Development of Diplexers Based on Dual-Mode Substrate Integrated Waveguide Cavities

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Abstract — Diplexers based on dual-mode Substrate Integrated Waveguide (SIW) cavities are proposed and implemented. The dual-mode cavities not only act as a resonator for both Rx and Tx channels, but also as the interconnect between these two channels which help to realize the isolation. The dual-mode cavities resonating at TE_{201} and TE_{103} modes in our design show several advantages than those dual-mode cavities operating at TE_{201} and TE_{301} modes. Single-mode cavities are cascaded with the dual-mode cavity to realize the two-order filters for Rx and Tx channels. Two design examples are presented with a normal printed circuit board process and verified by experiments.

Index Terms — Diplexer, dual-mode cavity, filter, Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

A T-junction, which connects the two filters and the common input port reserved for an antenna, is widely used in conventional diplexer designs [1-4] composed of waveguide or transmission lines. For recently developed diplexers based on Substrate Integrated Waveguide (SIW) [5-6], a T-junction is also in critical need. The lengths of the transmission lines/waveguides connecting the T-junction to the Rx and Tx filters are the most important design parameters to achieve a good isolation between two channels. In our previous work [7], a novel 40/50 GHz diplexer is proposed using two dual-mode (operating at TE_{102} and TE_{103} modes) cavities. The isolation of this 40/50 GHz diplexer between two channels is realized by properly choosing the geometric shape of the dual-mode cavities and positions of feeding probes instead of using T-junction. Anyhow, due to both of the resonators in the diplexer are of dual-mode cavities, the size of the diplexer is extremely large. Meanwhile, in our previous design, we have to use closely spaced microstrip lines to couple those two cavities which will result in a strong coupling between the microstrip lines and as a result, leading to a poor isolation performance.

In this letter, we propose two diplexers based on dual-mode SIW cavities working at TE_{201} and TE_{103} modes, instead of previous TE_{201} and TE_{301} modes. Same as the diplexer design in [7], the dual-mode cavities involved not only act as a resonator for both Rx and Tx channels, but also the interconnect between these two channels which help to realize the isolation. Anyhow, only one dual-mode cavity is used in each diplexer design in this letter, while two single-mode cavities resonating at TE_{101} mode are placed at different sides of the dual-mode one and cascaded with it. Obviously, the total size of the diplexer will be much smaller than previous design with two dual-mode cavities. Moreover, compared with the dual-mode cavity of TE_{201} & TE_{301} modes, the dual-mode cavity of TE_{201} & TE_{103} modes can be implemented in more cases and has a smaller size for some specific cases, which are explained in detail in Section II. Two design examples of 10/18 GHz and 10/10.5 GHz diplexers are given and verified by

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experiments, separately.

II. ANALYSIS OF PROPOSED DUAL-MODE CAVITY RESONATOR

Figure 1 shows the configuration of a rectangular cavity resonator, where L, W and h are the cavity's length, width and height, respectively. The resonant frequency of the TE_{mnl} or TM_{mnl} mode is decided by where μ_r and ε_r are the relative permeability and relative permittivity of the cavity substrate, c is the speed of light in free space and m, n, l are mode numbers of the resonator. Since the substrate is very thin, only TE mode need be considered in most applications. As a result, the wavenumber n is zero, and m and l are natural integers;

$$f_{mnl} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{h}\right)^2 + \left(\frac{l\pi}{W}\right)^2}. \quad (1)$$

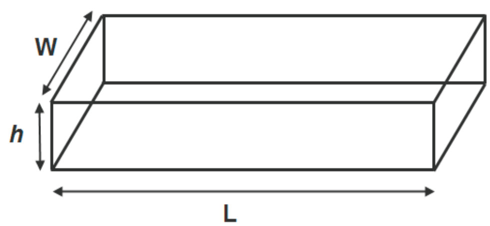


Fig. 1. Geometry of a rectangular resonator.

