines. Also, for extremely broadened frequency combs, there might be a problem in finding a tunable pump laser with the correct wavelength. However, within the C- and L-Band, this is not an issue.

3. Experiments

In order to provide multiple phase locked carrier frequencies for the Nyquist pulse sequence generation a FP-EO comb generator is used as the initial source. The initial frequency comb can be seen in Fig. 2. Afterwards, multiple modes are extracted with a WS and subsequently modulated with two cascaded MZM. In order to lock the phases of the initial extracted lines with the new comb lines generated by the MZM, the RF generator of the FP-EO comb generator is synchronized with the other generators, and all phases can be adjusted. If a MLL is used as the initial source, the RF generators must be locked to the repetition rate of the laser.

The experimental setup can be seen in Fig. 3. The light source is a distributed feedback laser diode (DFB) with a line width of 1 MHz and an output power of $P_{out} = 10$ dBm, equipped with an isolator in order to protect the device. Much smaller line widths in the kHz or even Hz range would be possible with external cavity or SBS lasers, for instance. The initial frequency comb is generated with a FP-EO modulator which is driven by a RF-generator with $f_{rep} = 28.56$ GHz and

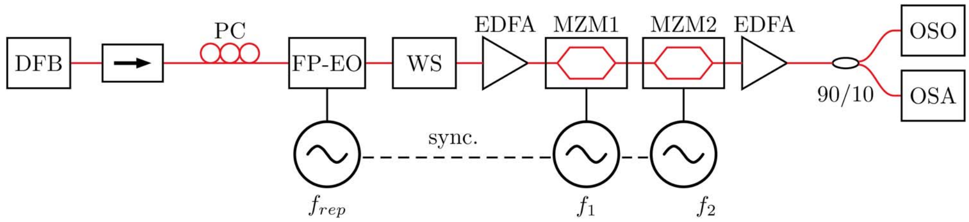

Fig. 3. Experimental setup for flexible Nyquist pulse generation. DFB: distributed feedback laser diode, PC: polarization controller, FP-EO: comb generator, WS: wave shaper, EDFA: erbium doped fiber amplifier, MZM: Mach-Zehnder modulator, OSO: optical sampling oscilloscope, OSA: optical spectrum analyzer.

$P = 25$ dBm. The input polarization needs to be adjusted to the slow axis with help of a polarization controller (PC). Afterwards, a specific number of comb lines is separated with a wave shaper (WS). The programmed filters in the WS are set to the minimum bandwidth of 10 GHz. Fluctuations within the intensities of the extracted lines can be controlled by the attenuation setting of each filter. This is possible up to a maximum accuracy of 0.1 dB. Accordingly, the carrier frequencies for the following comb modulation can be set very precisely. Please note that the wave shaper is not used to generate the comb, it just extracts single lines out of the initial comb in order to deliver the phase-locked input sources with equally and defined frequency spacing as discussed in Fig. 1. Due to the high insertion loss of the WS and the distribution of the optical power among all of the frequency comb lines, the signal is amplified by an erbium doped fiber amplifier (EDFA) to an output power of 15 dBm. According to the discussion above, the frequency comb and therefore the Nyquist pulse sequence is generated with two cascaded MZM [17]. The modulators are equipped with PC (not shown) to align the input polarization for optimum modulation and driven by RF-generators with f_1 and f_2. According to the desired number of comb lines and therefore the operation point setting of the MZMs, the division ratio between the frequencies needs to be adapted. Additionally, all of the electrical generators must be synchronized. Afterwards, the generated comb is amplified with a low noise EDFA to an output power of 8 dBm in order to provide sufficient input power to the optical sampling oscilloscope (OSO). The signal is splitted via a 90/10 coupler and the spectrum is recorded with an optical spectrum analyzer (OSA) in parallel.

