Active Metamaterial Transmission Line with Gain in SiGe BiCMOS Technology

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Abstract **─** We report the realization of an active composite right/left-handed (CRLH) metamaterial transmission line (TL) with gain. By employing the transistors in SiGe BiCMOS technology, an active CRLH TL has been realized exhibiting net gain, wide-band and flat S-parameter characteristics. Effective electromagnetic parameters of the active CRLH TL, including complex propagation constant γ, effective permittivity ε_{eff}, effective permeability μ_{eff} and index of refraction *n* are extracted, which reveal the left handed properties of the active CRLH TL. The electric plasma frequency f_{pe} and the magnetic plasma frequency f_{me} are observed in the proposed TL.

***Index Terms*─** Active, CRLH TL, metamaterial, SiGe BiCMOS.

I. INTRODUCTION

Metamaterials have special electromagnetic properties such as negative permittivity ε, negative permeability μ and negative index of refraction *n*, which are typically not observed in nature. Research on metamaterials has made great progress since experimental verification of negative index refraction [1] has been reported. Composite right/left-handed (CRLH) transmission line (TL) [2,3] and split ring resonators (SRRs) [4] are commonly two kinds of realization of metamaterials. However, the loss and narrow bandwidth inherently associated with the metamaterials are the main bottleneck that restrict their applications especially in high frequency. Active constituents, such as RF amplifer [5], gain medium rhodamine [6] and germanium tunnel diode [2] were adopted to alleviate the loss problem.

Silicon based SiGe CMOS technology is the most suitable platform for realization of the active CRLH TLs. Because it is available for producing various of active constituents such as transistors and diodes, and lumped elements such as inductance L and capacitance C. Also, it offers integration and small size which is a requirement as the unit length of the CRLH TL should be smaller than the wavelength. Thus, the operating frequency can be extended to microwave and millimeter-wave, even to terahertz (THz).

In this letter, an active CRLH TL with both gain and impedance matching in wideband is demonstrated. Effective electromagnetic parameters including transmission line complex propagation constant γ, effective permittivity ε_{eff}, effective permeability μ_{eff} and index of refraction *n* are extracted to analyze the characteristics of the active CRLH TL. The electric plasma frequency f_{pe} and the magnetic plasma frequency f_{me} are observed, which defined as the transition frequency between the negative and positive value of ε_{eff} and μ_{eff}, respectively.

II. DESIGN OF THE ACTIVE CRLH TL

The schematic of the active CRLH TL is shown in Fig. 1 (a), which contains two distributed unit cells and matching circuits. When the input signal is supplied to the base of the HBT transistor in one unit cell, the amplified output signal can be obtained in the collector. The output signals from each unit cell sum in phase as the delays of the input and output lines are made equal. Terminating matching loads are used to minimize destructive reflections. Its equivalent circuit model of one unit cell of the active CRLH TL is shown in Fig. 1 (b). The passive part of the active CRLH TL unit cell in Fig. 1 (b) is similar to the classic CRLH TL theory [7], including a series connection of inductance L_R and capacitance C_L and a shunt connection inductance L_L and capacitance C_R. They come from two parts: the lumped elements realized in Fig. 1 (a) and the parasitic effects of the HBT transistor. In this design, the designed values

Submitted On: January 30, 2016
Accepted On: May 3, 2016

of the passive part are: L_R =550.2 pH, L_L =249.0 pH, C_R= 220.1 fF, C_L=99.6 fF. Thus, the passive part is balanced at frequency:

$$f_0 = f_{se}(1/2\pi\sqrt{L_R C_L}) = f_{sh}(1/2\pi\sqrt{L_L C_R}) = 21.5 \text{ GHz}. \quad (1)$$

The active part of one unit cell in Fig. 1 (b) is an amplifier unit which provides a voltage-controlled current source to the traditional CRLH TL. It is used to not only compensate the loss from the lumped elements, but also providing gain to the CRLH TL.