In [7], resonant modes TE_{201} and TE_{301} are selected and can be controlled to resonant at desired frequency f_0 for Rx channel and f_1 for Tx channel with length L_1 and width W_1, by solving the two equations below:

$$f_0 = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{2\pi}{L_1}\right)^2 + \left(\frac{\pi}{W_1}\right)^2}, \quad (2)$$

$$f_1 = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{3\pi}{L_1}\right)^2 + \left(\frac{\pi}{W_1}\right)^2}. \quad (3)$$

However, the equations (2) and (3) can only be resolved when $f_0/f_1 > 2/3$. As a result, this kind of diplexer design using a dual-mode resonator of TE_{201} and TE_{301} mode is not suitable for applications such as Wireless Local Area Networks (WLAN) whose operating frequency bands are centered at 2.45 GHz and 5.2 GHz, separately.

If we choose TE_{201} and TE_{103} as the resonant modes of the dual-mode cavity instead, the length L_2 and width W_2 of the cavity can be obtained by solving:

$$f_0 = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{2\pi}{L_2}\right)^2 + \left(\frac{\pi}{W_2}\right)^2}, \quad (4)$$

$$f_1 = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{\pi}{L_2}\right)^2 + \left(\frac{3\pi}{W_2}\right)^2}. \quad (5)$$

The equations (4) and (5) will have a solution when $f_0/f_1 > 1/3$, which means this kind of dual-mode cavity can be implemented in more cases of applications. Meanwhile, based on the equations (2), (3), (4) and (5), the cavity's size W_2L_2 will be smaller than W_1L_1 when $f_0/f_1 > 2\sqrt{2}/3$ when these two diplexers operate at the same frequencies for both Rx and Tx channels.

III. DIPLEXER DESIGN EXAMPLES

We present two examples here to show the ability and advantages of using TE_{201}- and TE_{103}-mode cavity for the design of diplexers without a T-junction. Rogers 5880 substrate with relative permittivity of 2.2 and loss tangent of 0.0009 has been used for design. The dielectric thickness is 20 mil. 50-Ω microstrip lines with coupling slots are used for the input/output of cavities and the coupling is controlled by changing the length of the coupling slot with a fixed width. The internal coupling between resonant cavities is obtained by one magnetic post-wall coupling slot on the common wall and controlled by the slot's width.

The first example is a diplexer whose two channels are centered very far at f_0=10 GHz and f_1=18 GHz, respectively. The ratio f_0/f_1 equals 5/9 which is larger than 1/3. The center frequencies of the two channels for the second example are centered extremely closely at f_0=10 GHz and f_1=10.5 GHz, separately. The ratio of f_0/f_1 is 20/21 which is larger than $2\sqrt{2}/3$.

A. 10/18 GHz diplexer

The configuration of a 10/18 GHz diplexer is shown in Fig. 2. The diplexer consists of two two-order filters with fractional bandwidth of 1.0% for the 10 GHz filter and 1.4% for the 18 GHz filter. Cavity 1 is the dual-mode cavity resonating at 10 GHz for TE_{201} mode and 18 GHz for TE_{103} mode. Cavity 2 and cavity 3 are single-mode cavities whose resonant frequency is 10 GHz and 18 GHz, separately. The coupling slot between cavity 1 and 2 is centered at one-third of the shorter side-wall *aa'* of cavity 1, while the coupling slot between cavity 1 and 3 are placed at the center of the longer side-wall *aa''* of cavity 1. We also plot the electric field distributions of the diplexer at 10 GHz and 18 GHz in Fig. 3 in order to understand its working mechanism. As can be seen in Fig. 3, for the dual-mode cavity, the electric field in region A is strong at 18 GHz for TE_{103} mode but weak at 10 GHz for TE_{201} mode, while region B is strong at 10 GHz but weak at 18 GHz. Therefore, when a coupling slot is opened in region A, it causes a strong coupling at the TE_{103} mode and weak even null coupling at the TE_{201} mode. On the contrary, when a coupling slot is opened in region B, only TE_{201} mode will be excited. As a result, when slot in region B is used to couple a cavity resonated at 10 GHz and slot in region A is coupled to a cavity resonated at 18 GHz, isolation between 10 GHz and 18 GHz can be achieved. The electric field distributions of cavity 3 and cavity 2 shown in Fig. 3 are almost null at 10 GHz and 18 GHz, respectively, which also verify our analysis mentioned above. In order to excite the dual-mode cavity at both of 10 GHz and 18 GHz for the design of the common port of the diplexer, the feeding position of the input port P1 should be chosen at the places where the electric field of the two frequencies overlapped; e.g., at region C in Fig. 3.

