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Optical sampling of narrowband microwave signals using pulses generated by electroabsorption modulators

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Abstract

We demonstrate an optical system for sampling narrowband microwave signals with a very high carrier frequency, based on optical pulses generated by two electroabsorption modulators. A theoretical model, based on sampling theory, gives the necessary conditions to accurately reconstruct the sampled signal. The theory indicates that relatively long pulses can be used to sample narrowband electrical signals with a very high carrier frequency. Such pulses can be generated using an optical source based on electroabsorption modulators. The use of such a source instead of a fiber laser enables to reduce the size, the cost, and the power consumption of the optical sampler as well as to significantly improve its reliability. When the optical pulses and the carrier frequency of the sampled signal are synchronized, the sampling rate of the electronic analog to digital converter in the system can be reduced by a factor of two. Synchronous and asynchronous sampling of electrical signals with a carrier frequency of up to 20 GHz were demonstrated experimentally. The experimental results are compared to the results of the theoretical analysis.

Keywords: Microwave photonics; Analog–digital conversion; Optical data processing

1. Introduction

Sampling of narrowband microwave signals with a high carrier frequency is essential for several important applications in radars and in communication systems. Since the bandwidth of electronic samplers is limited, the frequency of the narrowband signals should be decreased to a low frequency using several stages of mixers and filters. Such electronic circuits increase the size, the weight, and the cost of the sampling system. Frequency down conversion can be obtained using an optical system based on a modulator driven by a sinusoidal signal with a frequency equals to the carrier frequency of the electronic signal [1,2].

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However, when the carrier frequency of the signal is significantly higher than the signal bandwidth, the modulator must be driven with a very high frequency wave. Moreover, the frequency of the sinusoidal wave supplied to the modulator must be adjusted when the carrier frequency of the sampled signal changes.

Optical analog to digital convertors (ADC), based on an optical pulsed source, enable to sample signals with a broad bandwidth [3–5]. In order to directly sample high frequency signals, the optical pulse duration must be short enough. For example in order to sample directly a sinusoidal wave with a frequency $f_c = 20$ GHz and with a resolution of $N = 8$ bits, the pulse duration should be narrower than about $\tau = \sqrt{(3)}/\pi f_c \sqrt{(2^{N-1})} =$ 2.4 ps and the sampling rate should be greater than 40 GHz [6]. Recently, a phase-encoded optical down-sampling of narrowband radio-frequency and microwave signals with a high linearity was demonstrated [7]. Since the bandwidth of the signals in this work was limited, broad optical pulses with a duration of about 30 ps were used. However, the pulses used in the optical samplers reported in previous works were based on a fiber laser [3–7]. Although such a source has an excellent performance, fiber lasers are bulky, complex, and expensive sources. Optical pulsed sources based on modulating a continuous wave laser using electroabsorption modulators were previously used in Optical Time Division Multiplexing communication systems [8,9] but not in optical samplers.

In this paper, we analyze, using sampling theorem, an optical system for sampling narrowband signals. The use of sampling theorem helps to simplify the analysis of the system and it explicitly gives the requirements from the optical sampler. In particular, we show that long pulses can be used to sample narrowband signals with an extremely high carrier frequency. Therefore, we could implement, for the first time to our knowledge, the optical source in the sampler using a continuous wave laser modulated by two electroabsorption modulators. Such a source is significantly more reliable, has a smaller size and weight, and is significantly cheaper than fiber lasers that were previously used in optical samplers. Moreover, the electroabsorption modulators, the laser, and an optical amplifier may be integrated together in a very small package. We have also found the explicit connection between the repetition rate of the optical source and the bandwidth of the sampled data. When a narrowband signal is sampled, the sampling rate should be only greater than twice the bandwidth of the signal. Since in many important cases, the carrier frequency is significantly higher than twice the bandwidth of the signal, the sampling frequency can be significantly lower than the carrier frequency. We have also shown that when the carrier frequency of the sampled signal and the optical pulses are synchronized, the sampling rate may be decreased by a factor of 2. We have demonstrated experimentally optical systems for a synchronous and asynchronous sampling. Using the optical sampler we could sample a signal with a carrier frequency of up to 19 GHz, with seven effective bits. The spurious free dynamic range of the system was greater than 61 dB. This measured spurious free dynamic range indicates that by improving analog electrical circuits in the system, the effective number of bits of the optical sampler can be as high as 10 bits. Therefore, the performance of our system, and especially the extremely broad frequency regime of the sampled signal carrier frequency, may be significantly better than obtained using electronic system, while the price, the size and the power consumption may be reduced.

