Compact Integrated MMIC Left-Handed Bandpass Filter

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Abstract

The design of a two-pole compact MMIC left-handed (LH) bandpass filter is presented. The filter consists of only one miniaturized left-handed transmission line (TL) and four left-handed open resonators, and exhibits transmission zeros at both sides of the passband. Due to the applications of compact MMIC left-handed transmission line and resonators, the size of the proposed bandpass filter is very compact, and provides sharp transition bands. The measurement results of filters designed at 1.27 GHz are given to validate the theory.

Keywords: Left-handed metamaterials, Left-handed resonators, Bandpass filter

Introduction

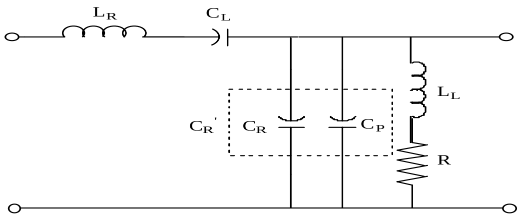
Back in 1968, Veselago first suggested theoretically that a material having simultaneously negative permittivity and permeability would support backward-wave propagation and exhibit negative refractive index [1]. Recently, Shelby et al. succeeded in experimentally demonstrating his prediction of the existence of left-handed (LH) medium [2] by combining an array of metallic wires to attain negative ε [3] and an array of split-ring resonators to achieve negative μ [4]. Several practical applications of LH structures have been developed based on the transmission line (TL) approach [5]-[7]. However, these applications, while having a great significance in microwave circuit designs, are not compatible with RF/MMIC technology. Although the vertical multilayered LH TL was developed recently [8], it is only suitable for LTCC rather than MMICs. A fully integrated multilayered LH TL for RF/MMIC applications was first proposed in [9].

In this paper, as one novel application of left-handed metamaterial, we present a novel design of two-pole left-handed bandpass filter consisting of one left-handed transmission line and four open resonators. Since the open stubs are implemented by MMIC integrated left-handed technology, the resonant frequency of the open stub will no longer depend on the length, but only on the LC values. Therefore, a rather compact size can be achieved. Design examples at 1.27 GHz and measured result are given to validate the theory. It exhibits an operating centre frequency at 1.27 GHz and 32.8% fractional bandwidth with a rather compact size of 2.85 mm^2!

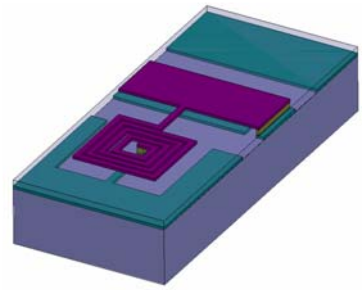
Design of LH TL and Open Resonators

A. LH TL

A LH TL is an artificial TL structure created by the repetition of series capacitance C_L and shunt inductance L_L. As a result, a LH band at lower frequencies and a RH band at higher frequencies are present. Figure 1(a) illustrates the corresponding equivalent circuit of the unit cell. In GaAs



(a)



(b)

Fig. 1 (a) Equivalent circuit model of an integrated LH TL unit cell: LH-series capacitance C_L, LH-shunt inductance L_L, RH-series inductance L_R, RH-shunt capacitance C_R, and C_R' (including fringing capacitance and series resistance of the spiral inductor C_P, and R) and (b) Unit cell structure

implemented in the form of two metal layer capacitors and spiral inductors, as shown in Fig. 1 (b). Thanks to the special structure of the proposed unit cell, the right-handed (RH) effect L_R and C_R' are so small that they can be ignored in the design.

The highpass cutoff frequencies $f_{cutoff,LH}$ can be obtained from [5]

$$f_{cutoff,LH} = \frac{1}{4\pi\sqrt{L_L C_L}} \qquad (1)$$

The dispersion of the left-handed transmission line can be split into additive positive linear RH and negative hyperbolic LH terms [5], and given as

$$\beta(\omega) = \beta_{RH} + \beta_{LH} = \frac{1}{d}\left(\omega\sqrt{L_R C_R'} - \frac{1}{\omega\sqrt{L_L C_L}}\right)$$

(2)

where d is the length of the unit cell.

When $1/\omega\sqrt{L_L C_L} > \omega\sqrt{L_R C_R'}$, the propagation constant is negative, meaning that the TL operates in the LH range otherwise the TL operates in the RH ranges. The input feeding line presented here was implemented by a CPW TL with a width of 100 μm and gaps of 70 μm, having a characteristic impedance of 50 Ω. The LH MMIC components were fabricated using two metal layers sandwiched between a polyimide dielectric which was placed on a GaAs substrate. The thickness of the polyimide layers was 1 μm and its dielectric constant is 3.8. The thickness of the GaAs substrate is 625 μm.

