Optical under-sampling by using a broadband optical comb with a high average power

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Abstract: We demonstrate a new method to improve the performance of photonic assisted analog to digital converters (ADCs) that are based on frequency down-conversion obtained by optical under-sampling. The under-sampling is performed by multiplying the radio frequency signal by ultra-low jitter broadband phase-locked optical comb. The comb wave intensity has a smooth periodic function in the time domain rather than a train of short pulses that is currently used in most photonic assisted ADCs. Hence, the signal energy at the photo-detector output can be increased and the signal to noise ratio of the system might be improved without decreasing its bandwidth. We have experimentally demonstrated a system for electro-optical under-sampling with a 6-dB bandwidth of 38.5 GHz and a spur free dynamic range of 99 dB/Hz$^{2/3}$ for a signal with a carrier frequency of 35.8 GHz, compared with 94 dB/Hz$^{2/3}$ for a signal at 6.2 GHz that was obtained in the same system when a pulsed optical source was used. The optical comb was generated by mixing signals from two dielectric resonator oscillators in a Mach-Zehnder modulator. The comb spacing is equal to 4 GHz and its bandwidth was greater than 48 GHz. The temporal jitter of the comb measured by integrating the phase noise in a frequency region of 10 kHz to 10 MHz around comb frequencies of 16 and 20 GHz was only about 15 and 11 fs, respectively.

OCIS codes: (060.5625) Radio frequency photonics; (320.7085) Ultrafast information processing; (350.4010) Microwaves; (070.1170) Analog optical signal processing.

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1. Introduction

One of the important challenges encountered in both electronic warfare and modern communication systems is the sampling of signals with a carrier frequency that can be located in extremely broadband frequency region that can span several tens of GHz. The main difficulty in sampling such signals is the extremely high sampling rate required by the Nyquist–Shannon sampling theorem, which is far beyond the capabilities of the available electronic analog to digital converters (ADCs). Recently, there has been a significant interest in applying photonic systems to extend the performance of electronic ADCs [1–3]. Optical systems have a significantly higher bandwidth and a lower jitter than can be obtained by purely electronic systems. Photonic assisted ADCs utilize photonics to overcome limitations of electronic ADCs but both the sampling and the quantization are performed by electronic systems [1]. The use of photonics enables in such systems to significantly decrease the sampling rate that is required by the electronic ADCs. Since the sampling rate of each of the electronic ADCs is smaller than required by the Nyquist–Shannon sampling theorem such sampling is referred to as under-sampling or sub-sampling. Photonic assisted ADCs are currently based on using a short optical pulse train with an ultra-low jitter that is often generated by mode-locked lasers (MLLs). The decrease in the required sampling rate of the electronic ADCs is obtained by time demultiplexing [4] or by time to wavelength mapping of the sampled data [2, 5]. In both cases, short optical pulses are required to obtain ultra-low timing jitter and sufficient effective number of bits (ENOB) [6]

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and the electronic sampling should be synchronized to the optical pulse train. Under-sampling can also be used to down-convert the entire spectrum into a low frequency region, called baseband [7, 8]. Then, the down-converted signal can be sampled by an electronic ADC. In many important applications the sampled signals are sparse, *i.e.*, the sampled spectrum is composed of several bandwidth limited signals and at a given time only a small portion of the spectrum is occupied. For sparse signals, under-sampling can be used to accurately reconstruct the original signal even when the carrier frequencies of the bandwidth-limited signals that compose the spectrum are not known a priori. The minimum sampling rate that is theoretically required in this case is equal to four times the occupied bandwidth of the spectrum. This rate can be significantly smaller than the Nyquist rate that equals in this case to twice the maximum frequency of the sampled signal.

In previous works [3, 8] we have experimentally demonstrated an optical system for under-sampling several bandwidth-limited signals with carrier frequencies that are not known a priori and can be located within a broad frequency region of $0-20$ GHz. The system was based on under-sampling synchronously or asynchronously at three different rates. The optical pulses used for the under-sampling were generated by a combination of an electrical comb generator and an electro-absorption optical modulator. Accurate reconstruction was obtained even in cases in which the spectrum of different signals overlaped in the baseband region of all sampling channels.

In all of the photonic assisted ADCs schemes described above the system was based on using short optical pulses with a very low jitter. The pulses were usually generated by a MLL. However, the performance of such systems is usually limited by thermal and electric noise of the photo-detecror (PD), the radio-frequency (RF) amplifiers, and the electronic ADC rather than by the jitter of the laser [9, 10]. One of the main causes for this limitation is the use of short optical pulses. The pulse duration should be decreased as the system bandwidth increases. However, since the signal at the input of the PD is a modulated train of short pulses that occupy only a very small fraction of the time, the signal energy is limited and hence the signal to noise ratio (SNR) at the PD often limits the system performance. Moreover, in most photonic assisted schemes described in the literature, there exists also a technical challenge to synchronize between the optical pulse train and the electronic ADC [2].

