OPTIARB: Arbitrary Optical Waveform Generation Using Electronic Techniques

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Abstract

Arbitrary waveforms can be composed of vector-modulated harmonics derived from a stable timebase. Here we implement this Fourier composition technique using a nonlinear transmission line (NLTL) pulse generator, channelizer, NLTL phase shifters, buffer amplifiers and combiner, and demonstrate results from a brassboard with four harmonics of a 1.0 GHz sinusoid. The result drives a broadband power amplifier and optical modulator in a new approach to arbitrary optical waveform generation.

1. INTRODUCTION

Arbitrary waveform generators have utility in a variety of test systems, spectrometers and wideband radars. Arbitrary optical waveforms for these applications can be generated by spatial light modulators that operate directly on the lightbeam[1], but this approach has drawbacks that include lack of scalability and three-dimensionality not conducive to integrated circuit implementation. Here we introduce the concept of arbitrary waveform generation by wholly electronic means, with subsequent application to broadband amplifiers and optical modulators to approach our goal of 100 GHz total bandwidth and 10 GHz instantaneous bandwidth.

2. BACKGROUND

As is well known from Fourier theory, by exerting individual control over the amplitude and phase of harmonics, any arbitrary waveform can be composed. Our arbitrary waveform generator is a circuit transcription of the mathematics of Fourier theory, and its modularity confers significant advantages: It is scalable to higher frequencies by geometric and process scaling, and its resolution can be increased by increasing the number of harmonics that are amplitude- and phase-modulated.

Most groups pursue arbitrary waveform generation through purely optical means. For example, the group of Kobayashi has demonstrated an electrooptic synthesis technique for generating arbitrarily shaped short optical pulses from a CW narrow linewidth laser. For optical pulse shaping, they specially fabricated a large-amplitude electrooptic phase modulator. The phase-modulated light is separated and phase-controlled by a liquid crystal modulator array. They then recombine the phase-modulated light by using a grating, and have measured 1.2 ps Fourier-transform-limited optical pulses[2, 3].

3. OPTIARB ARCHITECTURE

The system architecture of the arbitrary waveform generator is shown in Figure 1. The variable-gain bandpass amplifiers depicted are realized here as a cascade of broadband buffer amplifiers, voltage-variable attenuators, and directional filters. Each delay line phase modulator and attenuator is controlled by a 12-bit D/A that itself is corrected by a look-up table to compensate for nonlinearities in the individual components.

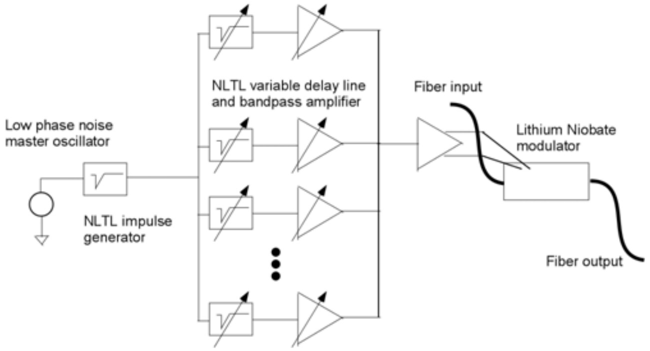

Figure 1. OPTIARB system architecture.

3.1 Nonlinear transmission lines

Nonlinear transmission lines (NLTLs) as used in the OPTIARB serve two purposes, one NLTL is used in large-signal mode as a short pulse compressor for harmonic generation[4-7]; others are used in small signal mode as voltage-variable delay lines for phase modulation of each harmonic[8].

The NLTL is formed by a high-impedance line $Z_o > 50\ \Omega$ loaded by reverse-biased varactor diodes to achieve a synthetic line with $Z_o = 50\ \Omega$ at an average bias voltage. A large-signal wave propagating along the line experiences a voltage-dependent propagation velocity, compressing one phase front at the expense of the other, as illustrated in Figure 2.

