

Fourier Synthesizer Using Left-Handed Transmission Lines

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Abstract — We propose an arbitrary waveform generator based on Fourier synthesis from left-handed (LH) transmission lines. Cascaded varactors and shunt inductors are used to construct the LH transmission line, which can be used as an efficient harmonic generator when driven with a large signal, and as a linear phase shifter when driven with a small signal. By controlling the amplitude and phase of each harmonic, and combining them together, we can generate pulses of arbitrary waveforms.

Index Terms — Arbitrary waveform generator, Fourier synthesizer, harmonic generator, left-handed material, nonlinear transmission line, phase shifter, varactor.

I. INTRODUCTION

In a conventional right-handed (RH) material, phase propagation and power flow are in the same direction. By contrast, in a left-handed (LH) transmission line, phase propagates opposite to power flow direction [1]. A synthetic LH transmission line can be constructed with series capacitors and shunt inductors [1] - [4]. Several new microwave devices using this property in the linear regime have been reported [2] - [4].

In a conventional nonlinear transmission line (NLTL), shunt varactor diodes are loaded along a transmission line which exhibits RH electrical properties. This RH NLTL can be used as pulse generator [5] and phase shifter [6]. Recently, a paper proved theoretically that a LH NLTL structure could be more efficient at harmonic generation than a RH NLTL [7]. Furthermore, in [8], the authors demonstrate a low loss and linearly tunable LH NLTL based phase shifter. Compared to RH NLTL, this LH NLTL can be made very compact with good performance, which is advantageous when used in MMIC.

As is well known from Fourier theory, any periodic waveform shape can be constructed by summation of a fundamental frequency and its harmonic components, with appropriate amplitude and phase modulation of the components. Here, we demonstrate a high frequency Fourier synthesizer using this LH NLTL harmonic generator and phase modulator. The resulting arbitrary waveform generator (AWG) and vector modulation scheme has applications in quadrature amplitude (QAM) modulators for digital communication, secure optical communication systems and harmonic cancellation in power amplifiers.

II. SYSTEM CONFIGURATION

Fig. 1 shows the system's circuit schematic. Harmonic signals generated from the LH NLTL are divided into 4 channels using a Wilkinson power divider. Each harmonic is then channelized using a band pass filter (BPF), vector modulated, and combined again. To suppress unwanted signals in each channel, additional channelizers are added before combining signals. The whole circuit is implemented on Rogers RT/Duroid 3010 board ($\epsilon_r = 10.2$). Though 4 harmonic components are used in this work, more harmonic signals will allow for increased detail in the output waveform.

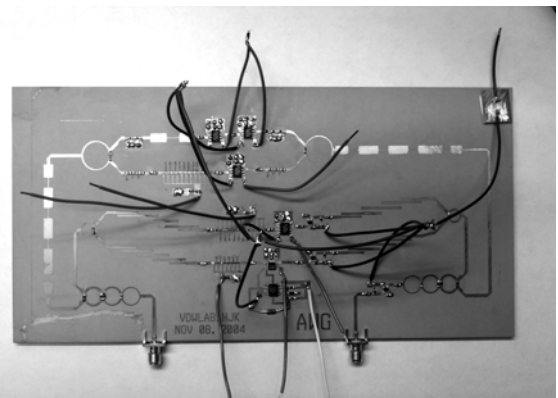
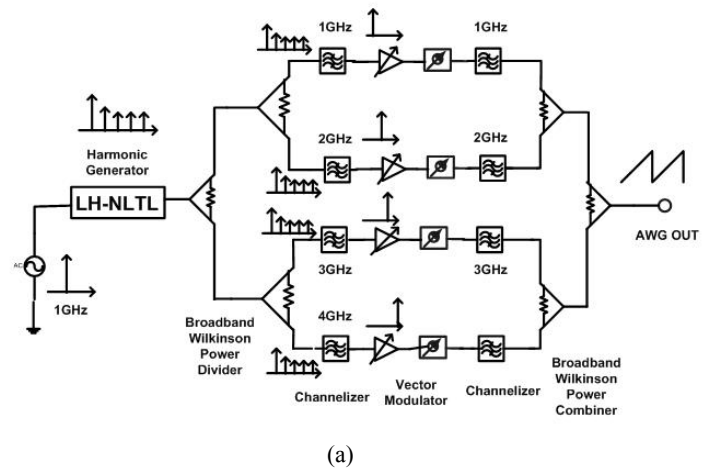


Fig. 1. (a) Schematic of Fourier synthesizer. The input is 1 GHz at +30 dBm. The output is a combination of four vector modulated harmonic signals. (b) Breadboard of tested circuit. A LH harmonic generator is attached separately for testing.

