LETTER

Duel-band filter with high out-of-band rejection using ACSRR-SIW technology

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Abstract A completely asymmetrical dual-band micro-strip filter combined with a complementary split ring resonator (CSRR) consisting of a circle and a square, and substrate integrated waveguide (SIW) is presented in this paper. The proposed design can be applied in the Industrial Scientific Medical (ISM) band. The CSRR of this completely asymmetrical filter, which has both square and circular parts, can realize two distinct passbands and shows higher out-of-band rejection than symmetrical filters; it is an asymmetrical complementary split ring resonator (ACSRR). The out-of-band rejection level between two passbands can reach 40 dB, compared to 35 dB in a circular filter and 30 dB in a square filter. The measured results are in good agreement with simulated results.

key words: asymmetrical complementary split ring resonator (ACSRR); substrate integrated waveguide (SIW); dual-band filter; high out-of-band rejection

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Industry, science, and medicine are basic tenets of human society and institutions which comprise the so-called Industrial Scientific Medical (ISM) band(0.9GHz-5.8GHz), which is related to the dual-band bandpass filter (BPF) [1] - [7]. Dual-band substrate integrated waveguide (SIW) [8] filters are advantageous in terms of the waveguide as well as micro-strips. Substrate integrated waveguide (SIW) technology, which is a very promising candidate for modern wireless communication systems, has been widely used for microwave and millimeter-wave applications as it features low cost, low profile, relatively high-Q, high power-handling capability, and high-density integration characteristics [9]-[10].

The stop-band characteristics of the split ring resonator (SRR) structure was originally proposed by Pendry et al. [11], while CSRRs was proposed by F. Falcone et al. [12] according to the duality principle in 2004. Compared with SRR, the complementary split ring resonator (CSRRs) structure are significantly different. There is a negative dielectric constant transmission line in the CSRRs design, and the sensitivity of a SIW based on a CSRRs structure is significantly higher that of the SIW without the CSRRs. The position of the transmission zeros is affected by any adjustment to the metal. Double-etching the CSRRs provides a lower resonant frequency through the coupling effect between the CSRRs of the roof and the backplane [13].

To date, most research on this subject has centered on the waveguides loaded by CSRRs [14-15 ] and does encompass a number of innovative structures. Incorporating a CSRRs in the SIW cavity markedly reduces the resonant frequency and produces a sharp roll drop in the higher stop-band, which can be easily miniaturized and becomes highly selective. The center frequency can also be independently controlled in the CSRRs-SIW.

In this paper, the equivalent circuit of traditional CSRRs structure and ACSRRs structure is given to explain the reason why ACSRRs structure can produce two passbands. Then, the electric field distribution of TE₁₀₁ and TE₂₀₁ modes in three kinds of ACSRRs structures is compared, which shows that the ACSRRs structure proposed in this paper has higher out-of-band rejection. Finally, the passband effect of the structure is improved by increasing the transition band.

2. CSRRs-SIW, ACSRRs-SIW Theories

2.1 CSRRs-SIW

SIWs are integrated waveguide-like structures fabricated by using two rows of conducting cylinders or slots embedded in a dielectric substrate. The SIW functions as a traditional waveguide on the substrate [16]. Owing to the similarity between the SIW and rectangular waveguide, an empirical relationship between the geometric size of SIW with the same propagation ability and the effective width of the rectangular waveguide can be established as follows [17]:

\[ W_{eff} = w - 1.08 \frac{d^2}{s} + 0.1 \frac{d^3}{w} \]  

(1)

Taking the SIW size in Fig. 3 (a) a s an example, in this structure, \( w = 23mm, d = 0.6mm, s = 1mm \), then the \( W_{eff} \) of the rectangular waveguide equivalent to this structure is 22.61mm.

Most importantly, like rectangular waveguides, they can only pass TEₙ₀ (\( n=1,2,3,\ldots \) ) mode but not TM mode, due to the gaps between metal vias: for TE₀₀ mode, the metal through holes on both sides of the substrate integrated...
waveguide and the current generated on the four walls are parallel to each other, which has little effect on the surface current of the four walls, so TE_{m0} mode can propagate smoothly in the SIW structure. On the contrary, TM mode is a kind of transverse magnetic wave. Its current on the four walls is perpendicular to the current on the metal through-hole, which makes the surface current cut off, thus causing serious attenuation.

