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A Novel Dual-Band Controllable Bandpass Filter Based on Fan-Shaped Substrate Integrated Waveguide

Sheng Zhang, Jia-Yu Rao, Jia-Sheng Hong, *Fellow, IEEE*, and Fa-Lin Liu

***Abstract*—A compact dual-band bandpass filter (BPF) with controllable center frequencies based on the 90° Fan-Shaped Substrate Integrated Waveguide Resonator (FSSIWR) is first proposed in this article. Dual-band response is achieved by the fundamental mode (TM_{101} mode) and high mode (TM_{201} mode) of the FSSIWR, respectively. In design, two pairs of the posts are loaded at the 45° direction of FSSIWRs, which produce perturbation to adjust the center frequency of the first-passband. In order to control the second-passband center frequency, the Complementary Split-Ring Resonators (CSRRs) are etched on the surface of the resonator. The etched CSRRs can not only adjust second-passband center frequency by changing the locations of the CSSRs, but also produce a transmission zero (TZ) in the upper stopband of the second-passband. In addition, other five TZs are obtained by introducing source-load coupling, which highly improve the frequency selectivity. Finally, the proposed filter is fabricated and measured. The measured results agree well with the simulated ones.**

***Index Terms*—Dual-band Bandpass filter, frequency controllable, Fan-Shaped Substrate Integrated Waveguide Resonator**

I. INTRODUCTION

RECENTLY, substrate integrated waveguide (SIW) technology has attracted lots of attentions with its compact size, high-Q, low cost and easy integration [1]. In the past few years, various BPFs are designed based on the SIW [2][3]. Meanwhile, with the development of the wireless communication system, dual-band or multi-band BPFs are playing vital roles in the modern radio frequency circuits. However, only few papers focus on the dual-band/multi-band BPFs using SIW technologies [4]-[12]. In [4], a synthesis technology is proposed to design a dual-band and a triple-band filter, but the sizes of the filters are too large. A miniaturized dual-band BPF is designed in [5], but it has a poor performance at the outside of the passband. In [6], two miniaturized dual-band BPFs with folded SIW technology are proposed, but both passbands are difficult to be controlled. Based on double-layer substrate, a dual-band BPF with controllable passbands is proposed in [7], but it costs much.

In this paper, an easy-to-cascade 90° FSSIWR is first proposed. Based on it, a novel single-layer compact second-order dual-band BPF with two controllable center frequencies is designed and fabricated. The TM_{101} mode and TM_{201} mode are utilized to achieve the dual-band response. Posts are placed at the 45°direction of FSSIWRs to generate perturbation, which can not only split the degenerate modes but also adjust the frequency of the first passband. Furthermore, a pair of CSRRs are introduced. Commonly, the CSRRs are excited by the fundamental mode [5][8]. But in this design, the degenerate modes are used to excite the CSRRs. One advantage is that a TZ can be produced in the upper stopband, and another is that the second passband center frequency can be controlled. In addition, the source-load cross coupling is introduced to improve performance of the out-of-band. To verify the design, a filter prototype with center frequencies operating at 7.45GHz and 10GHz is fabricated and tested. The measured results show low insertion loss ($<$2dB) and exhibit a stopband suppression better than 35 dB around the filter passbands.

II. ANALYSIS AND DESIGN

A. Center Frequency Adjustment Analysis

The proposed structure of the dual-band BPF is depicted in Fig.1(a). Two pairs of the posts, denoted by P_1 and P_2, are loaded at the 45° direction of the FSSIWRs. A pair of the rectangular CSRRs are etched on the upper layer of the FSSIWRs. Inductive window coupling and slot coupling are utilized between the two FSSIWRs to achieve the desired coupling strength. The coupling scheme is shown in Fig.1(b), where A and B represent the TM_{101} mode and TM_{201} mode, respectively. TM_{101} and TM_{201} mode are coupled from source to load via two separate paths, hence, two paths for the dual-band response can be easily designed and realized, independently.

Fig.2 shows the electric field distributions of the fundamental mode and the first degenerate modes. It can be found that the electric field strength of the fundamental mode reaches its maximum while those of the others are minimum in the center of the FSSIWR. By introducing the posts perturbation, the TM_{101} and TM_{102} mode are changed greatly while TM_{201} remained nearly invariable. Based on this interesting feature, the first passband can be adjusted by changing parameters P_1, P_2, while the second passband is invariable as shown in Fig.3. In addition, due to the perturbation, the TM_{201} and TM_{102} mode can be splited successfully. Because only the TM_{201} mode is used to achieve the second passband response, so the separation is benificial to suppress the parasitic mode TM_{102}.

