Substrate Integrated Folded Waveguide Filter with Out-of-Band Rejection Controlled by Resonant-Mode Suppression

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***Abstract*—This paper presents a new filter, based on substrate integrated folded waveguide (SIFW) technology, which exhibits compact size and good out-of-band rejection. The filter is based on a SIFW cavity, which guarantees size reduction, and the out-of-band rejection is controlled by the suppression and tuning of the high-order cavity modes. A detailed investigation of the cavity mode spectrum is presented, to illustrate the operation principle and the design of the filter. The interesting feature of this filter is the possibility to design the pass band and the return band by simply tuning the mode spectrum of the cavity, which is practically unaffected by the connection to the excitation ports. The fabrication and testing of a prototype operating at 4.5 GHz validate the proposed filter topology.**

***Index Terms*—Filters, Cavity resonators, Substrate integrated waveguide (SIW).**

I. Introduction

THE development of substrate integrated waveguide (SIW) technology in the last decade [1,2] has opened interesting perspective for the implementation of waveguide-like planar components, including filters. A variety of SIW filters has been proposed [2,3], including inline post filters, inductive iris filters, coupled cavity filters, dual-mode filters, wideband filters, and very compact filter topologies [4,5].

The substrate integrated folded waveguide (SIFW), consisting of an SIW folded around a metal septum [6,7], offers additional advantages, as it allows a reduction in width of a factor ranging from 2 to 3, at the cost of adopting a dual-layer topology. Several components in SIFW have been implemented, including some interesting SIFW filter topologies [6,8–10].

This paper presents the design and testing of a band-pass filter in SIFW technology. The design is based on the preliminary investigation of the resonant modes of a SIFW cavity, which is perturbed by the presence of three insets in the inner metal septum (Fig. 1). Subsequently, the filter is obtained by connecting the perturbed SIFW cavity to the exterior by input and output striplines. The presence of the insets permits to modify the resonance frequency of some cavity modes, thus properly locating them in the pass band. Conversely, the stripline ports prevent the excitation of other modes because of symmetry, thus permitting to improve the out-of-band rejection. The proposed perturbed SIFW cavity supports two closely spaced resonant modes: as a result, a more compact two-pole filter can be designed using only one cavity instead of two.

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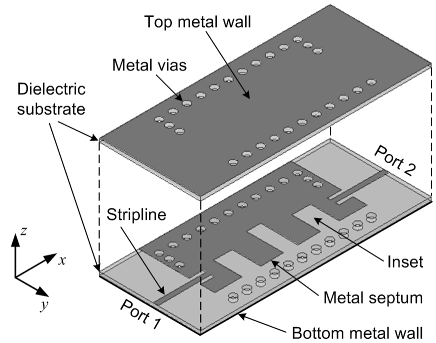

Fig. 1. Geometry of the SIFW filter.

II. Mode Spectrum of the SIFW Cavity

The design of this filter is based on the investigation of the mode spectrum of a SIFW cavity (Fig. 2*a*). The SIFW cavity practically exhibits the same mode spectrum as a standard rectangular cavity, apart from the folding [6]. The resonant modes of this cavity are denoted by three modal indices, in analogy with the standard rectangular cavity (Fig. 2*b*). The fundamental cavity mode is the $TM_{1,1,0}$, where TM refers to the *z* axis (Fig. 1).

The variation of the resonance frequency of the cavity modes is obtained by cutting three identical insets in the central metal septum (Fig. 2*c*). The presence of the insets affects the modes with a strong electric modal field in the gap region, corresponding to the modes with an odd first modal index (e.g., $TM_{1,1,0}$). The other modes, where the first modal index is an even number, are unaffected by the presence and shape of the metal septum, in terms of both resonance frequency and electric modal vector (Fig. 2*d*).

More specifically, the considered SIFW cavity is based on two layers of Taconic TLX-9 dielectric substrate, with relative permittivity ε_r=2.5, loss tangent $\tan\delta$=0.0019, and thickness *h*=0.76 mm. The dimensions of the unperturbed and modified cavities are given in the caption of Fig. 2.