2. Theory

A schematic description of an optical system used to sample narrowband electronic signals is shown in Fig. 1. The amplitude of an optical pulse train generated by a pulsed laser is modulated using a $LiNbO_3$ modulator according to the amplitude of a narrowband electronic signal. The optical signal is then converted into an electronic signal using a detector. At the output of the detector the carrier frequency of the signal is significantly reduced and after passing through a bandpass filter the signal can be sampled using

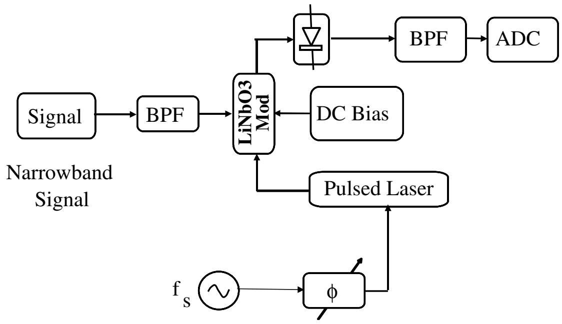

Fig. 1. Schematic description of the sampler. An optical pulsed source with a repetition rate of f_s is used for decreasing the carrier frequency of a narrowband electronic signal with a carrier frequency f_c. BPF is a bandpass electronic filter, ϕ is an electronic phase shifter, and ADC is an electronic analog to digital converter with a slow sampling rate.

an electronic analog to digital convertor with a slow sampling rate.

We analyzed theoretically the system shown in Fig. 1 using sampling theorem. We assumed that the optical pulsed source generates a pulse train with a periodicity (T) and a pulse shape $p(t)$. In case when the $LiNbO_3$ modulator is driven with a small enough electrical signal the transfer function of the modulator is approximately linear and therefore the output optical intensity after passing the modulator is equal to:

$$I(t) = s(t) \sum_{n=-\infty}^{\infty} p(t - nT), \tag{1}$$

where $s(t)$ is the amplitude of the narrowband electrical signal. Eq. (1) may be written as:

$$I(t) = s(t) \left\{ p(t) \bigstar \sum_{n=-\infty}^{\infty} \delta(t - nT) \right\}, \tag{2}$$

where $\delta(t)$ represents the Dirac delta function, and $\bigstar$ denotes a convolution operator. Assuming that the optical detector is linear the detector current, $i(t)$, is proportional to the optical intensity, $i(t) = \eta I(t)$. The electrical spectrum of the output detector current is obtained by performing a Fourier transform on Eq. (2):

$$i(\omega) = \eta \omega_s \sum_{n=-\infty}^{\infty} S(\omega - n\omega_s) P(n\omega_s), \tag{3}$$

where $\omega_s = 2\pi/T$, is the sampling frequency and $P(\omega)$, $S(\omega)$ are the Fourier transforms of the pulse shape, $p(t)$ and the electrical signal, $s(t)$, respectively. In deriving Eq. (3), we used the connection: $F\{\sum_{n=-\infty}^{\infty} \delta(t - nT)\} = \omega_s \sum_{n=-\infty}^{\infty} \delta(\omega - n\omega_s)$, where F denotes a Fourier transform. Eq. (3) gives the effect of the optical sampling on the electrical spectrum. The optical sampling generates an infinite series of duplications of the original electrical signal spectrum.

