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Research Article

Design of Wide-Band Bandpass Filter Using Composite Right/Left-Handed Transmission Line Structure

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A wide-band microstrip bandpass filter (BPF) based on the improved composite right/left-handed transmission line (CRLH-TL) structure is presented in this paper. Compared to the traditional CRLH-TL with via hole, the improved one is an all-planar structure, which owns the advantage of fabrication and loss. The equivalent lossless LC circuit model of the proposed structure is established. EM software Sonnet is adopted to design the wide-band filter with bandwidth of 1.4 GHz (from 1.9 GHz to 3.3 GHz). The circuit occupies only $20.6 \times 12.8\,\text{mm}^2$. Finally, the fabrication and measurement are implemented. A good agreement between simulation and measured results verifies the validity of the design methodology.

1. Introduction

In recent years, left-handed materials (LHMs) have received substantial attention in the scientific and engineering communities for their specific electromagnetic (EM) property (simultaneously negative permittivity ε and permeability μ) [1]. *Science* magazine named LHMs as one of the top ten scientific breakthroughs of 2003 [2]. The first artificial LHM composed of thin copper wires and copper split-ring resonators (SRRs) was realized by Smith group at the University of California [3]. However, this kind of structure is always difficult to implement for microwave applications because resonant units such as SRRs are lossy and narrow-banded [4]. Several researchers soon realized that transmission lines (TLs) approach towards LHMs was possible [5, 6]. In actual implementation, LHMs are considered to be a more general model of composite right/left-handed (CRLH) TLs, which also include right-handed (RH) effects that occur naturally in LH TLs. With CRLH structure, many new kinds of microwave devices are designed for low loss and broadband characteristics, such as divider, phase shifter, coupler, and leaky-wave antenna [7].

New ultra-wide-band radar and high-rate communication systems require very specialized RF devices capable of operating over wide frequency scope [8]. Thus, as the key element in RF system, high efficient wide-band bandpass filter (BPF) is no exception in this background. The popular way of designing wide-band filters is employing multiple-mode resonators [9, 10] or signal-interference concepts [11, 12]. However, the circuit sizes of the aforementioned are comparatively large. More recently, CRLH TL unit cells are applied to design compact wide-band filter [13, 14]. Nevertheless, a via hole or dual-layer structure is indispensable, which complexes the fabrication process. In our previous works, an all-planar CRLH resonator is proposed and fabricated on high-temperature superconducting film [15], which obtains a high performance filtering response with ultralow insertion loss, but the bandwidth is small.

In this paper, an improved CRLH TL is proposed to design a wide-band BPF. Patch capacitance replaces traditional via hole connected to shunt inductance in this new structure cell, which reduces the fabrication difficulty and circuit loss. The filter is simulated and optimized by EM software Sonnet and the obtained circuit size is $0.3\lambda_g \times 0.18\lambda_g$ (λ_g is the guided wavelength of the $50\,\Omega$ line at the center frequency). To observe the LH property, the dispersion diagram is given and researched in the paper. Simulation

