Communication

A Dual-Functional Triple-Mode Cavity Resonator With the Integration of Filters and Antennas

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***Abstract*—A novel concept for the two-in-one design with the integration of filters and antennas, using a single cavity, is presented in this communication. Basically, a triple-mode resonator (TMR) is utilized as a common feeder to achieve filtering and radiating functions at three different frequency bands. Each of the three bands adopts one of the three fundamental modes, namely, TE_{011}, TE_{101}, and TM_{110}, in a single TMR to realize the relevant functions. Owing to the modal orthogonality of these fundamental modes, high isolation can be effectively realized among these three channels. Based on the proposed TMR, three different prototypes are designed for different applications. For the first prototype, the structure of a dual-band filter plus an antenna is presented using a second-order TMR. Based on the combination of a duplexer plus an antenna, the second prototype is attained. To further explore the function of the proposed TMR, the structure of a filter plus a dual-polarization antenna is depicted as the third prototype. For verification, the third prototype is fabricated and tested. Good agreement between the simulated and the measured results is achieved, which proves the feasibility of the proposed design methodology.**

***Index Terms*—Antenna and filter, integration, rectangular cavity, slots, triple-mode resonator (TMR).**

I. Introduction

Multifunctional and low-cost passive components have attracted significant interests in recent decades [1]–[4] for their applications in the modern wireless communication systems. For this reason, the concept of codesigning several circuit components has been considered as a promising solution tackling multiple tasks in a simple but efficient way, for example, the elimination of distribution network by implementing multiplexers [5]–[7] and the integration of diplexers and antennas [8]. In [9]–[14], the integration approach is adopted for the design of filtering antennas, where the last resonator of the bandpass filters is substituted by an antenna. All the codesigns not only decrease the volume but also reduce the insertion loss caused by the interconnections. Due to the excellent performance of these reported works, the explorations about the approach of circuits' integration continuously attracts the interests from both academia and industry. However, to the best of our knowledge, there are few studies referring to the combination of filters/diplexers and antennas in a single structure [15], [16].

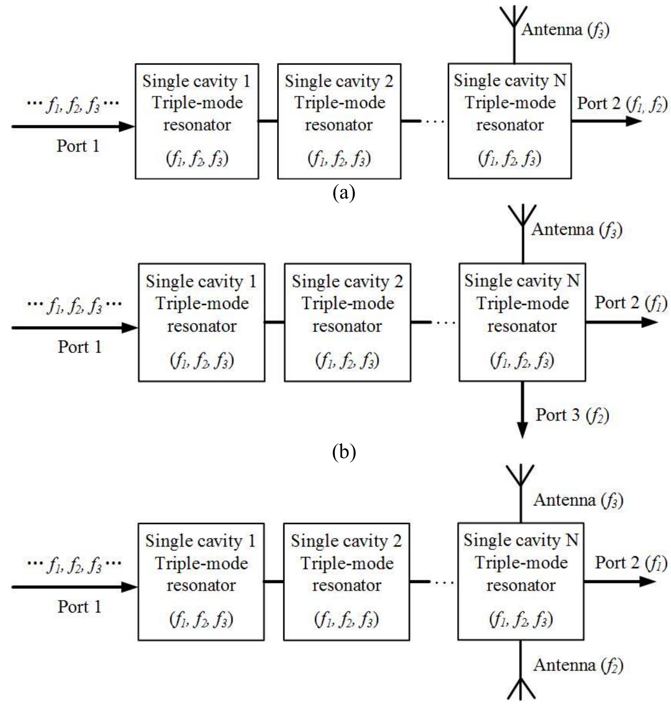

Fig. 1. Block diagrams of the presented structures. (a) Nth order response of a dual-band filter plus one antenna. (b) Nth order response of a diplexer plus one antenna. (c) Nth order response of a filter plus a dual-polarization antenna.

Lin *et al.* [7] present several simplified triplexer structures which miniaturize the whole volume and decrease the insertion loss. However, only the triplexer function can be implemented using that technology, which is not enough for the multifunctional design.

In this communication, instead of using these circuit networks mentioned earlier, we make full use of the three orthogonal fundamental modes, namely, TE_{101}, TE_{011}, and TM_{110} modes, in one triple-mode resonator (TMR) cavity to construct a series of novel circuits for the implementation of filtering and radiating dual-functional designs with matched in-band performance and miniaturized cavity volume. Fig. 1 shows the block diagrams of all the proposed structures. In our design, only one type resonator TMR needs to be implemented in these structures, which can miniaturize the circuit volume of the structure. According to Fig. 1(a), the common TMRs are adopted from the first order to the last order in terms of Butterworth filter response at the three frequency channels of f_1, f_2, and f_3.