4. Results

During the experiments several Nyquist pulse sequences were generated. Therefore, a different number of equidistant frequencies was extracted from the initial comb and modulated by two cascaded MZM, which are adjusted via the bias voltage and RF-power to generate an almost even power distribution. The experimental results can be seen in the following figures. Within the first measurement 2 lines from the comb generator were extracted. The repetition rate of the comb generator is $f_{rep} = 28.56$ GHz (see Fig. 2). The extracted lines have a spacing of $\Delta f_c = 57.12$ GHz. This results in modulation frequencies of $f_1 = 19.04$ GHz and $f_2 = 6.346$ GHz for the two modulators. The first modulator was driven with a RF power of 5 dBm and a bias voltage of 1.11 V and the second one with 13 dBm and a bias voltage of 2.08 V. The generated frequency comb with a flatness of 0.6 dB and a SNR of 36 dB can be seen in Fig. 4(a). The according time domain signal, basically the Nyquist pulse sequence, can be seen in Fig. 4(b). Due to 2 initial frequencies for the modulators, the comb consists of 18 lines and the pulse sequence has 17 zero-crossings. The bandwidth of the comb is 114.228 GHz. The pulse width is $1/N\Delta f = 8.75$ ps and the repetition rate of the pulses is $T_R = 1/\Delta f = 157.6$ ps. Accordingly, the duty cycle is 5.5%. The red dashed line shows the calculation of a perfect shaped Nyquist pulse sequence. As can be seen, the generated pulse sequence fits very well with the theoretical prediction.

Fig. 5(a) and (b) shows the results for the extraction of three lines out of the spectrum of the comb generator. The spacing between the lines is again 57.12 GHz. Therefore, the

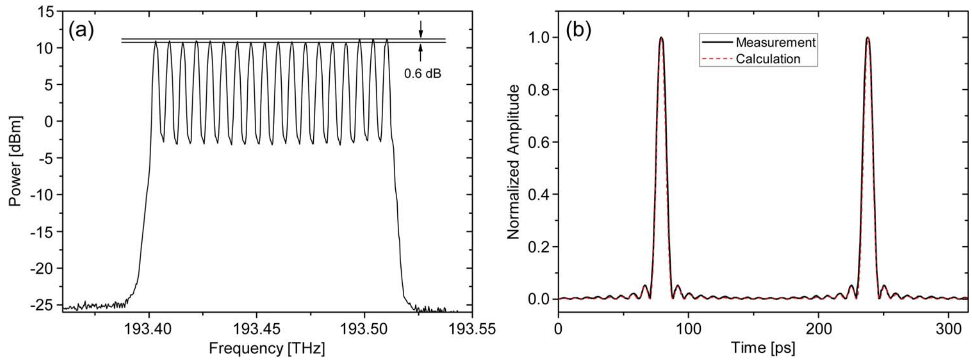

Fig. 4. (a) Generated frequency comb with 18 Lines and a spacing of 6.346 GHz. The line width in the figure is a result of the limited resolution of the spectrum analyzer. (b) Corresponding Nyquist pulse sequence with a repetition rate of 157.6 ps, a pulse width of 8.75 ps, and a duty cycle of 5.5%.

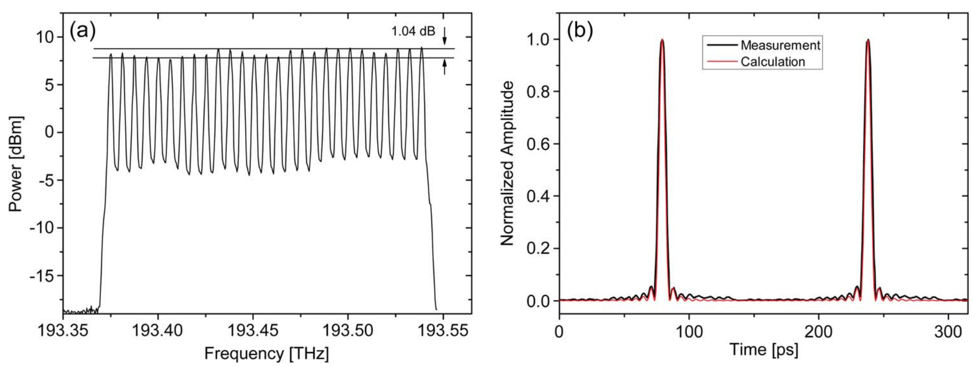

Fig. 5. (a) Generated frequency comb with 27 lines and a spacing of 6.346 GHz. (b) Corresponding Nyquist pulse sequence with a repetition rate of 157.6 ps, a pulse width of 5.8 ps, and a duty cycle of 3.6%.

modulation frequencies for the modulators remain the same. This results in a frequency comb with 27 lines with a bandwidth of 171.342 GHz and a spacing of 6.346 GHz. The flatness of the comb is 1.04 dB and the SNR is 27.4 dB. The pulse width is 5.8 ps and the repetition rate is again 157.6 ps, which leads to a duty cycle of 3.6%. Again, the red line shows the theoretical calculation of the Nyquist pulse sequence. It must be noted that there are some small distortions in the generated pulse-sequence. The zero-crossing are at the correct position, but they do not reach the zero-level at every designated point. We address this to the not equal power distribution of the initial lines.

