

SIW Diplexer Loaded with Complementary Stepped Impedance S-Shaped Resonators

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Abstract—In this letter, we present a diplexer implemented on a substrate integrated waveguide (SIW) with stepped impedance complementary S-shaped resonators (CSSRs). The variable frequency response of the stepped impedance concept adjoining SIW technology leads to improved device performance in terms of matching and isolation. Simulated and measured results show input matching, $|S_{11}|$, better than -15 dB and output isolation, $|S_{32}|$, below -30 dB for the frequency range 1–4 GHz. Furthermore, CSSRs offer a degree of freedom to design fundamental and higher order frequencies by selectively tuning the geometrical parameters. This simple yet effective approach eliminates the complexity to design diplexers based on complementary split ring resonator (CSRRs).

1. INTRODUCTION

Modern communication systems require compact, low cost, and high isolation diplexers for different microwave and millimeter-wave transceivers [1, 5]. When designed carefully, diplexers based on stepped impedance resonators provide much better isolation due to equal velocities division in even and odd mode waves [3, 4, 8]. Lately, increased attention has been paid to realize new filters by combining complementary split ring resonators (CSRRs) and substrate integrated waveguide (SIW) structures [2, 6, 7]. SIW is a guided wave structure synthesized by metallic vias on a planar substrate with several advantages in terms of high quality factor, power handling capability, and low loss. In this context, S-shaped resonator was first presented as left handed material (LHM) by Chen et al. in 2004 [9], where both the permittivity and permeability bands overlap, making it a better candidate compared to split ring resonators (SRRs) or complementary split-ring resonators (CSRRs) [9]. More recently, complementary S-shaped CSRRs have been implemented to design compact band-pass filters which have better out of band rejection compared to conventional CSRRs [9, 10]. Hence, complementary S-shaped resonators (CSSRs) incorporated with stepped impedance concept can be better candidates for the design of SIW devices.

This letter, therefore, proposes a diplexer with high isolation on SIW loaded with complementary stepped impedance S-shaped resonators. The approach is simple yet effective. In our design, higher order resonant frequencies can be controlled by adjusting the structural parameters. The diplexer consists of two channel filters each operating below the integrated waveguide cutoff frequency. Simulation and measurement results are found to be in excellent agreement.

2. DESIGN EXPLANATION

Figure 1 shows the layout of the designed diplexer, which consists of one transmitter and one receiver filter cascaded in series. A $50\text{-}\Omega$ insert feed technology known as CPW-SIW is adopted to act as a

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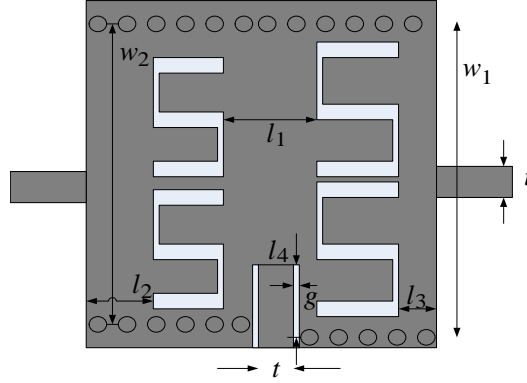


Figure 1. Configuration of the proposed diplexer ($w_1 = 36$, $w_2 = 35.2$, $l_1 = 17$, $l_2 = 8$, $l_3 = 2.643$, $l_4 = 8$, $g = 0.35$, $t = 4$). All dimensions are in mm.

T-junction connecting the two filters to common input. Considering a RT/Duroid 5880 substrate with relative permittivity of 2.2, and thickness of 0.508 mm, the layout of the proposed diplexer along with the associating dimensions is illustrated in Figure 1. The ground remains as a solid ground in the design to decrease the noise and reduce the radiation loss, which is not depicted in Figure 1. In the proposed design, two channel filters employing CSSRs and a 50- Ω insert feed technology known as CPW-SIW to act as a T-junction connecting the two filters to common input are adopted.

