Incoherent photonic processing for chirped microwave pulse generation

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***Abstract*—We propose and experimentally demonstrate a fully reconfigurable generator of chirped microwave pulses based on the processing of an incoherent optical signal by means of a dispersive element with a non-uniform optical spectral shaping. The system performance has been proved by the generation of different chirped microwave pulses. Different capabilities of the system has been experimentally demonstrated as frequency tunability and TBWP control by means of the dispersive element and optical source power distribution. Furthermore, the possibility for generating chirped microwave pulses with positive and negative chirp characteristic has been shown achieving similar chirps in terms of magnitude but opposite sign. For it, chirp characteristic is introduced by the proper shaping of the signal power distribution of the optical source.**

***Index Terms*— Chirped pulses, Incoherent optical signal, Dispersive element, Reconfigurability, Instantaneous frequency, Chirp sign.**

I. INTRODUCTION

PHOTONIC generation of microwave/millimeter-wave signals has been a field of interest in the last years due to its important impact on applications such as radar systems, wireless communications, medical image processing, software defined radio or modern instrumentation where high frequency and large bandwidth signals are required [1]. The use of microwave photonics (MWP) technology in microwave signal generation offers new features and improved performance related to the inherent advantages of operating in the optical domain such as low losses, high bandwidth, immunity to electromagnetic interference (EMI) and, especially in this case, also the possibility of tuning and reconfiguration [2, 3].

Different techniques have been developed to generate a wide variety of signals using schemes from a single electronic oscillator to an arbitrary waveform generator. For instance, high spectral purity microwave signals can be generated without a reference microwave signal by means of opto-electronic oscillators (OEO) [4]. Besides, other signals such as ultra-wideband (UWB) can be achieved by means of more flexible schemes including MWP arbitrary waveform generators [5]. More specifically, one of these interesting signals corresponds to the chirped microwave pulse with the main characteristic of having a frequency variation along the time duration pulse which involves a large bandwidth signal processing. Among the diverse applications where chirped microwave pulses are used, spread spectrum communications, pulsed compression radars or tomography for medical imaging [6-8] can be highlighted.

In this context, approaches based on different photonic techniques to generate chirped microwave pulses have been reported. Spectral shaping of coherent optical sources and wavelength-to-time mapping is one of the most popular technique [9, 10]. In this case, chirped pulses generation can be implemented by two different methods. In the first one, the spectrum of an ultrashort optical pulse is shaped using a spectral filter with a non-uniform free spectral range, and the spectrum-shaped pulse is then linearly mapped to the time domain in a dispersive element [9]. In the second one, chirped pulses are generated using a spectral filter with a uniform free spectral range followed by a dispersive element with higher order dispersion for non-linear wavelength-to-time mapping [10]. Other technique which makes use of coherent optical sources to generate chirped microwave pulses is the unbalanced temporal pulse-shaping [11]. In this case, an ultrashort optical pulse is processed by a Mach-Zehnder modulator and two dispersive elements with dispersions of opposite sign but not identical in magnitude. All previous techniques are based on the processing of coherent sources limiting the flexibility to reconfigure the output waveform.

Recently, we theoretically analyzed [12] and experimentally demonstrated [13] the generation of chirped pulses based on the processing of incoherent optical signals by means of non-linear dispersive elements. The use of incoherent sources permits to increase the reconfigurability of the generated pulses in comparison to coherent techniques. In fact, waveform reconfigurability in terms of envelope, central frequency and chirp magnitude was experimentally proved [13]. However, chirp sign is fixed by the dispersion parameters of the non-linear dispersive element limiting the control for a fixed magnitude value.