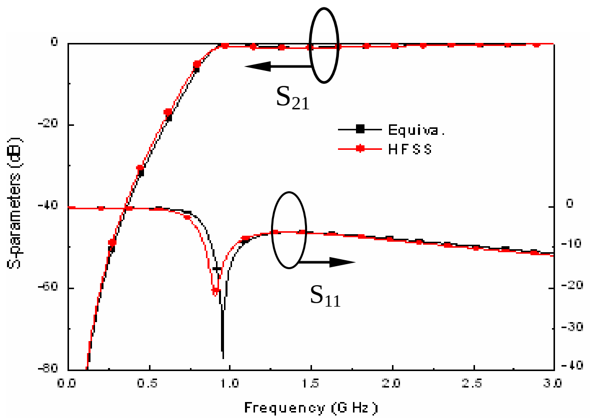


Fig. 2 Simulated results for two unit cells LH MMIC TL.

Fig. 2 shows the full wave and equivalent circuits simulated transmission coefficients of two unit cells LH MMIC TL for using in the bandpass filter. The full wave simulation was conducted using Ansoft HFSS simulator. In this case, the capacitor of the unit cell occupies 0.08 mm^2, providing a capacitance of about 2.7 pF. The spiral inductor, with 10 μm strip width and 10 μm gap, has an area of 0.09 mm^2 and an inductance of 4.65 nH. As can be seen in the figure, a very good agreement between the full wave and equivalent circuit simulations is achieved.

B. LH Open Resonators

As a basic microwave component, the resonant frequency of the conventional $\lambda/4$ open stub depends on the length of the TL.

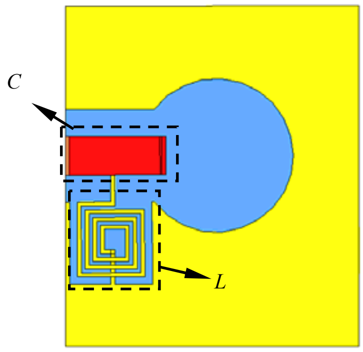


Fig. 3 The prototype of the one unit cell LH MMIC open stub

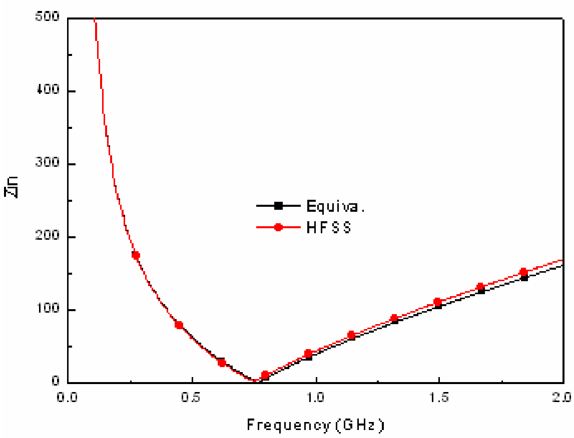


Fig. 4 Simulated results for LH open stub performing at 0.76 GHz

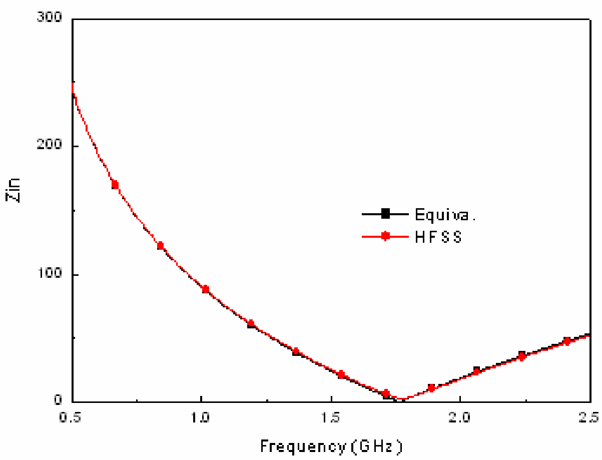


Fig. 5 Simulated results for LH open stub performing at 1.75 GHz

In contrast, the resonant frequency of a LH TL open stub is only determined by the LC values. Thus an open stub can achieve a rather compact dimension with appropriate values of L and C. To minimize the size and the loss, the proposed LH open stub consists of only one LH unit cell with a series capacitor and a shunt inductor. Since the two–poles of the proposed bandpass filter are designed at 0.76 GHz and 1.75 GHz, the parameters of these two left-handed open stubs with different resonant frequencies are C=2.7 pF , L=15.66 nH , and C=1.2 pF and L=6.5 nH , respectively. The prototype of the LH open stub is shown in Fig. 3. The LH MMIC open stubs consume very small areas equal to 0.33 mm^2 and 0.25 mm^2, respectively. The simulated results of Z_{in} are shown in Fig. 4 and Fig. 5. Z_{in} reach the minimum with a value close to zero, at 0.76 GHz and 1.75 GHz as expected. This means the LH MMIC open stub performs as a conventional $\lambda/4$ TL open stub at these resonant frequencies.