Fig. 6(a) shows the generated frequency comb from 5 extracted lines, which consists of an overall number of 45 lines with a spacing of 6.346 GHz. Therefore, the bandwidth is 285.57 GHz and the repetition rate is again 157.6 ps. Due to the large bandwidth of the generated comb, the pulse width is further decreased down to 3.5 ps, as can be seen in Fig. 6(b). In this case the duty cycle is 2.2%. The measurement fits well with the calculations. The small deviations are again a result of the uneven power distribution of the initial lines. For the pulse sequence shown in Fig. 6(c), two lines are extracted, but just one MZM was used. This results in a comb with six lines with a spacing of 19.04 GHz. Therefore, the pulse-sequence has 5 zero-crossings and the bandwidth is 114.24 GHz. The FWHM width of the pulse is 8.75 ps with a repetition rate of 52.5 ps, which leads to a duty cycle of 16.6%. The measurement fits almost perfectly with the theoretical calculations. Compared with Fig. 4(b), the pulses have the same width but a different repetition rate and accordingly a different duty cycle.

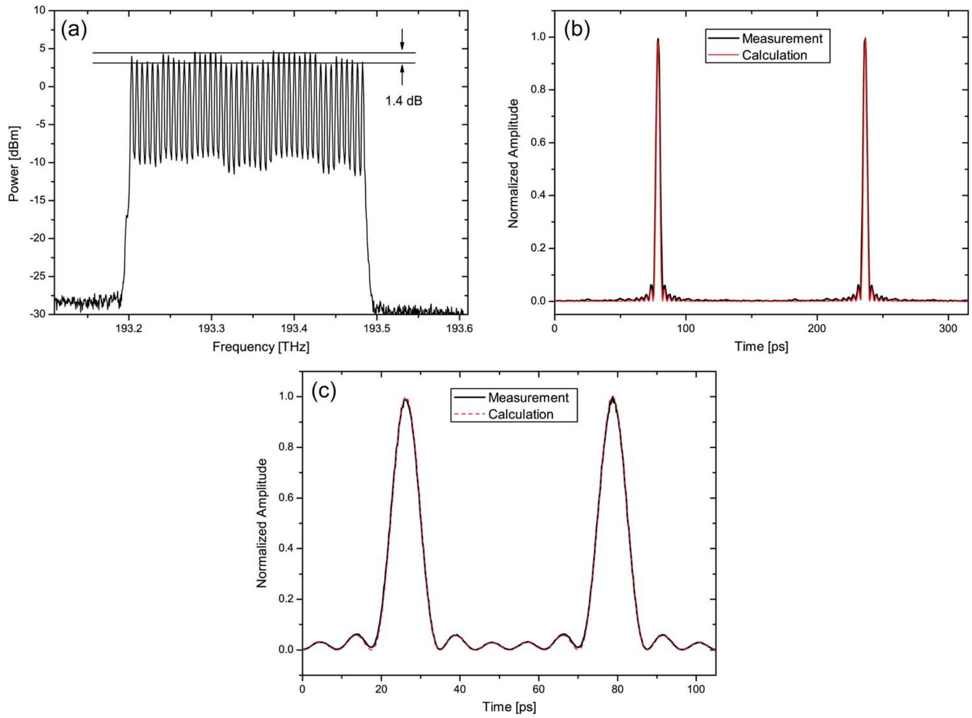

Fig. 6. (a) Generated frequency comb with 45 lines and a spacing of 6.346 GHz. (b) Corresponding Nyquist pulse sequence with a repetition rate of 157.6 ps, a pulse width of 3.5 ps, and a duty cycle of 2.2%. (c) Generated Nyquist pulse sequence with a repetition rate of 52.5 ps, a pulse width of 8.75 ps, and a duty cycle of 16.6%.