In this work we demonstrate a new method to improve the performance of photonic assisted ADCs that are based on frequency down-conversion by optical under-sampling. The under-sampling is obtained by using an optical comb rather than a train of short optical pulses. The RF spectrum of the comb is sufficiently broad so it does not limit the system bandwidth. However, in the time domain, the comb intensity has a smooth periodic waveform with a high average power and hence the SNR at the PD can be improved compared to systems based on short optical pulses. The optical comb is obtained by mixing two low-noise RF sources generated by two phase-locked dielectric resonator oscillators (DROs) in a Mach-Zehnder modulator (MZM). The frequency spacing between the comb lines was equal to 4 GHz and the jitter of the comb lines at a frequency of 16 GHz and 20 GHz, measured by integrating the phase noise in a frequency region of 10 kHz to 10 MHz with respect to the carrier frequency, equals 15 and 11 fs, respectively. The measured RF bandwidth of the comb was at least 48 GHz and the non-uniformity between the amplitudes of all the comb lines was only about 4.4 dB. The measured RF bandwidth of the comb was limited by bandwidth of our measurement system to 48 GHz. The theory indicates that the RF bandwidth of the comb can be as high as 80 GHz.

The comb generator enabled us to experimentally demonstrate an electro-optical system for under-sampling with a 6-dB bandwidth of about 38.5 GHz. The use of frequency comb rather than a train of short pulses allowed us to improve the spurious free dynamic range (SFDR) of the optical system to about 99 dB/Hz$^{2/3}$ for a signal with a carrier frequency of 35.8 GHz compared with SFDR of about 94 dB/Hz$^{2/3}$ for a signal at 6.2 GHz that was obtained in the same optical system when the comb generator was replaced by a short pulsed source [8]. We note that the SFDR was obtained without using a differential detection or a dual-output MZM that is used to compensate the nonlinearity of the MZM as used in [2] to significantly improve the performance. The phase locking of different comb lines enables overcoming aliasing of different signals at baseband due to under-sampling. Therefore, reconstruction methods such as multi-rate synchronous optical under-sampling can be employed [3]. The demonstrated system is robust against changes in the environmental conditions and there is no need to synchronize between the electronic samplers and the optical comb generator.

2. Principle of operation

We start by a mathematical description of the under-sampling operation obtained in the photonic assisted ADC described in this work. An RF signal with a spectrum $S(f)$ is sampled by using an optical periodic waveform with an intensity time profile in a single period $c_{\mathrm{opt}}(t)$ $(0 \leq t \leq T)$, where T is the waveform period. Without providing a signal $(s(t) = 0)$ the voltage in a single time period at the output of the photodetctor has time profile $c(t) = \eta c_{\mathrm{opt}}(t)Z$, where $Z = 50\ \Omega$ is the output impedance and η is the detector conversion efficiency. The RF spectrum of the photodetector voltage, $V_{PD}(f)$, is equal to: [11]

$$V_{PD}(f) = f_r \sum_{n=-\infty}^{\infty} C(nf_r)S(f - nf_r) \tag{1}$$

where $C(f)$ is the Fourier transform of the voltage waveform $c(t)$, n is an integer number, and $f_r = 1/T$ is the repetition frequency of the optical waveform. Equation (1) indicates that the voltage spectrum at the PD output contains replicas of the original spectrum $S(f)$ shifted by an integer multiple of the repetition frequency f_r. Therefore, the spectrum at the baseband region $(0 \leq f \leq f_r/2)$ contains the entire signal spectrum $S(f)$. This down-converted signal can now be sampled by an electronic ADC with a sufficient sampling rate $f_s \geq f_r$. In case that the down-converted signal is not deteriorated by aliasing effect, the sampled signal can be directly reconstructed. Usually the periodic waveform used for the sampling is a short pulse train generated by using a MLL [12–17]. For such a short pulses the average power at the detector input is very low compared with the pulse peak power and hence the SNR is limited. Increasing the pulse intensity can induce distortions [18] as well as damage to the photodetector. Therefore, it was reported in previous works [2, 9] that the main limitation on the implementation of a photonic assisted ADC was electronic noise and not the laser jitter.

Equation (1) indicates that the spectrum at baseband depends only on the RF spectrum of the comb, $C(f)$, and not directly on its waveform in the time domain, $c(t)$. Therefore, by controlling the relative phases between the different RF comb lines it is possible to significantly increase the average power of the signal at the detector without decreasing the bandwidth of the system. Equation (1) also indicates that the amplitude of all the RF comb lines, $C(nf_r)$, should be approximately equal to obtain a uniform frequency response of the system. We note that the RF spectrum of the comb should be uniform rather than the optical spectrum as is usually required in optical comb generators. The maximum allowed jitter of all the comb signals is determined by the maximum frequency of the sampled signal [2, 19] and therefore it should be kept sufficiently low. Since only the baseband spectrum is required for the reconstruction algorithm [3, 8], there is no need to synchronize the electronic ADC and the comb generator.

3. Experimental setup

The experimental setup is depicted in Fig. 1 and is divided into two sub-systems. The first is an optical comb generator and the second is a system for under-sampling based on a frequency

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down-conversion. The optical comb is generated by a novel method that is based on mixing of two low-noise RF sources in an electro-optical modulator - (MZM_1). This system is robust and is not significantly affected by changes in environmental conditions. The bandwidth of the Mach-Zehnder modulator used to generate the comb can be significantly narrower than the bandwidth of the generated comb. A detailed theoretical model that was used to design the comb generator will be described elsewhere. Here, we only report on the experimental results. A continuous-wave (CW) semiconductor laser (LD) with an optical power of about $P_0 = 20$ dBm that operates at a wavelength of 1546 nm is connected to a MZM (MZM_1) having an insertion loss of $\alpha = 2.7$ dB, extinction ratio of about 25 dB, and an electro-optic bandwidth of about 16 GHz. Two phase-locked dielectric resonators (DROs) are used to generate the comb. To obtain a frequency difference of $f_r = 4$ GHz between two adjacent comb lines, the frequencies of the DROs were chosen to be $2f_r = 8$ GHz, and $3f_r = 12$ GHz. The two DROs are phase-locked to the same 100 MHz low-noise reference oscillator and hence the relative phase between the two oscillators is locked.