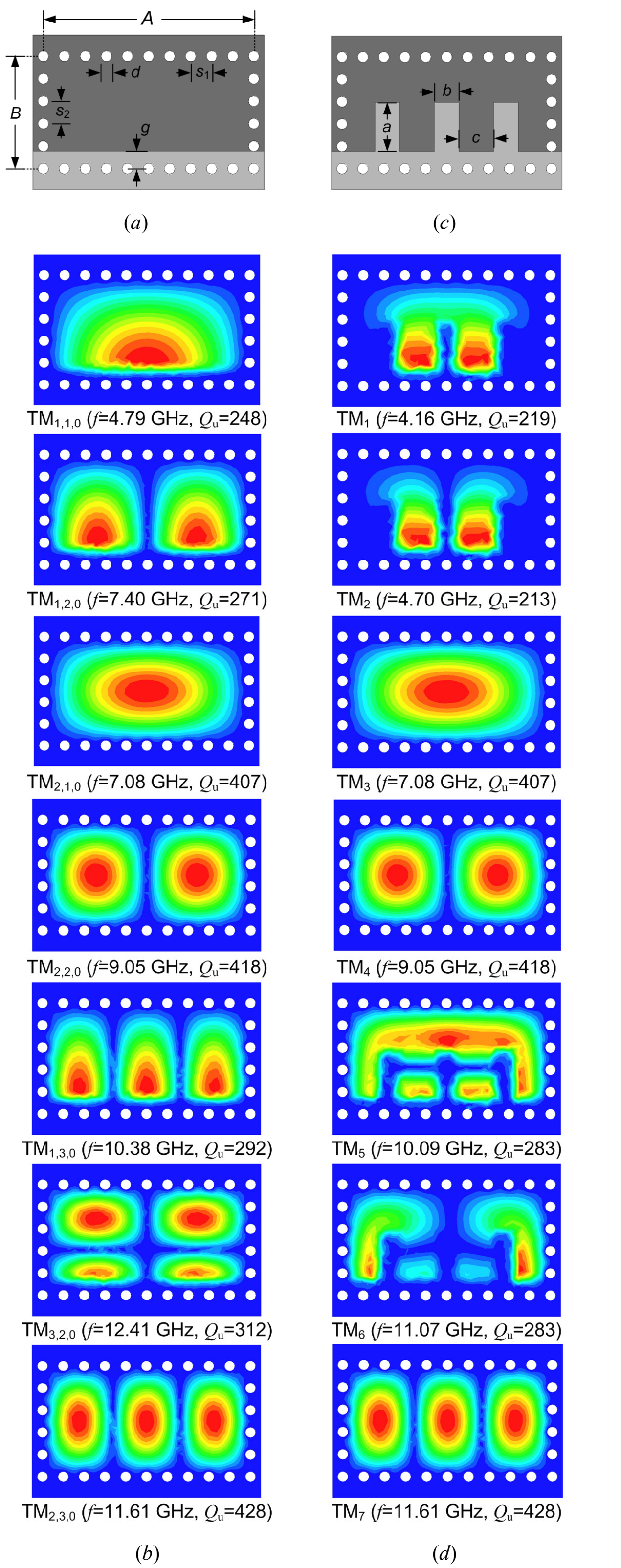

Fig. 2. Mode spectrum of the SIFW and modified SIFW cavities, calculated by using a commercial FEM code, including resonance frequencies f and unloaded quality factors Q_u (dimensions in mm: A=30, B=16, g=2.5, d=1.5, s_1=3, s_2=3.2, a=7, b=3.5, c=5; dielectric substrate with relative permittivity ε_r=2.5, loss tangent $\tan\delta$=0.0019, and thickness of each layer h=0.76 mm): (*a*) geometry of the SIFW cavity; (*b*) amplitude of the electric modal vectors of the SIFW cavity; (*c*) geometry of the modified SIFW cavity; (*d*) amplitude of the electric modal vectors of the modified SIFW cavity.