Considering the parasitic effects of the transistors, the designed parameters in Fig. 1 (a) are L_{R1}=L_{R2}=500 pH, L_{L1}=L_{L2}=406 pH, C_{R1}=C_{R2}=148 fF, C_{L1}=C_{L2}=162.4 fF. The simulated and measured S parameters are shown in Fig. 2. The measured gain of the active CRLH TL is about 10.5 dB from 10.7 GHz to 31 GHz with ±1 dB ripple and good impedance matching can be observed in this band. Compared with other kinds of CRLH, the proposed CRLH TL in this paper has net gain, wide-band, and flat S-parameter characteristics. The left-handed properties of CRLH TL will be discussed by extraction of effective electromagnetic parameters in the following section.

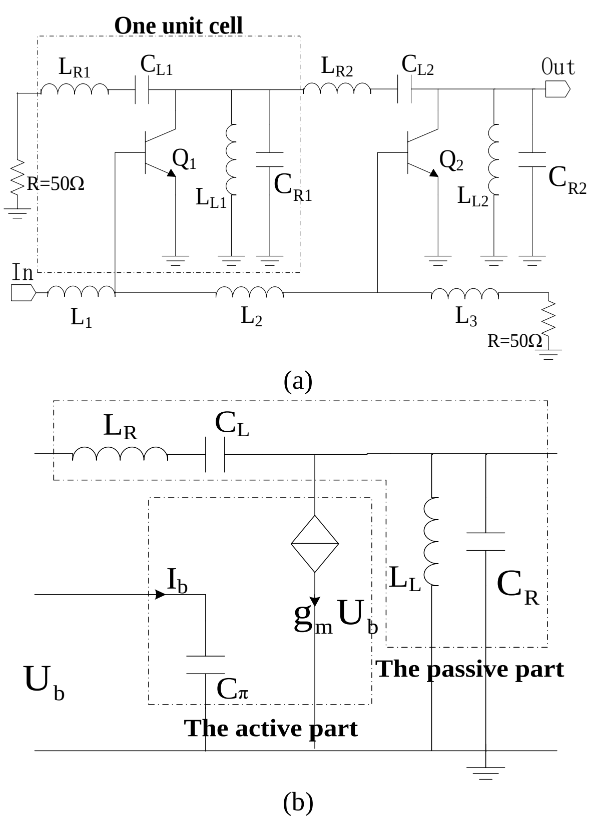


Fig. 1. (a) Schematic of the active CRLH TL. (b) The equivalent circuit model of one unit cell.

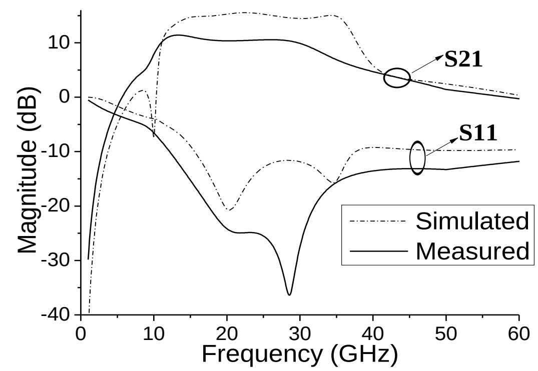
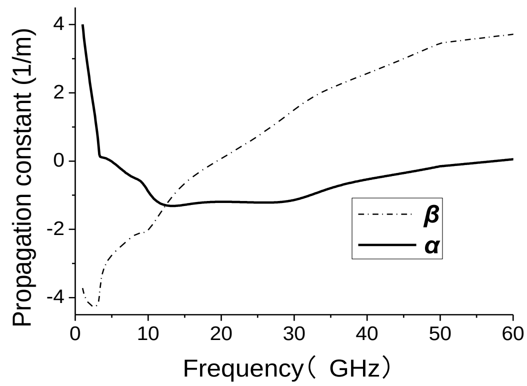


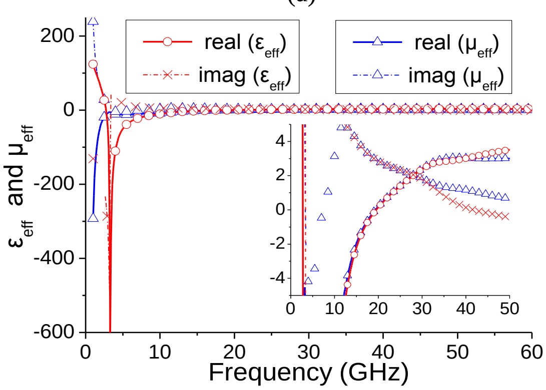
Fig. 2. Simulated (in dash line) and measured S-parameters (in solid line).