Fig. 2 shows a schematic description of the spectrum obtained at the output of the detector. Since the output current is a real function the original spectrum as well as the spectrum after the sampling are conjugate symmetric functions, $i(\omega) = i^*(-\omega)$. Therefore the signal contains frequency component centered around positive and negative frequencies. We assume a narrowband signal with a spectrum that is not equal to zero only in the frequency region $f_c - BW/2 < f < f_c + BW/2$ and $-f_c - BW/2 < f < -f_c + BW/2$. When different duplications of the spectrum do not overlap it is possible to reconstruct the signal without an error. Note that frequency components of the original signal at negative frequencies are duplicated due to the sampling operation to positive frequencies. Such components should not overlap with the components originated from positive frequency components of the original signal. Duplications of the original signal do not overlap

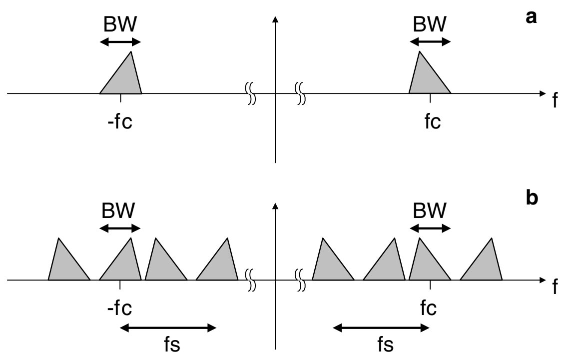

Fig. 2. Schematic description of the original spectrum around a carrier frequency f_c with a bandwidth $BW > 0$ (a) and the spectrum obtained at the output of the system (b) f_s is the sampling frequency. Duplications of the original spectrum are obtained due to the sampling.

if and only if there is not a natural number n that fulfills the condition:

$$f_c - \mathrm{BW} < -f_c + n \cdot f_s < f_c + \mathrm{BW}. \quad (4)$$

Therefore, duplications of the spectrum do not overlap if and only if there is no natural number, n, that fulfills the condition:

$$\frac{(2 \cdot f_c - \mathrm{BW})}{f_s} < n < \frac{(2 \cdot f_c + \mathrm{BW})}{f_s}. \quad (5)$$

One of the cases when the condition, given in Eq. (5), is not met occurs if

$$\frac{(2 \cdot f_c + \mathrm{BW})}{f_s} - \frac{(2 \cdot f_c - \mathrm{BW})}{f_s} > 1. \quad (6)$$

Therefore, a necessary condition to avoid a duplication overlap is $f_s \geqslant 2 \cdot \mathrm{BW}$. Such a condition can be directly obtained from sampling theorem [10].

In a special and important case when $f_c = n \cdot f_s$, where n is a natural number and the electrical signal is obtained by an amplitude modulation:

$$s(t) = x(t)\cos(\omega_c t + \theta) \quad (7)$$

$$F[s(t)] = \frac{e^{i\theta}}{2} X(\omega - \omega_c) + \frac{e^{-i\theta}}{2} X(\omega + \omega_c), \quad (8)$$

where θ is a relative phase, $x(t)$ is a real signal, $X(f)$ is the Fourier transform of the signal, $x(t)$ with a bandwidth equals to BW, i.e. $X(f) = 0$ for $f \geqslant \mathrm{BW}/2$ and $f \leqslant -\mathrm{BW}/2$, it is possible to decrease the sampling rate of the electronic system at the output of the system by a factor of 2, and the sampling rate of the electronic system becomes BW, instead of $2 \cdot \mathrm{BW}$, as obtained in the general case. In this case the condition in Eq. (5) is not met and a spectrum originated from negative frequency components overlaps in the baseband region with a spectrum originated from positive frequency components. However, the two replicas originated from negative and positive frequency components have for each frequency of the baseband region the same amplitude and the same phase up to a constant phase difference, θ. Therefore, the replicas can be coherently added at the baseband region and the signal can be reconstructed. A constructive addition of the two overlapping replicas is obtained when the carrier frequency of the electronic source and the source used for the optical pulse generator in the sampler are synchronized and when the relative phase is equal to zero, $\theta = 0$. In case when the relative phase is equal to $\theta = \pm \pi/2$, no signal is obtained at the output of the system since the two replicas at the baseband region of the spectrum destructively interfere.