The input voltage $V_m(t)$ of the modulator (MZM_1) is given by:

$$V_m(t) = m_0 + m_2 \sin[2\pi(2f_r)t] + m_3 \sin[2\pi(3f_r)t + \pi\Delta\phi_{23}] \tag{2}$$

where $m_0 = \mathrm{V_{BIAS}}/\mathrm{V_{\pi,DC}}$ is the normalized MZM bias voltage, $\mathrm{V_{\pi,DC}} = 5.1$ V is the modulator half wave DC voltage, $\mathrm{V_{BIAS}}$ is the MZM bias voltage, $m_2 = \mathrm{V_{m,2}}/\mathrm{V_{\pi,2f}}$ and $m_3 = \mathrm{V_{m,3}}/\mathrm{V_{\pi,3f}}$ are the normalized RF driving voltages, $\mathrm{V_{m,2}}, \mathrm{V_{m,3}}$ are the peak amplitudes of the input RF signals, and $\mathrm{V_{\pi,2f_r}}, \mathrm{V_{\pi,3f_r}} = 4.5, 5$ V are the modulator half wave voltage at frequencies $2f_r, 3f_r$, respectively. $\Delta\phi_{23}$ is the relative phase difference between the two RF signals at $t = 0$ normalized to π. By controlling the parameters $(m_0, m_2, m_3, \Delta\phi_{23})$ we could control the bandwidth, the comb uniformity, the jitter, and the average power of the comb signal. To obtain a theoretical 3-dB voltage bandwidth of the comb of about 80 GHz, the required parameters are: $(m_0, m_2, m_3, \Delta\phi_{23}) = (0.2, 1, 1.9, 0.5)$. However, since the bandwidth of our measurement system was limited to 50 GHz, we optimized the parameters in our experiments to obtain a uniform comb with a bandwidth of more than 48 GHz as discussed below.

To obtain under-sampling, the output of MZM_1 is connected to a second MZM (MZM_2) having an insertion loss $\alpha = 4.5$ dB, dynamic extinction ratio of 20 dB, $\mathrm{V_{\pi,DC}} = 5.5$ V, $\mathrm{V_{\pi,AC}} = 4.6$ V, and a 6-dB electro-optic bandwidth of about 40 GHz. The output of this modulator is transformed into an RF signal via a PD having a bandwidth of about 5 GHz. It is then amplified by an RF amplifier (G_3) having a 3-dB bandwidth of 3 GHz and a gain of about 30 dB. Since the repetition rate of the RF comb signal is $f_r = 4$ GHz, the baseband region is located at $0-2$ GHz. Hence, RF amplifier (G_3) functions also as a low-pass filter that transfers to the electronic ADC only the low frequency region of the sampled signal. To minimize the sampling rate of the electronic ADC the bandwidth of the amplifier should be equal to 2 GHz.

4. Experimental results

In our experiments the measured parameters of the comb source, defined in Eq. (2), were $(m_0, m_2, m_3, \Delta\phi_{23}) = (0.3, 1, 1.5, 1)$. The parameters are close to the theoretical parameters required to obtain a comb with a bandwidth of 48 GHz and a uniformity of less than 4 dB: $(m_0, m_2, m_3, \Delta\phi_{23}) = (0.33, 0.99, 1.45, 1.05)$. The spectrum of the RF comb shown in Fig. 2(a) was measured by using a broadband PD having a 3-dB bandwidth of about 50 GHz and an RF spectrum analyzer with a bandwidth of 50 GHz. We note that the increased noise floor at high frequencies was obtained due to the RF spectrum analyzer and not due to the comb. Indeed, the same noise floor is obtained even without providing an input signal to the spectrum analyzer as shown in Fig. 2(b). The figure indicates that a comb with a frequency spacing of 4 GHz and a bandwidth of at least 48 GHz was obtained. The maximum change of the RF power between