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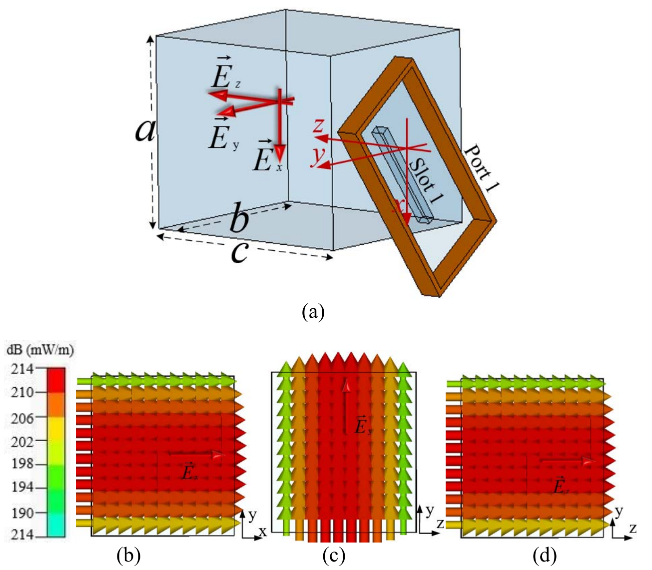


Fig. 2. (a) 3-D physical model of the proposed first TMR. (b)–(d) Distribution of electric field of TE_{011}, TE_{101}, and TM_{110} modes.

Taking advantage of this approach, the occupation of the complicated matching network can be left out. Moreover, the channels of f_1 and f_2 are separated into port 2 simultaneously, while the f_3 channel is dedicated as an antenna radiating the high band signals into the air. The topology of Fig. 1(b) is the same as that of Fig. 1(a) in terms of the first order to the Nth order of the proposed structure. Different from Fig. 1(a), in the Nth order, the channels f_1 and f_2 are separated into ports 2 and 3, respectively, and f_3 channel remains as an antenna for radiating function. In order to implement sufficient radiations at different frequency channels, a structure with one filtering band plus two radiation bands is proposed, as shown in Fig. 1(c). In Fig. 1(c), these three channels are separated at the last TMR order and only the f_1 channel is poured into port 2 as the filter signal, while the frequency channels of f_2 and f_3 are separated into different radiating slots to implement the radiations of these two channels.

As demonstrated in this communication, all the three designs have successfully achieved the combination of filtering and radiating functions using a single resonant structure. Meanwhile, the proposed single cavity structure for multifunctional purpose has significantly reduced the overall volume of these designs.

II. Dual-Band Filter Plus One Antenna

As previously studied in [7], the rotation and the offsetting of a coupling slot can be realized in a single TMR cavity. As shown in Fig. 2(a), a single TMR cavity can be utilized to excite three fundamental modes: TE_{101}, TE_{011}, and TM_{110}, respectively, whose electric field distributions are depicted in Fig. 2(b)–(d).

Taking investigation on the structure shown in Figs. 1(a) and 3(a) indicates the 3-D physical model of the proposed second-order structure. Port 1 is adopted as the input port to receive the electromagnetic (EM) wave, and then inputs through a rotated and shifted slot to the first TMR cavity. Therefore, this TMR cavity can generate three resonant modes with three electric field components: $\overrightarrow{E_x}$, $\overrightarrow{E_y}$, and $\overrightarrow{E_z}$ as marked in Fig. 2(a). When three resonant modes are coupled into the second TMR, $\overrightarrow{E_x}$ and $\overrightarrow{E_y}$ are separated by port 2 because of the rotation of the slot without offsetting, this incorporates the electric field components of these two modes. As for $\overrightarrow{E_z}$, the orientation of radiating slot is in accordance with its electric field component to implement the beam radiation of this mode. The parameter values of the proposed structure are tabulated in Table I.