The resonant frequency of TE_{m0} mode in the cavity can be determined as:

\[ f_{TE_{m0}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \left( \frac{m}{W_{eff}} \right)^2 + \left( \frac{q}{L_{eff}} \right)^2 \]  

(2)

where \( \mu_r \) and \( \varepsilon_r \) are relative permeability and relative permittivity of dielectric, \( c \) is the light velocity in vacuum, \( W_{eff} \) and \( L_{eff} \) are the effective width of the rectangular waveguide.

According to research [29], while \( W_{eff}/L_{eff} \in [1, (8/3)^{1/2}] \):

\[ f_{TE_{m0}} < f_{TE_{m1}} < f_{TE_{m2}} < \cdots \]  

while \( W_{eff}/L_{eff} > (8/3)^{1/2} \):

\[ f_{TE_{m0}} < f_{TE_{m3}} < f_{TE_{m4}} < \cdots < f_{TE_{m0}} < \cdots \]  

(3)

(4)

CSRR structure is tuned by the original metal part of the SRR. An equivalent circuit diagram of the is shown in Fig. 1(a) [14,18-19]. In this model, material loss is neglected. As shown in Fig. 1(a), the SIW structure can be considered as a common two-wire transmission line in which numerous small cell circuits are loaded. From the center of the SIW structure, the two rows of metal through-holes (magnetic walls) on both sides produce inductive characteristics on the transmission line (marked "LD" in Fig. 1(a)); this component is responsible for the high pass characteristics of the SIW structure. The CSR structure has CR and LR unit circuits in the equivalent circuit diagram, that’s why the CSRRs-SIW structure can generate a passband. In symmetric CSRRs-SIW, LR1/CR1 and LR2/CR2 are the same. In the SIW structure etched with CSRRs, LC represents the inductive coupling between the waveguide transmission line and CSRR outer ring while CC represents the capacitive coupling between them. Also in this part, LC1/CC1 and LC2/CC2 are the same. LS and CS represent the inductive and capacitive coupling between the two CSRRs structures. Among them, the resonant center frequency in the cavity which is determined by CSRR can be calculated from the following formula:

\[ f_0 = \frac{1}{2\pi \sqrt{L_{eff}C_{eff}}} \]  

(5)

The bandwidth of the passband for this unit cell can be adjusted by changing the mutual coupling. Fig. 2(a) presents the simulation by changing \( t \) between the two CSRRs. When \( t \) is smaller, which means the middle strip is thinner and CSRRs are closed to center, LS increases, while LC decreases because the magnetic coupling becomes easier. These changes make the passband smaller, which can be easily seen in Fig. 2(a).

2.2 ACSRRs-SIW

Different from CSRRs-SIW, the equivalent circuit diagram of ACSRRs-SIW (Fig. 1) contains two asymmetrical CSRRs structures in the form of CR1, LR1, CR2, and LR2 unit circuits. Two different resonant frequencies are generated in the two cell circuits which cause two passbands to appear. The CC1/LC1 cell circuit and CC2/LC2 cell circuit are coupled with the outer rings of the two CSRRs cells and their corresponding waveguide transmission lines, respectively.

In order to obtain two passbands in ISM frequency band, the size of circular CSRR and square CSRR are adjusted according to formula (5). The first low-frequency passband is obtained by square CSRR resonance unit, and the second high-frequency passband is obtained by circular CSRR resonance unit. Different from the symmetrical CSRRs structure, changing the value of \( t \) only influences the coupling between the two CSRRs structures, that is, LS / CS cells. When \( t \) get smaller, which means two ACSRRs get closer, the coupling between the two CSRRs structures is strengthened, and the two passbands will be closer. Fig. 2(b) presents the results from full-wave simulation by changing the distance \( t \) between two ACSRRs.
In this study, we attempted to load asymmetrical CSRRs-SIW consisting of a circle and a square to generate a new passband. We conducted a series of experiments on an ACSRRs-SIW with circular and square designs and three types of asymmetrical loads: square (Fig. 3(a)), circular (Fig. 3(c)), and a circle-and-square combination (Fig. 3(e)). The sizes we tested are shown in Table 1. Our simulation and test results further prove that that the asymmetrical structure can produce two passbands.

The performance of out-of-band rejection between two passbands is the criterion for judging the performance of dual-passband filters as per the value of S21. As shown in Fig. 3, the maximum out-of-band S21 value (Fig. 3(b)) of the asymmetric square structure can reach -35dB; the maximum out-of-band S21 value (Fig. 3(d)) of the asymmetrical circular structure is -30dB and the maximum out-of-band S21 value (Fig. 3(f)) of the asymmetrical square structure is -40dB.