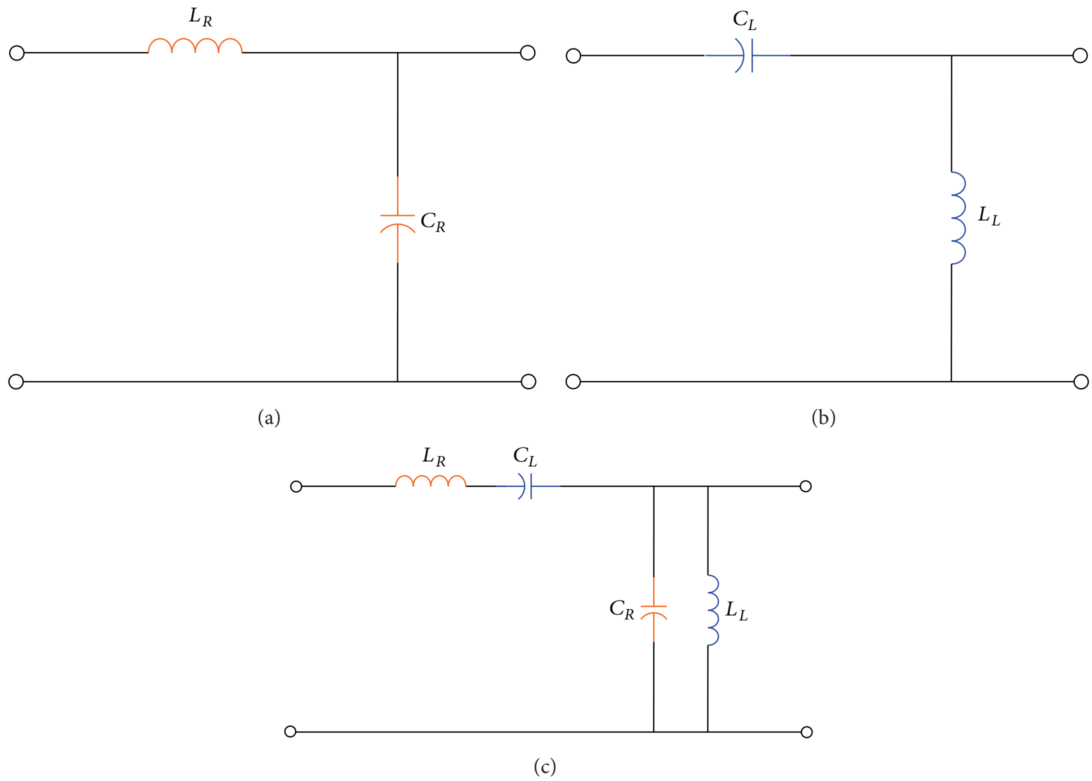

FIGURE 1: Equivalent circuits: (a) pure RH TL, (b) pure LH TL, and (c) CRLH TL.

and measurement conducted validate the proposed design principle.

2. Theoretical Analysis

In the ideal condition, the equivalent circuit of the pure RH TL and pure LH TL is depicted in Figures 1(a) and 1(b), respectively. It can be seen from Figure 1(a) that the pure RH TL includes series inductance L_R and shunt capacitance C_R, which provides a low-pass filtering response. Opposite to RH TL, the pure LH TL is composed of series capacitance C_L and shunt inductance L_L and indicates a high-pass response, as shown in Figure 1(b). The cutoff frequencies of these two responses can be expressed as

$$\begin{aligned} \omega_{cR} &= \frac{1}{\sqrt{L_R C_R}}, \\ \omega_{cL} &= \frac{1}{\sqrt{L_L C_L}}, \end{aligned} \tag{1}$$

where subscripts R and L represent RH and LH, respectively.

In reality, a pure LH structure is not possible because of unavoidable RH parasitic parameters. Therefore, a CRLH structure represents the most general form of a structure with attributes. Figure 1(c) shows the general model of CRLH TL, which consists of inductance L_R in series with capacitance C_L and shunt capacitance C_R in parallel with inductance L_L. Thus, when $w_{cL} < w_{cR}$, a bandpass characteristic can be constructed under the balanced case. The center frequency of the passband w_0 can be calculated by

$$\omega_0 = \sqrt{\omega_{cR}\omega_{cL}} = \frac{1}{\sqrt[4]{L_R C_R L_L C_L}}. \tag{2}$$

Because the passband is formed by two parts, that is, LH part and RH part, the bandwidth can be enlarged and a wide-band response is always provided. Certainly, the other EM properties can also be achieved when $w_{cL} \geq w_{cR}$.

3. Filter Implementation

Based on the discussion above, a wide-band BPF can be designed with CRLH structure, and a wider bandwidth can be realized with larger L_L, C_L and smaller L_R, C_R. Therefore, a symmetrical circuit model of improved CRLH structure is proposed and illustrated in Figure 2. It can be seen that there are two shunt tanks such that a larger L_L will be provided. Moreover, it should be noted that an additional capacitor C_{R1} is added to the branch of L_L, which avoids the grounded operation directly and realizes the all-planar structure.