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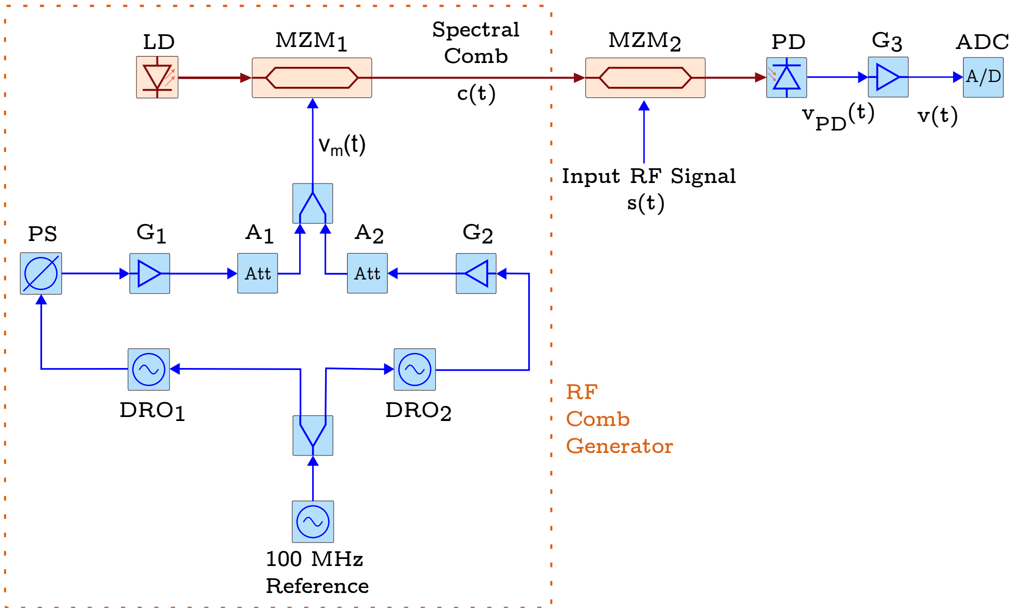

Fig. 1. Schematic description of the experimental setup. The RF comb generator is outlined with a dashed red line. LD is a semiconductor continuous wave laser, MZM_1 is a MZM used to generate the RF comb, MZM_2 is MZM used for under-sampling, PD is a photo-detector, G_3 is an RF amplifier with a bandwidth of $0.1-3$ GHz and a gain of about 30 dB, G_1 and G_2 are RF amplifiers having a bandwidth of $5.9-18$ GHz, gain of 35 dB, and a noise figure of 5.5 dB. A_1 and A_2 are variable RF attenuators, PS is a RF phase shifter, DRO_1 and DRO_2 are a phase-locked DROs generating 8 GHz and 12 GHz signals, respectively. A 100 MHz crystal oscillator is used to phase lock the two DROs.

the comb lines was about 4.4 dB. The RF power of each comb line, at the output of MZM_2 was about -27 dBm. Equation (1) indicates that system bandwidth is determined by the RF spectrum of the comb source. Therefore, the decrease of the system response at 48 GHz due to the comb bandwidth is only 2.2 dB. Figure 3 shows the optical spectrum of the comb measured by an optical spectrum analyzer with a resolution of about 2 GHz. We would like to emphasize that the shapes of the optical and the RF spectrum of the comb signal are different since each line in the RF spectrum is obtained by beating of several comb lines of the optical domain. The method to generate the comb signal described in this work enables generating a uniform RF comb as required for under-sampling rather than a uniform optical comb as usually obtained in optical systems. The time-domain waveform of the generated comb at the output of the PD is shown in Fig. 4. The repetition period of the waveform is $T = 250$ ps. The repetitiveness of the signal waveform indicates that the relative phases between the comb lines are locked. However, the phases between the comb lines do not equal zero and hence the time waveform has a complex structure.

Since the performance of photonic assisted sampler can be limited by the jitter of the comb waveform, we have measured the phase noise and calculated the RMS jitter of the comb lines by using Rohde & Schwarz FSUP26 Signal Source Analyzer (FSUP26). The maximum comb frequency that could be measured by the phase analyzer is 26 GHz. Typical results of the phase noise measurements are shown in Fig. 5 for the comb lines at 16 and 20 GHz. For comparison we also show the measured phase noise of the 8 GHz DRO (DRO_1) and the 12 GHz DRO (DRO_2) at the output of the amplifiers G_1 and G_2. We have experimentally verified that the RF

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amplifiers did not degrade the phase noise performance of the DROs beside adding some few spur lines. The jitter of each comb line can be obtained by integrating the phase noise around the frequency of the line [20]. By connecting the output of the modulator MZM_1 into a PD with a bandwidth of 50 GHz, the measured RMS jitter at the 16 GHz comb line was 18 and 15 fs for an integration bandwidth of 100 Hz to 1 MHz and 10 kHz to 10 MHz, respectively. At 20 GHz the measured RMS jitter was 13 and 11 fs for an integration bandwidth of 100 Hz to 1 MHz and 10 kHz to 10 MHz, respectively. The RMS jitter of the amplified 8 GHz DRO (DRO_1) and the 12 GHz DRO (DRO_2) were about 16 fs, respectively, taken over an integration bandwidth of 100 Hz to 1 MHz. The temporal jitter results are comparable to those attained in optically assisted sampling schemes that are based on passively MLLs [2] and actively mode-locked fiber lasers [21].