By testing the resonant frequencies of different modes, we found that two passbands are generated by TE\textsubscript{101} and TE\textsubscript{201} (mode 1 and mode 2). Fig. 4(a), 4(b) and 4(c) show the simulated E-fields of the first mode of the square structure (Fig. 3(a)), circular structure (Fig. 3(c)) and a circle-and-square combination (Fig. 3(e)). Fig. 4(d), 4(e) and 4(f) show the simulated E-fields of the second mode of the square structure (Fig. 3(a)), circular structure (Fig. 3(c)) and a circle-and-square combination (Fig. 3(e)). The electric field between the ACSRRs-SIW combined with square and circular is much weaker than the other ones. In both two modes, which indicates that the coupling between the circle-and-square combination is relatively weak. This is also the reason why the asymmetric CSRRs structure has better out-of-band suppression than the other structures we tested.

| Parameter      | Fig. 2(a) CSRRs | Fig. 2(a) ACSRRs (left) | Fig. 2(c) CSRRs | Fig. 2(c) ACSRRs (left) | Fig. 2(e) ACSRRs | Fig. 2(e) ACSRRs | Fig. 4(a) Second-order S21 |
|---------------|-----------------|-------------------------|-----------------|------------------------|-----------------|-----------------|--------------------------|
| r1 (mm)       | 1.1             | 1.1                     | 1.1             | 1.1                    | 1.1             | 0.9             |
| e1 (mm)       | 0.9             | 0.9                     | 0.9             | 0.9                    | 0.9             | 1.1             |
| e2 (mm)       | 1.5             | 1.5                     | 1.5             | 1.5                    | 1.5             | 0.4             |
| e3 (mm)       | 0.9             | 0.9                     | 0.9             | 0.9                    | 0.9             | 1.1             |
| r2 (mm)       | 1.2             | 1.2                     | 1.2             | 1.2                    | 1.2             | 0.65            |
| t2 (mm)       | 1.1             | 1.1                     | 1.1             | 1.1                    | 1.1             | 0.65            |
| c11 (mm)      | 0.9             | 0.9                     | 0.9             | 0.9                    | 0.9             | 1.4             |
| c22 (mm)      | 1.5             | 1.5                     | 1.5             | 1.5                    | 1.5             | 0.8             |
| c33 (mm)      | 0.9             | 0.9                     | 0.9             | 0.9                    | 0.9             | 0.8             |
| rd (mm)       | 1.2             | 1.2                     | 1.2             | 1.2                    | 1.2             | 2.6             |
| rd2 (mm)      | 1.2             | 1.2                     | 1.2             | 1.2                    | 1.2             | 2.6             |
| td (mm)       | 10.3            | 10.3                    | 10.3            | 10.3                   | 10.3            | 10.3            |

3. second-order ACSRRs-SIW dual-pass bandpass filter

3.1 Second-order ACSRRs-SIW dual-pass bandpass filter without translation

We adopted a second-order structure in order to extend the bandwidth of the dual-pass band, and its size is reported in Table 2. Because the circuit schematic diagram of second-order ACSRRs bandpass filter is too complex, we chose to illustrate the principle with the coupling diagram between the parts (Fig. 6). In Fig. 6, S represents the transmission line and 1, 2, 3, and 4 represent the four respective CSRR...
structures; 1 and 2 have the same circular CSRR structure while 3 and 4 have the same square structure. M12, M13, M14, M23, M24, and M34 represent the coupling between the four CSRRs, respectively. MS1, MS2, MS3, and MS4 represent the coupling between transmission lines and CSRR structures, respectively. Among them, MS1, MS2, MS3 and MS4 correspond to the CC / LC unit in the first-order circuit (Fig. 1). The difference is that there are four CSRR structures in the second-order circuit, each of which will produce a coupling resonance unit, which mainly depend on the transition between microstrip line and SIW structure. Also, they play an important role in the energy transfer between SIW structure and ACSSRs. M13, M24 are mainly determined by the above-mentioned t, corresponding to the CS / LS unit of the first-order equivalent circuit, which will not be repeated here. Finally, it should be noted that the values of M12, M23, M14 and M34 mainly depend on lt (Fig. 7(a)). Each CSRR structure will produce the same resonant frequency. For example, two circular CSRRs form a passband, while M12 which represents the coupling between two circular CSRRs, determines the width of the passband. But if the value of M12 is too large, it will cause a breakpoint in the passband, so as M34. M14 and M23 represent the coupling between circular and square CSRRs structures in diagonal direction. These two parameters will affect the gap between the two passbands. In order to increase the range of lt to test the influence of lt on the performance of the SIW, the microstrip width W can be calculated by the microstrip characteristic impedance formula [28]:

