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HALF MODE SUBSTRATE INTEGRATED FOLDED WAVEGUIDE (HMSIFW) AND PARTIAL H-PLANE BANDPASS FILTER

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Abstract—In this paper, a half mode substrate integrated with folded waveguide (HMSIFW) and a HMSIFW partial H-plane bandpass filter are proposed. The proposed filter employs H-plane slot of open-ended evanescent waveguide and H-plane septa of short-ended evanescent waveguide as admittance inverter and impedance inverter, respectively. The filter has advantages of convenient integration, compact size, low cost, mass-producibility and ease in fabrication. In order to validate the new proposed topology, a four-pole ultra-narrowband bandpass filter, with quarter wavelength resonators, is designed and fabricated using standard printed circuit board process. The tapered line is used as transition between HMSIFW and microstrip-line for easy integration and measurement. The measured results are in good agreement with simulated ones, and good selectivity is achieved.

1. INTRODUCTION

The rapid development of microwave and millimeter-wave technology has increased the demand for high performance bandpass filters with low cost and compact size. Traditional metallic rectangular waveguide bandpass filters such as E-plane filter [1, 2], H-plane filter [3], and fin-line filter [4] have been widely used in microwave and millimeter-wave systems due to their merits of low insertion loss and high power handling capacity. But classical rectangular waveguide filters are bulky, heavy, high cost, and also difficult to integrate with planar circuits, being three-dimensional (3-D) structures. In [5], the partial

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H-plane waveguide whose cross section is one quarter of that of conventional waveguide is proposed. It has been utilized to design compact waveguide filters named as partial H-plane filters [6, 7]. Compared with conventional rectangular waveguide filters, these filters have reduced volume. But they are still 3-D structures and difficult to integrate with planar circuits. Microstrip line bandpass filters also have been widely applied to diversified systems for its compact size. However, microstrip line filters cannot provide required performances due to low Q-factor, especially at millimeter-wave frequencies [8–10]. In order to overcome these disadvantages, substrate integrated waveguide (SIW) technology that can be fabricated within printed circuit board (PCB), low temperature co-fired ceramic (LTCC) and thin film process has been proposed recently [11, 12]. It has attracted much interest because of its clear advantages over metallic waveguide, such as easy fabrication, easy integration with planar transmission lines and low cost. Diversified filters based on SIW have been realized [13–17, 27, 28]. However, compared with microstrip or stripline components, the width of SIW may be too large for some circuits. In order to reduce the width, the concept and geometry of substrate integrated folded waveguides (SIFW), half mode substrate integrated waveguides (HMSIW) and folded half mode substrate integrated waveguides (FHMSIW) are presented [18–21]. In [18] and [19], two different SIFW structures are proposed, and in [20] and [21], a HMSIW and a FHMSIW are proposed, which all keep the advantages of SIW, but the width is nearly reduced in half. Several components have been studied to demonstrate these structures [18, 21–23, 29].

Based on the SIFW structure in [18], this paper proposes a novel HMSIFW structure, which results in a considerable size reduction compared with conventional metallic waveguide. Based on the HMSIFW, the design and development of a quarter wavelength resonator partial H-plane bandpass filter is presented. The proposed filter employs H-plane slot of open-ended evanescent waveguide and H-plane septa of short-ended evanescent waveguide as admittance inverter and impedance inverter, respectively. A tapered transition from HMSIFW to microstrip-line is also designed for the convenience of measurement and integration. The proposed filter has advantages of low cost and mass-producible property, and more importantly, its performances are defined purely by the metallization on the upper metal layer, which can be defined very accurately using photolithography. An X-band narrowband bandpass filter, using the proposed filter structure, is implemented. Simulated and measured results are presented to demonstrate the promising performances of the proposed filter.