Unlike in electronic samplers, the sampling in optical systems is performed using short pulses generated by an optical source. Eq. (3) gives the effect of the optical pulse duration on the system performance when a narrowband signal is sampled. The equation shows that the optical pulse spectrum only affects the intensity of the electrical pulse spectrum duplications. The replica of the spectrum in the baseband region is obtained for $n \cdot f_s \approx f_c$. Therefore, Eq. (3) shows that the attenuation of the spectrum duplication around the baseband frequency depends only on the electrical spectrum component of the detected optical pulses at a frequency close to the carrier frequency of the electrical signal. Therefore, relatively long optical pulses can be used to sample electrical signals with a very high carrier frequency. Since the sampling of narrowband signals can be performed with long optical pulses we could implement the optical source in the sampler using a continuous wave laser modulated by two electroabsorption modulators.

3. Experimental setup and discussion

3.1. Synchronous sampling

In the case of synchronous sampling, the electrical synthesizer used to generate the optical pulses and the synthesizer used to generate the carrier frequency of the sampled signal are synchronized. A schematic description of the experimental setup is shown in Fig. 3. The relative phase between the signal carrier frequency and the optical pulses was adjusted using a phase shifter, ϕ_1.

The optical source was a continuous wave semiconductor laser with a power of 20 mW that operates at a wavelength, $\lambda = 1550$ nm. Fig. 4 shows the generated pulses measured using a sampling

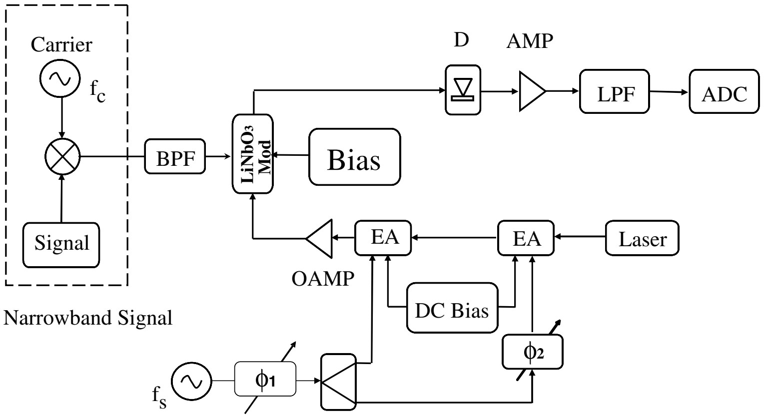

Fig. 3. Schematic description of the synchronous sampler. Optical pulses are generated using a CW laser, modulated by two electroabsorption modulators. EA is an electrabsorption modulator, AMP and AMP1 are electrical amplifiers, D is an optical detector, OAMP is an optical amplifier, LPF is an electrical low pass filter, BPF is an electrical bandpass filter, ϕ_1 and ϕ_2 are phase shifters, and ADC is an electronic sampler. The electrical signal is obtained by mixing a narrowband signal with a high frequency carrier wave.

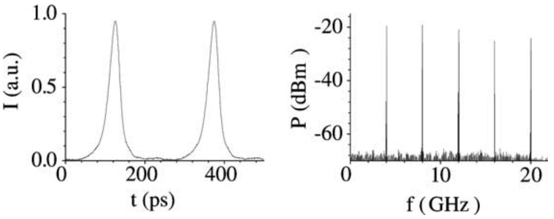

Fig. 4. Optical pulses measures using a sampling oscilloscope and an electrical spectrum analyzer. The repetition rate of the pulses equals 4 GHz.

scope and an electrical spectrum analyzer. When the repetition frequency of the source was equal to 4 GHz, the average power at the output of the optical amplifier, OAMP, was equal to 14 mW and hence the pulse energy was equal to 3.5 pJ. The full width at half maximum of the generated pulses was 32 ps. The difference between the electrical power of the harmonic wave at 4 GHz and the harmonic wave at 20 GHz, measured using a spectrum analyzer, was only about 5 dB. The output of the pulsed source was modulated using a $LiNbO_3$ modulator biased at quadrature in order to minimize nonlinear distortion. The electrical power at the input of the $LiNbO_3$ modulator was about 0 dB in order to minimize nonlinear distortion. The V_π voltage of the modulator was about 5.3 V and therefore the modulation depth of the optical pulse train intensity was about 10%. The output of the system was converted into an electric signal using a slow detector with a bandwidth of 2 GHz, and sampled after passing through an electrical amplifier (AMP1) with a gain of about 20 dB and a bandwidth of 1 GHZ, and a low pass electrical filter with a cutoff frequency of 700 MHz.