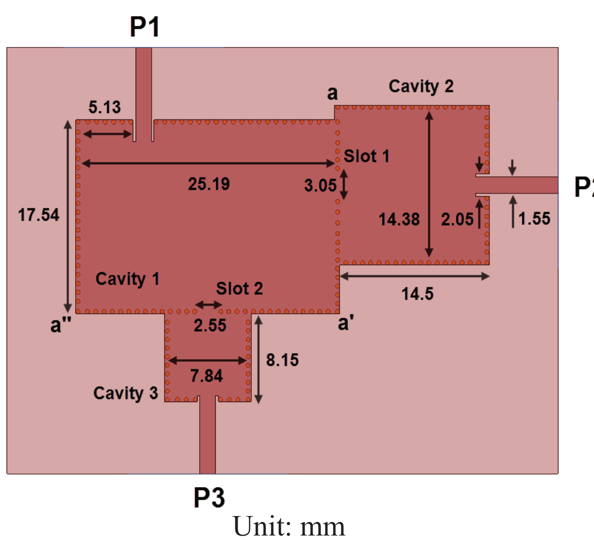


Fig. 2. Geometry of proposed 10/18 GHz diplexer.

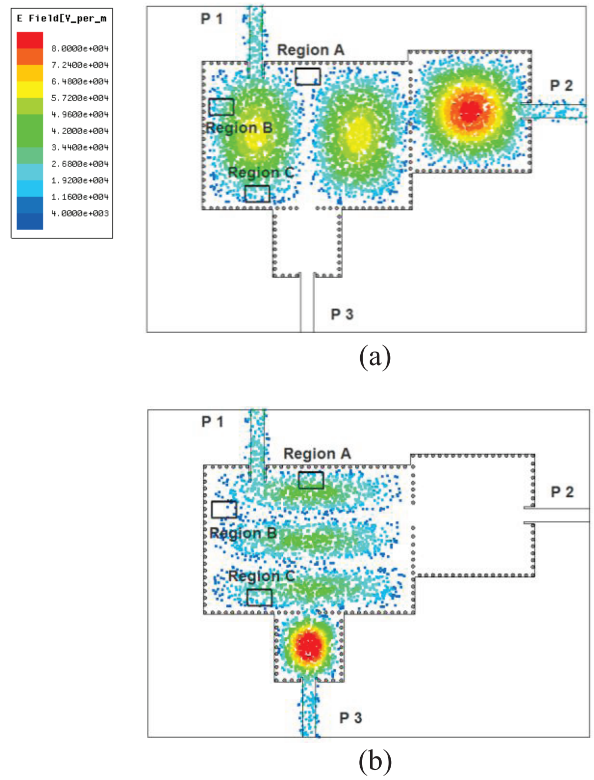


Fig. 3. Electric field distributions of the diplexer at: (a) 10 GHz, and (b) 18 GHz.

Using the equations (4)-(5) and a tuning analysis of the HFSS full-wave simulator, the cavity sizes are determined to be 25.19×17.54×0.508 mm^3 for cavity 1, 14.5×14.38×0.508 mm^3 for cavity 2 and 8.15×7.84×0.508 mm^3 for cavity 3.