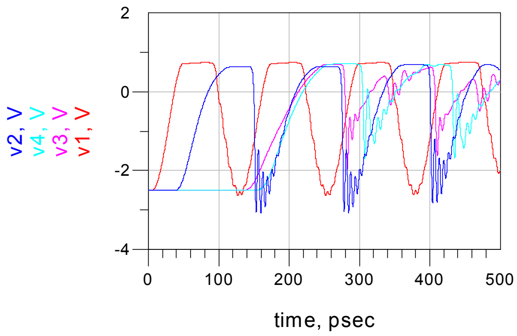

Figure 2. Harmonic-balance simulations of NLTL showing voltage waveform at different points along the line. Note both wavefront compression and ringing due to line periodicity.

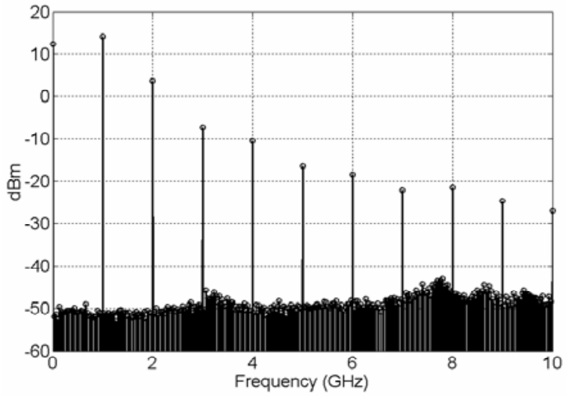

Figure 3. Measured output of NLTL harmonic generator with 1.0 GHz, + 19 dBm input.

Used in small-signal mode, the NLTL can be an effective voltage-variable delay line, hence phase shifter, as shown in Figure 4. For operation at 1.0 GHz, 20-section and 15-section phase shifters are cascaded to achieve full 360-degree modulation, while 20-section phase shifters are used at 2 GHz and above. The circuits are realized on Rogers RT/Duroid 5880 using Alpha Industries hyper-abrupt junction varactor diodes (GMV-9821). Typical results show a variation of 4-6 dB in insertion loss versus bias voltages ranging from –3 to –10 V for complete 360-degree phase modulation (Figure 5).

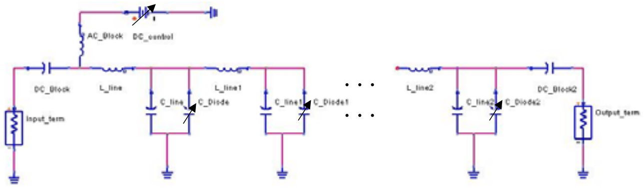

Figure 4. Equivalent circuit of NLTL phase shifter.

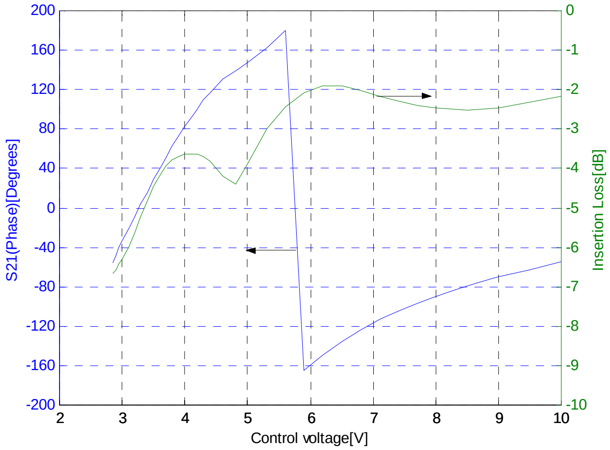

Figure 5. Phase and insertion loss vs. control voltage for 4.0 GHz phase shifter.