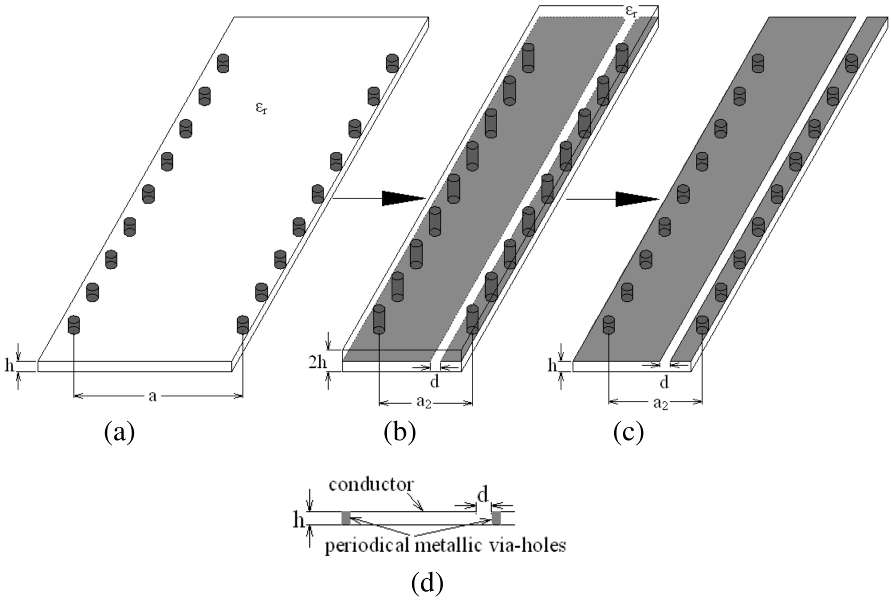

Figure 1. Configuration of SIW, SIFW and HMSIFW: (a) SIW, (b) SIFW, (c) HMSIFW, (d) the side view of the HMSIFW.

2. FILTER DESIGN

The configuration of an SIW is shown in Fig. 1(a), that of an SIFW in Fig. 1(b), and that of the proposed HMSIFW in Fig. 1(c), with a_2 being the width of the SIFW and HMSIFW and d being the spacing between the H-plane metal vane and the right sidewall of metallic via-holes. Fig. 1(d) shows the cross section of the HMSIFW. It can be seen that the SIFW is a SIW whose sides have been folded together from its central part. Metallic via-holes are used to synthesize the conducting side walls. The diameter and spacing of the holes are much shorter than the operating wavelength, and therefore is equivalent to a conducting wall [12]. The top, bottom and central metal layers are formed by patterned metallization on the surfaces of substrates. The thickness $2h$ of the SIFW of Fig. 1(b) is twice of the h of the SIW in Fig. 1(a), while its width a_2 is nearly half of a. The dominant mode of the SIFW is TE_{10} mode as the SIW. For the correct choice of a_2, h and d, the SIFW can be made to have the identical propagation characteristics to that of the SIW [24]. The maximum E-field of the dominant mode of the SIFW is presented at the edge of the guide between the middle conductor and sidewall. Therefore, the central metal plane can be approximated by a virtual magnetic wall. Based on this concept, the SIFW can be further bisected with a fictitious magnetic wall along its symmetric plane, and each half of the SIFW becomes a new guided wave structure, which is called half mode substrate integrated folded waveguide (HMSIFW), as shown in Figs. 1(c) and (d). The dominant mode field distribution and propagation characteristics are similar to SIFW and SIW, because of the large width-to-height ratio (WHR) and small spacing between the H-plane metal vane and the right sidewall of metallic via-holes. The dominant field distributions in SIW and HMSIFW are shown in Figs. 2(a) and (b). Compared with the HMSIW in [20], the maximum E-field of the dominant mode of the HMSIFW is presented at the edge of the guide between the H-plane metal vane and the right sidewall of metallic via-holes. The characteristic provides convenience for filter design.

In this paper, the proposed HMSIFW partial H-plane bandpass filter employs quarter wavelength resonator. Fig. 3 shows the equivalent circuit of the bandpass filter with quarter wavelength resonators. The quarter wavelength resonators are coupled alternately by admittance inverters (J-inverters) and impedance inverters (K-inverters) [25]. Here, the admittance and impedance inverters are

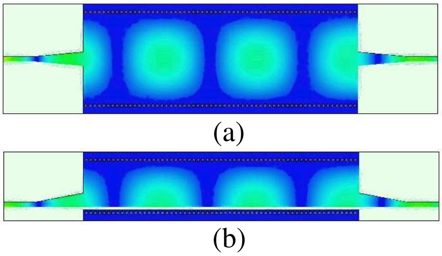

Figure 2. Dominant field distribution in SIW and HMSIFW: (a) SIW, (b) HMSIFW.

