Adaptive RF-Photonic Arbitrary Waveform Generator

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***Abstract*—Optical and radio-frequency waveforms with wide-band arbitrary modulation are generated using spectral shaping of a supercontinuum source followed by wavelength-to-time mapping. Adaptive computer control is used to mitigate the nonideal features inherent in the optical source and in the spectrum modulation process.**

***Index Terms*—Microwave generation, signal generators, signal synthesis.**

I. Introduction

THE ABILITY to generate high frequency and complex waveforms is central to many commercial and military applications. Arbitrary waveform generators (AWGs) are used in testing of communication receivers. The military relies on a sophisticated and agile radio-frequency (RF) environment in applications such as low-probability-of-intercept (LPI) radar. Hybrid LIDAR-RADAR requires a wide-band amplitude-modulated optical carrier in order to attain high range resolution [1]. The development of electronic AWGs is hindered by the limited speed and dynamic range of digital-to-analog conversion (DAC) technology, which has its root in the tradeoff between the transistor speed and dynamic range. In this letter, we introduce an all-optical approach to generating arbitrary waveforms that free of fundamental electronic limitations.

II. Approach

The proposed photonic AWG is illustrated in Fig. 1. A wide-band optical pulse is spectrally shaped by a spatial light modulator (SLM) and then passed over a dispersive medium such as an optical fiber. Dispersion performs wavelength-to-time mapping converting the spectral function to an identical temporal waveform. Hence, any arbitrary temporal waveform can be generated by modulating the spectrum of the broad-band optical source. For a given spectral waveform, the frequency of the temporal waveform is determined by the amount of dispersion. Implemented using presently available commercial components, the system's maximum frequency will be limited by the photodetector. We use an SLM array to shape the spectrum of the broad-band pulse. SLMs have been successfully used by Weiner for femptosecond pulse shaping via spectral phase control [2]. The approach was a coherent Fourier transform process where a temporal waveform was synthesized through manual control of optical phase. The approach described here is incoherent. Instead of performing a Fourier transform, we create the desired temporal waveform by direct wavelength-to-time mapping. Another group recently demonstrated a technique for electrical signal generation by creating a pulse sequence through a space-to-time mapping which is converted into an analog signal after a photodetector [3]. Our current method differs from our previous work on waveform generation [4] in that an SLM is used for spectrum modulation instead of an arrayed waveguide grating. This offers a higher degree of control over the spectral shaping. The present work is also different from those in [1] and [2] through the use of an adaptive computer control that mitigates the nonideal characteristics of the optical source and of the spectrum modulation process.

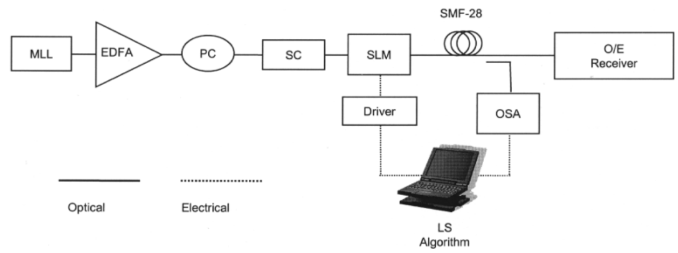

Fig. 1. Block diagram of AWG. MLL: mode-locked laser. PC: polarization controller.

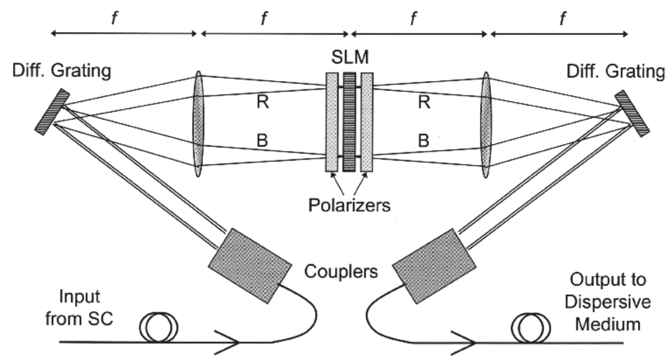

Fig. 2. Experimental setup of SLM in a 4-f grating and lens configuration [2].