3.2 Channelizer

The channelizer circuits serve to filter and separate the harmonics in the output of the NLTL pulse compressor that is driven with a 1.0 GHz, +19 dBm sinusoid. Each harmonic from 1 to 4 GHz is directed to an independent vector modulation circuit. A second channelizer is used to recombine the outputs of these modulators into a single line. The channelizer is a series of rectangular half-wave ring resonators realized in microstrip. Both input and output sections of each ring are parallel coupled lines, resulting in directional filters[9].

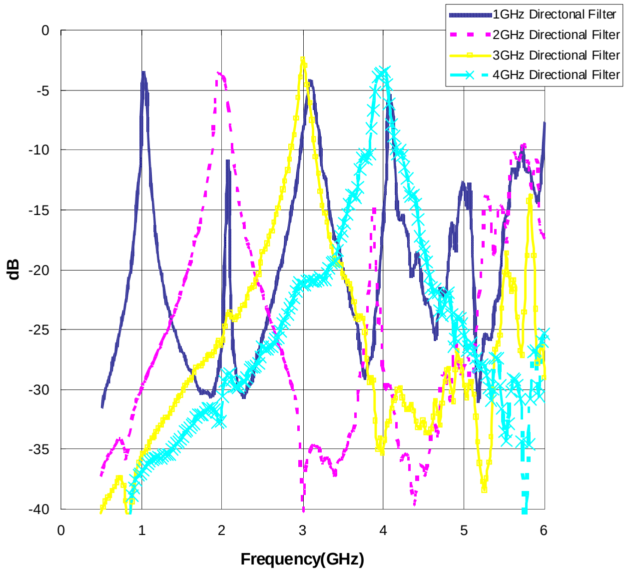

Figure 6. Measured transmission coefficient (S_{21}) magnitude for 1-4 GHz channelizer. Note subsidiary 3λ/2 response of 1 GHz channel at 3 GHz.

To help equalize the harmonic output of the NLTL pulse generator, higher-frequency harmonics are coupled out first. This also serves to limit the effect of subsidiary 3λ/2 responses (e.g. the 3 GHz response of the 1 GHz channel) since most of the NLTL energy at the higher harmonic is already coupled out. For each harmonic, the insertion loss of the channelizer is around 3.5 dB except at 1 GHz, where it is 5 dB due to the size of the ring resonator.

3.3 Attenuators and buffer amplifiers

To achieve consistent vector modulation of each harmonic, we employ voltage-variable attenuators at the input and buffer amplifiers at output of each NLTL delay line/phase shifter. The attenuators serve both to modulate the vector magnitude and to dampen from the delay line input, which are dependent upon control voltage V since the delay line capacitance C changes, changing the characteristic impedance of the line as $Z_o(V) = 1\big/\sqrt{LC(V)}$, where L is the line inductance per unit length. The circuits, Hittite HMC346MS8G DC-8 GHz chips, enable 0-32 dB attenuation with a 0 to –2.7 V control input. The chips were integrated onto coplanar-waveguide (CPW) transmission lines realized on Rogers 3010 substrate material.

The buffer amplifiers, RFMD NBB-300, use Darlington-pair transistors with degenerated emitter resistors and R_{cb} feedback to improve their bandwidth. One provides 10 dB gain for the third harmonic and one provides 25 dB gain for the fourth harmonic.

3.4 Optical modulator and driver

The optical modulator in this brassboard scale model system is a Codeon Mach-40 Mach-Zender $LiNbO_3$ traveling wave modulator. We drive the modulator with a NARDA amplifier, which is a 2-stage distributed amplifier using GaAs/AlGaAs pHEMT transistors, providing 22 dB gain and a bandwidth of 40 GHz with 6 V_{pp} output.

4. RESULTS

The individual components are arranged as shown in Figure 1, with control over amplitude and phase of each harmonic accomplished through LabVIEW driving a National Instruments D/A card. The electrical output of the arbitrary waveform generator is displayed on a LeCroy 6 GHz real-time oscilloscope, and further used to modulate a 1.55 μm laser, whose modulated output is detected by a fast photodiode. The output of the photodiode is also displayed.