In order to overcome this lack of flexibility, we propose a technique for generating chirped microwave pulses based on the processing of incoherent optical signals by a dispersive element in which the control of the chirp characteristic of the pulse is achieved by means of the non-uniform optical shaping. Particularly, the generated waveforms are given by the spectral power profile of the processed incoherent optical signal. In order to evaluate the feasibility of the proposal,

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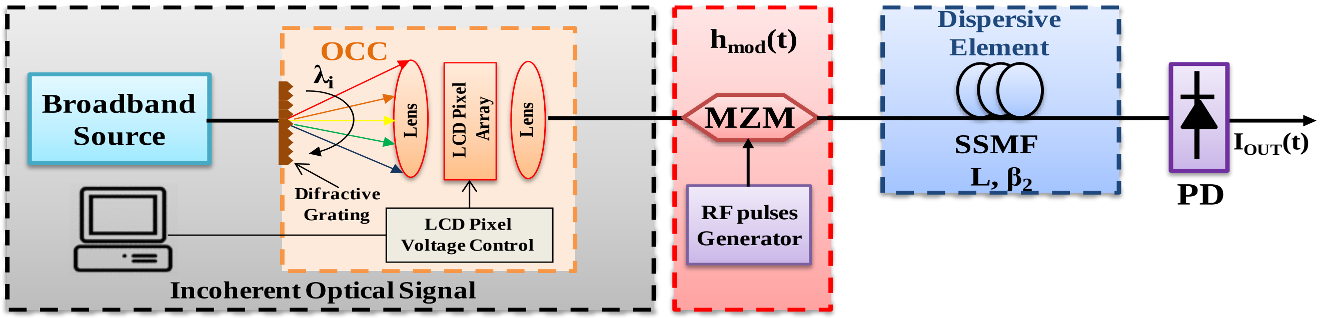

Fig. 1. Experimental setup of chirped microwave pulse generator by means non-uniform optical spectral shaping and dispersive element processing.

different chirped pulses have been generated. In this sense, frequency tunability, TBWP and, most importantly, chirp characteristic sign control have been experimentally proved.

II. System Performance

The experimental setup of the proposed chirped microwave pulse generator is shown in Fig. 1. According to [12], this approach can be considered as an incoherent frequency-to-time mapping when the second-order dispersion is neglected. We consider a broadband optical source which is given by the power spectral density S(ω), centered at ω_0, such that the optical field of the light source describes a stationary random process. Each optical frequency in the broadband spectrum emitted by the optical source is modulated by means of a modulator with impulse response $h_{mod}(t)$. Then, the modulated signal is launched into an optical processor which is determined by the first-order dispersion (φ_2) evaluated at ω_0. In this case, average intensity output is given by [12]:

$$I_{out}(t)=\frac{I_o}{2\pi\varphi_2}S(\omega=t/\varphi_2)\otimes\left|h_{mod}(\omega_o,t)\right|^2 \qquad (1)$$

where the first term corresponds to a time-domain scaled version of the power spectrum S(ω) and the second term $h_{mod}(\omega_0,t)$ represents the output pulse when a monochromatic source is considered. Note that, apart from the frequency-to-time mapping proccess, the generated waveform will be also given by $h_{mod}(t)$.

For generating the incoherent optical signal we use a Broadband Source (BBS) and an Optical Channel Controller (OCC) (Peleton QTM100C). The BBS has a total optical bandwidth of 80 nm centered around 1550 nm (λ_0). The OCC employs a diffractive grating and a voltage-controlled liquid crystal (LCD) pixel array to perform the attenuation function for 0.8 nm spaced channels with λ_i central wavelength according to the ITU grid. The total number of channels considered is 48 with 20 dB of maximum attenuation. In this way, a computer-control of the OCC permits to perform the spectral density power of the generated incoherent optical signal. The optical signal is launched into a Mach-Zehnder Modulator (MZM) (Avanex SD40) to be modulated by a Radio Frequency (RF) pulse coming from an electrical signal generator (Anritsu MP1800A). The 3-dB bandwidth of MZM is 30 GHz. The electrical generator is configured with a bit rate of 12.5 Gbps using a pattern of one "1" and one hundred and twenty-seven "0". Therefore, the repetition rate is close to 97.6 MHz and the pulse width is 80 ps. The modulated optical

