A Novel Bandpass Filters Using Complementary Split Ring Resonator Loaded Half Mode Substrate Integrated Waveguide

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Abstract **—** A half mode substrate integrated waveguide with hexagon shaped complementary split-ring resonators (CSRRs) etched on the top of the waveguide is presented in this paper. The simulated results show that extra low insertion loss of about -0.1 dB and the return loss of -10 dB can be achieved. The proposed structure allows the implementation of a forward wave below the characteristic cutoff frequency of the waveguide. By changing the radius of the hexagon shaped CSRR, which is incorporated on top of the waveguide, the pass frequency band can be tuned easily. Finally, a compact band pass filter is fabricated and validated.

Index Terms **-** Complementary split-ring resonator (CSRR) and half mode substrate integrated waveguide (HMSIW).

I. INTRODUCTION

The rectangular waveguide acting as an effective transmission line has already been widely used in the microwave and millimeter wave systems for many years. Recently, some new planar waveguide structures called substrate integrated waveguide (SIW) as well as laminated waveguide or post-wall waveguide were proposed and applied to develop many high-quality microwave and millimeter wave components [1]. Since SIW can be fabricated using the standard print circuit board (PCB) process, it is low-lost, mass-productive and easily integrated with planar circuits. In recent research, a split-ring resonator has been designed in a way to be embedded in thin substrates. It is shown that an SIW can be miniaturized when it is loaded by these embedded SRRs. However, sometime the sizes of the SIW blocks may be too large for practical circuits, and affect the integration [2]. To overcome such drawbacks, an improved guided wave structure, called "half model substrate integrated waveguide (HMSIW)" is proposed.

When SIW is used only with the dominant mode, the maximum E-field is at the vertical center plane along the propagation direction, so the center plane can be considered as an equivalent magnetic wall. If an SIW is divided into two parts along this plane, each can support a half of the field structure independently because of the large width-to-height ratio [3]. The substrate should be extended only a little bit in the horizontal direction to enclose any possible but negligible radiating energy or fringing field. The HMSIW can easily achieve low insertion loss, high power capacity in planar configuration, and also reduce the size in significant way [4]. This advantage is very important for highly integrated circuits and systems.

On the other hand, since the left-handed behaviors have been experimentally verified by Smith in 2001, there have been growing interests in the development and characterization of artificial structures with negative permittivity and permeability. Up to now, two types of structures have been proposed to realize such metamaterials, which have not been observed in nature. One is the periodic structure containing metallic strips and split ring resonators (SRR) [5], shown in Fig. 1 (a). The strips and resonators can be designed to exhibit negative ε and μ simultaneously in the same frequency band, and therefore the effective refraction index becomes less than zero. The CSRR is the negative image of the SRR, which can provide a negative effective permittivity in the

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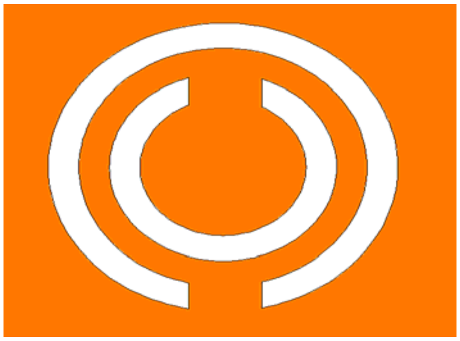
vicinity of its resonant frequency, shown in Fig. 1 (b). Some special designs have also been proposed to replace the strip-resonator structure mentioned above, such as the Ω-shaped or S-shaped unit, which can broaden the left-handed bandwidth and lower the material loss obviously. These types have attracted a great deal of interest for the design of negative permeability and left-handed (LH) effective media. Another kind of structure is the planar LC network, composed of series capacitors and shunt inductors [6]. A number of applications have been realized in the microwave circuit design like filters, leaky wave antennas, and nonlinear phase shifters. The planar structures also include the left-handed transmission line (LHTL) implemented using microstrip lines, coplanar waveguides or finlines, which are loaded with different SRR structures [7].

(a)



(b)

Fig. 1. The geometries of (a) SRR and (b) CSRR (orange region is metal, white region is substrate).

In this paper, the HMSIW is used for the design of the bandpass filter. This paper presents a new type of planar filter based on HMSIW technology for low microwave frequency band. An S-band filter is simulated by using HFSS software and fabricated with a single layer PCB process [8]. The filter operates at the center frequency of 3.05 GHz with the fractional bandwidth of around 7 %. Compared with SIW BPF, the HMSIW BPF with nearly half reduction in size has a wider stop band due to the HMSIW intrinsically cannot support the $TE_{2m,n}$ modes as well as TM modes [9]. The measured results, which show good agreement with the simulated results, are provided [10].