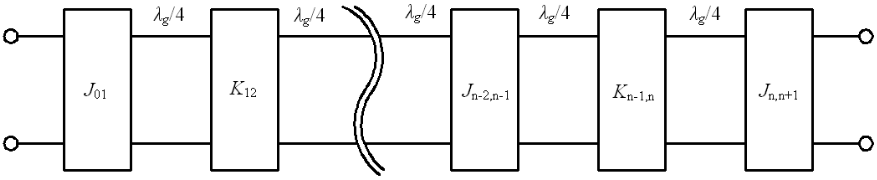

Figure 3. The equivalent circuit of the proposed bandpass filter with quarter wavelength resonators.

realized by H-plane slot of open-ended evanescent waveguide and H-plane septa of short-ended evanescent waveguide, respectively, as shown in Figs. 4 (a) and (b). Figs. 5(a) and (b) show the J- and K-inverters which are modeled as π- and T-equivalent circuits, respectively. The normalized inverter values and negative electrical

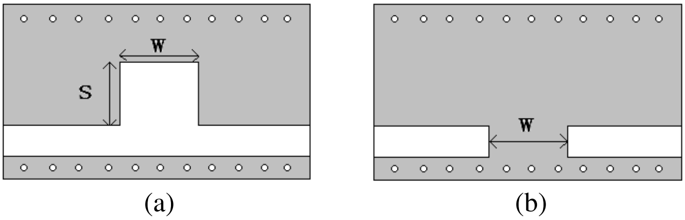

Figure 4. Evanescent waveguide unit cells of the proposed bandpass filter: (a) Partial H-plane slot. (b) Partial H-plane septa.

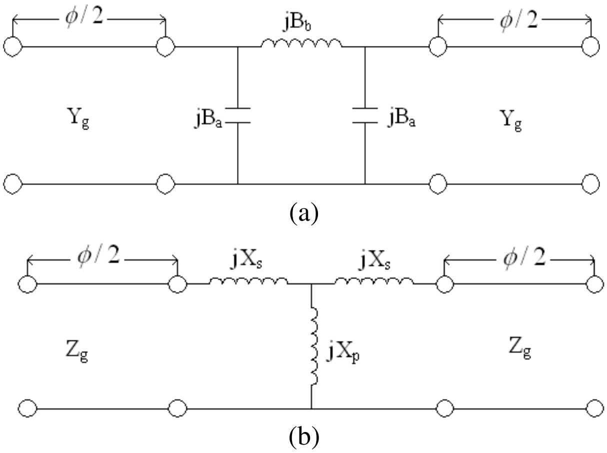

Figure 5. (a) Admittance inverter (J-inverter) for H-plane slot. (b) Impedance inverter (K-inverter) for H-plane septa.

length are given by [25, 26].

$$\frac{J}{Y_g} = \left|\tan\left(-\frac{1}{2}\tan^{-1}\left(\frac{2B_b}{Y_g}+\frac{B_a}{Y_g}\right)+\frac{1}{2}\tan^{-1}\frac{B_a}{Y_g}\right)\right| \tag{1}$$

$$\frac{K}{Z_g} = \left|\tan\left(-\frac{1}{2}\tan^{-1}\left(\frac{2X_p}{Z_g}+\frac{X_s}{Z_g}\right)+\frac{1}{2}\tan^{-1}\frac{X_s}{Z_g}\right)\right| \tag{2}$$

$$\phi_J = -\tan^{-1}\left(\frac{2B_b}{Y_g}+\frac{B_a}{Y_g}\right)-\tan^{-1}\frac{B_a}{Y_g} \tag{3}$$

$$\phi_K = -\tan^{-1}\left(\frac{2X_p}{Z_g}+\frac{X_s}{Z_g}\right)-\tan^{-1}\frac{X_s}{Z_g} \tag{4}$$

where Y_g and Z_g are wave admittance and impedance of a partial H-plane HMSIFW.

The proposed HMSIFW partial H-plane bandpass filter with quarter wavelength resonators is shown in Fig. 6. In the proposed HMSIFW partial H-plane filter, two adjacent quarter wavelength resonators are coupled by connecting H-plane slot of open-ended evanescent waveguide and H-plane septa of short-ended evanescent waveguide alternately, as shown in Fig. 6. A tapered transition from HMSIFW to microstrip-line is employed for the convenience of test and integration. Design of the tapered transition requires simultaneous matching of the fields and impedance. Several transition designs have been reported [11, 18]. It is easy to achieve a fairly good field matching by their dominant vertical E-field components. Their impedance is also matched using the tapered line without significant disturbance of their vertical E-field components. A commercial full-wave 3-D FEM simulator (Ansoft HFSS) is used to analyze and optimize the transition structure. The external coupling Q_e controls the insertion loss and ripple properties in a multi-pole filter. This external coupling can be extracted by using simulated values of a single HMSIFW resonator connected with a microstrip-line. The coupling scheme that provides the desired coupling for the input and output cavities can be obtained

