A Novel Design of Frequency Tripler Using Composite Right/Left Handed Transmission Line

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***Abstract* — A novel frequency tripler using a composite right/left-handed transmission line is proposed. The left-handed transmission line (LH TL) in the proposed frequency tripler suppresses the fundamental component (f_0), while the composite right/left-handed transmission line (CRLH TL) λ/4 open stub diminishes unwanted harmonics. Due to the combination of the LH TL and CRLH TL λ/4 open stub, the only desirable multiplied frequency component ($3f_0$) is obtained at the output port. For the example of the proposed design, a frequency tripler was designed at 1 GHz as f_0, and measured. The measured output power at $3f_0$ was -5.67 dBm when the fundamental input power was 0 dBm.**

***Index Terms* — Frequency tripler, harmonic suppression, composite right/left handed transmission line.**

I. INTRODUCTION

Modern communication systems require high frequency signal sources with high stability and low phase noise. High frequency signal sources can be obtained by multiplying the low frequency signal that has relatively high stability and low phase noise. In general, frequency multipliers include the unwanted fundamental and harmonic components, and the spectral quality of the fundamental signal directly influences the multiplied frequency components. Therefore, the phase noise in oscillators has been an important subject in theoretical and experimental papers [1][2].

When a multiplier operates with other microwave circuits--such as mixers, amplifiers, etc.--serious problems may occur due to the undesirable frequency components and poor phase noise characteristics. Band pass filters (BPF) are often used to diminish the fundamental and undesirable harmonic components, but the high insertion loss of BPF's causes multiplied signal to be less than the required signal level. In addition, it is difficult to design BPF's with a high Q factor in monolithic microwave integrated circuits; a fully monolithic frequency tripler design is very difficult.

On the other hand, it might be effective for feedforward structures to suppress the fundamental signal [3]. The feedforward structure is widely used in linearizing amplifier systems. However, because the feedforward structures have to include couplers, variable attenuators, and variable phase shifters, the size of the frequency multiplier would be large.

Artificial materials (metamaterials) with simultaneously negative permeability and permittivity are known as left-handed (LH) materials. LH materials often use arrays of metallic wires and split-ring resonators [4] (or planar transmission lines) periodically loaded with series capacitors and shunt inductors [5][6]. A theoretical model and practical implementation of an artificial LH transmission line (TL) using interdigital capacitors and short circuit stub inductors was proposed [7].

The CRLH TL, which is the combination of an LH TL and a conventional transmission line (RH TL) was proposed in [8]. The equivalent lumped element model of the LH TL exhibits positive phase response (phase lead). On the other hand, the RH TL has negative phase response (phase lag). They are applied to the design of a dual-band λ/4 open stub, in which the phase response of the CRLH TL is manipulated to yield electrical lengths of ±90° at two arbitrary frequencies [9].

In this paper, we propose a frequency tripler having the LH TL with high pass characteristics for suppressing the fundamental component, and the CRLH TL with dual-band λ/4 open stub for canceling the unwanted harmonic components. Since the LH TL is composed of several lumped elements, its size is much smaller than feedforward structural tripler. The proposed frequency tripler has a very simple structure since it is not necessary to control the variable attenuator, variable phase shifter, and coupling coefficient.

II. FREQUENCY TRIPLER THEORY

The output current waveform of transistors is explained according to bias conditions or conduction angle. The DC current consumption and harmonic signals are estimated by calculating the average and correlation between the drain (or collector) current and the n^{th} harmonic, as shown in eqs. (1) and (2), where α is a conduction angle of input signal and I_{max} is the maximum allowable current. The amplitude of the 3^{rd} harmonic is maximized when α is around 75°. Therefore, the bias point for the frequency tripler should be selected in the vicinity of pinch-off, between class B and C. Once the bias point is determined, the input and output ports have to be matched for the fundamental (f_0) and 3rd harmonic ($3f_0$), respectively.

$$I_{\mathrm{dc}} = \frac{1}{2\pi}\int_{-\alpha/2}^{\alpha/2} \frac{I_{\max}}{1-\cos(\alpha/2)}\left[\cos\theta-\cos(\alpha/2)\right]d\theta \qquad (1)$$

$$I_{\mathrm{n}} = \frac{1}{\pi}\int_{-\alpha/2}^{\alpha/2} \frac{I_{\max}}{1-\cos(\alpha/2)}\left[\cos\theta-\cos(\alpha/2)\right]\cos n\theta\, d\theta \qquad (2)$$

Fig. 1 shows the proposed frequency tripler. Even though the wanted harmonic component is larger than the unwanted signals at point “A”, the magnitudes of unwanted components are not ignorable. However, they are suppressed totally by CRLH TL λ/4 open stub and LH TL. Finally, the desirable harmonic component appears only at the output port.