The coupling matrix synthesized for 10 GHz filter is:

$$M = \begin{bmatrix} 0 & 0.0122 & 0 & 0 \\ 0.0122 & 0 & 0.0166 & 0 \\ 0 & 0.0166 & 0 & 0.0122 \\ 0 & 0 & 0.0122 & 0 \end{bmatrix}.$$

The coupling matrix synthesized for 18 GHz filter is:

$$M = \begin{bmatrix} 0 & 0.0171 & 0 & 0 \\ 0.0171 & 0 & 0.0232 & 0 \\ 0 & 0.0232 & 0 & 0.0171 \\ 0 & 0 & 0.0171 & 0 \end{bmatrix}.$$

Then, the external quality factor and the inter-resonator coupling coefficients for the two filters of the diplexer will be obtained by de-normalizing the above generalized coupling matrixes:

$$k_{ij}=FBW\times M_{ij} \quad Q_e=\frac{1}{FBW\times \mathrm{M}_{1S}^{2}} \quad FBW=\frac{BW}{f_0}, \quad (6)$$

where *FBW* is the frantional bandwidth, *BW* is the absolute bandwidth and f_0 is the center frequency of the passband. The final parameters of the diplexer are then optimized to meet those external quality factor/coupling coefficients given above [8]. It is also noted that, the external quality factors required by these two filters of the two passband are different for the common cavity (cavity 1), which works as a resonator in both filters. Therefore, the final dimension of the external coupling slot for cavity is chosen to find the balance of meeting the calculated external quality factors for both filters [9]. The detailed dimensions of the diplexer are shown in Fig. 2.

The photograph of the fabricated diplexer is shown in Fig. 4. The S-parameter results of the diplexer were measured using a 2.92 mm southwest super SMA connector. The simulated and measured results for the diplexer are shown in Fig. 5 and Fig. 6. A good agreement between simulations and measurements has been achieved. The measured central frequencies are 10 GHz and 17.9 GHz, and minimum insertion losses are 2 dB at both channels, which are about 0.5 dB larger than simulation predicts. The errors are conjecturally caused by the SMA connectors and manufacturing tolerances. The group delays for both channels are smaller than 0.6 ns in the measurement. The isolation is better than 42 dB for both channels.

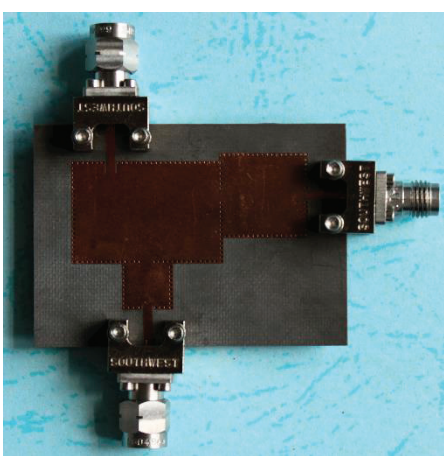


Fig. 4. Photograph of the fabricated diplexer operating at 10 GHz and 18 GHz.

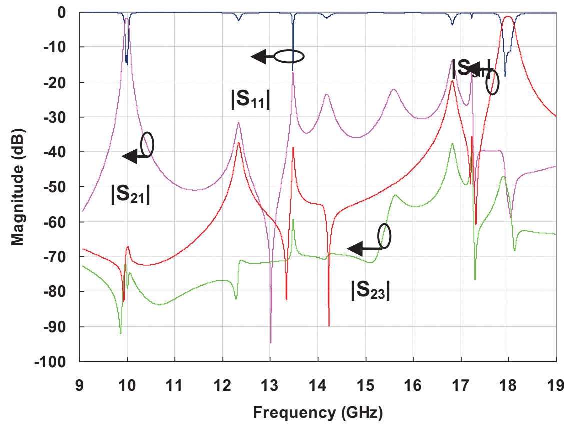


Fig. 5. Simulated S-parameter results of the diplexer.