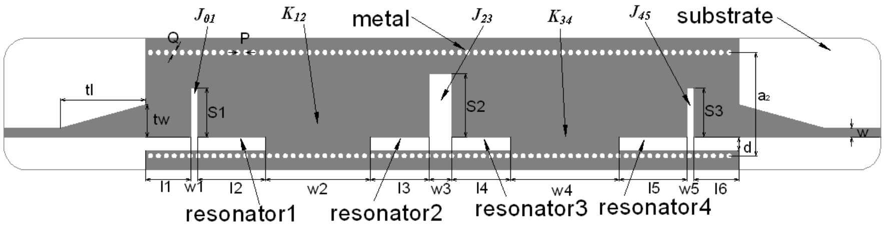

Figure 6. The proposed HMSIFW partial H-plane bandpass filter.

Table 1. The geometric dimensions of the designed HMSIFW partial H-plane bandpass filter (unit: mm).

l_1	l_2	l_3	l_4	l_5	l_6	w	w_1
4	6	5.2	5.2	6	4	0.76	0.6
w_2	w_3	w_4	w_5	tw	S_1	S_2	S_3
9.24	2	9.6	0.6	2.86	4.3	5.6	4.3
d	Q	P	a_2	tl	h		
0.3	0.5	0.7	8.2	7.5	0.254		

by performing a parametric analysis on a single resonator. Q_e can be evaluated by the formula $Q_e = (2f_0/\Delta f_{-3\text{ dB}})$ [25], which is mainly affected by the transition between microstrip-line and HMSIFW. The geometric dimensions of the designed transition are shown in Table 1.

The design method of the proposed partial H-plane bandpass filter based on HMSIFW can be summarized into three steps.

Firstly, according to the design requirement, the normalized inverter values for an equal-ripple bandpass filter are confirmed by [25]:

$$\frac{J_{01}}{Y_g} = \sqrt{\frac{\pi\omega_\lambda}{4g_0g_1\omega_n}} \tag{5}$$

$$\frac{K_{i,i+1}}{Z_g} \text{ or } \frac{J_{i,i+1}}{Y_g} = \frac{\pi\omega_\lambda}{4\omega_n}\frac{1}{\sqrt{g_ig_{i+1}}} \tag{6}$$

$$\frac{J_{n,n+1}}{Y_g} = \sqrt{\frac{\pi\omega_\lambda}{4g_ng_{n+1}\omega_n}} \tag{7}$$

$$\omega_\lambda = \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g0}} \tag{8}$$

where $g_0, g_1, \ldots, g_{n+1}$ are element values for an equal-ripple low-pass prototype and, ω_n is a normalized cutoff frequency. λ_{g0}, λ_{g1}, and λ_{g2} are waveguide wavelengths at center frequency and at lower and upper passband edge frequency. ω_λ is a relative bandwidth, and n is the order of the filter.

The next step of the filter design is to characterize the normalized inverter values and negative electrical length in terms of physical structures, so that the physical dimensions of the filter can be determined against the design parameters in Equations (5)–(7). There are two different types of coupling structures encountered in the filter design, i.e., H-plane slot of open-ended evanescent waveguide and

H-plane septa of short-ended evanescent waveguide, respectively, as shown in Fig. 4. The simulation models of unit cells can be made using HFSS or CST, which are composed of an evanescent waveguide in the middle and two sections HMSIFW at both sides of the unit cells. The S-parameters of the unit cells with different widths (W_j) and depths (S_j) of the H-plane slot, and different widths (W_j) of the H-plane septa can be gained easily by simulation. The S-parameters gained are put into the Advanced Design System (ADS). At the same time, the equivalent circuit of the evanescent waveguide cell is shown in Fig. 5. By parameter extraction, the admittances B_a and B_b are extracted for different widths (W_j) and depths (S_j) of the H-plane slot, respectively, and the impedances X_p and X_s are extracted for different widths (W_j) of the H-plane septa. Then, for the H-plane slot, the relationships between the normalized inverter value (J/Y_g)