II. FILTER DESIGN

As we know, the electric field within HMSIW is orthogonal to the top and bottom surfaces of HMSIW, it is thus appropriate to etch the CSRR cells either on the top surface of HMSIW or bottom plane, which can guarantee that CSRR are properly excited. The behavior of the complementary structure excited by an axial electric field will be similar to that of the original SRR excited by an axial magnetic field. However, it is better to etch the CSRR cells on the top surface to preserve the integrity of the bottom plane, which is usually required in practical engineering [11]. The resultant HMSIW-CSRR bandpass filter is illustrated in Fig. 2, which is implemented in a substrate with thickness of 0.508 mm and dielectric constant 2.2. The orange part is a metallic conductor on HMSIW top plane and blue part is non-metallic [12]. The size of the inner-square (R_1, R_2) should be adjusted to determine the resonance frequency of CSRR resonators [13]. If other parameters are fixed, the resonance frequency will increase with the decrease of R_1 and R_2. If R_1 and R_2 are fixed, the resonance frequency could be also enhanced by increasing the slit width of squares (g). For the convenience of optimization work, the width of squares (d_1, d_2) and distance between squares are set to be the same as (g). This resonance structure will bring a sharp stop band. After that, the distance (C_1, C_2) between these two CSRRs should be also optimized. These optimization works were managed by using the commercial 3-D electromagnetic software HFSS. The proposed filter consists of a transmission line of HMSIW, a CSRR on HMSIW, and a transition between microstrip and HMSIW as shown in Fig. 2. The two symmetrical hexagon shaped slots are etched on the circuit board.

The topology of the proposed structure is shown in Fig. 3, which is divided into three parts. The proposed filter consists of a transmission line of HMSIW, a CSRR array on HMSIW, and a transition between microstrip and HMSIW [14]. The left and right parts are HMSIW-microstrip tapered transition including a segment of 50 Ω microstrip, a segment of tapered microstrip, and the discontinuity between microstrip and HMSIW. The tapered microstrip is used to excite the waveguide mode and match the impedance with HMSIW [15]. The middle part is an etched hexagon shaped CSRR cells on the top surface. The arrays of the metallized vias are designed to mimic the effect of the electric wall for the waveguide modes.

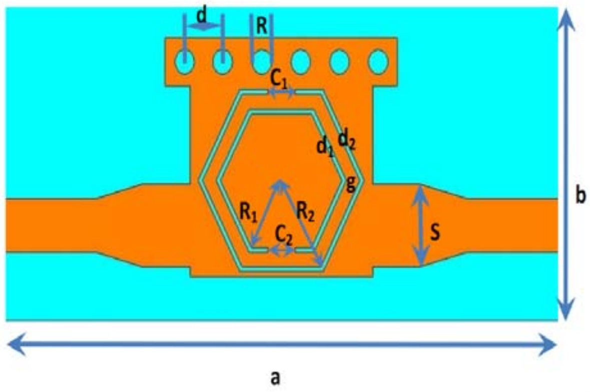


Fig. 2. Geometry of broadband bandpass filter, with dimensions $R_1 = 2.98$ mm, $R_2 = 3.27$ mm, $d_1 = 0.35$ mm, $d_2 = 0.15$ mm, $C_1 = 0.2$ mm, $C_2 = 0.2$ mm, g = 0.13 mm, R = 0.5 mm, d =0.7 mm, b = 6 mm, a = 20 mm, and S = 2.35 mm.

As shown in Fig. 3, the impedance of each resonator for the wave propagating in transverse direction, can be calculated considering the loading at the center and using the well known transmission line formula,

$$Z_{in} = Z_0 \frac{Z_l + jZ_0 \tan(\beta_u l)}{Z_0 + Z_l \tan(\beta_u l)} \tag{1}$$