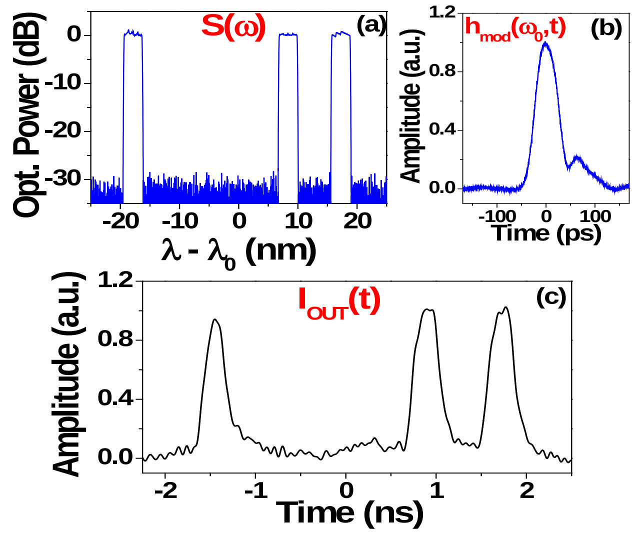

Fig. 2. (a) Spectrum of the optical source used, (b) $h_{mod}(\omega_0,t)$ and (c) corresponding waveform $I_{OUT}(t)$.

signal is processed by means of a dispersive element. In our experimental setup, we have used a standard single mode fiber (SMF-28) link of length L and with a first order dispersion parameter β_2 = -22 ps^2/km around 1550 nm. The total first-order dispersion induced in the system is $\varphi_2 = \beta_2 L$. After the processing by the dispersive element, the generated electrical signal is obtained by means of a 50 GHz Photodetector (PD). Finally, a sampling oscilloscope (Tektronix DSA8200) has been employed to measure the generated waveform.

In order to show the feasibility of the system, the incoherent optical signal power profile is set according to the shown in Fig. 2(a). In this case three groups of four OCC channels have been activated at different wavelength. The optical signal is propagated through a 5 km (φ_2 = -110 ps^2) standard single mode fiber link. Fig. 2(b) shows the generated waveform retrieved by the sampling oscilloscope. As can be observed, the generated waveform presents three positive lobes according to the optical signal power spectral density. Therefore, the generated waveform can be controlled by the proper adjustment of the optical signal distribution using the OCC. Note that a waveform softened from square forms of the optical source power density is achieved due to the contribution of the modulator impulse response according to Eq. (1). All the experimentally generated waveforms are retrieved by the sampling oscilloscope using an average factor of 10 in order to reduce the effects of the system noise.

III. Chirped Microwave Pulses

A. Generation

In this section, we show the capability of the proposed technique for generating chirped microwave pulses. As we have previously mentioned, a microwave chirped pulse is a waveform whose instantaneous frequency is varying along the pulse duration. The most characteristic parameter of the chirped pulses corresponds to the Time-Bandwidth Product (TBWP) parameter which is defined as the product of the full-width time duration of the pulse at half-maximum (T_{FWHM}) and the differential value of its frequency variation.

Fig. 3 depicts an example of negative chirped microwave pulse. In this case, a fiber link of L = 3.5 km (φ_2 = -77 ps^2) is considered. Fig. 3(a) shows the spectrum of the optical source when a profile is performed using OCC by enabling properly the corresponding channels. The power of all activated channels has been adjusted to be similar by the attenuation control. In Fig. 3(b), the generated negative chirped pulse and its corresponding instantaneous frequency are shown. The waveform, which is according to the optical signal power profile, has a temporal duration of 2.16 ns. The instantaneous frequency has been obtained by the reciprocal of the time period. As can be observed, it shows a negative chirped behavior from 1.50 to 5.59 GHz. According to the pulse duration and frequency variation the TBWP is 8.83.

As it is known, the use incoherent broadband sources could be noisy for the system. In our case, the upper limit of the noise figure for all RF frequency range is close to 32 dB in all experimental waveforms obtained in the paper. In literature, we can found methods to reduce that noise such as the use of an incoherent broadband light source based on cascading an superluminiscent laser diode and an semiconductor optical amplifier [14] or the use of a suitable photodetection scheme based on differential configuration [15].

