Left-handed Miniaturized Microstrip Dual Mode Bandstop Filter

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Abstract

An innovative compact microstrip line left-handed dual mode notch bandstop filter is presented, showing that the size of the bandstop filter can be significantly reduced by employing the left-handed meta-materials. The fabricated filter has the size of 11 mm×50 mm, five times smaller than that of the conventional filter of the same class. The filter has a center frequency of 1.12 GHz.

Keywords: Left-handedness, Left-handed Transmission Line, Meta-materials, Bandstop filter.

Introduction

Materials that exhibit simultaneously negative electric permittivity ε and permeability μ, termed left-handed (LH) meta-materials, were first envisioned by Veselago in 1968 [1]. The first experimental structure exhibiting backward-wave propagation characteristics, and therefore negative refractive index, was developed by Shelby et al in 2001 [2], using an array of split-ring resonators and thin wires. More recently, LH meta-materials were realized by periodically loading a conventional transmission line (TL) with lumped-element series capacitors and shunt inductors in a dual-TL configuration [3], [4]. Various devices that have been developed based on the LH TL-meta-material structure include dominant mode leaky-wave antennas [5], directional couplers [6], and compact, broadband meta-material phase-shifting lines [7]. However, the techniques employed there are not compatible with MMIC technology. To make MMIC compatible LH components, we have proposed to combine the MMIC multilayer technology with LH mechanism [8], resulting in a significant size reduction of LH devices.

In this paper we presents a LH miniaturized microstrip L band dual mode notch bandstop filter with very narrow fractional bandwidth, 1.43%.

Many conventional filters need λ/4 resonators to achieve 90^o phase shift, which leads to a rather large dimension, especially in RF range. The LH filter reported in this paper is believed to be a valuable alternative technique to miniaturize filters, showing to be capable of more than 80% size reduction.

This paper is organized as follows. Section II presents the design details of the LH TL to achieve the required bandstop filter specifications. The circuit modeling and electrical characteristics of the filter are given in Section III, where even-odd mode decomposition analysis for left-handed filter design is proposed. The bandstop phenomenon is demonstrated mathematically and confirmed by full-wave simulation. Finally, Section V presents experimental results of the LH L band dual mode notch bandstop filter. In addition, it shows the comparison of the size and performance between the LH bandstop filter and the conventional one.

Design of Left-handed Transmission Line

A typical LH TL is depicted in Figure1, combining LH series capacitance C_L and shunt inductance L_L. The detailed analysis of the LH TL has been presented in [3].

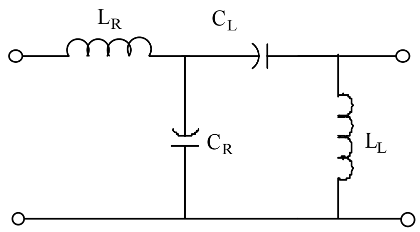

Figure 1 *Circuit model of an idea LH TL.*

To achieve the requirement of the bandstop filter, the LH section plus interconnects should supply + 90° phase shift at resonant frequency, as shown in Figure 2. Considering - 26° phase shift brought by two conventional TLs with total length of 14.2 mm, which connect LH TL to the coupled line, the pure LH TL section needs to offer + 116° phase shift. The LC parameters of the LH TL can be obtained from,

$$\varphi = \beta \cdot l = \left(\omega \sqrt{L_R C_R} - \frac{1}{\omega \sqrt{L_L C_L}} \right) \cdot l \qquad (1)$$

$$Z_0 = \sqrt{L / C} \qquad (2)$$

The artificial LH TL described above can be implemented by microstrip implementation introduced in [3]. The unit cell of the microstrip LH TL consists of a series interdigital capacitor and a stub inductor shorted to the ground plane by via. A LH TL consisting of two unit cells plus interconnects are depicted in Figure 2.

The unit cell's capacitance and inductance are 2.1 pF and 5.5 nH, calculated from (1) and (2), respectively. The unit cell has the length of 15 mm and is loaded periodically. The inductance is offer by a meander inductor with the length of 16.4 mm. In our case, both the strip and slit widths in the unit cell are set to be 0.25 mm in order to achieve the required capacitance and a relaxed fabrication tolerance. Meanwhile, the width of the conventional part of the TL is 2.4 mm. The filter was designed on the RT/d5870 substrate with thickness of 0.787 mm and relative permittivity of 2.33. The phase shift and transmission parameters of the whole TL calculated by full-wave FEM simulation software Ansoft HFSS@ are shown in Figure 4 and Figure 5, respectively.