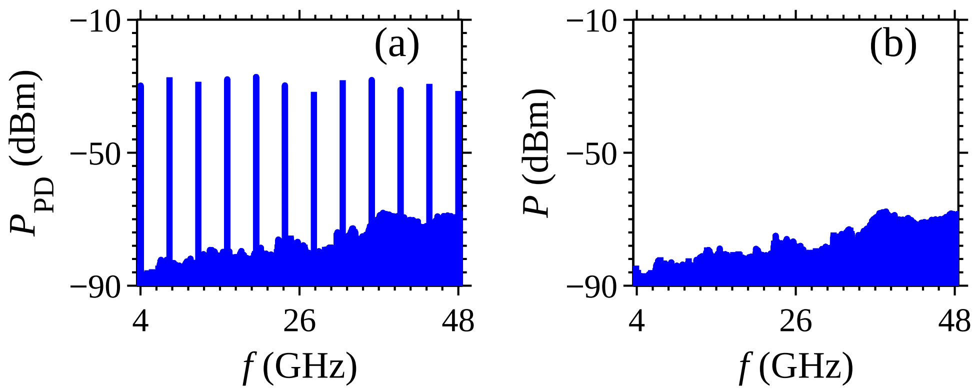

Fig. 2. (a) Measured spectrum of the RF comb and (b) noise floor of the RF spectrum analyzer measured without an input signal. The maximum change of the comb line amplitudes between 4 to 48 GHz is only about 4.4 dB. The RF spectrum analyzer resolution bandwidth (RBW) was set to 100 kHz.

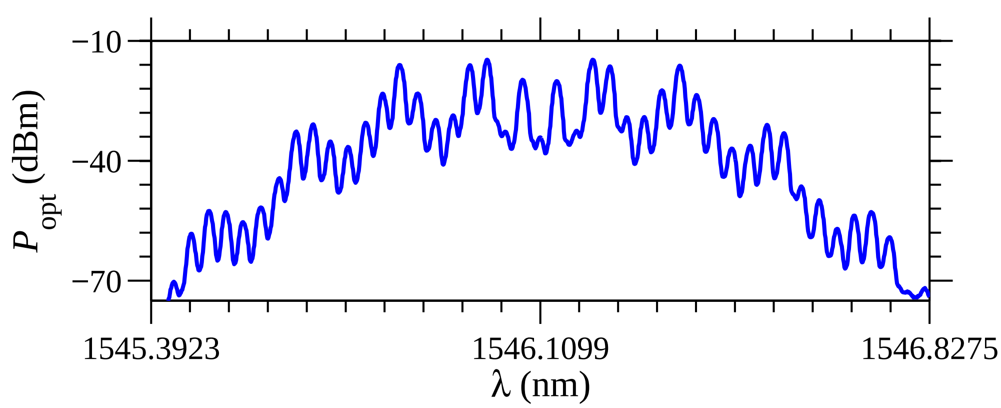

Fig. 3. Optical spectrum of the frequency comb measured by using an optical spectrum analyzer with a frequency resolution of about 2 GHz. The optical signal was measured via a 1% optical coupler that was connected to the output of MZM_2.

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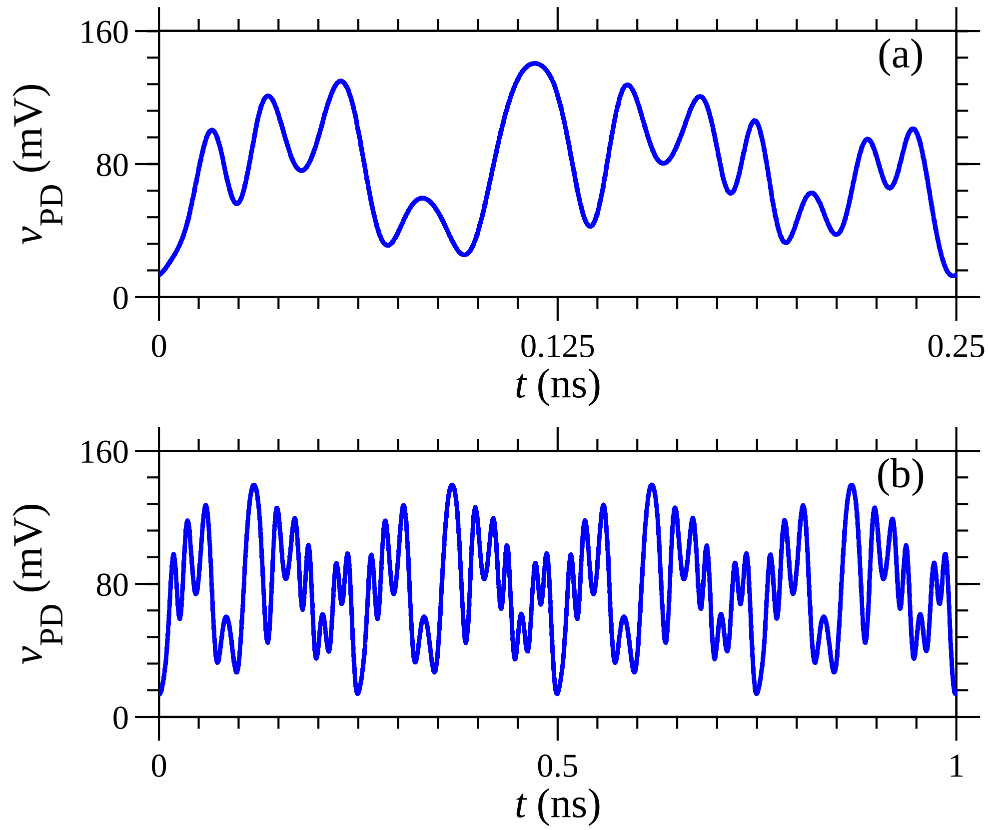

Fig. 4. (a) Waveform of a single period and (b) of 4 periods of the comb signal measured by using a sampling oscilloscope. The repetition period equals $T = 250$ ps.