B. Frequency Tunability and TBWP control

Next, we show the possibility of tuning the generated waveform frequency and controlling the TBWP. Firstly, the

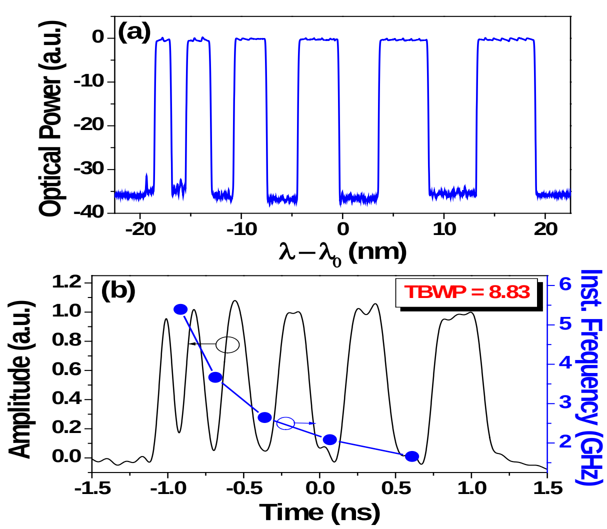

Fig. 3. (a) Spectrum of the optical source used and (b) corresponding waveform (black line) and instantaneous frequency (●) and for a SMF link of L = 3.5.

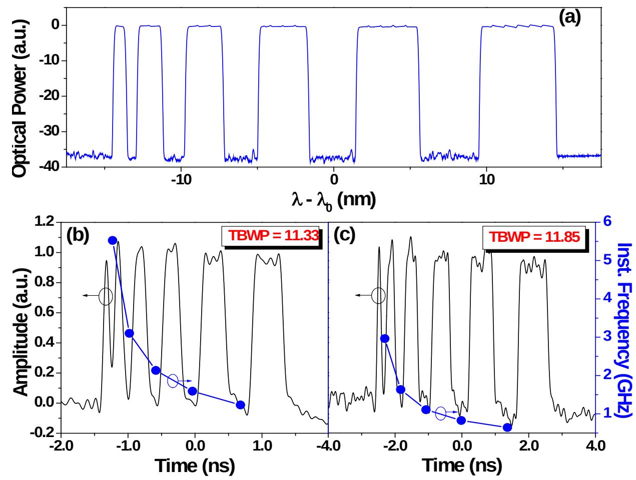

Fig. 4. (a) Optical signal power distribution. Waveform (black line) and instantaneous frequency (●) for (b) L = 5 km and (c) L = 10 km.

OCC is adjusted to perform a pattern which gives the optical signal power distribution shown in Fig. 4(a). For an optical fiber link length L = 5 km (φ_2 = -110 ps^2), the generated waveform and its corresponding instantaneous frequency can be observed in Fig. 4(b). In this case, the waveform temporal duration is around 2.69 ns and the instantaneous frequency varies from 1.35 to 5.56 GHz achieving a TBWP of 11.33. In the following, maintaining the same optical signal power distribution, an optical fiber link length of L = 10 km (φ_2 = -220 ps^2) is selected. Fig. 4(c) shows the generated waveform and the corresponding instantaneous frequency. For this case, the frequency range varies from 0.66 to 2.97 GHz and the temporal duration has been increased up to 5.13 ns given a TBWP of 11.85. Comparing with 5 km results (Fig. 4(b)), the instantaneous frequency range has been modified to the half and the waveform duration has been doubled according to the length of the fiber link used (10 km). Nevertheless, the TBWP has been quasi maintained. Therefore, the frequency range of the generated waveform can be controlled through the dispersive element maintaining the characteristic in terms of TBWP.

On the other hand, comparing Fig. 3(b) and Fig. 4(b), we can observe as the TBWP has been increased from 8.83 (3.5 km) to 11.33 (5 km) when the total dispersion induced in the system is larger. Nevertheless, the instantaneous frequency variation is in reality maintained as a consequence of optical signal power distribution readjustment. Note as the system restrictions in terms of frequency range and TBWP due to channels bandwidth of the optical source can be overcome by commercial optical waveshapers with higher resolutions. Moreover, by commercial optical shapers with higher resolution, larger frequencies bandwitdth and linearly chirped microwave waveforms could be generated.