Fig. 5 shows the electrical spectrum measured at the output of the modulator using an electrical spectrum analyzer connected to a fast detector with a bandwidth of 25 GHz. The electrical signal was generated by mixing two continuous wave

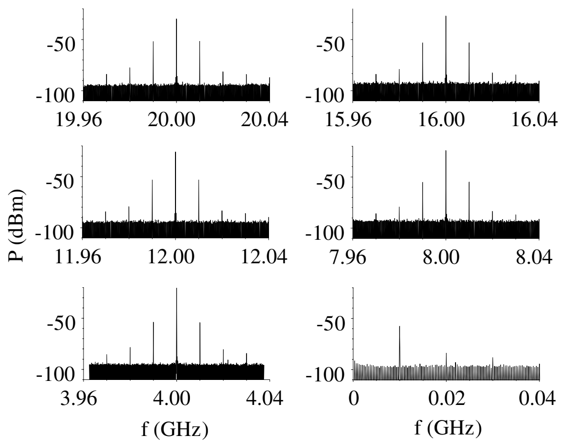

Fig. 5. Electrical spectrum at the output of the sampler for an input signal with a carrier frequency of 20 GHz. The repetition rate of the optical sampler equals 4 GHz. A replica of the spectrum is obtained at the baseband frequency regime.

electrical sources in an electrical mixer. The frequency difference between the two sources was about 10 MHz. Several mixing components were obtained at the output of the electrical mixer, as can be seen in Fig. 5, since the mixer was driven with a high power. The sampled signal was generated by an amplitude modulation, and therefore it could be accurately sampled using synchronous sampling. The electronic source used for generating the carrier frequency and the electric source used for generating the optical pulses were synchronized. The phase shifter, ϕ_1, was adjusted in order to maximize the output of the system as obtained in the theory. The output amplitude of the system could be decreased to about zero by adjusting the phase shifter. The ratio between the minimum and the maximum output electrical power due to the adjustment of the phase shifter was about 22 dB. There was no need to dynamically adjust the phase shifter in order to obtain a stable output.

Fig. 5 shows that duplications of the electrical signal spectrum are measured as obtained theoretically in Eq. (3). The frequency difference between two nearby duplications is equal to the repetition frequency of the optical pulses −4 GHz. We note that duplications of the electrical spectrum were also obtained at higher frequencies than the carrier frequency such as 24 and 28 GHz. Fig. 5 indicates that the power of the spectrum replica obtained near the baseband is only about 6 dB smaller than the spectrum replica measured around 20 GHz. For example, the power of the harmonic component measured at a frequency 20 GHz + 10 MHz was equal to −51.6 dB while the power of the corresponding component at a frequency 10 MHz was equal to −57.6 dB. The power difference between the spectrum duplications is in accordance with Eq. (3) and the measured pulse spectrum shown in Fig. 4. For example, the power difference between the spectrum replica at 20 GHz and the spectrum replica at 4 GHz measured at the output of the sampler was equal to 4 dB. Eq. (3) and the measured electrical pulse spectrum shown in Fig. 4 indicate that the difference between the harmonics should be equal to the difference between the powers of the harmonic wave of the pulse spectrum at 4 GHz and the power of the harmonic wave at 4 GHz to 4.5 dB.

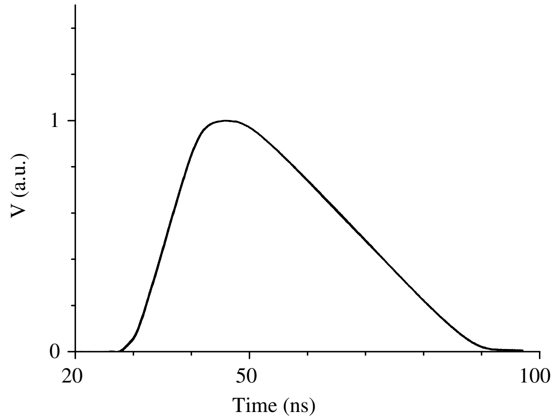

Fig. 6. Comparison between the original electrical signal before mixing with the high carrier frequency (solid line) and the electrical signal at the output of the sampler (dashed line). The carrier frequency of the electrical signal is equal to 18 GHz and the repetition frequency of the optical source is equal to 3 GHz.

