20 GHz arbitrary radio-frequency waveform generator based on incoherent pulse shaping

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Abstract: We demonstrate a new approach of photonically assisted radio-frequency (RF) waveform generation using a spectrally incoherent light source. The system is based on the so-called generalized frequency-to-time mapping operation. In this work, external modulation of the source is done by concatenating two electro-optic Mach-Zehnder modulators properly biased to achieve short pulse gates which allow for broad bandwidth electrical signals. Also, the spectral shaping stage is performed prior to O/E conversion. A detailed theoretical analysis demonstrates that even in this case the frequency-to-time mapping is preserved. The key is that the noise level is greatly reduced because the amplitude filter serves as noise rejecter. Experimental results show up to ~20 GHz electrical bandwidth signals using 10 Gb/s standard telecommunication equipment with the nice feature of repetition rate control on the generated electrical waveform.

OCIS codes: (060.0060) Fiber optics and optical communications; (070.6020) Signal processing; (060.5625) Radio-frequency photonics; (320.5540) Pulse shaping

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1. Introduction

The generation of arbitrary electromagnetic signals with 1-50 GHz frequency content is a current challenge for purely electronic systems. The ability to generate such broad bandwidth signals can have a positive impact on high-speed wireless communication systems, as well as finding interesting applications in radar, remote sensing and electronic equipment test measurements [1]. Thanks to the inherent broadband nature of photonics, all-optical approaches for arbitrary waveform generators (AWGs) can achieve easily this frequency range [2-7]. Actually, the upper limit in terms of the analog radio-frequency (RF) bandwidth that can be achieved with photonic approaches is only limited by the optoelectronic (O/E) conversion bandwidth.

Currently, there exist many solutions for photonically assisted AWGs [2], but those relying on spatial light modulator (SLM)–based pulse shaping offer a better performance in terms of reconfigurability [3-7]. Among these solutions, the wavelength-to-time mapping technique [4] has the potential for a broader range of operation because it can easily achieve the low-frequency regime of RF bandwidth. In this technique, the spectrum of a coherent signal (e.g., a mode-locked laser) is manipulated in a Fourier-transform pulse shaper (FTPS). Later, the synthesized energy spectrum is mapped into the time domain just by stretching the pulse in a dispersive medium. A physical interpretation of this phenomenon can be done in terms of the space-time analogy, since it is the temporal equivalent of the Fraunhofer (or far-field) diffraction [8].

Recently, we proposed the incoherent version of this last approach. Specifically, we pointed out that this setup constituted a new regime for pulse shaping [9] and showed that it could be potentially used for RF-AWG applications [6]. In our original configuration, the energy spectrum of an incoherent broadband signal, e.g. amplified spontaneous emission (ASE) radiation, is manipulated in an FTPS. Note that since the spectral components of the light are fully uncorrelated, light is not pulsed at this stage. However, by using an external modulator with a pulse gate longer than the coherence time of the light, the spectral components become partially correlated with no significant modification of the amplitude spectral profile. Later, after stretching the pulse in a dispersive medium, an incoherent frequency-to-time mapping occurs: the synthesized energy spectrum of the light source is mapped into the averaged intensity profile. After optical-to-electrical (O/E) conversion, the desired RF signal is obtained. The physical mechanism of this setup can be understood in the framework of the space-time analogy too. It corresponds to the temporal counterpart of the van Cittert-Zernike theorem [10]. It is important to note that, unlike in the coherent approach, the incoherent setup performs the shaping for the average intensity profile. In practical terms, this means that there are uncontrolled variations from single pulse realizations. Thus, this technique may become more practical for optoelectronic equipment measurements, where averaged measurements of spectral transfer functions are usually performed. Recently, we have reported the first experimental evidence of this technique. We achieved ~ 0-10 GHz electrical signals using a single electro-optic modulator (EOM) driven with a 60 ps impulse generator as the external gate [11]. This approach offers the possibility of electrical tuning of the repetition rate of the generated RF waveform. This feature is not possible with its coherent counterpart because the repetition rate is fixed by the cavity of the mode-locked laser.