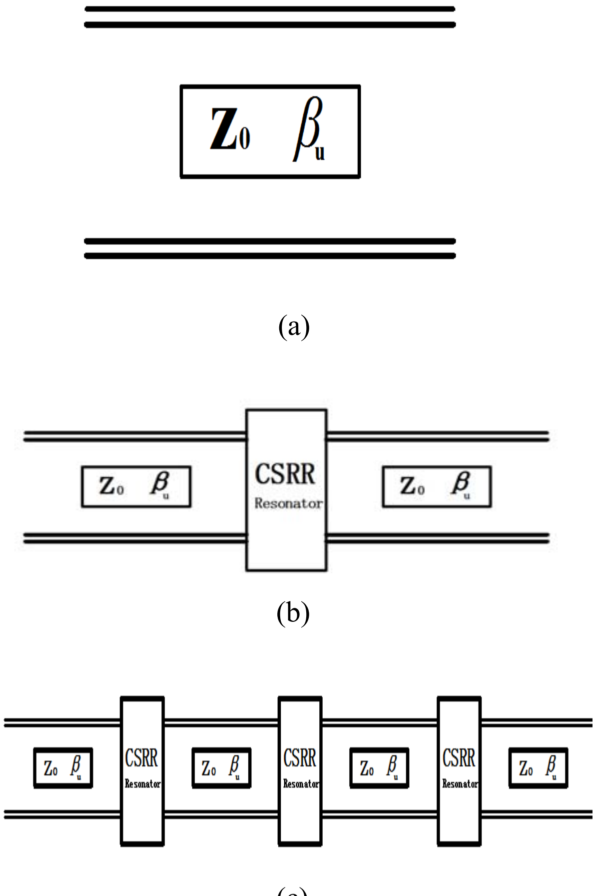
where Z_o is the characteristic impedance and β_u is the phase constant (losses of the transmission line are assumed to be zero) of the transmission line, Z_L is the loading impedance, and l is the line length. The transmission line is approximated either by the microstrip line or other transmission line depending on the width-height ratio of the line and the dielectric material [16].

The propagation constant, γ for the infinite periodic structure is [17],

$$\cosh(\gamma a) = \cos(\beta_u a) + j\frac{Z}{2Z_0}\sin(\beta_u a). \tag{2}$$

Z_o is the characteristic impedance and Z is the impedance of the CSRR resonance, and the phase constant γ in equation (2) are all the same as those of the resonators. With $\gamma = \alpha + \beta$, equation (2) can be rearranged as follows,

$$\cosh(\alpha a)\cos(\beta a) + j\sin(\alpha a)\sin(\beta a) =$$
$$\cos(\beta_u a) + j\frac{Z}{2Z_0}\sin(\beta_u \alpha). \tag{3}$$



(a)

(b)

(c)

Fig. 3. Equivalent circuit of transmission line (a) loss-less ideal transmission Line, (b) equivalent circuit of a unit circuit representing HMSIW-CSRR resonator structure, and (c) equivalent circuit of periodic circuit representing HMSIW-CSRR structure.

Since the right hand side of equation (3) is real, as impedance is imaginary for loss-less resonators (as assumed), either $\beta = 0$, or $n\pi/a$, where “a” is the structure period. Condition $\alpha = 0$ corresponds to a non-attenuated, propagating wave on the periodic structure, and defines the pass-band of the structure. Equation (3) reduces to

$$\cos(\beta a) = \cos(\beta_u a) + j\frac{Z}{2Z_0}\sin(\beta_u \alpha) \quad , \qquad (4)$$

which can be solved for β if the magnitude of the right hand side is less than or equal to unity. Condition $\beta = 0$, $n\pi/a$ in equation (3) is given as

$$\cos(\alpha a) = \cos(\beta_u a) + j\frac{Z}{Z_0}\sin(\beta_u \alpha) \quad . \qquad (5)$$

As known, within the passband, the propagation constant is zero or $n\pi/a$, within the passband, the propagation constant β can be obtained from equation (5) at different frequencies. Based on the above concepts and the design principles of half mode substrate integrated waveguide, we can get the initial HMSIW-CSRR resonator parameters. A full-wave simulation is needed for the reason that the inductive and capacitive values for any periodic structure are not entirely independent because of the coupling effects.

III. SIMULATED AND MEASURED RESULTS

Figure 4 shows the simulated and measured results distributions at different frequencies. The simulated resonant frequency is 3.05 GHz. The simulations are in agreement with the measurements except 100 MHz frequency offset. The CSRR filter at 3.15 GHz has an insertion loss less than 3.5 dB and a return loss more than 10 dB for a 200 MHz bandwidth, and the minimum insertion loss is 3 dB. The discrepancy between the measured and simulated results is probably owing to the fabrication tolerance of the prototype and may be caused by the soldering effects of an SMA connector, which have been neglected in our simulations, even mainly due to lack precision of filter processing and assembly of the deviation caused due to the loss tangent of the substrate and the tolerance in manufacturing [18]. The width of microstrip transmission line is 1.5 mm. However, the manufacture microstrip transmission line usually has a certain tolerance. The used substrate in the simulation model is for ideal homogeneous materials (high purity, performance good consistency, and high surface finish). But in fact, there are certain tolerances in permittivity and thickness (details can be found in RT5880 datasheet), which are critical for designing center frequency. Also, there are tolerances in the fabrication of the microstrip by using the photolithography process, which can change the center frequency. Moreover, the RT5880 is of a 0.508 mm thickness and is of relatively soft and easy deformation. In order to fix the substrate with filter circuit on the measurement fixture, a process with epoxy is used. This process makes the substrate out of flatness while ideal model used in the simulation. However, these factors are difficult to be considered in the simulation.