A broad-band optical source is produced by amplifying the output of a modelocked laser and passing it through a supercontinuum (SC) fiber [5]. Optical nonlinearities in the SC fiber cause broadening of the optical spectrum to over 100 nm. Next, a spatial light modulator filters and shapes the spectra according to the desired optical waveform. We use a 4-f grating and lens apparatus such that each wavelength will be focused and incident normal onto the SLM plane, shown in Fig. 2, [2], [6]. The grating has 1000 lines/mm and lens focal length is 20 cm. The distances between gratings and lenses are set for zero net temporal dispersion [7]. Two high extinction polarizers are placed in parallel before and after the liquid crystal to achieve amplitude modulation. As illustrated in Fig. 3, the pixels are independently

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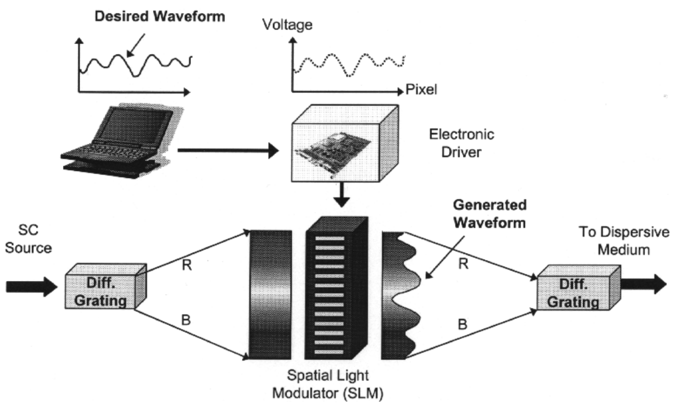

Fig. 3. Desired waveform is sent to an electronic driver which determines the voltage for each liquid crystal pixel. The SLM performs spectral shaping to a dispersed broad-band pulse.

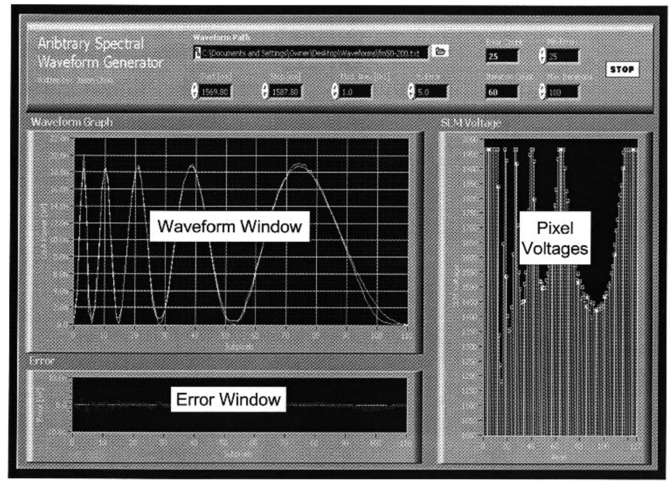

Fig. 4. The system's graphical user interface (GUI).

controlled by a computer-operated electronic driver which manipulates the voltage, and thus the attenuation, to gray-scale accuracy. The 128-pixel dual-layer SLM was manufactured by CRI Inc. A maximum optical dynamic range of 30 dBo (60 dBe) is achievable in amplitude modulation. Finally, the beam is coupled back into single-mode fiber through an identical optical path.

The system has an optical insertion loss of 6.2 dB and a spectral passband of 9.5 nm at 3-dB width and 20 nm at 15-dB width. In our experiments, we use 20 nm of optical bandwidth which corresponds to 110 SLM pixels available for waveform generation.

A length of Corning SMF-28 fiber having a dispersion parameter D of 17 ps/nm$\cdot$km is used for wavelength-to-time mapping. The system will generate arbitrary waveforms at the repetition rate of the source (20 MHz in this case). The time aperture T of the waveform is related directly to the length of optical fiber L by $T = D \cdot \Delta\lambda \cdot L$, where $\Delta\lambda$ is the optical bandwidth (20 nm). The maximum frequency that can be generated for a given fiber length L is determined by the Nyquist requirement,

$$f_{\max} = \frac{1}{2 \cdot D \cdot \delta\lambda \cdot L} \tag{1}$$

where $\delta\lambda$ (0.73 nm) is the spectral resolution of the filter. The spectral resolution is 0.73 nm and is given by the ratio of the spot size (0.4 mm) at the pixel plane to the spatial dispersion $(\Delta x/\Delta\lambda = 0.55$ mm/nm$)$ of the 4-f grating-lens configuration.