III. ANALYSIS OF THE ACTIVE CRLH TL

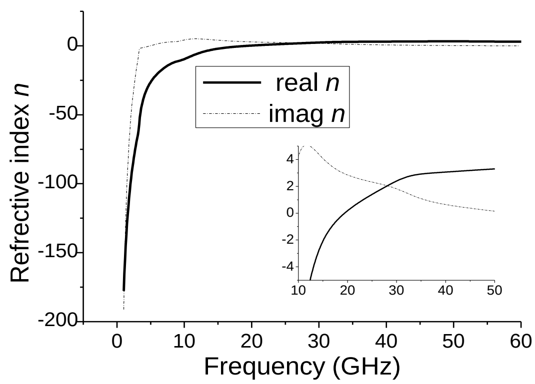
Effective electromagnetic parameters of passive metamaterials can be extracted from measured two-port S-parameters by Nicolson-Ross-Weir (NRW) approach [8-10]. In this method, the choice of sign of the transmission factor T and reflection factor Γ is determined by $|\Gamma| \le 1, |T| \le 1$. While for active metamaterials TL with gain in this design, the constraint is modified to $|\Gamma T| \le 1$. .With this method, the complex propagation constant γ=α+jβ (α is the propagation attenuation constant and β is the phase constant), effective permittivity ε_{eff}, effective permeability μ_{eff} and index of refraction *n* are shown in Fig. 3. From Fig. 3 (a), the negative β from 0 GHz to 19.5 GHz is observed. Thus, the TL exhibits left-handed property below 19.5 GHz and right-handed property above 19.5 GHz. This frequency is shifted downward compared with the designed frequency 21.5 GHz, which could be caused by the inaccuracy of the parameter extraction of the transistors and interconnects. Also, we can obtain negative α from 5 GHz to 57.5 GHz, which means that the magnitude of S21 is larger than 0 dB in this range. For further insight into the electromagnetic properties of the CRLH TL with gain, the effective permittivity ε_{eff} and permeability μ_{eff} are extracted and plotted in Fig. 3 (b). The inset shows the details of the original graph near zero-Y-axis. The real part of μ_{eff} is negative below 19.3 GHz and from 2.8 GHz to 19.5 GHz the real part of ε_{eff} is negative, which verify the left-handed properties below 19.5 GHz. Thus, the electric plasma frequency f_{pe} and the magnetic plasma frequency f_{me} is 19.3 GHz and 19.5 GHz, respectively. Below 3.4 GHz and above 7.2 GHz, the imaginary part of μ_{eff} is positive and from 3.4 GHz to 41.7 GHz, the imaginary part of ε_{eff} is positive, which account for the gain properties of the TL. The corresponding index of refraction *n* is calculated and plotted in Fig. 3 (c). The inset shows the details of the original graph near zero-Y-axis. The real part of n is negative below 19.5 GHz, which indicates left-handed property of the CRLH TL in this band. From 5 GHz to 57.5 GHz, the imaginary part of n are negative, indicating the gain property of the CRLH TL.



(a)



(b)



(c)

Fig. 3. (a) Extracted complex propagation constant $\gamma(\alpha+j\beta)$ from measured two-port S-parameter. (b) Extracted effective permittivity ε_{eff} (red) and effective permeability μ_{eff} (blue) from measured two-port S-parameter. The inset shows the details near zero-Y-axis. (c) Extracted index of refraction n from measured two-port S-parameter. The inset shows the details near zero-Y-axis.

IV. CONCLUSION

In conclusion, we present an active CRLH TL based on BiCMOS technology. Improved performances were experimentally demonstrated in terms of high gain, wideband impedance matching and flat S-parameter characteristics. Effective electromagnetic parameters of the active CRLH TL are analyzed, which can be the basis to the design and application of active metamaterials. Potential applications of the proposed CRLH TL can be foreseen in filters, amplifiers, phase shifters etc.

ACKNOWLEDGMENT

This work is supported in part by NSFC under Grant No. 61401202.

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