Adaptive RF-Photonic Arbitrary Waveform Generator

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Abstract – The system uses spectral shaping of a supercontinuum source followed by wavelength-to-time mapping to generate ultra wideband RF waveforms with arbitrary modulation. It employs adaptive computer control to mitigate the non-ideal features inherent in the optical source and in the spectrum modulation process. As proof of concept, ultra-wideband frequency hopped CDMA waveforms are demonstrated.

I. INTRODUCTION

RF waveform generation is central to many applications in the commercial and military fields. Arbitrary waveform generators (AWG) are used in testing of communication receivers. The military relies on a sophisticated and agile RF environment in applications such as Low Probability of Intercept (LPI) radar. Currently there is a need for waveform generators with wider bandwidths encountered in next generation applications. The development of electronic arbitrary waveform generators is hindered by the limited speed and dynamic range of Digital-to-Analog (DAC) technology. This is a fundamental physics limitation whereby in order to reduce carrier transit time, transistor dimensions need to be minimized. As a result, the breakdown voltage along with dynamic range is reduced. In this paper, we introduce an all-optical approach to generating arbitrary waveforms that is completely free of fundamental electronic limitations.

II. PRINCIPLE OF OPERATION

The proposed photonic arbitrary waveform generator is illustrated in Figure 1. A wideband 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 broadband optical source. The frequency of the resulting temporal waveform is determined by the amount of dispersion used. Implemented using presently available commercial components, the system's maximum frequency will be limited by the photodetector. This limit is currently around 60 GHz. We use a SLM array to shape the spectrum of the broadband pulse. SLMs have been successfully used by Weiner et al. for optical pulse shaping via spectral phase control [1]. The approach was a coherent Fourier transform process where a temporal waveform was synthesized through manual control of optical phase. This approach may also be used for generation of RF waveforms. Our approach is fundamentally different from the work of Weiner et al. in that it is an optically incoherent method relying on amplitude shaping of the spectrum. Instead of performing a Fourier transform, we use direct wavelength-to-time mapping, achieved via dispersion, to create the desired temporal waveform. The present paper differs from our previous work on RF-photonic arbitrary waveform generation [2] in that a SLM is used for spectrum modulation instead

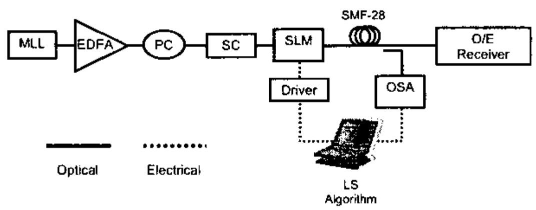

Figure 1. Block diagram of AWG. MLL: Mode Locked Laser. PC: Polarization Controller. SC: Supercontinuum. SLM: Spatial Light Modulator. OSA: Optical Spectrum Analyzer.

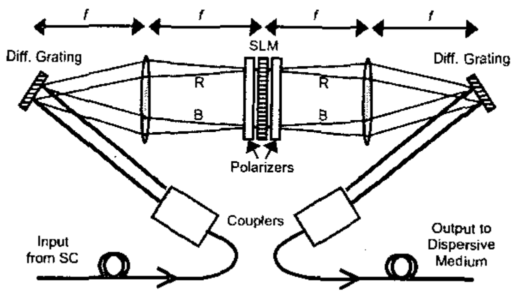

Figure 2. Experimental setup of SLM in a 4-*f* grating and lens configuration [1].

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 References [1], [2] though the use of an adaptive computer control that mitigates the non-ideal characteristics of the optical source and of the spectrum modulation process.

A broadband optical source is produced by amplifying the output of a modelocked laser and passing it through a supercontinuum fiber [3]. 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 (1200 lines/mm) and lens (20 cm focal length) apparatus such that each wavelength will be focused and incident normal onto the SLM plane [1,4]. The distances between gratings and lenses are set for zero net temporal

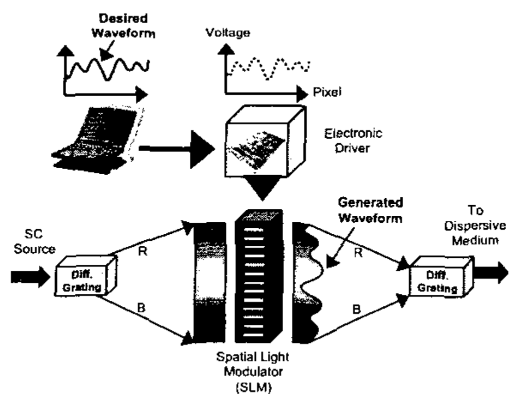

Figure 3. A desired waveform is sent to an electronic driver which determines the voltage for each liquid crystal pixel. The SLM performs spectral shaping to a dispersed broadband pulse.

dispersion [5]. Two high extinction polarizers are placed in parallel before and after the liquid crystals to achieve amplitude modulation. The pixels are independently controlled by a computer-operated electronic driver which manipulates the voltage, and thus the attenuation, to gray scale accuracy. 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 a symmetric 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·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,

$$f_{max} = 1/(2 \cdot D \cdot \delta\lambda \cdot L) \quad (1)$$

where $\delta\lambda$ (0.73 nm) is the spectral resolution of the filter. The spectral resolution is determined by dividing a spot size (0.4 mm) at the pixel plane by 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 supercontinuum 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 is entered into the computer which in turn is sent to the SLM driver. Before photodetection, a portion of the optical signal is coupled out and into an optical spectrum analyzer (OSA) as illustrated in Figure 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 defined tolerance is reached. This solution is implemented using the LabVIEW data acquisition and programming tool. The user interface is shown in Figure 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 with simple manual control of pixel voltages.