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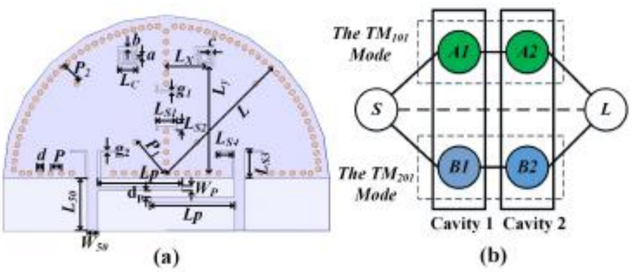

Fig. 1. (a) Structure of the dual-band filter. (b)Coupling scheme of the dual-band filter

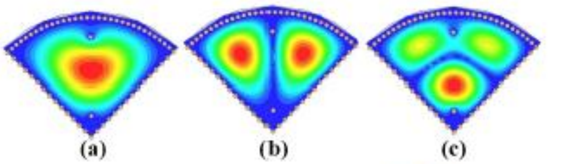

Fig. 2. electric field distributions of the fundamental mode and the first degenerate modes.(a)TM101.(b)TM201.(c)TM102.

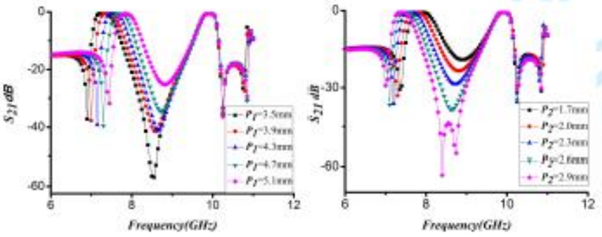

Fig. 3. Variation in resonant frequency as a function of P1, P2.

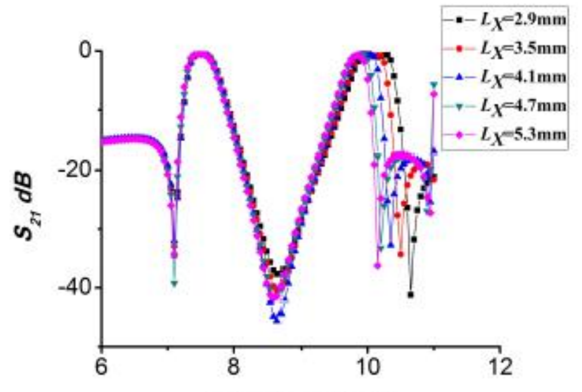

Fig. 4. Variation in resonant frequency as a function of L_X.

To control the second passband and suppress the TM_{102} mode, a pair of CSRRs are etched on the surface of the FSSIWR. The CSRRs can be excited by degenerate mode (TM_{102}, TM_{201}) and hardly affected by fundamental mode (TM_{101}). By optimizing the sizes and positions of the CSRRs(L_C,L_X,L_Y), a TZ can be produced to suppress the TM_{102} mode in the upper stopband of the second passband, meanwhile, the second passband can be controlled by adjusting the parameter L_X as shown in Fig.4.

B. Dual-Band Filter Design

As shown in Fig.1(a), slot coupling is employed between the two FSSIWRs to achieve the desired coupling strength. In order to improve the selectivity of the out-of-band, source-load coupling is introduced[9]. In Fig.5, it can be found that five TZs (TZ1-TZ2,TZ4-TZ6) are obtained by introducing the source-load coupling(S-L-C). TZ3 is attributed to the feature of the CSRRs.

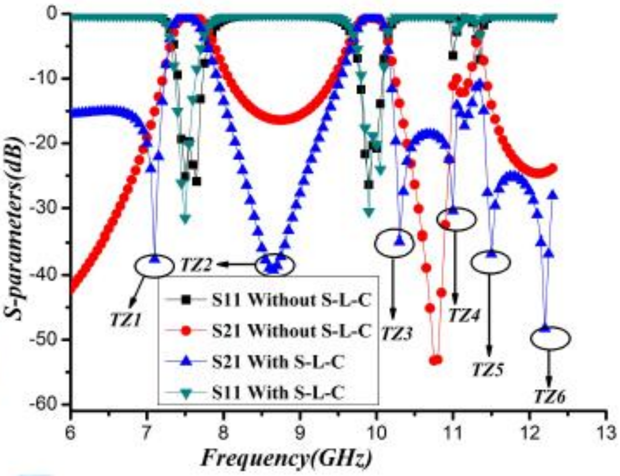

Fig. 5. Simulated scattering parameters the dual-band filter.

The whole design procedure can be summarized as follows. First, according to [10] and by means of the least square method, the resonant frequency of the fundamental mode can be calculated by the following formula (1)

$$f \approx \frac{c}{\sqrt{\epsilon_r \times \mu_r}} \times \frac{0.84}{R_0} \tag{1}$$

Where c is velocity of light in the vacuum, μ_r and ϵ_r are relative permeability and permittivity of the substrate, and R_0 is equivalent radius of the Fan-Shaped cavity.