In practice, the process of wavelength-to-time mapping is not ideal because of the following two issues. First, the finite focal size spanning multiple pixels removes the 1:1 correspondence between wavelength and pixel. Second, the SC spectrum is not uniform resulting in the distortion of the desired waveform. Because of these issues, the control voltage for our SLM array cannot be a simple replica of the desired waveform. To create a practical and robust system, we have developed and implemented an adaptive algorithm to ensure correct wavelength-to-time mapping. The desired waveform serves as the input to an adaptive algorithm running on a laptop computer. Before photodetection, a portion of the optical signal is coupled out and into an optical spectrum analyzer (OSA) as illustrated in Fig. 1. A feedback loop is made such that a least-square (LS) algorithm iteratively adjusts the pixel voltages until the input waveform matches the measured spectrum. The error is reduced until a user-specified tolerance is reached. This solution is implemented using the LabVIEW data acquisition and programming tool. The user interface is shown in Fig. 4. Once a desired waveform is generated, the pixel voltage information can be saved and used to generate the same waveform at a later time. The algorithm plays an important role since complex waveforms cannot be generated trivially by manual manipulation of the pixel voltages.

III. Results

Fig. 5 shows a variety of RF waveforms generated by the system; (a) sinusoid, (b) phase modulation, (c) frequency modulation, and (d) amplitude modulation. A 2.5-km SMF fiber was used to generate the waveform in (a) whereas 10 km was used for waveforms in (b)–(d). The highest frequency that could be generated by the system was limited by the 10-GHz bandwidth of the optical receiver. RF waveforms generated in our system exhibited peak-to-peak amplitudes of 15 mV. Both time domain and spectra are shown for comparison.

Fig. 6 shows generation of ultrawide-band frequency-hopped waveforms using 10 km of fiber. The frequency hops between 1.25 and 5 GHz in increments of 1.25 GHz. Both the spectra and the time domain waveforms are shown for comparison.

IV. Discussion

The erbium-doped fiber amplifier (EDFA) used in the SC generation has an undesirable effect on system performance. Fig. 7(a) shows the SC spectra along with the amplified spontaneous emission (ASE) noise of the EDFA. Due to its continuous-wave (CW) nature, the ASE component of the SC does not contribute to the wavelength-to-time mapping process. This is shown in Fig. 7(b) which is the temporal waveform associated with the spectrum in Fig. 7(a). The long-wavelength portion of the SC directly maps into time, whereas the short-wavelength portion, being dominated by ASE, does not. For this reason, we operate in the long-wavelength portion where the effect of ASE is small.

Our system generates finite-length replicas of arbitrary waveforms at the repetition rate of the SC source. The repetition rate