5. Conclusion

In [17], the generation of extraordinary high-quality sinc pulse sequences with different repetition rate and pulse width based on two cascaded intensity modulators was presented. However, the maximum achievable bandwidth of the pulses, respectively the comb, was restricted by the bandwidth of the modulators to 160 GHz. With the method presented here bandwidths in the THz and pulses in the fs-range can be produced. The theoretical maximum is the spectral width of the MLL or the optical bandwidth and nonlinearity of the used modulators. For the proof-of-concept a Fabry-Perot comb generator was used, which restricts the tunability of the sinc pulse sequence repetition rate. However, this can be overcame by the exploitation of a fiber fs-Laser together with polarization pulling assisted stimulated Brillouin scattering as the initial source. Additionally, with a multiple carrier input, only one MZM is needed to generate sinc-shaped Nyquist pulse sequences, which is cost-effective and would reduce the energy consumption. Even higher repetition rates can be achieved if the modulators are driven with more than one sinusoidal frequency. Within a first proof of concept experiment extraordinary high-quality sinc pulse sequences with pulse widths from 3.5 ps to 8.75 ps, repetition rates from 52.5 ps to 157 ps and duty cycles from 2.2% up to 16.6% could be generated. However, much higher tuning ranges are possible. The generated sinc pulse sequences have such a high quality that they can bring benefits to optical communications regarding the maximum baud rate, all-optical buffering, microwave photonic filters, arbitrary waveform generation, and many other fields.