TABLE I

Physical Dimensions of the Prototype for Case I

l_1 = 42 mm	w_1 = 3 mm	s_1 = 15 mm	θ_1 = 35 °	l_2 = 35 mm
w_2 = 3 mm	s_2 = 18 mm	θ_2 = 35 °	l_{xy} = 62 mm	w_{xy} = 3.9 mm
t_{xy} = 64 mm	θ_{xy} = 45 °	l_z = 64 mm	w_z = 3.3 mm	t_z = 39.7 mm

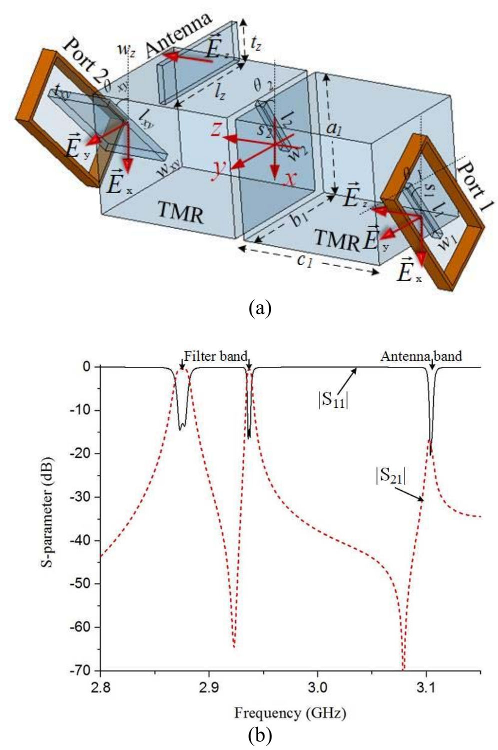
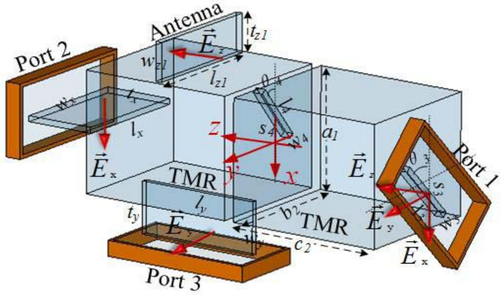


Fig. 3. Proposed structure implementing dual-band filter plus an antenna. (a) Second-order physical model. (b) Simulated S-parameter curves.

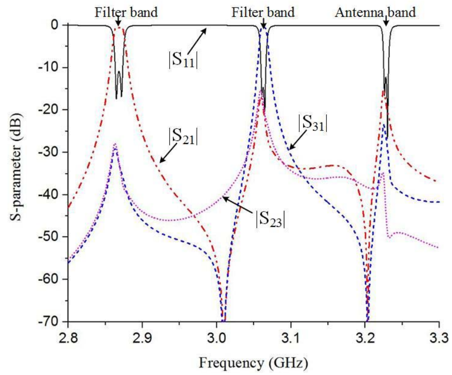
Fig. 3(b) presents the simulated S-parameter curves of the proposed structure. By setting the dimensions of the cavity as: $a_1 = 67$ mm, $b_1 = 69.2$ mm, and $c_1 = 78$ mm, S-parameter curve $|S_{11}|$ shows three bands of transmission poles representing good impedance matching of the three resonant frequencies in port 1, while only two of the three frequencies transmit to port 2 as denoted in $|S_{21}|$. Therefore, it is evident that the first and the second bands of the dual-band filter are operating in TE_{011} mode resonating at 2.88 GHz and TE_{101} mode resonating at 2.94 GHz with simulated insertion loss of 0.4 and 0.5 dB, respectively. And owing to the generation of one transmission zero [17] at 2.93 GHz, high isolation between two filtering channels is achieved. The third orthogonal mode of TM_{110} mode is resonating at 3.10 GHz and is radiating through the radiating slot with main lobe antenna gain of 5.6 dBi. WR284 rectangular waveguide is utilized to feed all ports.

III. Diplexer Plus an Antenna

In this section, we consider the situation for a diplexer plus an antenna. As discussed earlier, there are no interactions exist among these three fundamental modes owing to the modal orthogonality, and three channels controlled by these modes will be independent, respectively. Therefore, the filter synthesis method is then utilized



(a)



(b)

Fig. 4. Proposed structure implementing diplexer plus an antenna. (a) Second-order physical model. (b) Simulated S-parameter curves.