In order to reduce the temporal variations of the individual signals, any simple method to reduce the noise while keeping the high bandwidth generation would be welcome. In this work, we introduce two modifications with respect to our previous system that provide several additional advantages. First, we have generated a shorter pulse gate (around 25 ps) by concatenating two EOMs. This solution permits to achieve electrical signals with higher bandwidth, while still preserving the repetition rate tuning. Second, we placed the FTPS immediately before the photodetector, in contrast to before the optical gate as in our previous work. In this way, we reduce the ASE noise from optical amplification. A comparative experimental study between the previous and the current configuration is also presented. In global, ~ 20 GHz RF bandwidth signals have been successfully achieved for the first time with an incoherent approach.

2. Experimental setup

2. 1 Description

A schematic view of the proposed photonically-assisted AWG is shown in Fig. 1. The output from an Erbium-doped fiber amplifier (EDFA) is used as an ASE source. The light is polarized and modulated with a sequence of two $LiNbO_3$ Mach-Zehnder 10 Gb/s EOMs. The first one is biased at V_π and driven with a 12.5 GHz clock signal. The other EOM is biased at quadrature and driven with a data pattern at 12.5 Gb/s. We can easily select a single overdriven pulse just by launching a data sequence comprising a single "1" data bit followed by *n* "0" data bits. In this way the resulting repetition rate is 12.5/*n* GHz. Working with optimal biasing conditions, the optical pulse gate is nearly Gaussian shape with a 25 ps full-width at half maximum (FWHM) temporal duration. The average optical power is -22 dBm with $n = 40$. Later, light is stretched in a conventional single-mode fiber (SMF) with a 2 km length and a group-velocity-dispersion (GVD) coefficient $\beta_2 = -21.68$ ps^2/km. We verified that this is the optimal length to achieve the higher radio-frequency bandwidth. In other words, this is the minimum fiber length required to map into the time domain the minimum spectral feature available in the optical spectrum of the source. After stretching, light is amplified with an EDFA and the spectrum of the radiation is modified with a commercially available FTPS (Peleton, QTM). This device is primarily designed as a dense-wavelength division multiplexing (D-WDM) channel controller. Although phase spectral tuning is not possible, it offers amplitude control with 0.1 dB accuracy in a 20 dB range over the whole C-band with 100 GHz resolution and insertion losses as low as 6 dB. System parameters are chosen such that

$$\Delta\omega >> \sigma_\omega \quad \text{, and} \tag{1a}$$

$$\Phi_2 >> (2\pi\sigma_\omega\Delta\omega)^{-1} \tag{1b}$$

where $\Delta\omega$ and σ_ω are the spectral widths of the filtered ASE source and the modulator, respectively, and $\Phi_2 = \beta_2 z$ is the group-delay-dispersion (GDD) amount of the fiber. The above selection ensures that, at this stage, the so-called incoherent frequency-to-time mapping takes place, i.e., the averaged intensity profile at the output is a scale version of the spectral shape synthesized in the channel controller [6]. Finally, O/E conversion is done with a photodiode with either 20 or 30 GHz bandwidth.

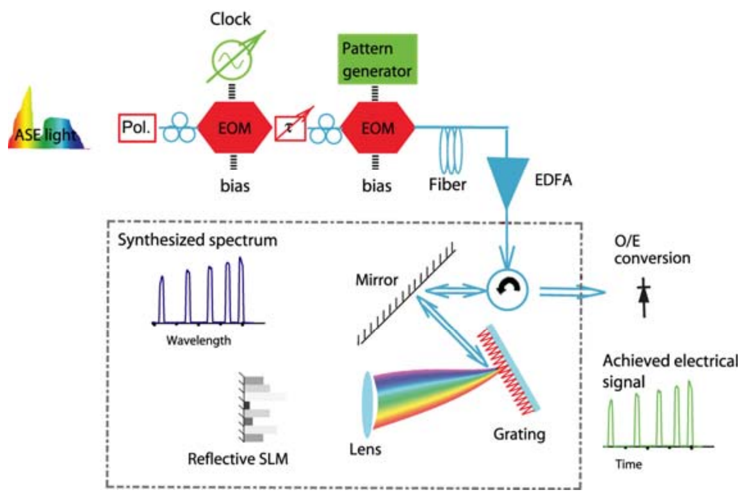

Fig. 1. Proposed experimental setup

2. 2 Analysis of the channel controller position

Let us now describe how the channel controller affects the averaged light intensity distribution. For the sake of completeness, let us remind that by placing the channel controller *before* the modulation stage, the averaged output intensity results [12]