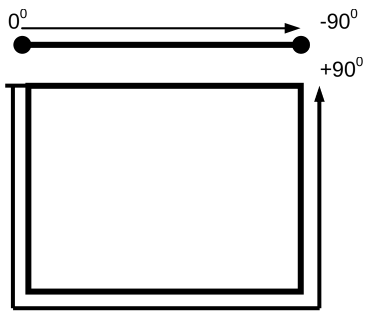

Figure 2 *Generalized model of a dual modes bandstop filter.*

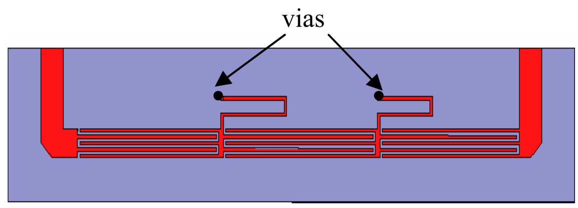

Figure 3 *The LH TL plus interconnects with +90° phase shift at 1.1GHz.*

It can be seen from Figure 4 the left-handedness starts from 0.8 GHz and + 90° degrees phase shift occurs at 1.1 GHz. The

LH frequency bands can also be confirmed with S-parameters in Figure 5. It can be seen in Figure 5 that the insertion loss in the LH frequency region is very small, nearly 0 dB. However the return loss S_{11} is only around 10 dB, meaning there are still some works needed to be done to improve the matching. In this paper, however, we are focusing on the demonstration of the new application of miniaturizing RF/microwave components using LH materials. No attempt has been made to match the LH TL to interconnects, and hence the coupler.

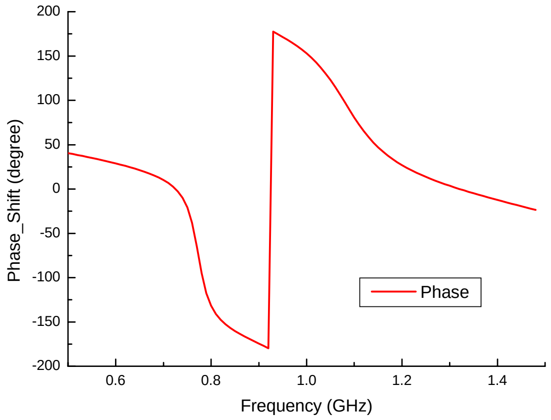

Figure 4 *Simulated Phase shift of LH TL*

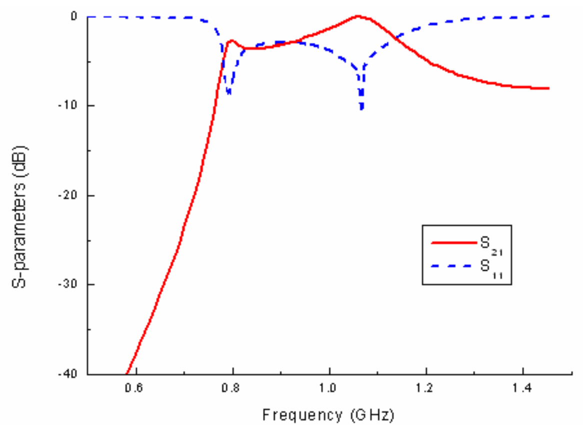

Figure 5 *Simulated transmission parameters of LH TL*

Design of LH Bandstop Filter

The bandstop filter is based on the dual mode notch bandstop filter [9]. Figure 2 shows the general model of this kind of filter. At resonance the power coupled off from the resonator at output is equal in magnitude but 180° out of phase with the signal exiting on the thru-line, and a bandstop is produced. However, in comparison with conventional dual mode notch bandstop filter, where the 180° phase difference is provided by –270° phase shift of the coupled mode, the LH coupled mode provides + 90° phase shift, hence much short length.

The even/odd mode models of the bandstop filter are shown in Figure 6. From the fundamental microwave theory [10], V_2 and V_3 can be obtained by:

$$V_3 = V_3^0 + V_3^e = V \frac{jC \tan\theta}{\sqrt{1-C^2} + j\tan\theta}\Big|_{l=\frac{\lambda}{4}} \quad (3)$$
$$= CV$$

$$V_2 = V_2^0 + V_3^e = -V \frac{\sqrt{1-C^2}}{\sqrt{1-C^2}\cos\theta + j\sin\theta}\Big|_{l=\frac{\lambda}{4}} \quad (4)$$
$$= -j\sqrt{1-C^2}$$

where C is the voltage coupling factor at design frequency. Since Port 4 in the coupler is isolation port, the total power of Port 4 is only supplied by Port 3 through the + 90° phase shift LH transmission line. The voltage of Port 4 can be derived as,

$$V_4 = jV_3 = jCV \quad (5)$$

If the power is equally divided by coupling and through, which leads C=1/2, $|V_2|$ will equal to $|V_4|$ with anti-phase. Therefore, the energy will be cancelled at the Port 4 at the resonance frequency.

Experimental Results and Analysis

A photograph of the fabricated prototype of the LH dual mode notch bandstop filter together with the conventional one is shown in Figure 7. Both circuits are fabricated on the substrate of Rogers DR5870. It can be seen that the size of the proposed LH filter is about 5 times smaller than that of conventional one. The LH TL offers + 90^0 phase shift whereas the thru-line of the coupler provides - 90^0 phase shift. Both these two modes are set to resonate at around 1.1 GHz.