to design both bands of the proposed diplexer. Considering the specifications of the fractional bandwidths of 0.53% and 0.35% for the two passbands, the external quality factors and the coupling coefficients of these two bands can be calculated as follows:

$$Q_e^{\mathrm{I}} = \frac{g_1}{\mathrm{FBW}^{\mathrm{I}}} = 265 \tag{1a}$$

$$M_{12}^{\mathrm{I}} = \frac{\mathrm{FBW}^{\mathrm{I}}}{\sqrt{g_1 g_2}} = 0.00376 \tag{1b}$$

$$Q_e^{\mathrm{II}} = \frac{g_1}{\mathrm{FBW}^{\mathrm{II}}} = 408.7 \tag{1c}$$

$$M_{12}^{\mathrm{II}} = \frac{\mathrm{FBW}^{\mathrm{II}}}{\sqrt{g_1 g_2}} = 0.0025 \tag{1d}$$

where the superscripts stand for the channel numbers, $g_1$and g_2 are the low-pass prototype element values of the second-order Butterworth polynomial which can be set as $g_1 = g_2 = 1.4142$, and $\mathrm{FBW}^{\mathrm{I}}$ and $\mathrm{FBW}^{\mathrm{II}}$ are the fractional bandwidths of the first and the second frequency channels, respectively.

The relationships between the coupling coefficients and the external quality factors based on the physical model dimensions of coupled resonators can be extracted according to [7]

$$M_{ij} = \pm\frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2} \tag{2a}$$

$$Q_e = \frac{f_0}{\Delta f_{3\ \mathrm{dB}}} \tag{2b}$$

where f_{p1} and f_{p2} are the resonant frequencies of the two coupled resonators, and f_0 stands for the center frequency while $\Delta f_{3\mathrm{dB}}$ stands for bandwidths between ±90° phase offsetting of the resonant frequency, respectively.

Fig. 4(a) depicts the 3-D physical model of the second-order structure. Similarly, port 1 is adopted as the input port to receive the EM wave, and then inputs through a rotated and shifted slot to

TABLE II

PARAMETER VALUES FOR CASE II

l_3 = 42 mm	w_3 = 3 mm	s_3 = 10 mm	θ_3 = 45 °	l_4 = 35 mm
s_4 = 15 mm	θ_4 = 39 °	l_x =62 mm	w_x =3 mm	t_x =69.2 mm
w_y = 2.6 mm	t_y = 50 mm	l_{z1} = 64 mm	w_{z1} = 3.2 mm	t_{z1} = 35.5mm
w_4 = 3 mm	l_y = 62 mm			

TABLE III

PARAMETER VALUES FOR CASE III

l_5 = 40 mm	w_5 = 2 mm	s_5= 14 mm	θ_5 = 45 °
l_{y2} = 40 mm	w_{y2} = 5.6 mm	l_{z2} = 40 mm	w_{z2} = 3.2 mm
l_{y3} = 40 mm	w_{y3} = 2.68 mm	l_{z3} = 40 mm	w_{z3} = 2 mm
w_{x3} = 2.92 mm	l_{x2} = 40 mm	l_{x3} = 40 mm	w_{x2} = 3.4 mm

the first TMR cavity. Therefore, this TMR cavity can generate three resonant modes with three electric field components: $\overrightarrow{E_x}$, $\overrightarrow{E_y}$, and $\overrightarrow{E_z}$ as marked in Fig. 4(a). Different from the first case, when three modes are coupled into the second TMR cavity, TE_{011} mode will be coupled by the slot orientation perpendicular to x-axis with the electric field distribution $\overrightarrow{E_x}$ at port 2, while port 3 will couple TE_{101} mode with the electric field component $\overrightarrow{E_y}$ at port 3. With regard to $\overrightarrow{E_z}$, it is still coupled into the radiating slot for beam radiation. The parameter values of the proposed structure are listed in Table II.

Fig. 4(b) shows the simulated S-parameter curves of the proposed structure. By setting the dimensions of the cavity as: $a_2 = 62.2$ mm, $b_2 = 69.2$ mm, and $c_2 = 78$ mm, S-parameter curve $|S_{11}|$ shows that three bands of transmission poles represent good impedance match of three resonant frequencies in port 1. One of the three frequency signals transmits to port 2 as denoted in $|S_{21}|$ with the 3 dB absolute bandwidth of 15 MHz and the simulated insertion loss of 0.3 dB while another frequency energy reaches into port 3 as denoted in $|S_{31}|$ with the 3 dB absolute bandwidth of 10 MHz and the simulated insertion loss of 0.4 dB. Meanwhile, the first and the second bands of the diplexer are operating in TE_{011} mode and TE_{101} mode, respectively, corresponding to the resonant frequency bands at 2.87 and 3.06 GHz, respectively. While TM_{110} mode resonating at 3.22 GHz is radiating through the antenna slot with main lobe antenna gain of 5.4 dBi, WR284 rectangular waveguide is utilized to feed all ports.