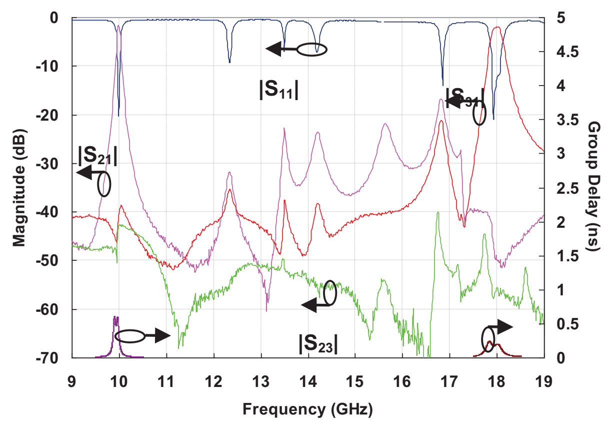
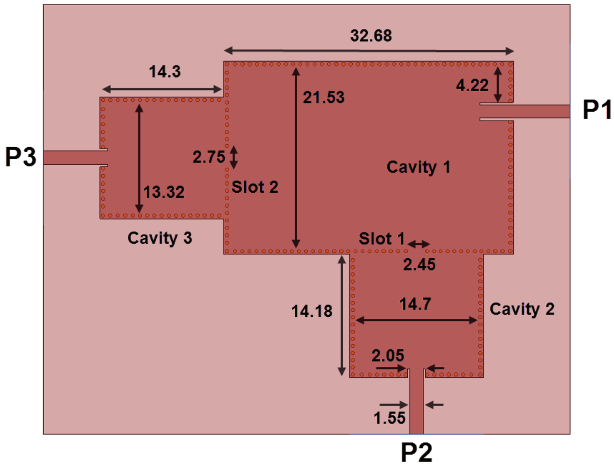


Fig. 6. Measured S-parameter and group delay results of the diplexer.

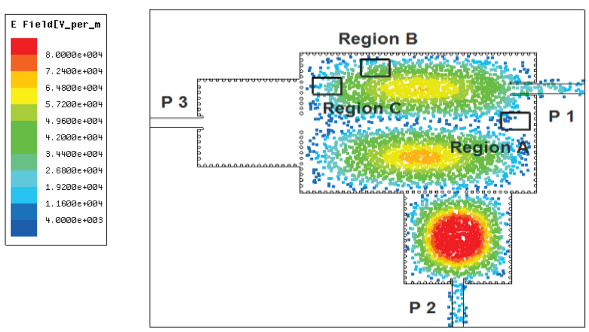
B. 10/10.5 GHz diplexer

The configuration of the 10/10.5 GHz diplexer is shown in Fig. 7. A fractional bandwidth of 0.5% is required for the 10 GHz filter while it is of 0.8% for the 10.5 GHz filter. The basic configuration and working mechanism of the diplexer is almost the same as the 10/18 GHz one. Cavity 1 is the dual-mode cavity resonating at 10 GHz for TE_{201} mode and 10.5 GHz for TE_{103} mode. Cavity 2 and cavity 3 are single-mode cavities whose resonant frequency is 10 GHz and 10.5 GHz, separately. The coupling slot between cavity 1 and 2 are centered at one-third of the longer side-wall *bb′* of cavity 1. The coupling slot between cavity 1 and 3 are placed at the center of the shorter side-wall *bb″* of cavity 1. The electric field distributions of the diplexer at 10 GHz and 10.5 GHz are plotted in Fig. 8 (a) and (b), respectively.

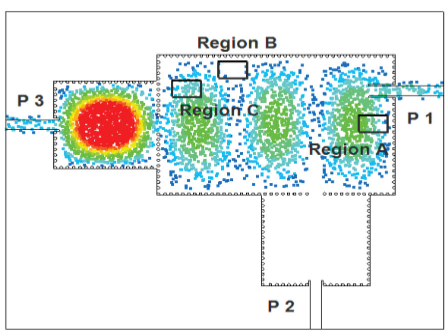


Unit: mm

Fig. 7. Geometry of proposed 10/10.5 GHz diplexer.



(a)



(b)

Fig. 8. Electric field distributions of the diplexer at: (a) 10 GHz, and (b) 10.5 GHz.

Based on the equations (4)-(5), the cavity sizes are optimized to be 32.68×21.53×0.508 mm^3 for cavity 1, 14.7×14.18×0.508 mm^3 for cavity 2 and 14.3×13.32×0.508 mm^3 for cavity 3. As a contrast, if we use a dual-mode cavity of TE_{201} and TE_{301} modes to design this kind of a diplexer, the size of cavity 1 will be 70.8×10.6×0.508 mm^3 and larger than the one of TE_{201} and TE_{103} modes, obviously. The detailed design procedure of this diplexer has been described in Section III.A and is omitted here for brevity.