Optimal design of the proposed structure is carried out considering the resonance condition for the even and odd mode resonances [8]:

$$R_z^o = \cot \theta_1 \cot \theta_2 \quad (1)$$

$$R_z^e = -\tan \theta_1 \cot \theta_2 \quad (2)$$

where $R_z = Z_2/Z_1$ is the impedance ratio corresponding to the electrical lengths θ_1 and θ_2 . The length ratio α of the CSSR is defined as:

$$\alpha = \frac{\theta_2}{\theta_1 + \theta_2} = \frac{\theta_2}{\theta_t} \quad (3)$$

where θ_t is the total length of the CSSR. Substituting (3) in (1) and (2) yields:

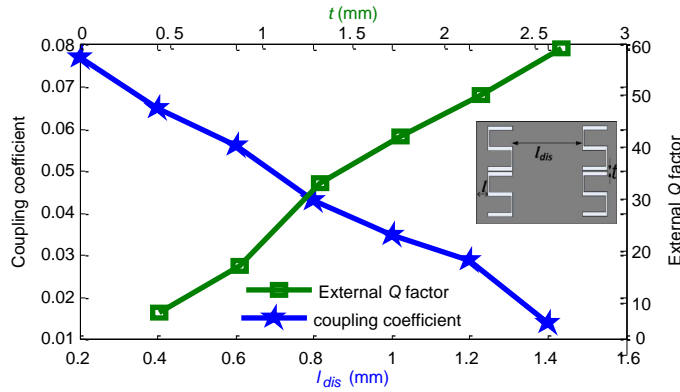
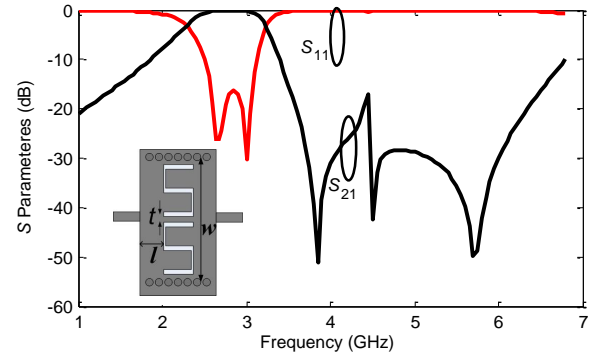
$$R_z^o = \cot(\alpha\theta_t) \cot(1-\alpha)\theta_t \quad (4)$$

$$R_z^e = -\tan(\alpha\theta_t) \cot(1-\alpha)\theta_t \quad (5)$$

The fundamental and other higher order frequencies for the channel filters can be determined by properly choosing a suitable combination of the impedance and length ratios of the CSSR. The ratio of the first spurious frequency to the fundamental frequency is $f_{s1}/f_0 < 2$ for $R_z > 1$. The smaller the impedance ratio R_z , the larger the distance between the fundamental, and the first spurious frequency can be obtained. Furthermore, it is observed that for a given impedance ratio R_z , it is better to choose $\alpha \sim 0.7$ in order to obtain smaller value of f_{s1}/f_0 . In order to achieve wide stopband characteristics (i.e., $f_{s1}/f_0 > 2$), the impedance ratio $R_z < 1$ has been chosen. To obtain the physical dimensions of the channel filters, coupling coefficients and external quality factor are extracted with the aid of ANSYS-HFSS based on the two resonance frequencies and 3-dB bandwidth [7] as depicted in Figure 2. The design parameters of the two channel filters 1 and 2 are listed in Table 1. A passband is generated by CSSRs which is located below the cutoff frequency of the SIW [3]. Figure 3 depicts the filtering response of the channel filters and the topology of the same appears as the inset. Multiple transmission zeros are observed due to coexistence of electric and magnetic couplings. Once the two channel filters are designed with desirable frequencies, a T-junction is further designed to match the two filters. An insert feed type has been adopted to obtain a proper coupling at the input port. The three ports are designed to be matched to an input impedance of 50- Ω .

Table 1. Design parameters for CSSRs.

| Parameters | Channel Filter 1 | Channel Filter 2 |
|-----------------------------------|------------------|------------------|
| Impedance ratio R_z | 0.72 | 0.68 |
| Stepped percentage α | 0.21 | 0.18 |
| Fundamental frequency f_0 (GHz) | 2.7 | 3.6 |
| Stepped section length (mm) | 6 | 3 |
| Stepped section width (mm) | 2 | 2 |
| Central section length (mm) | 10 | 7 |
| Central section width (mm) | 0.2 | 0.2 |

**Figure 2.** Simulated coupling coefficient versus l_{dis} and external Q factor versus t for the SIW-CSSR filter.**Figure 3.** Simulated filtering response of the CSSR channel filter ($w = 36$ mm, $l = 2.643$ mm, $t = 1$ mm).