Fig. 6 shows the output of the system when the sampled electrical signal was a pulse with a duration of about 35 ns and a carrier frequency of about 18 GHz. The output signal was sampled using a real-time oscilloscope (HP54846B) with a bandwidth of 2.25 GHz, and a resolution of 8 bits. The output pulse was compared to the input pulse. The repetition rate of the optical pulses was 3 GHz. Fig. 6 shows that an excellent agreement was obtained between the input and the output pulses. The difference between the input and the output electrical pulses was only in the last bit. Therefore, the effective number of bits was equal to 7. The difference between the input and the output pulses was not caused by noise since it did not change when the measurement was repeated. Moreover, the difference was also not strongly affected by the input electrical pulse power. Therefore, we believe that the error between the input and the output electrical pulses is caused by the response function of the electrical circuits and is not caused by basic limitations of the optical system. The distortion added by the filter, LPF, in Fig. 3 may be reduced using a filter with an impulse response function that does not contain ripples. However, such a filter may not have a high enough extinction ratio in order to reject the undesired replicas of the output electrical signal. An integrate-and-reset circuit may be used to solve this problem as well as to reduce the distortion due to the detection circuit [7].

3.2. Asynchronous sampling

A schematic description of the system used for asynchronous sampling is shown in Fig. 7. In an asynchronous sampling the optical pulsed source and the sampled signal are not synchronized. The optical pulsed source was the same as used in the system for synchronous sampling, described above. The pulse duration was about 41 ps at a repetition frequency of 3 GHz.

The electrical sampled signal was a pulse with a duration of about 32 ns, a carrier frequency of about 18.950 GHz, and a repetition rate of about 1 MHz. The repetition rate of the optical pulsed source was 3 GHz. The carrier frequency and the sampling rate were chosen in order to ensure that there is not an integer number, n, that fulfill Eq. (5). The frequency replica of the signal spectrum at the baseband region, measured using an electronic spectrum analyzer, had a central frequency of 950 MHz, as predicted by the theory. A bandpass filter, BPF2, with a center frequency of 800 MHz and a 3-dB bandwidth of 400 MHz was used to filter the signal spectrum replica in the baseband region. An envelope detector, composed of a resistor, R and a capacitor, C with a time constant of about $1/RC = 60$ MHz, removed the low carrier frequency −950 MHz. The output signal was sampled using a real-time oscilloscope (HP54846B) with a bandwidth of 2.25 GHz, and a resolution of 8 bits. Fig. 8 shows a comparison between the input pulse and the output electrical pulses. The figure shows that an excellent agreement was obtained between the input and the output pulses. The difference

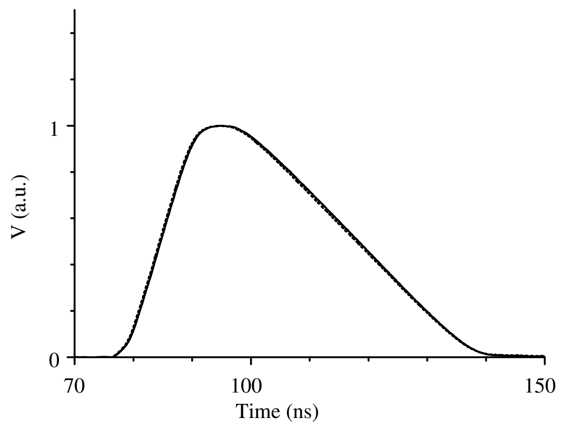

Fig. 8. Comparison between the original electrical signal before mixing with the high carrier frequency (solid line) and the electrical signal at the output of the sampler (dashed line). The carrier frequency of the electrical signal is equal to 18.950 GHz and the repetition frequency of the optical source is equal to 3 GHz.