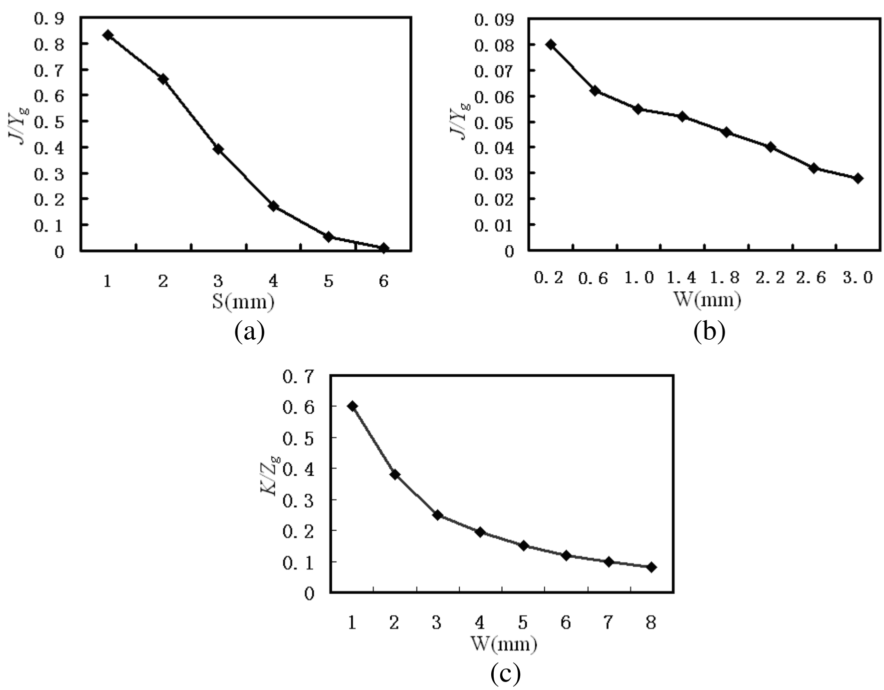

Figure 7. (a) The relationship between the normalized inverter value J/Y_g and the depth S of the H-plane slot ($W = 2$ mm), (b) the relationship between the normalized inverter value J/Y_g and the width W of the H-plane slot ($S = 5$ mm), (c) the relationship between the normalized inverter value K/Z_g and the width W of the H-plane septa.

and width (W_j), the normalized inverter value (J/Y_g) and depth (S_j), the negative electrical length ϕ and width (W_j), the negative electrical length ϕ and depth (S_j) can be confirmed using Equations (1) and (3). And for the H-plane septa, the relationships between the normalized inverter value (K/Z_g) and width (W_j), the negative electrical length ϕ and width (W_j) can be confirmed using Equations (2) and (4). Fig. 7 shows several examples of these relationships: Fig. 7(a) shows the relationship between the normalized inverter value and the depth of the H-plane slot (with width of 2 mm). Fig. 7(b) shows the relationship between the normalized inverter value and the width of the H-plane slot (with depth of 5 mm). Fig. 7(c) shows the relationship between the normalized inverter value and the width of the H-plane septa. The length of the quarter wavelength resonators is given by [25]:

$$ln = \frac{\lambda_{g0}}{2\pi}\left[\frac{\pi}{2} + \frac{1}{2}\left(\phi_j + \phi_{j+1}\right)\right] \tag{9}$$

Thus the initial physical parameters of filter can be determined. The chart for the design process of initial physical parameters of the proposed filter is shown in Fig. 8.

Finally, Ansoft HFSS is used to analyze and optimize the filter after the initial design. To validate the proposed novel partial H-plane filter based on HMSIFW, a four-pole narrowband bandpass filter is designed using a substrate with relative dielectric of 2.22 and thickness

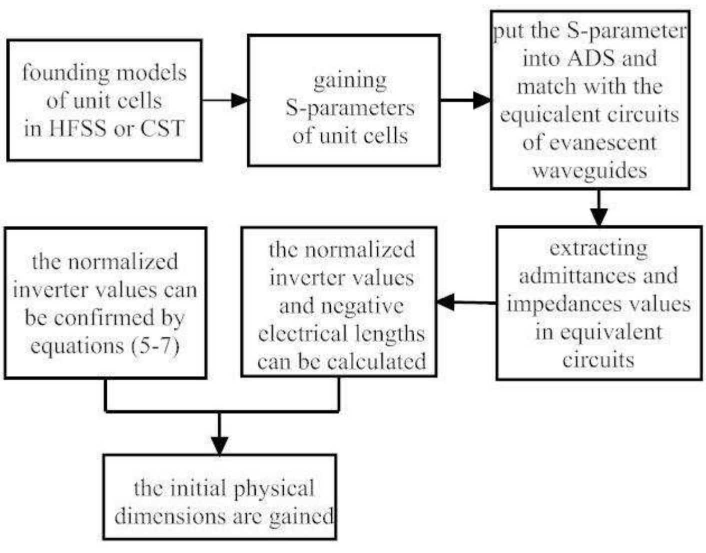

Figure 8. The chart for design process of initial physical parameters.