3. RESULTS AND DISCUSSION

Following the design process mentioned in previous section, a diplexer working in the S-band is designed and optimized. The resonant frequencies of filter 1 and 2 are designed to be 2.7 and 3.55 GHz respectively. The optimal diplexer response is shown in Figures 4–5. Figure 6 shows a photograph of the fabricated diplexer. The diplexer occupies a size of $0.36\lambda_0 \times 0.327\lambda_0$ (λ_0 is the free space wavelength at centre frequency of the first channel). It is noteworthy that the size of the proposed diplexer is larger than previously reported structures, though S-shaped metamaterials, in contrast to CSRR, provides more flexibility and easiness to the design procedure. The measurement is carried out using a Rhode & Schwarz ZVB20 vector network analyzer.

Figures 4 and 5 show the simulated and measured reflection, transmission, and isolation coefficients of the proposed diplexer. An excellent matching performance at the input port is obtained ($|S_{11}|$ below -15 dB); whereas the achieved rejection of the undesired band is in the order of 45 dB and 20 dB for channel filter 1 and 2 respectively. However, it is noteworthy that the stopband rejection for filter 2 at 2.7 GHz is less than the first filter which is thought to be due to the propagation of the TE_{10} waveguide mode. It has been observed that the larger the distance between the two CSSRs the better the stopband rejection with a tradeoff of the size and insertion loss [2]. The measured insertion loss is around 1.64 and 1.35 dB (Figure 4(b)) in the two bands, respectively, which includes the extra loss from SMA connectors. For better illustration of the diplexer performance, $|S_{22}|$ and $|S_{33}|$ plots are provided in Figure 5. As can be seen, return loss at both output channels are 30 dB and 15 dB, respectively, which agrees with the simulation results. Furthermore, the stopband suppression for both filters is better than 20 dB at 3.65 and 2.65 GHz, respectively. One extra transmission zero can be observed for filter 1 at other filter's passband due to coexistence of electric and magnetic coupling; thus much better isolation can be observed. Furthermore, as the diplexer incorporates the concept of stepped impedance resonators, an improvement in isolation can be witnessed due to equalization of velocities of odd and

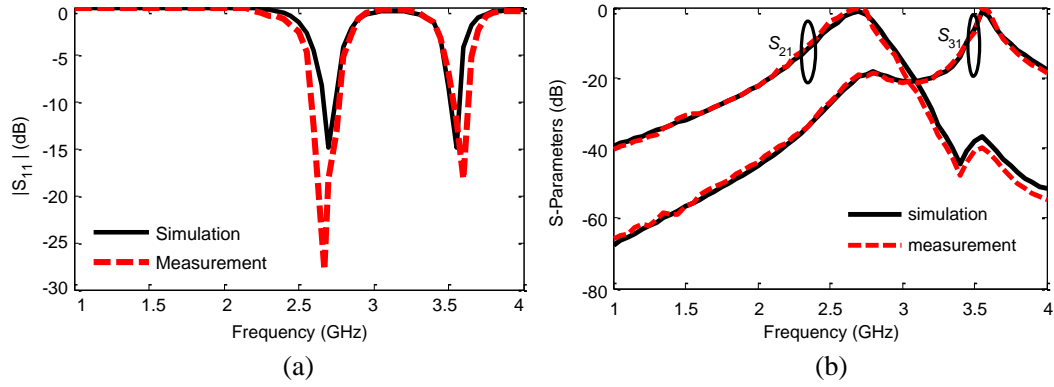


Figure 4. Simulated and measured S -parameters of the proposed diplexer: (a) $|S_{11}|$; (b) $|S_{21}|$ and $|S_{31}|$.