Acknowledgment

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References

[1] D. Hillerkuss *et al.*, "Single-laser 32.5 Tbit/s Nyquist WDM transmission," *J. Opt. Commun. Netw.*, vol. 4, no. 10, pp. 715–723, Oct. 2012.
[2] M. Pawlak and E. Rafajlowicz, "On restoring band-limited signals," *IEEE Trans. Inf. Theory*, vol. 40, no. 5, pp. 1490–1503, Sep. 1994.
[3] G. C. Valley, "Photonic analog-to-digital converters," *Opt. Exp.*, vol. 15, no. 5, pp. 1955–1982, Mar. 2007.
[4] V. Supradeepa *et al.*, "Comb-based radiofrequency photonic filters with rapid tunability and high selectivity," *Nat. Photon.*, vol. 6, no. 3, pp. 186–194, Feb. 2012.
[5] M. Song *et al.*, "Reconfigurable and tunable flat-top microwave photonic filters utilizing optical frequency combs," *IEEE Photon. Technol. Lett.*, vol. 23, no. 21, pp. 1618–1620, Nov. 2011.
[6] E. Hamidi, D. Leaird, and A. Weiner, "Tunable programmable microwave photonic filters based on an optical frequency comb," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3269–3278, Nov. 2010.
[7] M. Santagiustina, S. Chin, N. Primerov, L. Ursini, and L. Thèvenaz, "All-optical signal processing using dynamic Brillouin gratings," *Sci. Rep.*, vol. 3, Apr. 2013.
[8] D. Pestov *et al.*, "Optimizing the laser-pulse configuration for Coherent Raman spectroscopy," *Science*, vol. 316, no. 5822, pp. 265–268, Apr. 2007.
[9] S. Preußler *et al.*, "Quasi-light-storage based on time–frequency coherence," *Opt. Exp.*, vol. 17, no. 18, pp. 15 790–15 798, Aug. 2009.
[10] T. Schneider, K. Jamshidi, and S. Preussler, "Quasi-light storage: A method for the tunable storage of optical packets with a potential delay-bandwidth product of several thousand bits," *J. Lightw. Technol.*, vol. 28, no. 17, pp. 2586–2592, Sep. 2010.
[11] R. Schmogrow *et al.*, "512QAM Nyquist sinc-pulse transmission at 54 Gbit/s in an optical bandwidth of 3 GHz," *Opt. Exp.*, vol. 20, no. 6, pp. 6439–6447, Mar. 2012.
[12] R. Schmogrow *et al.*, "Real-time Nyquist pulse generation beyond 100 Gbit/s and its relation to OFDM," *Opt. Exp.*, vol. 20, no. 1, pp. 317–337, Jan. 2012.
[13] G. Bosco, A. Carena, V. Curri, P. Poggiolini, and F. Forghieri, "Performance limits of Nyquist-WDM and CO-OFDM in high-speed PM-QPSK systems," *IEEE Photon. Technol. Lett.*, vol. 22, no. 15, pp. 1129–1131, Aug. 2010.
[14] M. Nakazawa, T. Hirooka, P. Ruan, and P. Guan, "Ultrahigh-speed "orthogonal" TDM transmission with an optical Nyquist pulse train," *Opt. Exp.*, vol. 20, no. 2, pp. 1129–1140, Jan. 2012.
[15] T. Hirooka, P. Ruan, P. Guan, and M. Nakazawa, "Highly dispersion-tolerant 160 Gbaud optical Nyquist pulse TDM transmission over 525 km," *Opt. Exp.*, vol. 20, no. 14, pp. 15 001–15 007, Jul. 2012.
[16] A. Vedadi, M. A. Shoaie, and C.-S. Brès, "Near-Nyquist optical pulse generation with fiber optical parametric amplification," *Opt. Exp.*, vol. 20, no. 26, pp. B558–B565, Dec. 2012.
[17] M. A. Soto *et al.*, "Optical sinc-shaped Nyquist pulses of exceptional quality," *Nat. Commun.*, vol. 4, Dec. 2013.
[18] M. A. Soto *et al.*, "Generation of Nyquist sinc pulses using intensity modulators," presented at the CLEO, San Jose, CA, USA, 2013, Paper CM4G.3.
[19] M. A. Soto *et al.*, "Optical sinc-shaped Nyquist pulses with very low roll-off generated from a rectangular frequency comb," presented at the Asia Commun. Photon. Conf., Beijing, China, 2013, Paper AF2E.6.
[20] Z. Jiang, C.-B. Huang, D. E. Leaird, and A. M. Weiner, "Optical arbitrary waveform processing of more than 100 spectral comb lines," *Nat. Photon.*, vol. 1, no. 8, pp. 463–467, Aug. 2007.
[21] Q. Wang, L. Huo, Y. Xing, C. Lou, and B. Zhou, "Cost-effective optical Nyquist pulse generator with ultra-flat optical spectrum using dual-parallel Mach–Zehnder modulators," presented at the Optical Fiber Commun. Conf., San Francisco, CA, USA, 2014, Paper W1G.5.
[22] Y. Okawachi *et al.*, "Octave-spanning frequency comb generation in a silicon nitride chip," *Opt. Lett.*, vol. 36, no. 17, pp. 3398–3400, Sep. 2011.
[23] P. Del'Haye *et al.*, "Optical frequency comb generation from a monolithic microresonator," *Nature*, vol. 450, no. 7173, pp. 1214–1217, Dec. 2007.
[24] T. Kobayashi, T. Sueta, Y. Cho, and Y. Matsuo, "High repetition rate optical pulse generator using a Fabry Perot electro-optic modulator," *Appl. Phys. Lett.*, vol. 21, no. 8, pp. 341–343, Aug. 1972.
[25] D. H. T. Schneider and M. Junker, "Generation of millimetre-wave signals by stimulated Brillouin scattering for radio over fibre systems," *Electron. Lett.*, vol. 40, no. 23, pp. 1500–1502, Nov. 2004.
[26] T. Schneider, D. Hannover, and M. Junker, "Investigation of Brillouin scattering in optical fibers for the generation of millimeter waves," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 295–304, Jan. 2006.
[27] S. Preußler, A. Wiatrek, K. Jamshidi, and T. Schneider, "Brillouin scattering gain bandwidth reduction down to 3.4 MHz," *Opt. Exp.*, vol. 19, no. 9, pp. 8565–8570, Apr. 2011.
[28] S. Preußler and T. Schneider, "Bandwidth reduction in a multistage Brillouin system," *Opt. Lett.*, vol. 37, no. 19, pp. 4122–4124, Oct. 2012.
[29] A. Wiatrek, S. Preußler, K. Jamshidi, and T. Schneider, "Frequency domain aperture for the gain bandwidth reduction of stimulated Brillouin scattering," *Opt. Lett.*, vol. 37, no. 5, pp. 930–932, Mar. 2012.
[30] A. Zadok, E. Zilka, A. Eyal, L. Thévenaz, and M. Tur, "Vector analysis of stimulated Brillouin scattering amplification in standard single-mode fibers," *Opt. Exp.*, vol. 16, no. 26, pp. 21 692–21 707, Dec. 2008.
[31] S. Preussler, A. Zadok, A. Wiatrek, M. Tur, and T. Schneider, "Enhancement of spectral resolution and optical rejection ratio of Brillouin optical spectral analysis using polarization pulling," *Opt. Exp.*, vol. 20, no. 13, pp. 14 734–14 745, Jun. 2012.
[32] S. Preussler, N. Wenzel, and T. Schneider, "Flat, rectangular frequency comb generation with tunable bandwidth and frequency spacing," *Opt. Lett.*, vol. 39, no. 6, pp. 1637–1640, Mar. 2014.