$$I_{out}(t) = \int d\omega\, S(\omega) |F(\omega)|^2 \left| \int d\omega' M(\omega' - \omega) \exp\left(i \Phi_2 \omega'^2 / 2\right) \exp(-i\omega' t) \right|^2 \quad , \qquad (2)$$

where $S(\omega)$ is the energy spectrum of the ASE source centered at the baseband, $F(\omega)$ is the complex transfer function of the channel controller, and $M(\omega)$ is the spectral complex transfer function of the external modulator. When Eqs. (1a) and (1b) are satisfied, the output averaged intensity is

$$I_{out}(t) \approx S(t/\Phi_2) \left| F(t/\Phi_2) \right|^2 \quad , \qquad (3)$$

so that the incoherent frequency-to-time mapping takes place (see Ref.[6]).

However, by placing the channel controller *after* the modulation stage (note that it does not matter before or after the fiber as it behaves as a spectral filter), the averaged output intensity becomes

$$I_{out}(t) = \int d\omega\, S(\omega) \left| \int d\omega' M(\omega' - \omega) F(\omega' - \omega) \exp\left(i \Phi_2 \omega'^2 / 2\right) \exp(-i\omega' t) \right|^2 \quad . \qquad (4)$$

Thus, by comparing Eq. (2) with Eq. (4), we observe that, in general, the averaged output intensity is dependent of the spectral phase profile in $F(\omega)$. However, taking into account Eq. (1a), Eq. (4) can be approximately rewritten as in Eq. (2), and therefore the incoherent frequency-to-time mapping expressed by Eq. (3) is also achieved. The key of the new placement of the filter is that now part of the ASE noise from the fiber amplifier will be rejected, and therefore the new approach is expected to be offer lower noise. A comparative study will be presented in Section 4.

3. Experimental results

In order to highlight the capabilities of the new configuration for the generation of high-bandwidth electrical signals, we have generated two different waveforms with the shortest temporal feature in the time domain. The optical spectra measured after the two EOMs is displayed in Fig. 2(a) and (d), respectively. Figure 2 (b) shows the resulting waveform in the time domain of a synthesized burst and Fig. 2(c) its corresponding RF spectrum. Here, the minimum temporal feature size is synthesized by turning on individual channels in the channel controller with 100 GHz optical resolution. The signal in the time domain, displayed in linear scale, was obtained with a 30 GHz bandwidth photodiode and sampling oscilloscope operating in sample mode with 1s persistence time. The RF spectrum was measured with a 21.6 GHz electrical spectrum analyzer (ESA) using a 40 GHz photodiode followed by an electrical amplifier. As can be seen, the RF spectrum spans up to 20 GHz. This bandwidth is possible thanks to the short gate produced with the 2 EOMs, in contrast to the optical device in [11] where only 10 GHz was achieved. The red line in Fig. 2(c) indicates the expected theoretical spectrum from calculating the averaged intensity profile shown in Fig. 2(b). The discrepancy is attributed to the non-flat gain response of the electrical amplifier and the fact that the measured profile in the time domain was obtained with a different photodiode (i.e., in terms of bandwidth) than the one employed for the spectral measurements.