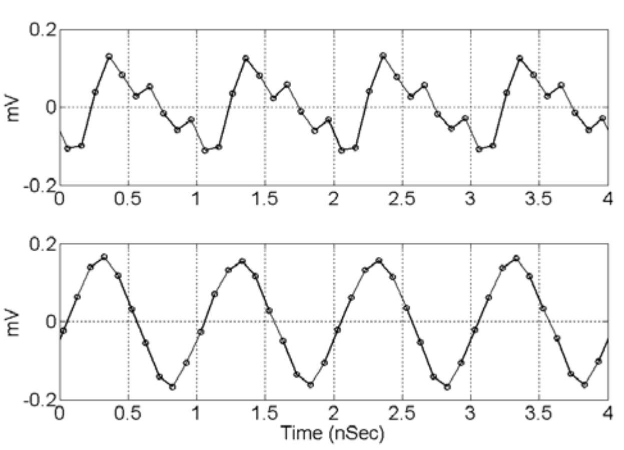

Figure 7. Sawtooth waveform at output of waveform generator (top) and sinusoidal reference.

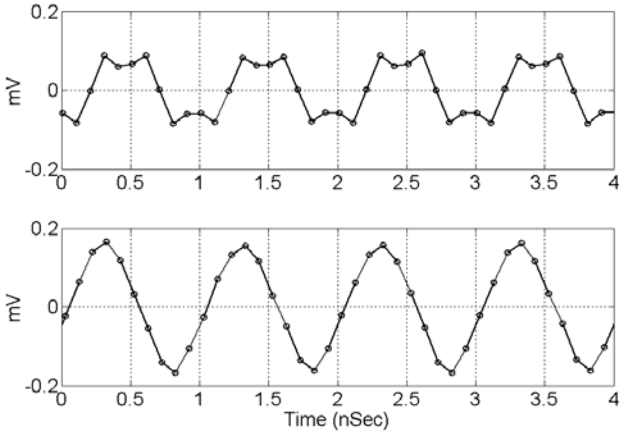

Figure 8. Square wave at output of waveform generator (top) and sinusoidal reference.

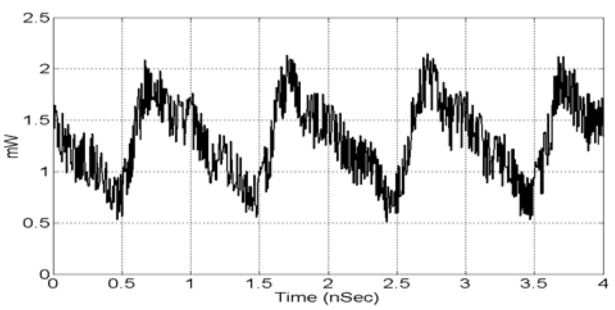

Figure 9. Sawtooth waveform at output of photodiode.

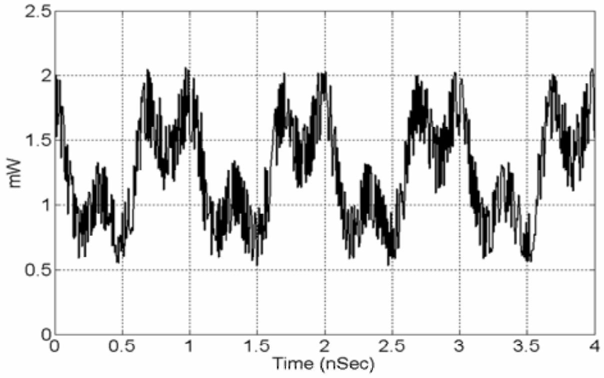

Figure 10. Square wave at output of photodiode.

5. ACKNOWLEDGEMENTS

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6. References

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7. BIOGRAPHIES

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