C. Chirp sign control

Finally, we show the capability of the proposed system to generate pulses with positive chirp by the proper adjustment of the optical source power distribution. Fig. 5 depicts different microwave chirped pulses which have been generated as a counterpart of those shown in Fig. 4. For both cases, the OCC has been adjusted to perform the optical power spectral distribution shown in Fig. 5(a). Note as this power distribution corresponds to the mirrored version of the one shown in Fig. 4(a). The generated waveform and its corresponding instantaneous frequency when an optical fiber link length of 5 km is considered can be observed in Fig. 5(b). Again, the generated waveform is according to the optical source power distribution with a temporal duration of 2.81 ns. The instantaneous frequency obtained has been also represented in Fig. 5(b) with a range between 1.20 and 5.22 GHz. In this case, the frequency is increasing with waveform duration showing a positive chirp characteristic in contrast to Fig. 4(b). The TBWP achieved is around 11.30. Finally, the results corresponding to a 10 km fiber link length are shown in Fig. 5(c). In this case, the temporal duration of the pulse is 5.30 ns and the instantaneous frequency varies from 0.60 to 2.75 GHz giving a TBWP of 11.39. Note that, comparing the results shown in Fig. 4 and 5 some slight differences can be observed in terms of temporal duration and instantaneous frequency range. Our previous work [12, 13] suggests that the optical signal could be affected by the nonlinear effects of the fiber link. Nevertheless, the consideration of this fact is far from the purpose of the approach presented in this paper which is focused in the chirp reconfigurability. Therefore, by means of the proper adjustment of the OCC, we have proved the possibility of obtaining a chirped pulse with similar frequency range and TBWP but with opposite chirp sign.

IV. Conclusions

In conclusion, we have proposed and experimentally demonstrated a technique for chirped microwave pulse generation based on the processing of an incoherent optical signal using a dispersive element in which the chirp characteristic is introduced by means of the non-uniform shaping of the optical signal. The feasibility of the proposed system to generate chirped microwave pulses has been experimentally proved by means of the synthesis of different pulses. Also different capabilities of the proposal have been demonstrated in terms of frequency tunability and TBWP control by the selection of the dispersive element and the proper adjustment of the optical signal power profile. Therefore, we have proved as our system can be adapted for a fully reconfigurable chirped microwave pulses generation. The use of incoherent optical sources permits to increase the flexibility to reconfigure the generated waveform in contrast to coherent techniques [9, 10]. The main novelties of our approach can be summarized as follows: (a) The consideration of the input electrical pulse opens the possibility of using it to control the generated waveform. For our case, the signals obtained experimentally have been softened from square form of the optical source power spectral density due to $h_{mod}(t)$. (b) In contrast to our previous work [13], the control of the chirp sign for being both positive and negative is achieved by means of the proper adjustment of the optical source. (c) The use of incoherent optical sources and dispersive elements permits to aim a full and independent reconfigurability of the central frequency, time-bandwidth product, envelope and chirp sign in comparison to fixed coherent techniques [9-11].

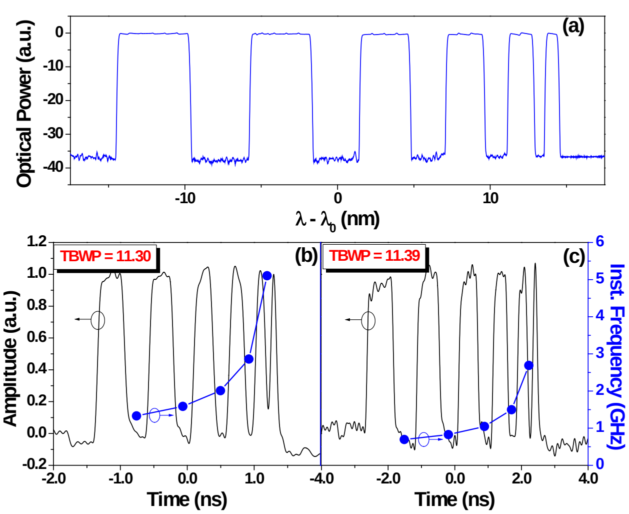

Fig. 5. (a) Optical signal power distribution for positive chirped pulses. Waveform (black line) and instantaneous frequency (●) for (b) L = 5 km and (c) L = 10 km.

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