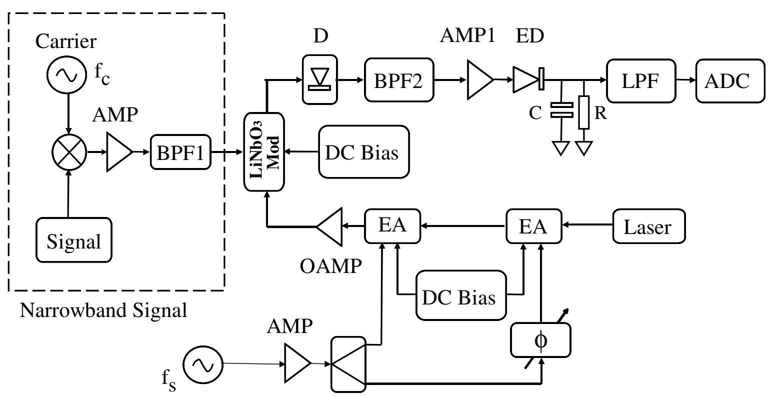

Fig. 7. Schematic description of the system used for asynchronous sampling. AMP and AMP1 are electrical amplifiers, D is an optical detector, ED is an electrical diode, EA is an electroabsorption modulator, OAMP is an optical amplifier, LPF is an electrical low pass filter, BPF1 and BPF2 are electrical bandpass filters, ϕ is a phase shifter, The electrical signal is obtained by mixing a narrowband signal with a high frequency carrier at a frequency of 18.950 GHz. An envelope detector implemented by a diode, a resistor R, and a capacitor, C, was used to obtain the amplitude of the generated replica around a frequency of 950 MHz.

between the input and the output electrical pulses was only in the last bit. We believe, as explained in the case of synchronous sampling, that the error in the measurement was cased by the response function of the electrical circuits and was not caused due to basic limitations of the system.

The use of the envelope detector causes that the phase relation between the signal envelope and the signal carrier frequency is lost. Since the bandwidth of our real-time oscilloscope was 2.5 GHz, we were also able to sample directly the signal replica around a carrier frequency of 950 MHz without using the envelope detector. In this case the signal could be reconstructed without loosing the relative phase between the signal and the carrier frequency. The electrical loss of the sampled signal, as measured at the input of the electrical amplifier (AMP1), was about 34 dB. This result is mainly caused by the conversion of the electrical signal into an optical signal and back into an electrical signal and therefore it is comparable to the loss in commercial optical fiber systems that are used to transmit microwave signals $\sim$30 dB.

The spurious free dynamic range of the system was measured by supplying the input of the modulator two continuous-wave electrical signals with a power of -2.5 dB at frequencies 18.840 and 18.841 GHz. The resolution bandwidth and the video bandwidth of the electrical spectrum analyzer were both equal to 15 kHz. The intermodulation signals measured at frequencies of 842 and 839 MHz were about 3 dB stronger than the noise level -77 dB. The spurious free dynamic range obtained in this case was more than 61 dB. The measured spurious free dynamic range indicates that the effective number of bits of the system can be as high as 10 bits.

4. Conclusions

We have demonstrated an optical system for sampling narrowband microwave signals with a high carrier frequency, based on optical pulses generated by two electroabsorption modulators. Such an optical source is more compact, reliable, integrable and inexpensive compared to fiber lasers that were previously used in optical samplers. A theoretical model, based on sampling theorem, gives the required conditions to reconstruct the sampled signal without an error. When the carrier frequency of the sampled signal and the optical pulses are synchronized, the sampling rate of the electronic analog to digital converter in the system can be reduced by a factor of two. Synchronous and asynchronous sampling of electrical signals with a carrier frequency up to 20 GHz were demonstrated experimentally and were compared to the theoretical results. The optical sampling of narrowband signals may enable to reduce the size, the power consumption, and the price in comparison to electronic samplers. Moreover, the optical sampling enables to improve the performance and especially the frequency regime of the carrier frequency of the sampled signal. The technique described in this work can be directly employed to sample narrowband signals with a carrier frequency of more than 40 GHz using commercial optical devices.

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