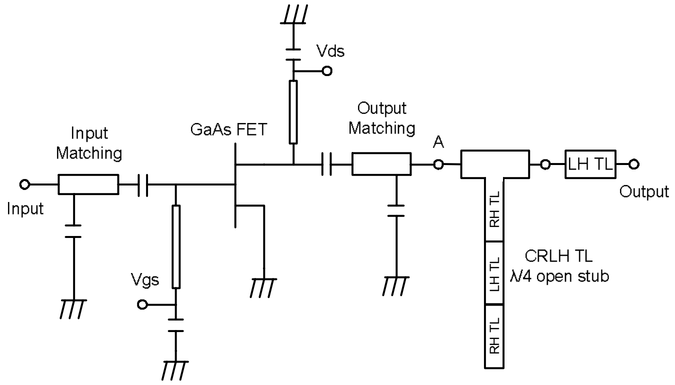


Fig.1. Block diagram of the proposed frequency multiplier.

III. CHARACTERISTIC OF THE LH TL

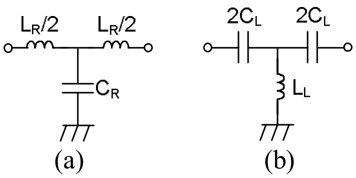
The equivalent circuits of RH TL and LH TL are shown in Fig. 2. The phase responses of two unit cells are expressed by (3)

$$\begin{aligned}\phi_R &= -\arctan\left[\frac{\omega}{2}\left(Z_{0R}C_R+\frac{L_R}{Z_{0R}}-\frac{\omega^2 L_R^2 C_R}{2Z_{0R}}\right)\Big/\left(2-\omega^2 L_R C_R\right)\right]<0\\ \phi_L &= -\arctan\left[\frac{\omega}{2}\left(C_L Z_{0L}+\frac{L_L}{Z_{0L}}-\frac{1}{\omega^2 C_L Z_{0L}}\right)\Big/\left(1-2\omega^2 L_L C_L\right)\right]>0\end{aligned} \qquad (3)$$

where Z_{0R} and Z_{0L} are characteristic impedances of the RH TL and LH TL, respectively, and expressed in (4).

$$Z_{0R}=\sqrt{\frac{L_R}{C_R}}, \qquad Z_{0L}=\sqrt{\frac{L_L}{C_L}} \qquad (4)$$

Since the electrical characteristics of the LH TL is similar to that of high pass filters, it is suitable to apply it to the output of the frequency tripler for suppression of the fundamental component. The LH TL has been designed to have 4 unit cells, and the element values are C_L=1.1pF and L_L=2.8nH, respectively. The characteristic impedance of the LH TL is about 50.5Ω. The RH TL with 50 Ω characteristic impedance is implemented with a microstrip line. Fig. 3 shows the simulation and measurement result of the designed LH TL.



(a) (b)

Fig. 2. T-type unit cells (a)RH TL (b)LH TL.

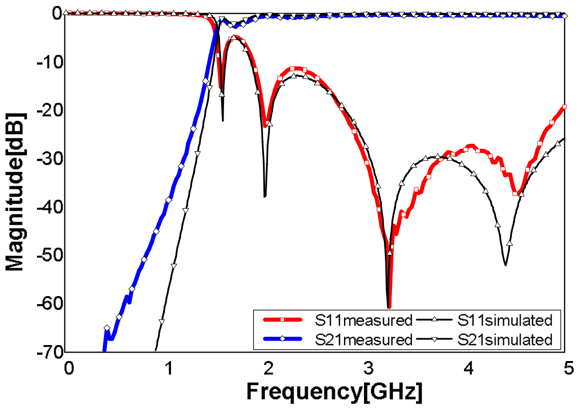


Fig. 3. Simulated and measured results of the LH TL.