III. THEORY AND IMPLEMENTATION

A. LH NLTL harmonic generator

A section of LH NLTL structure is shown in Fig. 2. Cascaded varactors and shunt inductors form the LH NLTL in a high pass filter structure. By cascading several of this unit cells together, we observe a periodic cutoff frequency (Bragg frequency (ω_B)) as follows :

$$\omega_B = \frac{1}{2\sqrt{L \cdot C_d(V)}} \quad (1)$$

For $\omega \gg \omega_B$, we can approximate propagation constant (β) and characteristic impedance (Z_0) as follows [8] :

$$\beta \approx -\frac{1}{\omega\sqrt{L \cdot C_d(V)}} \quad (2)$$

and

$$Z_0 \approx \sqrt{\frac{L}{C_d(V)}} \quad (3)$$

The term “left-handed” comes from the negative sign of (2) : phase propagation occurs in the opposite direction to the direction of power flow (the poynting vector).

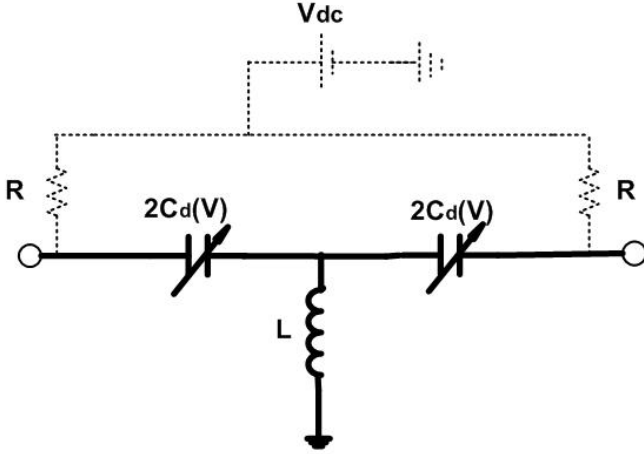
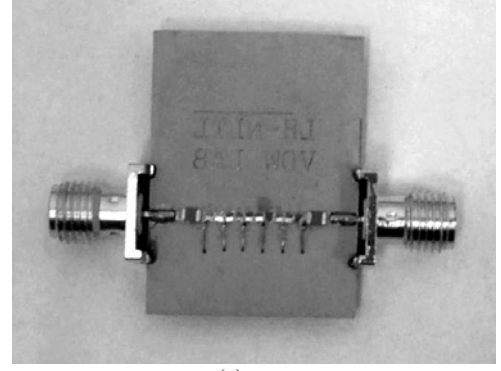


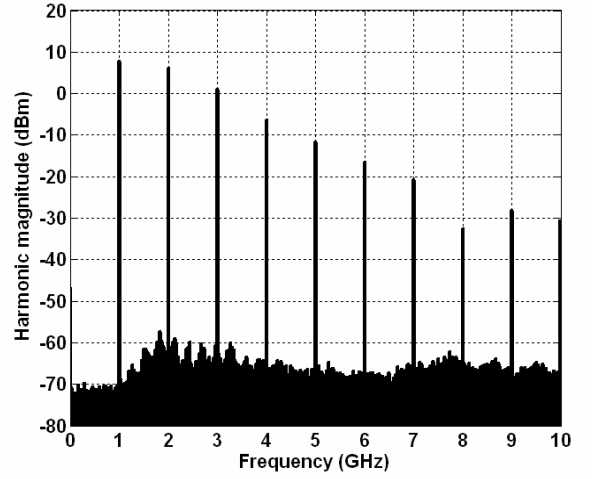
Fig. 2. A section of the LH NLTL and phase shifter. The dotted portion represents the DC control bias circuit for the phase shifter.

For LH NLTLs, cascaded varactors are realized by attaching MACOM hyper-abrupt junction GaAs flip-chip varactor diodes (MA46H120) using conductive silver epoxy. Shunt inductors are implemented by connecting self-resonance frequency (SRF) chip inductors and very thin wires to ground. Using (3), we set $Z_0 = 62 \Omega$ where the diode capacitance is maximum ($C_d(0)$). This is the procedure used in [7] to optimize the characteristic impedance for harmonic generation. Five identical sections of Fig. 2 are used in our structure.

Fig. 3 shows a fabricated LH NLTL and its output spectrum. Because we use the first through 4th harmonic, their magnitudes are sufficient.



(a)



(b)

Fig. 3. (a) Fabricated LH NLTL harmonic generator. (b) Harmonic generation with + 30 dBm at 1 GHz.