Figure 3 shows the corresponding microstrip structure of circuit model in Figure 2. It can be observed that the structure is mainly made up of three parts, that is, interdigital structure, meander lines, and rectangle patch. In this work, the series tank is realized with microstrip interdigital capacitor, and the shunt tank is implemented by meander line inductor and rectangle patch capacitor. The interdigital capacitor has a relatively larger value of the series capacitor C_L, while

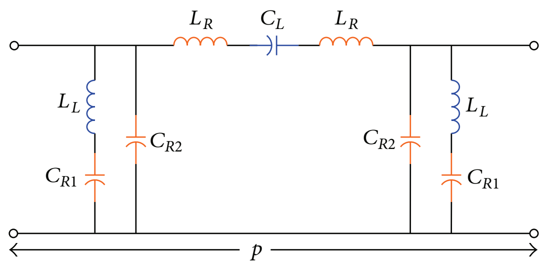

FIGURE 2: Symmetrical equivalent circuit of the improved CRLH structure.

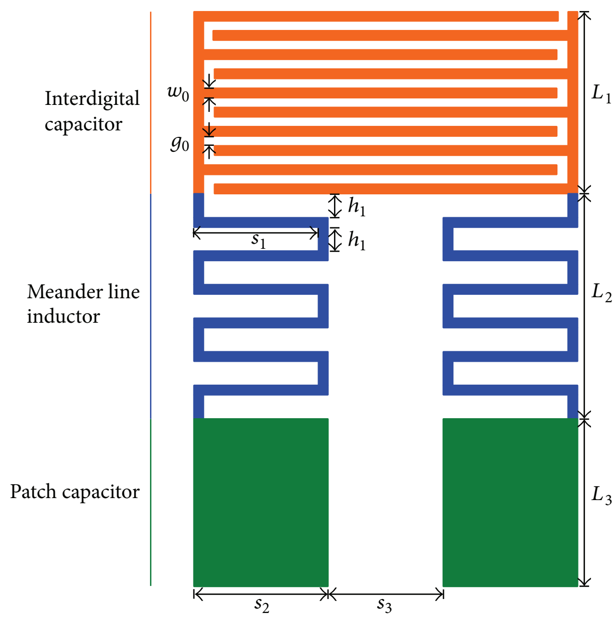

FIGURE 3: Microstrip implementation of the improved CRLH structure.

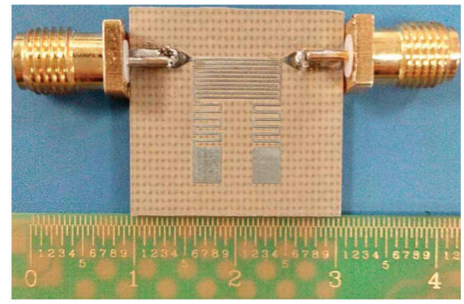

FIGURE 4: Photograph of the proposed filter.

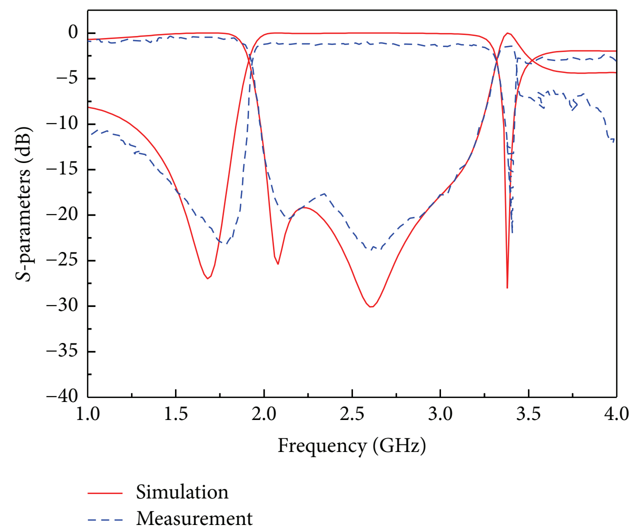

FIGURE 5: Measured and simulated responses of the wide-band filter.

two meander lines provide a large shunt inductor L_L, which ensure the wide-band BPF condition $w_{cL} < w_{cR}$. The other parameters are carefully selected to meet the balanced CRLH requirement, which averts the bandgap in the wide passband range.

EM simulated software Sonnet is applied to simulate the designed filter and optimize its size parameters. The *Taconic*-RF-35A2 substrate with a relative dielectric constant of 3.5 and a thickness of 0.76 mm is used. In this paper, a wide-band BPF with passband ranges from 1.9 GHz to 3.3 GHz (total 3 dB bandwidth is 1.4 GHz) will be designed. According to the parameters extracted and converted method described in [16, 17], the filter size can be obtained and finally optimized by Sonnet as follows: $w_0 = g_0 = 0.2$, $s_1 = 2.6$, $s_2 = 2.8$, $s_3 = 3$, $h_1 = 0.5$, $h_2 = 3.5$, $L_1 = 3.8$, $L_2 = 4.7$, and $L_3 = 3.5$ (unit: millimeters).