IV. CRLH TL λ/4 OPEN STUB

The λ/4 open stub is widely used for harmonic termination and terminates signals for f_0 and odd harmonics, but the CRLH TL, of which phase response is composed of that of RH and LH TL, has arbitrary dual-band termination characteristics. Therefore it can be designed to set termination frequencies for unwanted harmonic frequencies. As shown in the following equations, the phase response of the CRLH TL is -90° at f_1 and -270° at f_2, where f_2 is the unnecessary odd frequency of f_1, and N is the number of stages in LH TL. The element values of the LH TL can be obtained by using (6) and (7).

$$\phi_C(f)=\phi_R(f)+\phi_L(f) \qquad (5)$$

$$\phi_C(f_1)=-\left(2\pi N\sqrt{L_R C_R}\right)f_1+\frac{N}{2\pi\sqrt{L_L C_L}}\frac{1}{f_1}\approx-\frac{\pi}{2} \qquad (6)$$

$$\phi_C(f_2)=-\left(2\pi N\sqrt{L_R C_R}\right)f_2+\frac{N}{2\pi\sqrt{L_L C_L}}\frac{1}{f_2}\approx-\frac{3\pi}{2} \qquad (7)$$

In order to get a more stable signal source, one has to cancel the second and fourth harmonics for the tripler. Thus when the fundamental frequency (f_0) is 1GHz, the f_1 and f_2 of the CRLH TL λ/4 open stub are 2GHz and 4GHz, respectively.

Table I shows the lumped element values (C_L and L_L) when calculating them using (6) and (7). Simulated and measured results of the CRLH TL λ/4 open stub are shown in Fig. 4, and summarized in Table II.

TABLE I

LUMPED ELEMENTS VALUE OF THE CRLH TL λ/4 OPEN STUB

Elements	Values (Calculated / Used)
C_L(Designed/Available)	1.5pF / 1.5pF
L_L(Designed/Available)	3.8nH / 4.2nH

TABLE II

CRLH TL λ/4 OPEN STUB MEASUREMENT RESULTS

f_0=1GHz	S21[dB]		
	$2f_0$	$3f_0$	$4f_0$
Open stub for tripler	-24.77	-0.38	-24.97

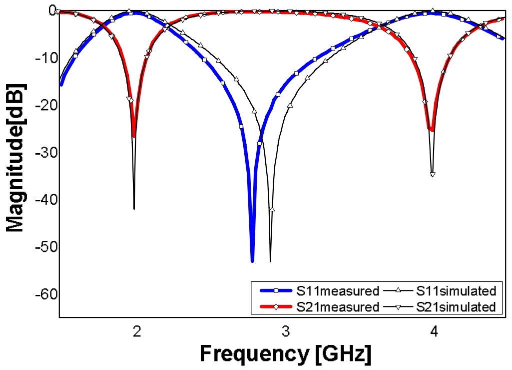


Fig. 4. Simulated and measured results of the CRLH TL λ/4 open stub for tripler.

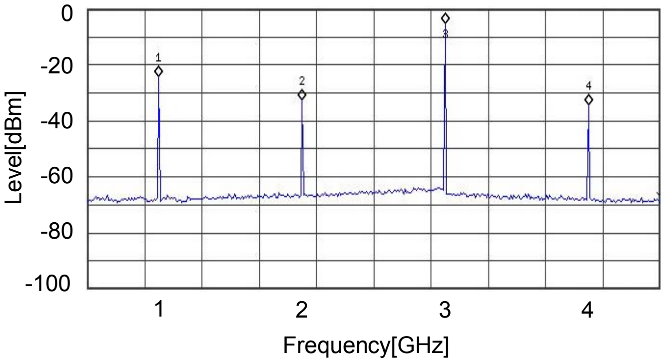
V. EXPERIMENT AND MEASURED RESULTS

We have designed a frequency tripler using the proposed design method when the fundamental signal (f_0) is 1GHz. The adopted transistor is ATF10136 MESFET. The drain and gate bias voltages were set to 1.3V and -1.3 V. The transistor operated near the pinch-off region between class B and C. The matching points for input and output networks have been extracted using source- and load-pull methods, implemented in simulation using Agilent ADS. Fig. 5 shows the measured output spectrum of the frequency tripler, and Fig. 6 is a fabricated frequency tripler. Three measured results are compared for each tripler, i.e. the measured performance of the fabricated tripler itself, the frequency tripler having the CRLH TL /4 open stub (OS), and the proposed frequency tripler having OS and the LH TL. Table III summarizes the output spectrum of the measured frequency triplers.