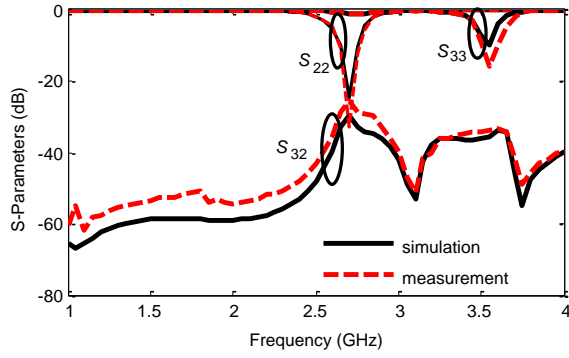


Figure 5. Simulated and measured S -parameters of the proposed diplexer: $|S_{22}|$, $|S_{33}|$ and $|S_{32}|$.

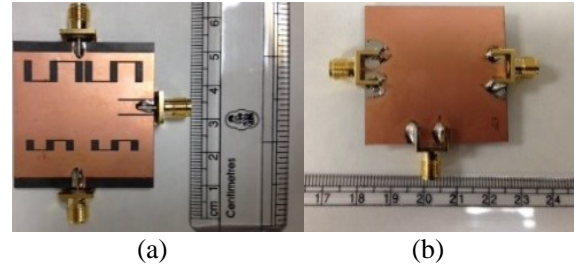


Figure 6. The fabricated diplexer: (a) top view; and (b) bottom view.

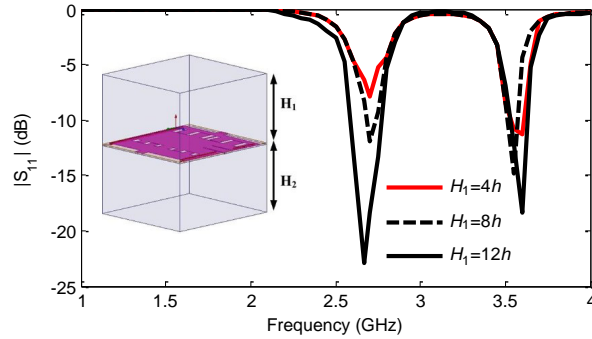


Figure 7. Effect of the metal shield on response of the proposed diplexer ($h = 0.508$ mm is substrate thickness and H_2 is set to be $12h$).

even-mode waves. The output isolation ($|S_{32}|$) is observed to be better than -30 dB for the frequency range 1–4 GHz. It should be noted that the larger the order of CSSRs, the better the isolation with a tradeoff of the size. Table 2 provides a comparison between the proposed work and the recent literature.

A metal enclosure is usually needed for shielding and packaging of a diplexer [3]. The diplexer with metal shields is shown in the inset of Figure 7. As can be seen, the height from the above and bottom to the substrate is denoted as H_1 and H_2 , respectively. A parametric study has been performed to observe the effect of H_1 on diplexer performance and the result appears in Figure 7. The examination shows that the degradation in $|S_{11}|$ is resulted from the nearness of the upper shield. Furthermore, it is also seen that the higher the H_1 the better is the diplexer performance. It can be concluded that, $H_1 > 10h$ is suitable for practical applications. As the bottom is a solid ground, no impact of bottom shield has been observed on performance of $|S_{11}|$.

Table 2. Comparison of proposed diplexer with recent works.

| Ref. | 2-D size | Insertion loss (dB) | | Isolation (dB) |
|------------------|---------------------------------------|---------------------|----------|----------------|
| | | 1st band | 2nd band | |
| [2] | $0.27\lambda_0 \times 0.217\lambda_0$ | 1.6 | 2.3 | 32 |
| [3] | $0.20\lambda_0 \times 0.18\lambda_0$ | 2.05 | 2.15 | 25 |
| [8] | $0.17\lambda_0 \times 0.272\lambda_0$ | 2.7 | 2.8 | 42 |
| This work | $0.36\lambda_0 \times 0.327\lambda_0$ | 1.64 | 1.35 | 30 |

4. CONCLUSIONS

This work presents an SIW diplexer design with high output channel isolation based on the employment of stepped impedance complementary S-shaped resonators. The measured device performance with insertion loss (approximately 1.64 dB and 1.35 dB in two bands) and isolation (better than -30 dB) are reported. Moreover, it has been shown that CSSRs integrated with the stepped impedance concept are a better substitution for CSRRs. The improved matching and out-of-band rejection are in line with several possible applications such as satellite and mobile communication systems.

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