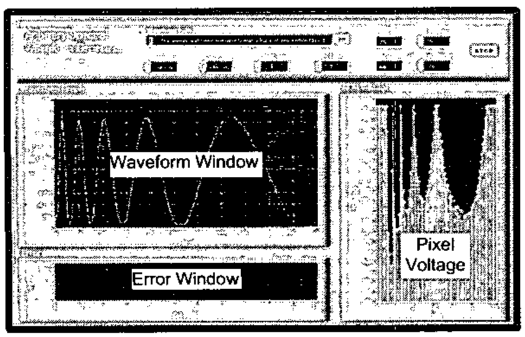

Figure 4. The system's graphical user interface (GUI).

III. Results

Figure 5 illustrates the generation of a variety of RF waveforms (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). Both time domain and spectra are shown for comparison. The highest frequency that could be generated by the system was limited by the 10 GHz bandwidth of the optical receiver.

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

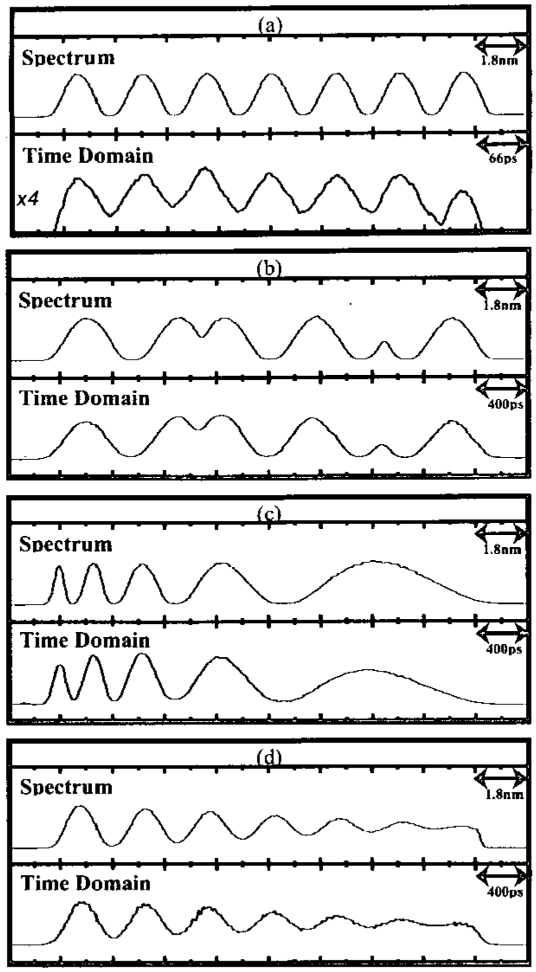

Figure 5. (a) 12.1 GHz Tone (b) PM (c) FM (d) AM modulations shown both in spectrum and time domains.

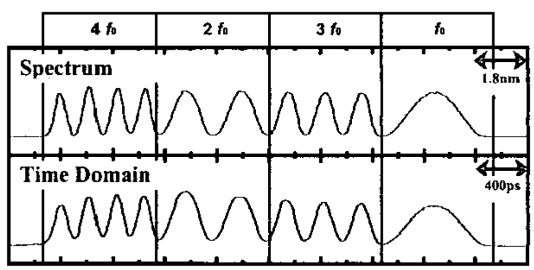

Figure 6. Ultra-wide-band Frequency Hopped CDMA. The frequency hops from 1.25 GHz to 5 GHz in increments of 1.25 GHz.

IV. Discussion

The Erbium Doped Fiber Amplifier (EDFA) used in the supercontinuum generation has an undesirable effect on system performance. Figure 7a shows the supercontinuum spectra along with the Amplified Spontaneous Emission (ASE) noise of the EDFA. Due to its incoherent nature, the ASE component of the supercontinuum does not contribute to the wavelength-to-time mapping process. This is shown in Figure 7b which is the temporal waveform associated with the spectra in 7a. The long-wavelength portion of the supercontinuum 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 supercontinuum source. The repetition rate can be easily increased by using a laser with higher repetition rate, for example, a harmonically modelocked fiber laser [1] or a semiconductor mode locked laser. Such sources have been developed for telecom applications at 10Gbit/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.

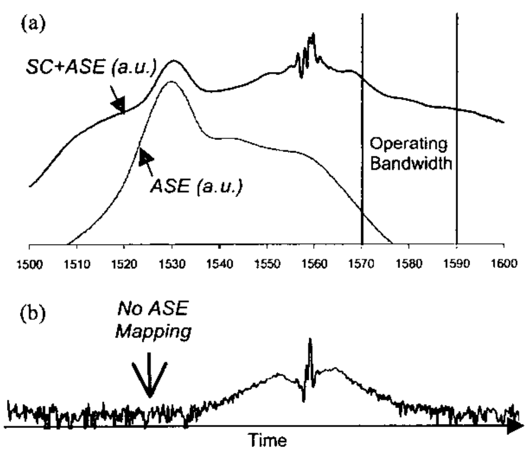

Figure 7. (a) The system is chosen to operate away from the ASE peak at 1530 nm to avoid distortion, (b) Time domain waveform showing the absence of wavelength-to-time mapping in the ASE dominated portion of the SC spectrum.

IV. Summary

In Summary, we have proposed and demonstrated a new RF-photonic arbitrary waveform generator. The proposed system is entirely free of electronic limitations that plague the conventional AWGs. 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 it is capable of generating mm-wave frequencies with arbitrary amplitude, phase or frequency modulation. To solve the practical problems and to create a robust and functional system, 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, ultra wideband frequency hopped CDMA waveforms were demonstrated.

Acknowledgement

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