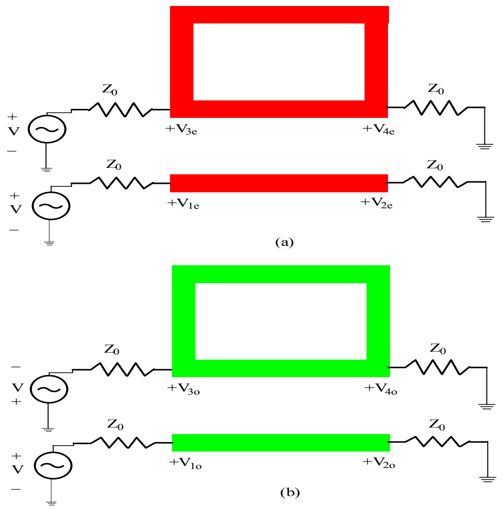

Figure 6 *Even-and odd mode excitations (a) even mode and (b) odd mode.*

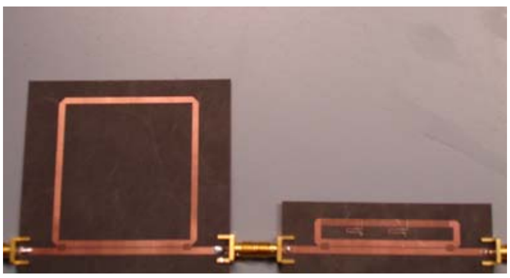

Figure 7 *A photograph of the proposed LH dual mode notch bandstop filter (Right) compared with the conventional one (Left).*

It should be pointed out that the dual mode notch filter is very sensitive to fabrication tolerance since it makes use of the phase cancellation to produce a bandstop. For example, the variation of vias to the ground results in a bit difference on the L_L. This leads the dislocation of the two modes, i.e., the two modes do not overlap tightly. To achieve the superposition of the two modes, the length of the wire needs to be tuned. The effects of the tuning are shown in Figure 8. It can be seen that one mode is always fixed at 1.1 GHz, while the other mode provided by LH TL moves with tuning of the L_L. It's clearly that the LH mode always moves against with the change of L_L.

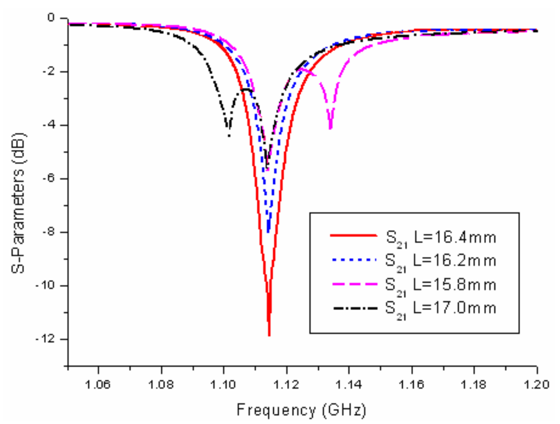

Figure 8 *Measured effects of tuning L_L*

Figure 9 shows the measured S-parameters of both filters. It can be seen that both filters has the centre frequency of 1.11 GHz. Below and above the rejection frequency band a flat and nearly perfect matched passband is present with very low insertion losses. As described in Section II, since no attempt has been made to match both the LH and conventional dual mode notch filters to the system impedance, the transmission coefficients at the resonant frequency are not as low as they can be [9].

Conclusion

A novel L band LH microstrip dual mode notch bandstop filter with significantly reduced-size has been presented. The working principle of this filter has been explained by even/odd mode analysis. The filter has a center frequency of 1.11 GHz. Although the rejection is about 12dB at resonance frequency, it's believed that it can be improved by the better matching of LH section. It is, however, undisputable, that by using the LH technology, the filter size can be significantly reduced, showing five times smaller than that of conventional one.

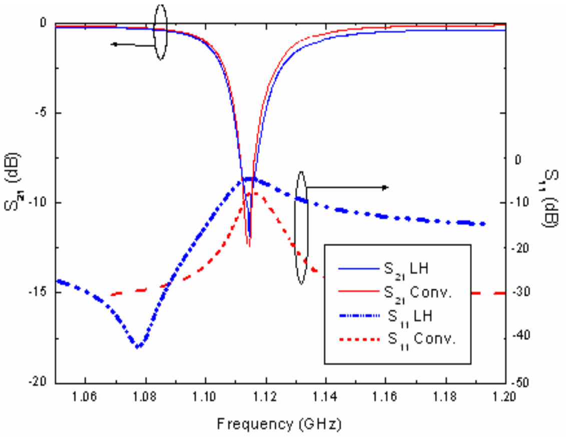

Figure 9 *Measured results of the proposed LH bandstop filter and the conventional one.*

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