IV. FILTER PLUS A DUAL-POLARIZATION ANTENNA

The last example is a filter plus two slot antennas. Here a dual-polarization antenna is formed up by two orthogonal radiating slots as depicted in Fig. 5(a). In terms of the filter, the approach described in the former part of the diplexer plus an antenna is used. Considering the specifications of the fractional bandwidth of 0.33%, the external quality factor and coupling coefficient of this band can be calculated as follows:

$$Q_e^{\mathrm{I}} = \frac{g_1}{\mathrm{FBW}^{\mathrm{I}}} = 423 \tag{3a}$$

$$M_{12}^{\mathrm{I}} = \frac{\mathrm{FBW}^{\mathrm{I}}}{\sqrt{g_1 g_2}} = 0.00233. \tag{3b}$$

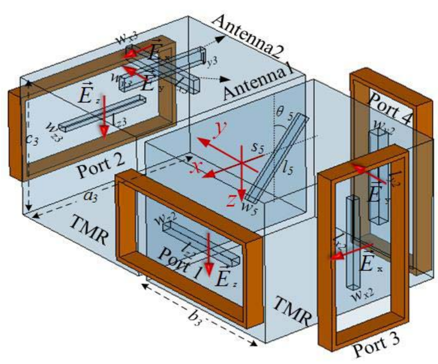
Then, the coupling coefficient and the external quality factor of the response based on the physical model dimensions of the coupled resonators can be extracted using formula (2). The method for extracting M_{12} and Q_e of TE_{011} mode is similar to that done for the hybrid resonator triplexer model in [7].

Fig. 5(a) depicts the 3-D physical model of the second-order structure with a filter plus a dual-polarization antenna. There are three

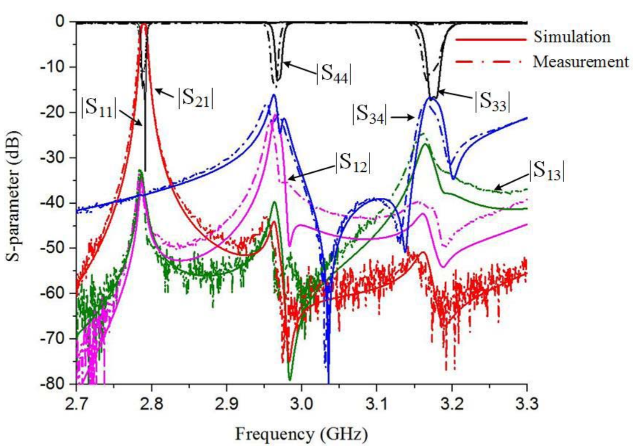
TABLE IV

COMPARISON BETWEEN THE PROPOSED DUAL-FUNCTIONAL DESIGNS AND OTHER REPORTED WORKS

	Filtering function	Radiation function	Dual-function feasibility	Insertion loss of filter	Main gain of antenna
[8]	Diplexer	Diplex-antenna	No	2.22/2.48	-
[12]	Filter	Filtering antenna	No	-	6.79
[15]	Filter	antenna	Yes	2.19	5
[16]	Filter	Dual antenna	Yes	1.7	-
Dual-band filter + antenna	Dual-band Filter	Filtering antenna	Yes	0.4/0.5	5.6
Diplexer + antenna	Diplexer	Filtering antenna	Yes	0.3/0.4	5.4
Filter + dual-polariation antenna	Filter	Dual-Filtering antenna	Yes	0.8	6.58/6

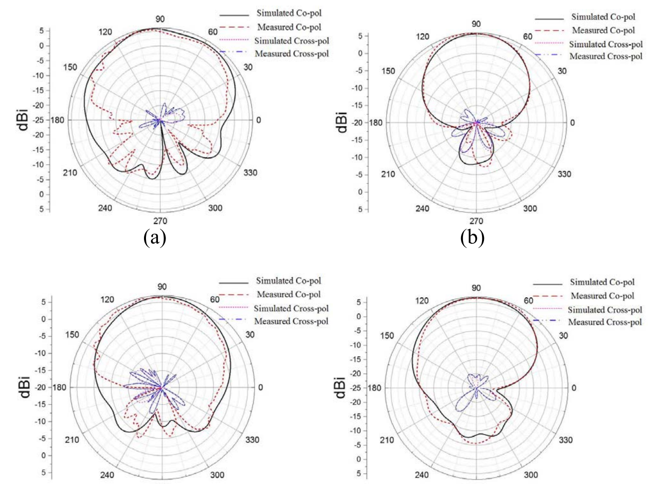


(a)