It is important to note that the two resonance frequencies of the resonator, which are mainly determined by the CSRRs, can be arbitrarily controlled, making it possible to work on arbitrary pass band locations [19]. Figure 5 shows the different transmission responses by scaling the size of the CSRRs. The PCB layout of the filter is shown in Fig. 6, in which the thickness of the Rogers 5880 is 0.508 mm with dielectric substrate 2.2. It can be reduced by nearly half of the structure size compared with the standard SIWs structure operating at the same frequency. It can easily be integrated into any other planar circuits, and can achieve high performance once integrated as, the losses caused by the tapered transitions and SMA connectors would be removed [20].

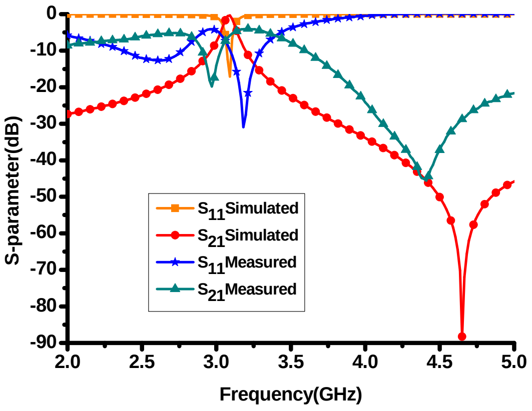


Fig. 4. Comparison of S-parameters between simulation and measured of CSRR-HMSIW BPF.

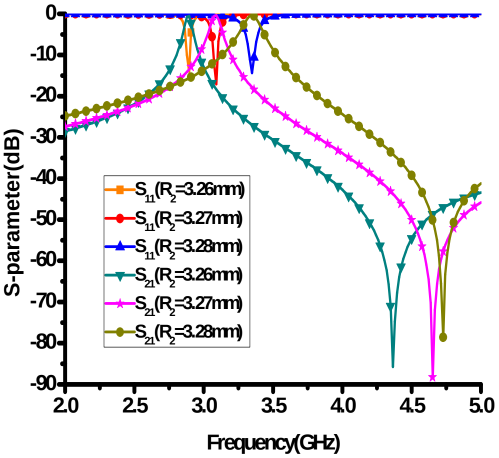
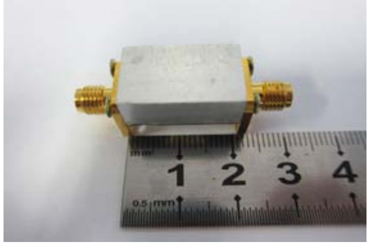


Fig. 5. S-parameters of different radius of CSRR.

(a)



(b)

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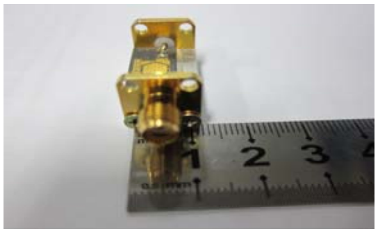

(d)

Fig. 6. The photograph of the fabricated filter; (a) top view, (b) bottom view, (c) front view and (d) side view.

IV.CONCLUSION

We have investigated the possibility of designing left-handed transmission line based on the half mode substrate integrated waveguide (HMSIW) technology. The hollow waveguide behave as a onedimensional plasma below the cut-off frequency of the dominant mode, and we have constructed a closed hexagon CSRR structure on the waveguide top produce magnetic response at the same frequency band. Therefore, the proposed structure has negative effective permittivity and effective permeability simultaneously and can guide electromagnetic waves in a left-handed way. The frequency responses have been simulated for HMSIW loaded with closed hexagon CSRR to determine the corresponding left-handed pass band. The pass band has a sharp rejection and relatively low insertion loss, which may find potential applications in microwave and millimeter wave integrated circuits like widening the bandwidth filters.

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