B. LH phase shifter

Fig. 4 shows the performance of the 4 GHz LH phase shifter. All the theories used in the LH NLTL above are applied to the implementation of a LH phase shifter. The difference is the bias circuit to control phase (2) and small-signal drive. Full 0° to 360° phase shifters are used for 2 GHz, 3 GHz and 4 GHz channels. Using (2), we can find phase change per section ($\Delta\beta$), and the total phase variation ($\Delta\phi$) as follows:

$$\Delta\beta = \frac{1}{\omega\sqrt{L}} \left(\frac{1}{\sqrt{C_d(V_{\max})}} - \frac{1}{\sqrt{C_d(V_{\min})}} \right) \quad (4)$$

and

$$\Delta\phi = \Delta\beta \cdot n \quad (5)$$

where V_{\max} and V_{\min} are the maximum and minimum reverse bias voltages respectively, and n is the number of identical unit cells.

To minimize reflections, we set $Z_0 = 50 \Omega$. Under this condition the diode capacitance values are required to satisfy the following equations (C_{ls} =large signal diode capacitance):

$$C_{ls} = \frac{\int_{V_{\min}}^{V_{\max}} C_d(V) dV}{V_{\max} - V_{\min}}. \quad (6)$$

The advantage of this LH phase shifter is its compactness and its linear phase variation. A linear phase variation according to voltage is possible because the phase constant of equation (2) compensates the diode nonlinearity. Due to its linearity, we can control the output phase precisely with an inexpensive DAC. With less than 0 dBm of input power, the largest harmonic magnitude is less than -40 dBm, offering low distortion. Theories related to this LH phase shifter are discussed in [8].

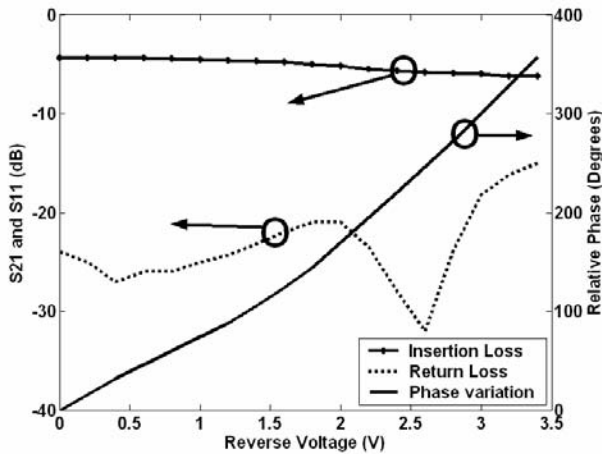


Fig. 4. LH phase shifter performance at 4 GHz. Maximum insertion loss is 6.5 dB. This circuit also exhibits a low variation in insertion loss, and a linear phase variation according to voltage (set S_{21} phase as 0° at 0 V).

C. Power dividers and combiners

Improved Wilkinson power dividers are used to split and combine signals, as was done previously [9]. Three power divider sections have enough bandwidth to split signals equally in the 1 GHz to 4 GHz range (see Fig. 5). Although 3 dB loss occurs when combining different signals, all the ports are matched to 50Ω so we can minimize power reflection. Wider bandwidth is possible with more sections at the expense of circuit size.

D. Channelizer

Channelizers split the harmonic output before vector modulating each of the harmonics. To reduce the circuit size, 1 GHz and 2 GHz channelizers were implemented with a combination of stepped impedance low-pass filter, lumped element low-pass filters and high-pass filters. For 3 GHz and 4 GHz, coupled line band-pass filters are used. Chebyshev type filters are used for sharp stop-band attenuation.

E. Gain block and gain control block

To compensate harmonic signals, ~ 10 dB gain blocks are used for the 3 and 4 GHz channels using Agilent MGA-53543

linear amplifiers. This broadband amplifier is used at the end of output to amplify the whole signal spectrum as well. For an amplitude modulator, we use a MACOM AT-108 voltage variable attenuator (VVA) for 1 GHz – 3 GHz and Hittite HMC346MS8G VVA for 4 GHz. These VVAs have more than 30 dB of dynamic range and cascades of VVAs result in increased dynamic attenuation control range.