of 0.254 mm. The specifications for the filter are four-pole, 0.01 dB passband ripple, center frequency $f_0 = 9.97$ GHz, and the fractional bandwidth $\Delta \approx 1\%$ (100 MHz). Ansoft HFSS is used to simulate and optimize the filter after initial design. To enable measurement, a tapered transition to HMSIFW has been developed, as shown in Fig. 6. The geometric dimensions are determined as shown in Table 1.

3. MEASURED RESULTS

The filter is fabricated on a substrate with relative dielectric constant of 2.22 and thickness of 0.254 mm, using standard printed circuit board process. Photograph of the fabricated HMSIFW partial H-plane filter is shown in Fig. 9 (including a pair of test cavities with SMA connectors). The filter is considerably smaller than its metallic waveguide structure filter.

The measurements were taken using Agilent E8363B vector

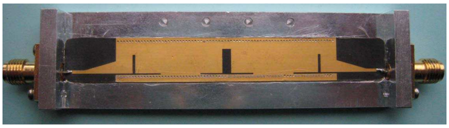

Figure 9. Photograph of the fabricated four-pole HMSIFW partial H-plane filter (including test cavity).

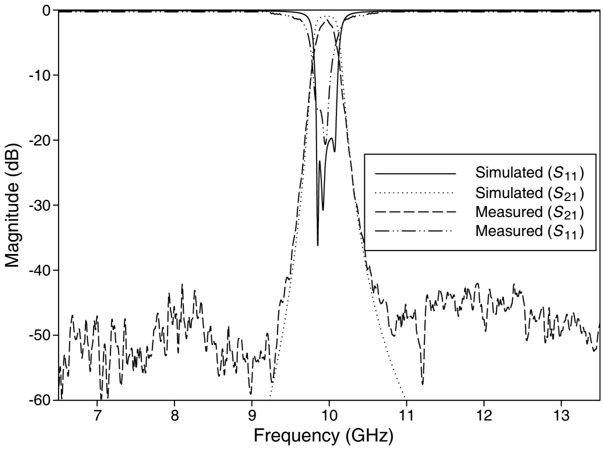

Figure 10. Simulated and measured S parameters of the fabricated four-pole HMSIFW partial H-plane filter.

network analyzer (VNA). The simulated and measured responses of the filter are shown in Fig. 10. It can be seen from Fig. 10 that the operated bandwidth of measurement results is little narrower than that of simulation ones, and insertion loss is higher. These could be attributed to tolerance of manufacture and relativity permittivity, dielectric loss, high order modes, material and radiation loss. In spite of these, the simulated and measured results still have a good agreement. The fabricated filter exhibits 1.5 dB insertion loss at center frequency 9.9725 GHz (including the loss of transitions and the influences of SMA connectors), a 0.5 dB-bandwidth of 80 MHz, and the return loss better than 12 dB. The measured out of band rejection is better than 59 dB and 47 dB at 1 GHz lower and higher separations from the center frequency of 9.9725 GHz. The proposed filter has excellent selectivity, as demonstrated by the stopband rejection.

4. CONCLUSION

A novel HMSIFW and a HMSIFW partial H-plane bandpass filter, with quarter wavelength resonators, have been developed and investigated in this paper. The proposed HMSIFW results in a considerable size reduction compared with metallic waveguide. The proposed filter employs H-plane slot of open-ended evanescent waveguide and H-plane septa of short-ended evanescent waveguide as admittance inverter and impedance inverter, respectively. Furthermore, the filter performances are defined purely in terms of photolithography on a planar layer. Transitions to microstrip-line are demonstrated allowing HMSIFW to be easily integrated with other planar circuits. A four-pole X-band bandpass filter is designed, fabricated, and measured. Sharp skirt characteristic is achieved, and good agreement between the simulated and measured results is presented. The proposed HMSIFW partial H-plane bandpass filter is compact, easy for fabrication, conveniet for integration with planar circuits, and attractive for many applications.

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