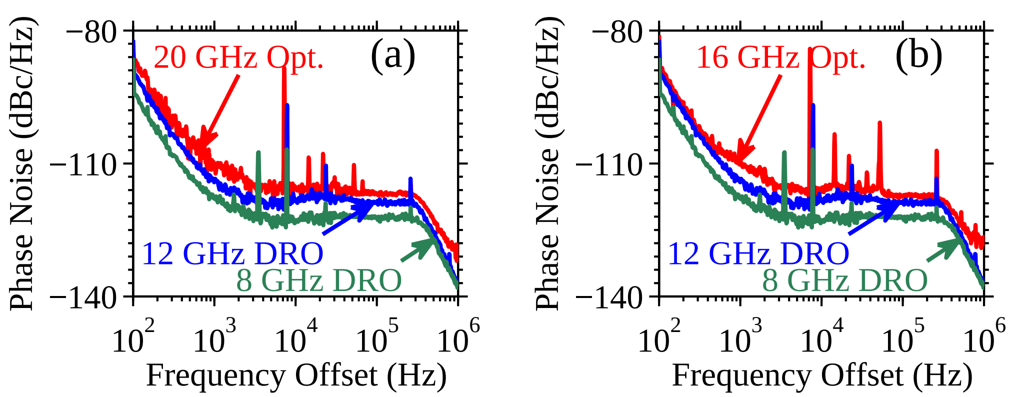

Fig. 5. Phase noise of the RF comb measured by using a signal source analyzer (FSUP26). The measured RMS jitter around (a) 20 and (b) 16 GHz was 11 and 15 fs, respectfully for an integration bandwidth of 10 kHz to 10 MHz. For the comparison, the phase noise of the two DROs that were used to generate the comb are also shown in the figure. The figure shows that the phase noise of the RF comb is dominated by the phase noise of the DROs.

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4.1. Optical down-conversion

To demonstrate frequency down-conversion we have built a RF source that could generate two chirped RF signals simultaneously. The first signal had a carrier frequency of 6.9 GHz and a bandwidth of 200 MHz and the second signal had a carrier frequency of 9.6 GHz and a bandwidth of 120 MHz. The spectrum of the input signals measured by an RF spectrum analyzer is shown in Fig. 6(a). The resulting down-converted signals are shown in Fig. 6(b). Figures 6(c) and 6(d) show a zoom on the original RF signal with a carrier frequencies of 6.9 GHz and on its down-converted baseband signal, respectively. The down-conversion loss, defined as the ratio between the amplitude of the input RF signal and its down-converted image, depicted in Fig. 6, was measured to be about -7.8 dB. The figure indicates that the signals were accurately down-converted with some additional noise that was added. The central frequencies of the down-converted signals were 1.1 and 1.6 GHz, as expected for a comb with a frequency spacing of $f_r = 4$ GHz. We note that the down-converted signal at 1.1 GHz is obtained from a component of the signal spectrum with a negative frequency. Therefore, the spectrum of the down-converted signal shown in Fig. 6(d) is a mirror image of the original signal spectrum shown in Fig. 6(c). Figure 7 shows the frequency response of the system, defined as the normalized ratio between the amplitude of the signal at baseband at the output of amplifier G_3 divided by the input signal amplitude. The decrease in system response for an input signal at 38.5 GHz compared to the response for an input signal at 2.5 GHz is about -6.0 dB. The 6-dB RF bandwidth of the system was limited by the bandwidth of the modulator (MZM_2) and not by the bandwidth of the RF comb. By increasing the bandwidth of modulator, MZM_2, the system bandwidth can be increased to a least 48 GHz.

The spurious free dynamic range (SFDR) was measured as described in [8]. Two CW RF tones having the same power were provided to the input of the modulator, MZM_2. The frequency difference between the two tones was set to 2 MHz. The power of the RF tones was changed between -6 to 0 dBm. For each input power level the signal and the third order intermodulation products were measured. The SFDR is defined as the difference in dB between the signals power and the power of the third order products in case that the power of the third order products is equal to the noise floor level assuming that the resolution bandwidth equals 1 Hz. The measured SFDR for signals at a carrier frequency of 3.8, 7.8, 11.8, 15.8, 19.8, 23.8, 27.8, 31.8, 35.8, 39.8 GHz equals 94, 97, 96, 97, 98, 95, 97, 97, 99, 97 dB/Hz$^{2/3}$, respectively. In a previous work we have demonstrated under-sampling by using an optical train of short pulses that were generated by an electronic pulse generator and an optical electro-absorption modulator [8]. The other parts of the optical system were identical to that used in the current work. The SFDR that was obtained in that work was equal to 94 dB for a signal at a frequency of 6.2 GHz and the system bandwidth was about half (20 GHz) than obtained in the current work. The improvement was mainly obtained by a decrease of about 11 dB in the noise floor because there was no need to use Erbium-doped Fiber Amplifier (EDFA) to compensate loss as done in [8]. Since the bandwidth of the current system is about twice than in [8], the optical power at the input of the PD was also increased by about 3-dB.