Left-Handed Bandpass Filter

As a demonstration of utilizing the basic LH MMIC components, a novel Left-handed MMIC bandpass has been designed, fabricated and measured. The bandpass filter topology adopts the proposed LH open stubs connected to left-handed transmission line to achieve the transmission zeros at both sides of the passband. To intensify the effect of rejection at transmission zeros, each zero pole is led by two identical left-handed open stubs. Therefore, our left-handed MMIC bandpass filter consists of four left-handed open stubs and one left-handed transmission line. (see Fig. 6)
To achieve a better matching, the tuning on the transmission line parameters is necessary after the connection of the proposed transmission lines and open stubs. Thus, the parameters for the bandpass filter are: C_1=6 pF, C_2=2.7 pF, C_3=2.7 pF, C_4=1.2

pF, L_1=3.7 nH, L_2=4.65 nH, L_3=15.66 nH, L_4=6.5 nH.

In contrast to a conventional microwave transmission line bandpass filter, the bandwidth and the centre frequency of the left-handed bandpass filter do not depend on the length of the transmission lines. Transmission poles and zeros can be created and tuned by adjusting the LC values of the open stubs.

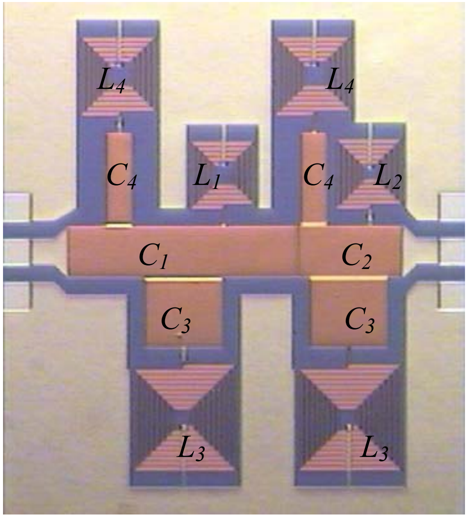


Fig. 6 Fabricated LH bandpass filter

Fig. 7 shows the measured and simulated results of the proposed filters with metal thicknesses of 0.2 um for the bottom layer and 1.4 um for the top layer under the fabrication limit of authors' lab. The main metal loss R taken into the equivalent circuit can be calculated from [10]. In the fabricated case, the thin metallization lead to a huge loss. However, this does not affect the validation of the design. A good agreement among the measured and simulated results demonstrates the validity of the design theory. Further more, a thicker metallization can solve the loss issue.

Fig. 8 illustrates the full wave and equivalent circuit simulated frequency responses of the left-handed MMIC bandpass filter with thicker metal thickness of 1 um (bottom layer) and 5 um (top layer). It can be seen that an operating centre frequency of 1.27 GHz and 32.8% fractional bandwidth of the proposed filter is achieved with a rather compact size of 2.85 mm^2. Two zeros are designed at 0.76 GHz and 1.75 GHz, respectively and give a 3 dB passband from 1.08 GHz to 1.49 GHz.

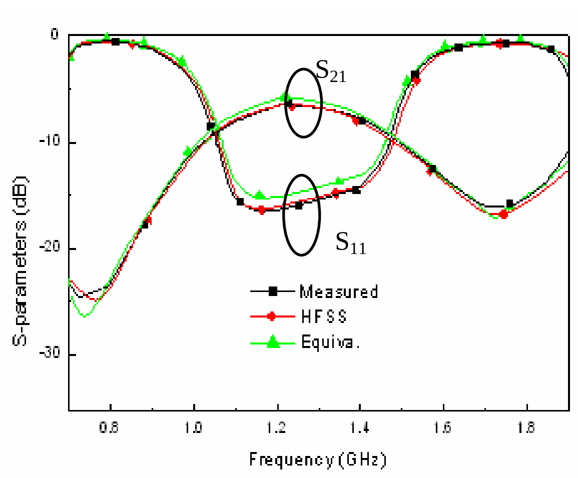


Fig. 7 Measured and simulated results of the proposed LH bandpass filter with metal thicknesses of 1.4 µm for top layer and 0.2 µm for bottom layer

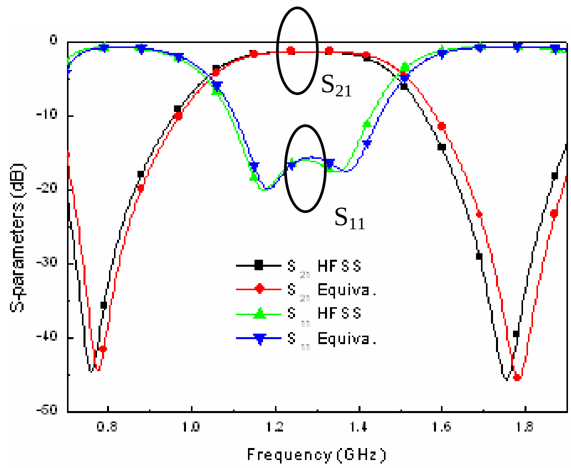


Fig. 8 Simulated results of the proposed LH bandpass filter with metal thicknesses of 5 µm for top layer and 1 µm for bottom layer

Conclusion

The design of compact banapss filter using miniature MMIC integrated left-handed transmission lines and open resonators is presented. The proposed bandpass filter with a rather compact size of 2.85 mm^2 exhibits an operating centre frequency of 1.27 GHz and 32.8% fractional bandwidth.

The experimental result is shown to prove the design theory.

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