Then the coupling coefficient between the two FSSIWRs can be calculated by [13]:

$$k = (f_1^2 - f_2^2)/(f_1^2 + f_2^2) \tag{2}$$

where f_1 and f_2 are the first and second resonant frequency of the FSSIWR, respectively. The external quality factor Q_e is calculated by[13]

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

where f_0 is the resonant frequency of the FSSIWR and Δf_{3dB} is the 3dB FBW.

Finally, the initial sizes of the filter can be calculated roughly. Then a fine tuning procedure by using HFSS is

TABLE I
COMPARISONS BETWEEN DUAL-BAND SIW FILTERS

Reference	Central Frequency(GHz)	Size(λ_0^2)	3dB FBW(%)	FR	IL(dB)	Attenuation Between PBs	layers	CF Controllability
[4]	20/21	1.98*1.30	1.5/1.4	1.05	1.39/1.10	55dB	single-layer	Not mentioned
[5]	3.5/5.7	0.21*0.18	3.3/6.4	1.63	0.98/0.81	30dB	single-layer	Not mentioned
[7]	4.6/5.3	1.1*1.25	2.0/1.5	1.15	1.95/2.75	46dB	double-layer	Controlled individually
[11]	2.41/3.51	0.45*0.67	10.8/6.4	1.46	1.45/1.74	20dB	single-layer	Only second-passband
[12]	2.7/3.2	0.44*0.44	7.78/6.25	1.18	1.14/1.32	24dB	double-layer	Not mentioned
This work	7.45/10.00	0.50*0.75	6.0/4.0	1.34	0.83*0.95	37dB	single-layer	Controlled individually

needed to optimize the design parameters. The final dimensions, on a 0.635mm thick substrate with relative dielectric constant of 6.15, are as follows (all in mm): L=14.00, L_{50}=5.00, W_{50}=1.02, L_P=8.02, dp=0.61, W_P=0.44, d=0.50, P=1.00, P_1=4.20, P_2=2.00, g_1=0.20, g_2=0.20, L_{S1}=1.96, L_{S2}=0.65, L_{S3}=2.30, L_{S4}=1.72, a=0.20, b=0.20, c=0.20, L-c=1.83, L_X=3.64, L_Y=10.36.

III. EXPERIMENTAL RESULTS

To verify the characteristics of the filter, a filter prototype is fabricated and shown in Fig.6. The substrate used in this paper is the RT/duroid6006, with ϵ_r =6.15, tanδ=0.0019 and thickness h=0.635 mm. In Fig.6, the measured results are in good agreement with the simulated ones. The losses are a little larger than the simulated ones becasuse of the unavoidable tolerance in fabrication and measurement. The two measured 3dB FBWs are 450MHz, 400MHz, respectively. The measured TZs with an attenuation level of are more than 35dB.

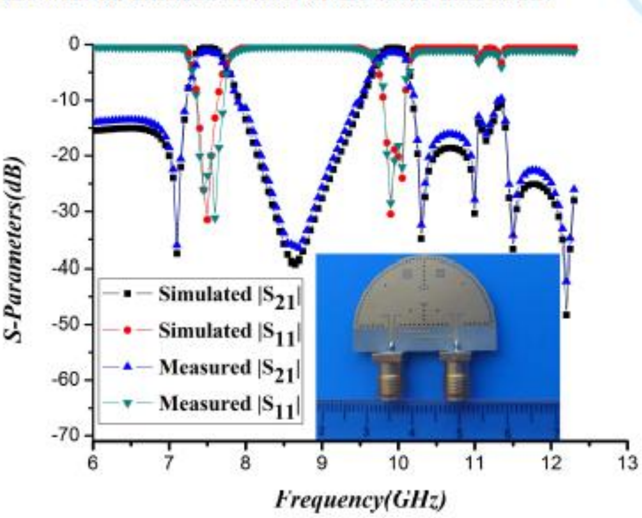

Fig. 6. Simulated and measured S-parameters of the dual-band filter.

Finally, some comparisons between our proposed and main previous dual-band SIW filters are summarized in Table I. From the comparisons, the advantages of this dual-band filter are obvious, such as individually controllable frequencies, simple structure, low cost, and small size.

IV. CONCLUSION

A novelDual-Band BPF filter is proposed in this letter. The main feature of the filter is that two passbands can be controlled individually. The first passband can be adjusted due to the posts perturbation, and the second passband can be adjusted by the etched CSSRs. Furthermore, the selectivity of the out-of-band is improved highly by using source-load coupling. Finally, the measured results agreed well with the simulated ones.

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