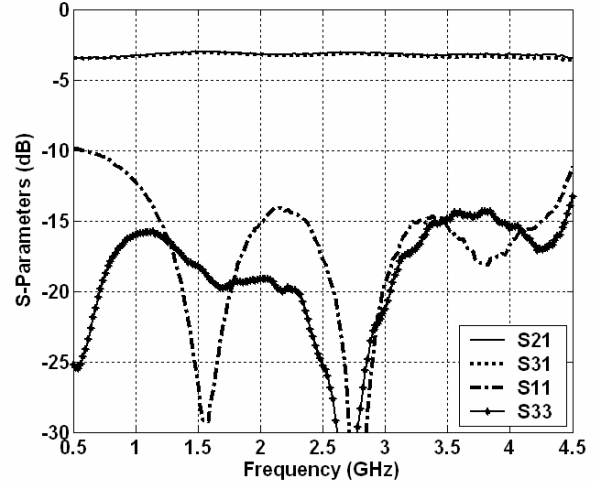
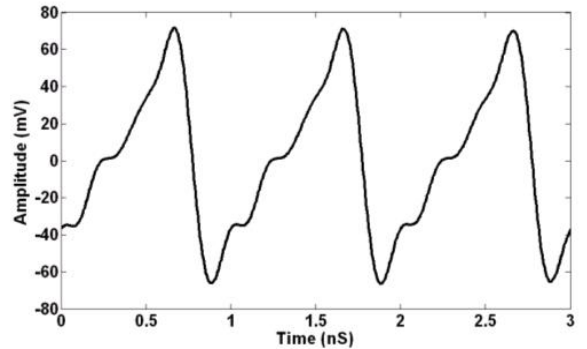


Fig. 5. S-parameters of the fabricated Wilkinson power divider. Equal amounts of power can be split with less than -12 dB return loss for the 1 GHz – 4 GHz range.

V. ARBITRARY WAVEFORM GENERATION RESULTS

To generate arbitrary waveforms, we combined previously described elements on a board as shown in Fig. 1 (b). Control of the amplitude and phase of each harmonic is achieved in LabVIEW, with a National Instruments analog output D/A card (NI 6733). A LeCroy 6 GHz real-time oscilloscope is used to record the output waveform. The output spectrum was also measured with an Agilent E4448 spectrum analyzer at the same time. Fig. 6. (a) & (b) show a sawtooth wave and its spectrum, and Fig. 7. (a) & (b) show a square wave and its spectrum. The unwanted frequency components at 2 GHz and 4 GHz in Fig. 7 (b) could be completely removed if we cascaded more variable attenuators in each channel.



(a)

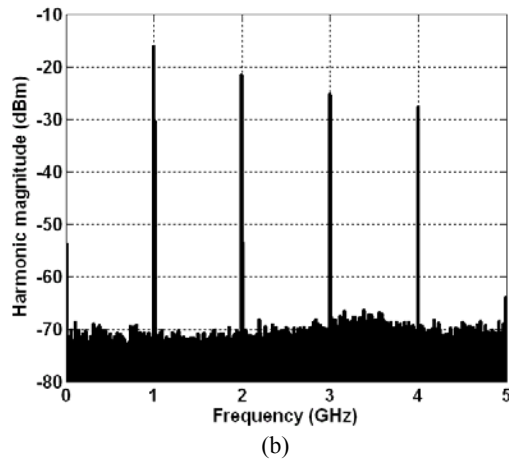


Fig. 6. (a) Sawtooth wave output waveform. (b) Sawtooth wave spectrum.

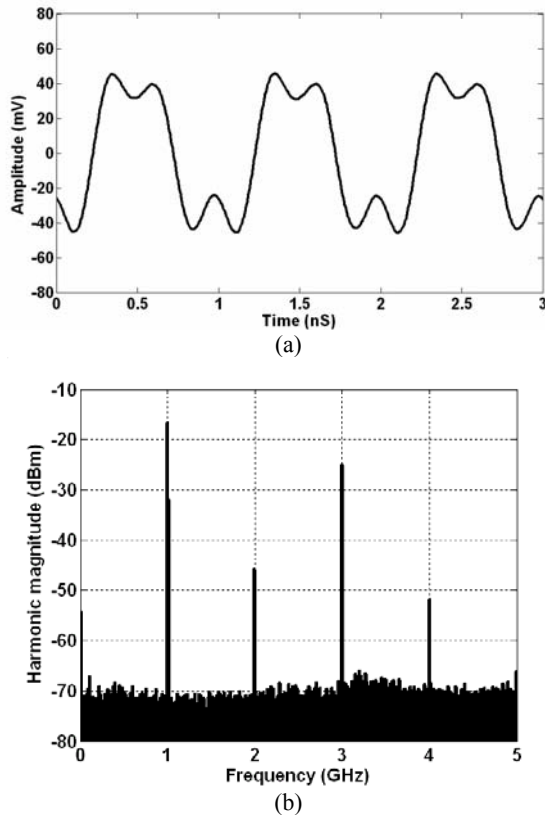


Fig. 7. (a) Square wave output waveform. (b) Square wave spectrum.

IV. CONCLUSION

We demonstrate a new type of Fourier synthesizer based on a LH transmission line. This LH NLTL structure gives excellent performance as harmonic generator and phase shifter. When combined with an amplitude modulator, a very compact vector modulator is possible with simple control because of the linear phase variation with voltage. This LH NLTL can also be made by using MESFETs as varactors, amenable to commercial fabrication.

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