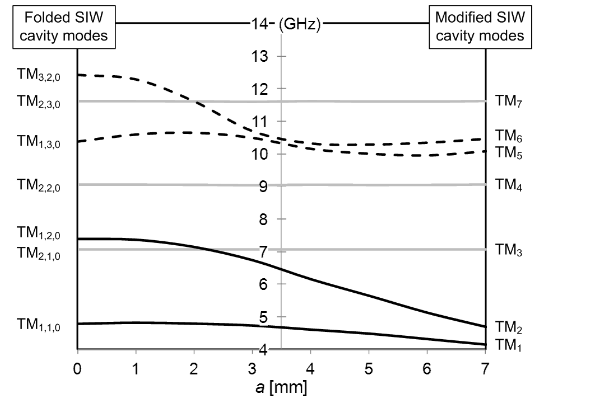

Fig. 3. Variation of the resonance frequency of the modified SIFW cavity modes, versus the penetration depth a of the insets.

Fig. 3 shows the effect of the inset depth a on the resonance frequency of the first seven cavity modes, in the case of three identical insets. The value of a ranges from zero (unperturbed cavity, Fig. 2*a*) to 7 mm (modified cavity, Fig. 2*c*).

The presence of the insets allows modifying the resonance frequency and relative separation of two cavity modes (TM_1 and TM_2, Fig. 2*d*). The fields of these two modes are very concentrated in the insets region, and they resemble the modes of the stripline cavity, obtained by removing the metal vias. Moreover, two other cavity modes (TM_5 and TM_6) are grouped around 10 GHz. Finally, three cavity modes ($TM_{2,1,0}$, $TM_{2,2,0}$, $TM_{2,3,0}$) are unaffected by the insets, as their fields naturally satisfy the electric wall condition on the plane of the metal septum (*xy* plane in Fig. 1).

III. The SIFW Filter

In order to design a band-pass filter, the modified folded SIW cavity is connected to input and output striplines, as shown in Fig. 1. The electric field of the fundamental stripline mode exhibits odd symmetry with respect to the plane of the metal septum. This feature prevents the excitation of some cavity modes (TM_3, TM_4, TM_7, …), which exhibit even symmetry, opposite to the one of the stripline mode. Incidentally, these modes are those unaffected by the presence of the insets. In the resulting filter, the pass band is determined by the two modes resonating around 4.5 GHz (TM_1 and TM_2, Fig. 2*d*) and the return band is determined by the two modes resonating around 10 GHz (TM_5 and TM_6).

Subsequently, the filter frequency response was optimized for operation around 4.5 GHz, with relative bandwidth of 10%. The geometry of the resulting filter is shown in Fig. 4*a*. The frequency response of the filter in terms of scattering parameters was computed by using a commercial finite element solver, and is shown in Fig. 5*a*.

A prototype of the filter was fabricated by milling machining (Fig. 4*b*). The two dielectric layers are connected by using TacBond bonding film (except a few millimeters near the stripline ports, where the connectors are mounted as shown in Fig. 4*c*). The metal vias are implemented by using a conductive paste. The measured scattering parameters of the filter are shown in Fig. 5*a*, compared with simulation results.

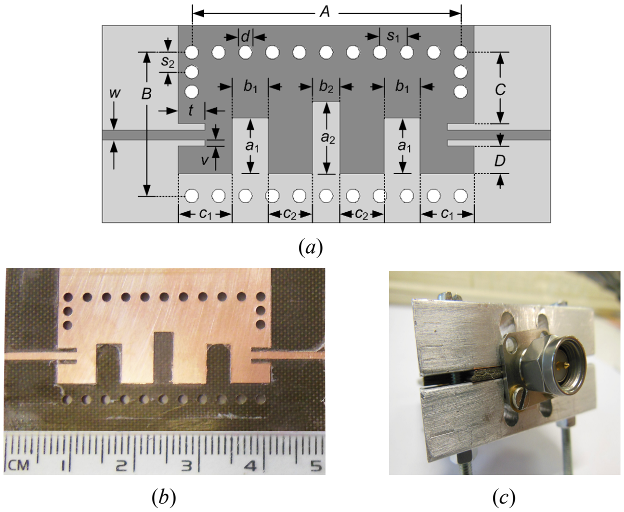

Fig. 4. Prototype of the SIFW filter: (*a*) geometry of the filter (dimensions in mm: A=30, B=16, C=7.95, D=3.05, d=1.5, s_1=3, s_2=2.2, a_1=6.2, a_2=8, b_1=4, b_2=3.2, c_1=6, c_2=4.95, w=1.1, t=3, v=0.7; dielectric substrate with relative permittivity ε_r=2.5, loss tangent $\tan\delta$=0.0019, and thickness of each layer h=0.76 mm); (*b*) photograph of the fabricated prototype (dielectric layer with the metal septum); (*c*) photograph of the measurement setup.