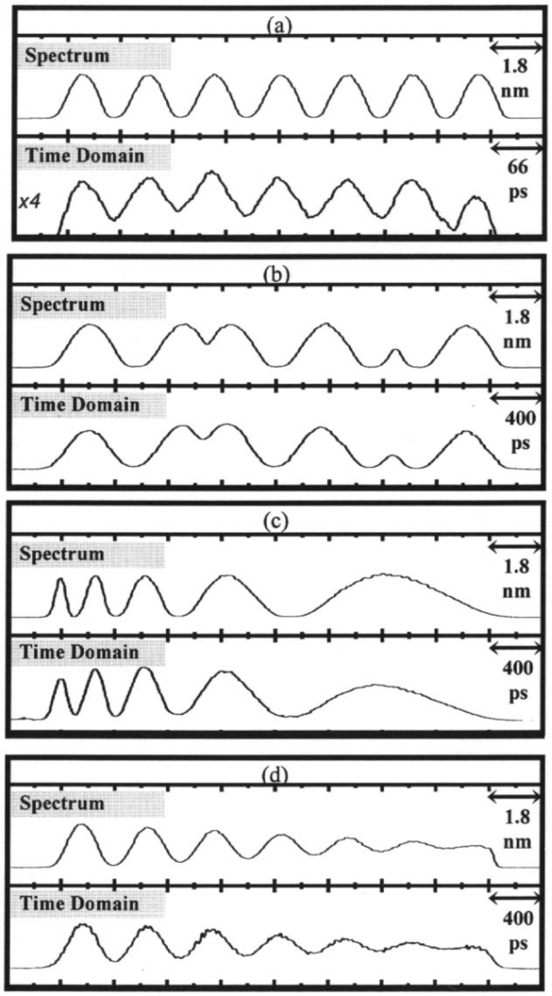

Fig. 5. (a) 12.1-GHz tone (b) phase (c) frequency (d) amplitude modulations shown both in spectrum and time domains.

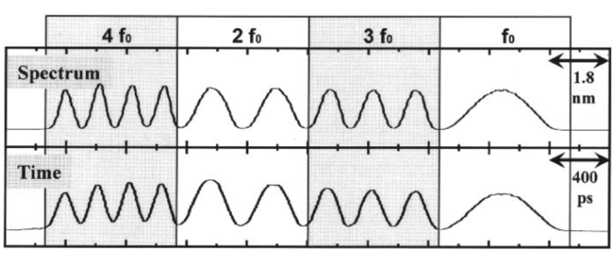

Fig. 6. Ultrawide-band frequency-hopped code-division multiple access (CDMA). The frequency hops from 1.25 to 5 GHz in increments of 1.25 GHz.

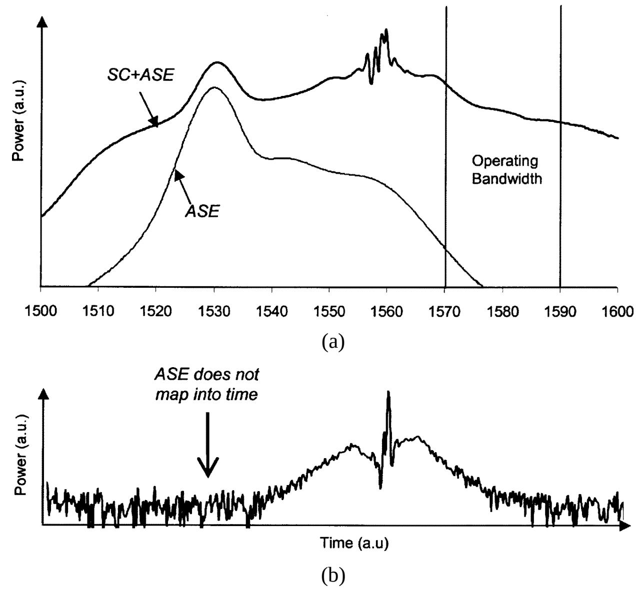

Fig. 7. (a) The system is chosen to operate away from the ASE peak at 1530 nm to avoid distortion, (b) Time domain waveform showing the absence of wavelength-to-time mapping in the ASE-dominated portion of the SC spectrum.

can be easily increased by using a laser with higher repetition rate, for example, a harmonically modelocked fiber laser or a semiconductor mode locked laser. Such sources have been developed for telecom applications at 10 Gb/s and beyond. The segment length (at a fixed RF bandwidth) can be increased by using a larger optical bandwidth along with an SLM with higher number of pixels.

V. Summary

We have proposed and demonstrated a new RF-photonic AWG. The proposed system is entirely free of electronic limitations that plague the conventional waveform generators. Implemented using presently available commercial components, the system's maximum frequency will be limited by the photodetector. This limit is currently around 60 GHz. Hence, we should be capable of generating millimeter-wave frequencies with arbitrary amplitude, phase, or frequency modulation. To solve the practical problems and to create a robust and functional system, a computer-based graphical user interface was developed. In addition to controlling the system, the software has an embedded optimization algorithm that adaptively controls the spatial light modulator such that the output waveform is a faithful replica of the desired waveform. As proof of concept demonstration, ultrawide-band frequency-hopped CDMA waveforms were demonstrated.

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