(b)

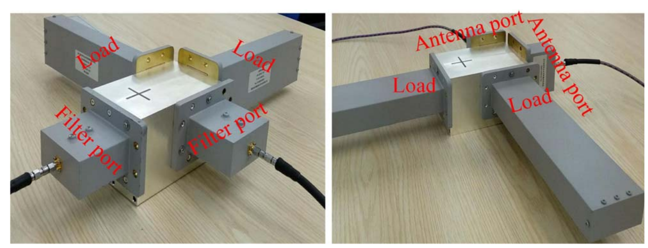
Fig. 5. Proposed structure implementing a filter plus a dual-polarization antenna. (a) Second-order physical model. (b) Simulated and measured S-parameter curves.



(a) (b)

(c) (d)

Fig. 6. Comparison of the simulation and measurement results in terms of radiation pattern of the proposed structure. (a) E-plane and (b) H-plane of the TE_{101} mode. (c) E-plane and (d) H-plane of the TE_{011} mode.



(a) (b)

Fig. 7. Photographs of the fabricated structure with a filter plus a dual-polarization antenna. (a) Operating state of filtering function. (b) Operating state of radiation function.

input ports with different orientations to achieve filtering/radiation functions. Port 1 couples to a slot whose long side vertical to the z-axis with the electric field distribution $\overrightarrow{E_z}$ so that TM_{110} mode can be derived in the port 1. Similarly, port 3 excites TE_{011} mode by coupling a slot vertical to the x-axis while port 4 excites TE_{101} mode by coupling a slot vertical to the y-axis. Different from the former case, when these three fundamental modes in the first TMR are coupled into the second TMR, TM_{110} mode will be coupled by the slot orientation perpendicular to z-axis with the electric field distribution $\overrightarrow{E_z}$ at port 2, while antenna 1 will couple TE_{011} mode with the electric field component $\overrightarrow{E_x}$ and antenna 2 will couple TE_{101} mode with the electric field component $\overrightarrow{E_y}$, so that both radiating slots form up a dual-polarization antenna for beam radiation. The physical dimensions of the structure are tabulated in Table III.

Fig. 5(b) shows the comparison between the simulated and the measured S-parameter curves of the proposed structure. By setting values of the dimensions of the cavity as: $a_3 = 83$ mm, $b_3 = 69.2$ mm, and $c_3 = 62.2$ mm, S-parameter curve $|S_{11}|$ shows three bands of transmission poles representing the good impedance matching of three resonant frequency energies in port 1, and one of the three frequencies transmits to port 2 as denoted in $|S_{21}|$, while another two frequencies radiate to the air. Therefore, it is evident that the band of the filter is produced by TM_{110} mode resonating at 2.79 GHz with the 3 dB bandwidth of 10 MHz with the measured insertion loss of 0.8 dB, while TE_{011} mode using the antenna 1 slot resonates at 2.97 GHz and TE_{101} mode using the antenna 2 slot resonates at 3.18 GHz. Fig. 6 shows the radiation patterns of the proposed structure. The E-plane and the H-plane of the TE_{101} mode are depicted in Fig. 6(a) and (b), respectively, and the main lobe antenna gain is 6.58 dBi. While the E-plane and the H-plane of the TE_{011} mode are depicted in Fig. 6(c) and (d), respectively, and the main lobe antenna gain is 6 dBi.

It is noted that two photographs including the operating state of filtering and radiation functions of the fabricated structure with a filter plus a dual-polarization antenna are depicted in Fig. 7(a) and (b). The structure uses the material silver-plated aluminum for fabrication. WR284 rectangular waveguide is utilized to feed all ports.

After analysis of the three proposed dual-functional structures, Table IV illustrates a comparison with the conventional individual/integrated designs. It is noted that the codesigns in this communication can achieve dual-functions with filtering and radiation simultaneously, which still include the low insertion loss and the high antenna gain.

V. Conclusion

In this communication, a novel concept to design a size-miniaturized dual-functional structure with the integration of filters and antennas in the TMR cavity has been presented. Taking advantages of sharing the common TMR cavities for three individual channels, three types of integration of filters and antennas are then designed for different applications. Meanwhile, only one type of the coupling slots need to be adopted in all structures in terms of this common TMR cavity technology. And owing to the modal orthogonality of three fundamental modes, high isolation between three channels controlled by three modes can be well-achieved. In final, the structure with one filter plus a dual-polarization antenna has been fabricated and tested. Accurate agreement between simulated and measured results has verified the proposed design methodology.

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