The photograph of the fabricated diplexer is shown in Fig. 9. The simulated and measured results for the diplexer are shown in Fig. 10 and Fig. 11, respectively. Good agreement between simulations and measurements can also be observed. The insertion losses are both 2.1 dB at the two channels, which are about 0.6 dB larger than those predicted by simulation. The errors are also conjecturally caused by the SMA connectors and manufacturing tolerances. The group delays for both channels are smaller than 1 ns in the measurement. The isolation is better than 49 dB for both channels.

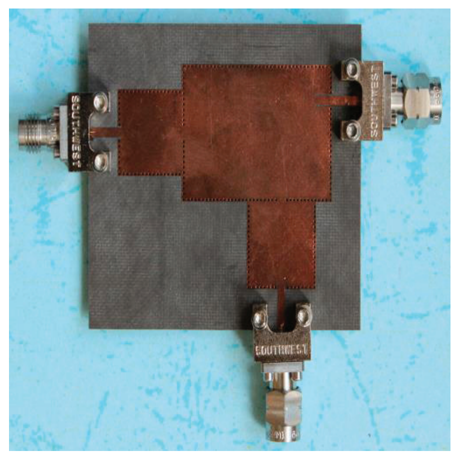


Fig. 9. Photograph of the fabricated diplexer operating at 10 GHz and 10.5 GHz.

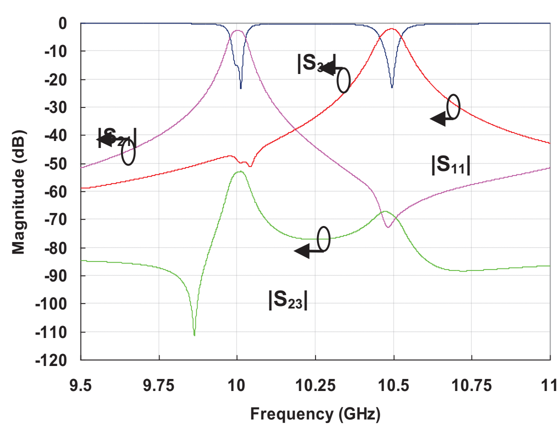


Fig. 10. Simulated S-parameter results of the diplexer.

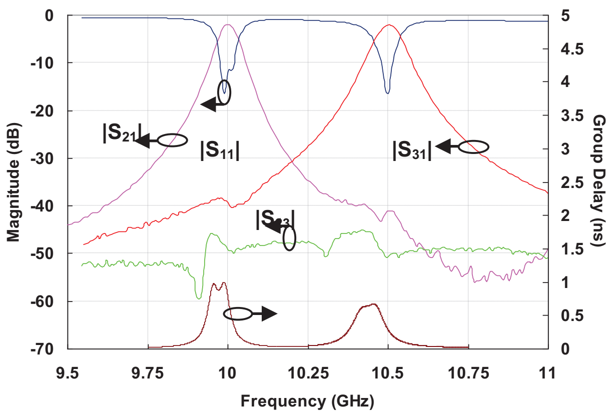


Fig. 11. Measured S-parameter and group delay results of the diplexer.

IV. CONCLUSION

Compared with the design method in our previous work, the diplexer's design method proposed in this paper, using dual-mode SIW cavities resonating at TE_{201} and TE_{103} modes, exhibits advantages of smaller size occupation, better isolation performance and more applicable cases. Two examples of diplexers are designed and implemented. The operating frequencies for the two channels of the two examples are centered either very far or very close for the verification of our design method. Meanwhile, it is easy to construct a higher order diplexer by simply connecting more resonators to those single-mode cavities [e.g., cavity 2 and cavity 3] for a better performance of selectivity. The proposed designs of diplexers are very suitable for different kinds of wireless communication applications.

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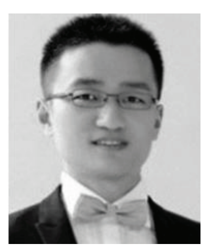

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