\[
\frac{w}{h} = \begin{cases} 
8e^4 - 2 & \text{for } \frac{w}{h} \leq 2 \\
\frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) \right] + \frac{e_r + 1}{\pi e_r} \left[ \ln(B - 1) + 0.39 - 0.61 \right] e_r & \text{for } \frac{w}{h} \geq 2 
\end{cases}
\]  

(8)

where

\[
A = \frac{Z_0}{60} \left[ \frac{e_r + 1}{2} + \frac{e_r - 1}{0.23 + 0.11 e_r} \right],
\]

\[
B = \frac{120 \pi^2}{2Z_0 \sqrt{e_r}}
\]

(9)

and \(Z_0\) is the characteristic impedance of the microstrip line.

3.2 Second-order ACSRRs-SIW dual-pass bandpass filter without translation

To this effect, the SIW can be simply regarded as an ordinary metal rectangular waveguide. The connection between the microstrip line and SIW can be transformed into impedance matching problem [20]. Several broadband transitions between the microstrip or coplanar waveguide and SIW have already been established. Microstrip-to-SIW transitions are typically based on a simple taper, provided that the microstrip and the SIW structure are integrated on the same substrate [20]. Design equations have been proposed recently for the fast implementation of microstrip-to-SIW transitions as well [21]. Microstrip-to-SIW transitions in a multi-layer substrate environment [33] can be used to connect a microstrip implemented in a thin substrate with a thicker SIW structure. In this study, we compared the effects of direct transition and oblique transition on filter performance.

The waveguide junction differs when components are different sizes, so we exploited the concept of equivalent impedance to resolve the waveguide junction matching problem. The equivalent impedance of the traditional rectangular waveguide is:

\[
Z_e = \frac{zh \mu}{2W} = \frac{zh}{2W} \sqrt{\varepsilon} \left[ \frac{1}{\lambda} + \frac{1}{2W} \right]^{-\frac{1}{2}}
\]

(6)

where \(h\) is the height of the rectangular waveguide, \(W\) is the width of the rectangular waveguide, \(\lambda\) is the working wavelength of the substrate, \(\mu\) is the permeability of the substrate, \(\varepsilon\) is the dielectric constant of the substrate, \(\omega = k / \mu \varepsilon^{0.5}\) is the angular frequency, and \(\beta = k / [1 - (\lambda / 2W)^2]^{0.5}\) is the wavenumber.

The equivalent impedance formula of the main mode \(TE_{10}\) of the SIW is as follows:

\[
z_e = \frac{zh_{eff} \rho_0}{2W_{eff} \varepsilon [1 - (\lambda / 2W_{eff})^2]^{2}}
\]

(7)

where \(\rho = 120 \pi\) is the wave impedance of the TEM mode in air, \(h_{SIW}\) is the thickness of the dielectric plate in the SIW structure, and \(\varepsilon_r\) is the relative dielectric constant of the dielectric plate.

Fig. 7 (a) Simulation results about change of lt, (b) Second-order model with transition zone

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\end{cases}
\]  

(8)

where

\[
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\]

\[
B = \frac{120 \pi^2}{2Z_0 \sqrt{e_r}}
\]

(9)

and \(Z_0\) is the characteristic impedance of the microstrip line.

Here, we chose to apply the linear transition structure to the impedance matching of asymmetrical SIW structures and transmission lines accordingly.

Firstly, by determining the width \(W\) and thickness \(h\) of SIW, we determined \(Z_e\) (the equivalent impedance of SIW).
By making $Z_0=Z_c$, we secured $W_S$ (the width of the boundary between the SIW structure and transition structure). Usually when setting the wave port, the default microstrip line impedance is 50 $\Omega$. When $Z_0=50 \, \Omega$, the width $W$ of the microstrip line can be secured.

The relationship between $l_s$, $W$, and $W_S$ is: $l_s = c \cdot W_S - W$, where $c$ is a constant, defined as the transition coefficient. When $c$ is smaller, $l_s$ is smaller that is, a shorter transition zone creates a steeper transition section.