4. Results and Discussion

For demonstration purpose, the well-designed wide-band filter is fabricated on *Taconic*-RF-35A2 substrate. Without the via hole, it is easy to process the circuit with ordinary technology. Figure 4 depicts the photograph of the fabricated filter. The tapped coupling structure is used to design the input/output structure and wedge shape is introduced for impedance matching. The fabricated filter is measured by network analyzer of CETC AV3629.

A comparison between simulation and measurement is presented in Figure 5, where the red solid lines and blue dashed lines indicate the simulated and measured results, respectively. A wide-band bandpass response with the passband ranges from 1.91 to 3.32 GHz is obtained and the corresponding 3 dB bandwidth is about 51.9%. The maximum measured insertion loss is approximately 1.38 dB and the return loss in passband is better than 17 dB. Two transmission zeros located at lower and upper side of passband enhance the filter selectivity. A good agreement obtained between the measured and simulated results indicates the validity of the design principle. Some discrepancy between the measured and simulated data can be attributed to the inevitable inaccuracy in fabrication and larger dielectric loss at high frequency.

Moreover, the complex propagation constant γ will be discussed to interpret behaviors of the proposed CRLH

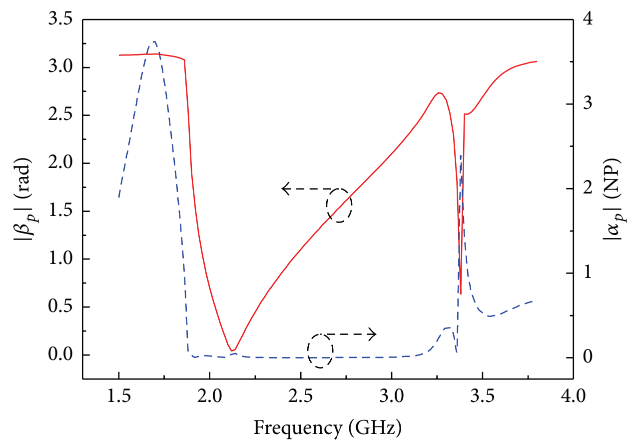

Figure 6: Dispersion characteristic diagram of the designed filter with improved CRLH structure.

device. According to circuit network analysis, $\gamma(w)$ can be expressed as

$$\gamma(\omega) = \alpha(\omega) + j\beta(\omega) = \frac{\cos^{-1}(A)}{p}, \tag{3}$$

where $\alpha(w)$ and $\beta(w)$ represent the attenuation factor and propagation constant, respectively. p is the total length of improved CRLH filter. Parameter A is a matrix element of ABCD-matrix and it can be obtained from

$$A = \frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}. \tag{4}$$

Therefore, $\gamma(w)$ can be easily calculated from the simulated or measured S parameters.

Figure 6 shows $\gamma(w)$ of the designed wide-band filter with CRLH TL structure. In general, the bigger the attenuation factor α is, the greater the electromagnetic wave is attenuated. If attenuation factor $\alpha = 0$, a passband will be presented since $\gamma(w) = j\beta(w)$ is an imaginary. Otherwise, a stopband occurs in certain frequency range. So, a passband occurs within the frequency ranges from 1.9 to 3.3 GHz. On the other hand, it can be found that the product of group velocity and phase velocity $v_g v_p < 0$ ($v_g = \partial\omega/\partial\beta$, $v_p = \omega/\beta$) in the frequency range from 1.91 to 2.12 GHz and shows the LH performance. Similarly, it can be obtained that $v_g v_p > 0$ in the frequency range from 2.12 to 3.32 GHz and indicates the RH performance.

5. Conclusions

In this paper, a wide-band BPF is designed with the improved CRLH TL. Additional patch capacitance is added to remove traditional via hole, which reduces the fabrication difficulty and circuit loss. The filter is simulated and optimized by EM software Sonnet. Good agreement between simulation and measurement validates the validity of the proposed design principle. To observe the LH property, the dispersion diagram is given and explained in the paper.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

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