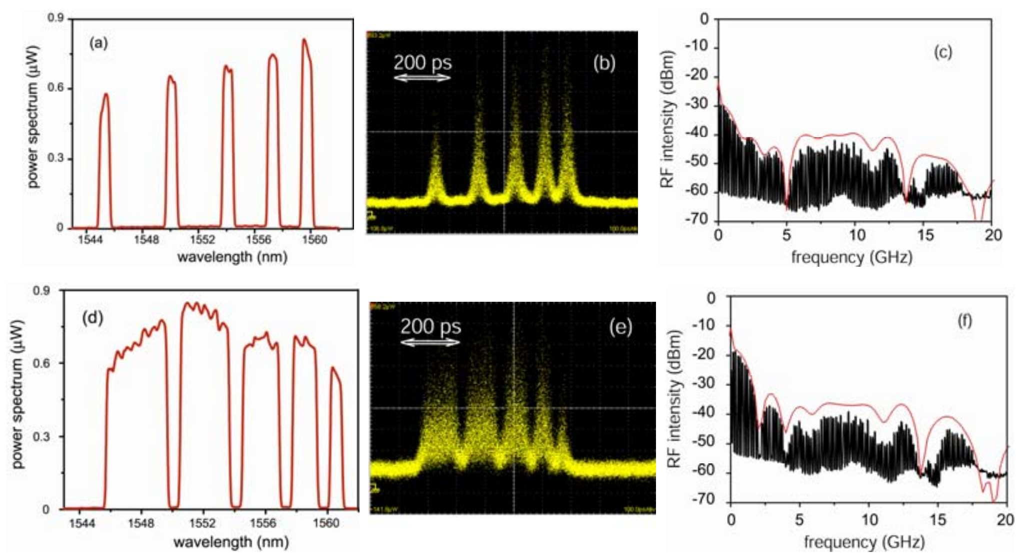

Fig. 2. Generation of two different signals with minimum temporal feature. (a) and (d) show the synthesized optical spectrum, the time domain acquisition is shown in (b) and (e), and their corresponding RF spectra in (b) and (d). See text for setting parameters.

Figures 2(e) and 2(f) show the time and frequency domain measurements of a different waveform whose minimum temporal feature size is synthesized by turning "off" single channels of 100 GHz optical resolution in the spectral shaper (carving dips in the time domain), as can be appreciated from the optical spectrum measurements in Fig. 2(d). The same setting parameters as in Fig. 2(b) and 2(c) were used. The main noise sources are the thermal noise in the photodiode and the unfiltered beating noise arising from the ASE. These noise contributions can be partially reduced using lower bandwidth photodiodes, as we will show in the next Section.

4. Comparison of system configurations

It is the aim of this Section to show that the experimental setup displayed in Fig. 1 offers the best capabilities in terms of noise. Figure 3(a) displays the same waveform as in Fig. 2(b), but this time using a 20 GHz photodiode. The simplified scheme (corresponding to Fig. 1) is shown in the upper part of the figure. The waveform is cleaner because part of the broadband thermal noise spectrum is electrically filtered by the lower bandwidth photodiode. In Fig. 3(b) we illustrate the same waveform but using the original configuration demonstrated in [11] where the channel controller is placed before the modulation stage. In this configuration, the averaged optical power at the output of the external modulator is -39.6 dBm. A second amplifier is used to increase the power before transmission in the fiber; however, the extra ASE noise that it introduces does not map into the time domain. With the configuration presented in Fig. 1, the channel controller acts itself as a spectral filter for ASE noise, and therefore constitutes the best possible configuration for this modulation scheme.

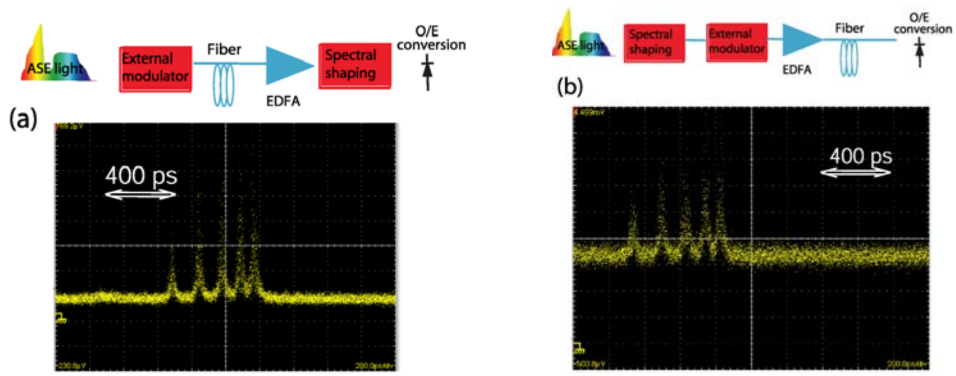

Fig. 3. Comparative of the chirped sinusoidal signal displayed in Fig. 2 (a) for the different configurations that are schematically sketched in the upper part. Case (a) corresponds to Fig. 1, and (b) to the original configuration of incoherent pulse shaping. A 10 times reduction of the floor level is measured.

5. Conclusions

We have proposed and experimentally verified an arbitrary waveform generator based on the incoherent pulse shaping technique. As pulse gate we have concatenated two 10 Gb/s EOMs. In this way a pulse gate with ~ 25 ps FWHM is achieved. This allowed us to obtain ~0-20 GHz RF signals. More importantly, we have shown that by placing the FTPS *after* the external modulation the incoherent frequency-to-time mapping is preserved. This key configuration permits to remove part of the extra ASE noise from the secondary fiber amplifier. We have provided a comparative study that shows clearly the new advantageous features.

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