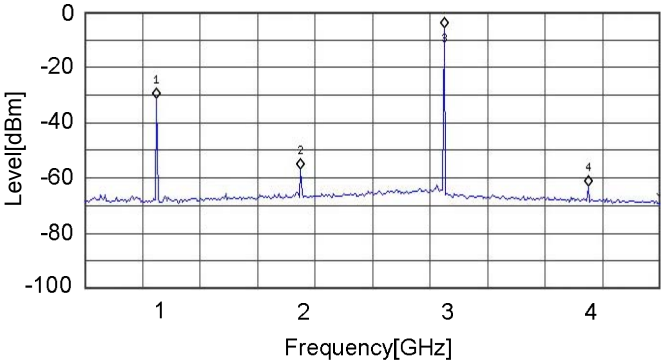
TABLE III

OUTPUT SIGNAL COMPARISON OF FREQUENCY TRIPLER STRUCTURES [dBm]

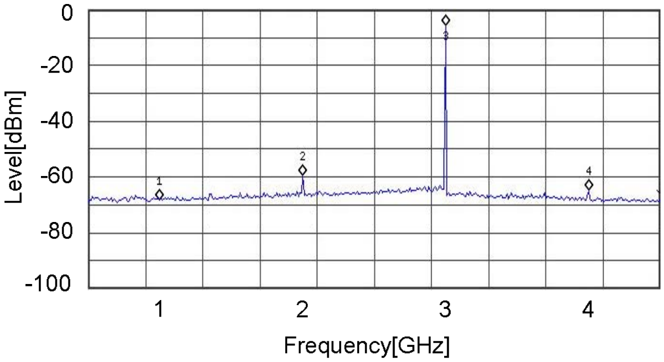
	P_{f0}	P_{2f0}	P_{3f0}	P_{4f0}
Only Tripler	-24.43	-32.72	-5.48	-34.17
Tripler + OS	-31.25	-56.92	-5.75	-62.93
Tripler + OS + LH TL	-68.39	59.27	-5.67	-64.68



(a) Only Tripler



(b) Tripler + OS



(c) Tripler + OS +LH TL

Fig.5. Measured spectrum of the frequency tripler.

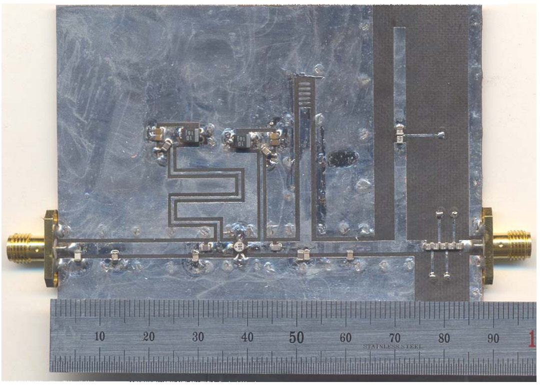


Fig.6. Fabricated frequency tripler ([mm]).

The measured phase noise data of the output signal of the fabricated tripler is -96.18dBc/Hz (at 10KHz offset), when that of the input signal is -101.5dBc/Hz. This is better than the theoretical phase noise degradation condition expressed by 20log(3)=9.5dB, by 4.18 dB. It is believed that the measured phase noise data was caused by the clear elimination of the fundamental signal and unwanted harmonic signals. The λ/4 CRLH TL open stub operated as a harmonic short, so the phase noise of the proposed frequency tripler has improved over the conventional one.

VI. CONCLUSION

A new design method for frequency triplers has been proposed to obtain signal sources with high stability and low phase noise. The fundamental signal was suppressed using LH TL, and the unwanted harmonics were removed due to CRLH TL λ/4 open stubs. We could also obtain a high stable signal source with the improved phase noise. It is believed that the proposed frequency tripler can be integrated in monolithic microwave integrated circuits by adopting CPW or microwave transmission line circuits because the fabricated frequency tripler consists of a transistor and lumped elements. This design method can be applied to a frequency doubler and quadrupler designs. We expect that the proposed frequency tripler design method is a great contribution to improving the quality of communication systems without the need for high Q band-pass filters.

VII. ACKNOWLEDGMENT

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