The average optical power at the PD was about 7.3 dBm, which is close to the maximum rated average optical power of the PD. A further improvement in the system can be obtained by increasing the laser power and the maximum optical power of the PD. Increasing the optical power of the comb lines by 1 dB will improve the SFDR by $4/3$ dB assuming that the limiting noise in the system is caused by electrical amplifiers and the system non-linear behavior is dominated by the non-linearity of MZM_2. By lowering the noise floor by 1 dB the SFDR can be improved by $2/3$ dB. The SFDR can be further increased by using differential detection and by using a dual-output MZM to compensate the nonlinearity of the sinusoidal transfer function of the modulator as was done in [2]. We would also like to emphasize that the SFDR

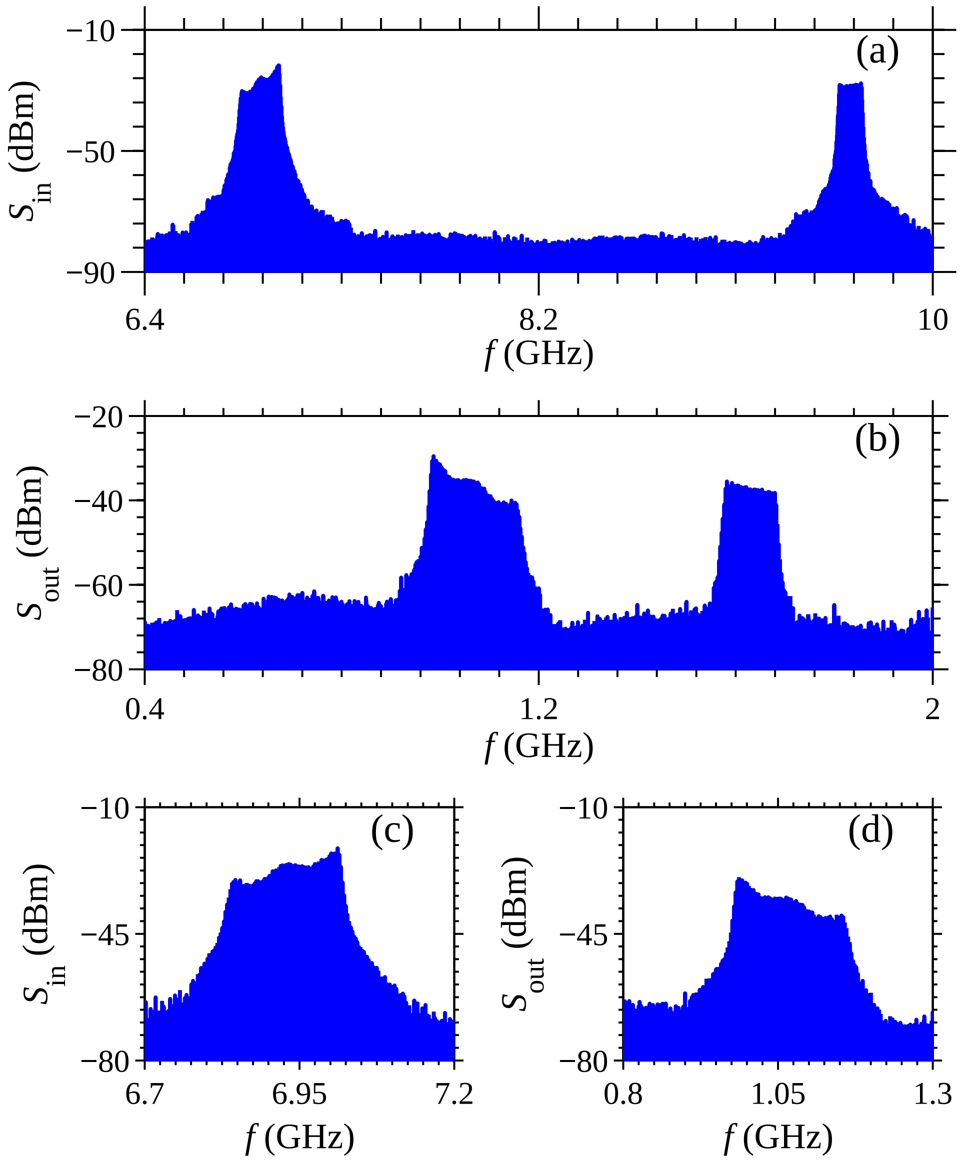

Fig. 6. Down-conversion of two chirped RF signals centered around 6.9 and 9.6 GHz with a bandwidth of 120 and 200 MHz, respectively. Figure 6(a) shows the input signals spectrum measured by an RF spectrum analyzer and Fig. 6(b) shows the down-converted signals at baseband. Figures 6(c) and 6(d) give a zoom on the spectrum of the RF signal with a carrier frequency of 6.9 GHz and on its down-converted baseband signal, respectively. The down-conversion loss was measured to be about −7.8 dB. The RF spectrum analyzer RBW was set to 150 kHz.