As expected, the filter exhibits two poles, corresponding to the first two cavity modes (TM_1 and TM_2), and the out-of-band rejection is guaranteed by the suppression of all cavity modes up to TM_5, due to the stripline port excitation. The size of the filter is quite compact, corresponding to $0.45\lambda_0 \times 0.24\lambda_0$, where λ_0 is the wavelength in vacuum at 4.5 GHz.

As an interesting feature of this filter, the connection to the input/output striplines does not practically affect the cavity mode spectrum, being the only practical effect on the input matching of the filter (a sensitivity study is shown in Fig. 5*b*). This is demonstrated in Table I, which compares the resonance frequencies of the four relevant modes of the cavity shown in Fig. 4*a* (closed with SIW walls) and the four poles of the filter frequency response (two in the pass band and two in the return band). This feature is useful to design the filter by tailoring the cavity mode spectrum.

IV. Conclusion

This paper has presented the proof of concept of a novel filter in substrate integrated folded waveguide. The filter is based on a folded cavity, with properly designed insets in the metal septum, which permit to tune two closely spaced resonant modes in the pass band. The reject band is enhanced by suppressing some cavity modes, thanks to stripline excitation. While the first two modes, that define the pass band, are similar to stripline modes, the presence of the SIW cavity plays a key role in the out-of-band mode suppression.

TABLE I
Cavity Resonance Frequencies vs Filter Poles

mode	Resonance frequencies of the final cavity	Poles of filter frequency response
TM_1	4.26 GHz	4.31 GHz
TM_2	4.62 GHz	4.65 GHz
TM_5	10.12 GHz	10.24 GHz
TM_6	10.49 GHz	10.67 GHz

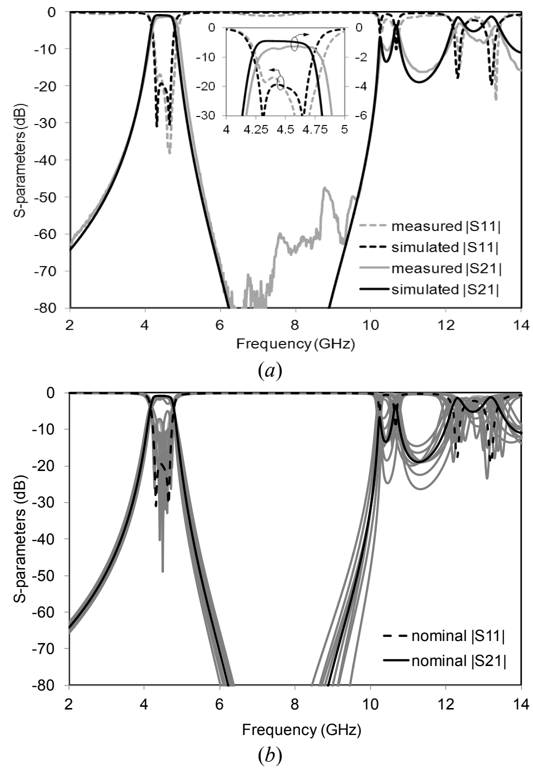

Fig. 5. Frequency response of the SIFW filter: (*a*) scattering parameters of the filter; (*b*) sensitivity study of the input/output coupling, showing the frequency response with nominal values of the geometrical dimensions (black lines) and with values of t and D (Fig. 4*a*) randomly changed of ±0.5 mm (gray lines).

A prototype of a dual band filter at 4.5 GHz has been reported, to demonstrate the feasibility of the proposed approach.

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