The transmission performance of the linear transition structure is greatly affected by the transition length $l_s$ and parameter $c$. We found that when $c$ is less than 3, the reflection coefficient and fluctuation coefficient of the transmission coefficient are large, which is not conducive to the transmission of energy. When $c$ is between 3 and 4, the reflection coefficient and transmission coefficient better meets the filter design requirements. When $c$ is greater than 4, the reflection coefficient increases and the transmission performance decreases. In this study, $c = 3$.

In our model, $w=2.12 \; \text{mm}$, $W_S=6.38 \; \text{mm}$, $l_s=12.77 \; \text{mm}$. Compared with Fig. 8(a), the electromagnetic wave is better propagated in the structure with transition zone (Fig. 8(b)) and the coupling between the structures is markedly enhanced. Simulation results with and without an added transition zone are shown in Fig. 10. In particular, the length of SIW structure mentioned above is 36mm. Here, it has been adjusted to 23mm and $l_t = 12 \; \text{mm}$. The passband effect appears to have been greatly improved after adding the transition zone. There are stopbands in the passband of the structure through the transition. As shown in the simulation results, the passband of the filter without transition zone is broken and incomplete. After adding the transition structure, the passband is complete and the filtering effect is greatly improved.

![Fig. 8](image)

**Fig. 8** (a) Electric field from Fig. 5(a). (b) Electric field from Fig. 7(a).

![Fig. 9](image)

**Fig. 9** Asymmetrical structures (a) without transition zone (b) with transition zone added.

### 4. Simulation and Experimental Results

We next fabricated a test filter on a 0.508 mm-thick Alon AD260A substrate characterized by $\varepsilon_r=2.6$. The diameter of the metallic through-holes is around 0.6 mm and the spacing between two adjacent through-holes is around 1 mm. The spacing between two adjacent through-holes is around 1 mm. 10(b) shows a comparison between the simulated and measured results of the first-order ACSRRs structure without the transition band, while Figs. 10(d) show a comparison between the simulated and measured results of the second-order ACSRRs-SIW structure without the transition band. Figs 10(f) show a comparison between the simulated and measured results of the proposed BPFs on a full-wave Ansoft HFSS simulator and network analyzer. The first passband is centered at 3 GHz with a 3-dB bandwidth of 950 MHz. The second passband is centered at 4.5 GHz with a bandwidth of 800 MHz. In other words, the actual measurement results are very close to the simulation results.

![Fig. 10](image)

**Fig. 10** (a) Physical object of Fig. 3(c). (b) Simulated and measured S-parameters against frequency of fabricated filter for design presented in (a). (c) Physical object of Fig. 5(a). (d) Simulated and measured S-parameters against frequency of fabricated filter for design presented in (c). (e) Physical object of Fig. 7(b). (f) Simulated and measured S-parameters against frequency of fabricated filter for design presented in (e).

### 5. Conclusion

In the device proposed in this paper, square and circular hybrid filters use a combination of SIW and CSRRs to create two passbands with effective out-of-band inhibition. Both passbands are in the ISM band. The filter design is simple and can be easily optimized by adjusting the effects of different components. The overall performance is affected by the design parameters. We tested the proposed filter to
find it has good selectivity and out-of-band suppression which can be realized by optimizing the waveguide width and the size of the CSRRs structure. The microstrip filter is small in size, low in cost, easy to fabricate, and easily integrated with other circuit structures. The filter effectively meets the requirements of the ISM band. Compared with the dimensions in other papers, as shown in table 2, it is found that both bandpass characteristics and out-of-band inhibition are superior to the filters in the comparative literature.

### Table 2. Filters performance comparison

| Filter | S11 (dB) | S21 (dB) | Passband (GHz) | S11 between passband (dB) | ε |
|--------|----------|----------|----------------|---------------------------|---|
| [22]   | 1        | -15      | -1             | 2.96-10.75                | 4.5 |
| [23]   | 2        | -20      | -1             | 8.8-12                    | 3.66 |
| [24]   | 1        | -20      | -2             | 11-11.1                  | 3.66 |
| [25]   | 2        | -20      | -0.53          | 1.55-1.59                | 2.22 |
| [26]   | 3        | -20      | -0.45          | 1.55-1.59                | 2.4  |
| our work | 2        | -20      | -0.14          | 2.53-4.8                 | 2.2  |

### Acknowledgments

This research was funded by Postgraduate Research & Practice Innovation Program of Jiangsu Province and High-Talent Projects of Nanjing Forest University.

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