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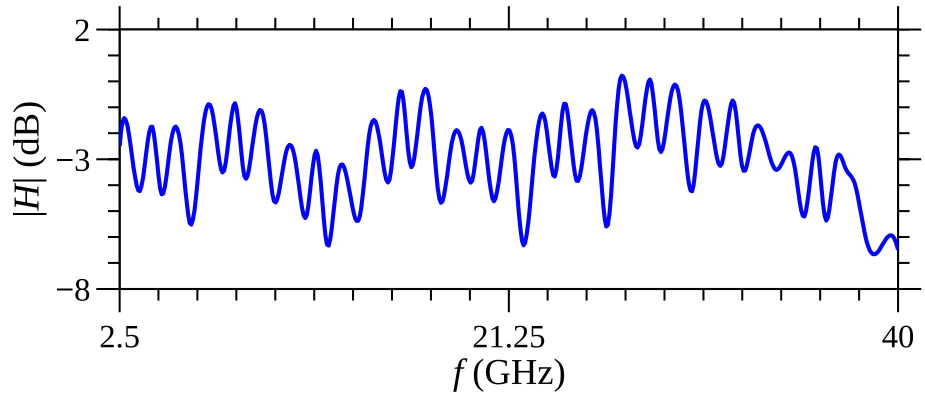

Fig. 7. Normalized response of the system as a function of the input signal frequency, defined as the signal amplitude at baseband that is measured at the output of amplifier G_3, divided by the input signal amplitude. The result was normalized to a down-conversion loss of -7.8 dB.

is defined with respect to the noise floor of the system. However, in photonic assisted ADCs that are based on frequency down-conversion the performance of the system is also limited by low frequency noise that is added to the down-converted signal due to accumulated jitter of the comb in the sampling window interval. This effect adds a low frequency noise with a bandwidth on the order of kHz−tens of kHz around each of the down-converted tones that are used for SFDR measurement. Such noise is not taken into account in SFDR measurements. It can be characterized, for example, by using a high performance electronic ADC that is connected to the output of the system.

We have estimated the potential improvement in the system performance that can be obtained in case that a train of short pulses is replaced by an RF comb, as described in the current work. We have calculated for the measured pulse waveform, shown in Fig. 4, the voltage spectrum and obtained that the ratio between the average harmonics amplitude to the peak pulse voltage is about -9 dB. We have compared this ratio to that obtained if the comb generator was replaced by a train of short Gaussian pulses with a time period $T = 250$ ps, and a time profile of a single voltage pulse at the PD output, $c(t) = A\exp\left[-(1/2)(t/T_0)^2\right]$. Assuming that the spectrum of the Gaussian pulse decreases by 2.2 dB at $f = 48$ GHz, the ratio between the maximum pulse voltage, A, and the amplitude of the spectrum line at 24 GHz equals -18.3 dB. Thus, for a Gaussian pulse the peak power of the optical pulse should be 9.3 dB higher than that required for the waveform shown in Fig. 4 in order to obtain a comb with approximately the same bandwidth and the same average power. It is also expected that the difference between the peak powers will approximately linearly increase as the number of comb lines increases. Hence, the advantage of the method described in this work over under-sampling by using a short pulse train will be further emphasized as the system bandwidth increases.

The results above indicate, that under the assumption that the optical comb signal and its equivalent pulse train have the same maximum intensity and the same bandwidth, the signal energy at the input of the photo-detector can be increased by a factor of 9.3 dB if the pulsed source is replaced by the RF comb described in this work. Assuming that at the input of the electronic ADC the noise floor is dominated by thermal and electric noise at the RF amplifiers, as reported in [9, 10], the SNR of the system can be improved by 9.3 dB. Thus, the potential improvement in ENOB, defined by $\mathrm{ENOB} = (\mathrm{SINAD} - 1.76)/6.02$, is equal to $9.3/6.02 = 1.5$

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bits. Since, the jitter of pulsed sources is usually limited by the pulse energy [22], a further increase in the ENOB may be theoretically obtained by developing novel sources that generate smooth rather than short pulses.

5. Conclusion

We have demonstrated a new method to improve the performance of photonic assisted ADCs that are based on frequency down-conversion by using optical under-sampling. The frequency down-conversion is obtained by multiplying the RF signal with a broadband RF comb spectrum. In the time domain the comb signal has a smooth periodic function with a high average power compared with its maximum power. Short optical pulses generated by MLLs that are currently used in photonic assisted ADCs may limit the attainable SNR at the detector. Therefore, the performance of such samplers is often limited by electronic noise rather than by the jitter of the lasers, as was mentioned, for example in [2]. The comb source described in this work has a high average power and a broad spectrum. The bandwidth of the comb can be easily tailored to the required bandwidth of the system. The source is robust and has a jitter that is comparable to that obtained by mode-locked fiber lasers. For example, the measured RMS jitter of the comb source at 20 GHz was 13 and 11 fs for an integration bandwidth of 100 Hz to 1 MHz and 10 kHz to 10 MHz, respectively. The system described in this work does not require the synchronization between the electronic samplers and the optical waveform. It is also robust against changes in environmental conditions. We have demonstrated a photonic assisted ADC with a 6-dB bandwidth of 38.5 GHz. The bandwidth was limited only by the bandwidth of the modulator used for the under-sampling and not by the bandwidth of the comb source that was at least 48 GHz. A theoretical model indicates that the 3-dB bandwidth of the voltage comb generated by the experimental setup described in this work can be as high as 80 GHz. The SFDR can be further increased by using differential detection and by using a dual-output MZM to compensate the nonlinearity of the sinusoidal transfer function of the modulator as was done in [2]. Since, the jitter of pulsed sources is often limited by the pulse energy [22], a further increase in the ENOB may be theoretically obtained by developing novel sources that generate smooth rather than short pulses.

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