Staggered Filter Topology for Robust Fabrication of Air-Filled Substrate-Integrated-Waveguide Filters

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***Abstract*—In this work, a novel air-filled substrate-integrated waveguide (AFSIW) filter topology is proposed to overcome the challenges of AFSIW printed circuit board (PCB) fabrication by eliminating small protrusions and feature sizes. The topology is further enhanced with a coupling slot to improve the out-of-band rejection by 20 dB. A prototype covering the n257 (26.5 GHz-29.5 GHz) band is synthesized, fabricated and measured to validate the topology, demonstrating its applicability at millimeterwave (mmWave) frequencies with a measured insertion loss of 2.7 dB and out-of-band rejection of over 30 dB.**

***Index Terms*—air-filled substrate-integrated-waveguide (AFSIW), filter, mmWave, sub-terahertz, PCB manufacturing, Staggered filters**

I. Introduction

With the ongoing development of millimeterwave (mmWave) applications, there is an increasing need for cost-effective, high-quality (Q) filters with high-power handling and steep roll-off. Many filter topologies exist based on substrate-integrate-waveguide (SIW) technology, leading to a reliable class of filters resistant to interference effects with little radiation leakage [1], [2]. This makes them attractive for mmWave antenna systems, requiring tight filter integration with electronics and multiple compact antennas. Even higher Q-factors and improved power handling capability can be achieved by removing the dielectric inside the resonant cavities, leading to the air-filled substrate-integated-waveguide (AFSIW) technology [3], [4].

Owing to their similarities, topologies of SIW-cavity based filters can theoretically be translated to AFSIW by adjusting their dimensions taking into account the reduced dielectric constant. Yet, most of these topologies require coupling irises that, due to the lack of a mechanically stabilizing dielectric, lead to long, thin metal protrusions, which are very sensitive to mechanical stress when employing stacked printed circuit board (PCB) AFSIW technology. This limits the use of AFSIW filters to more expensive technologies such as silicon micromachining waveguide technology and 3D-printing [5], where these protrusions can remain connected to the surrounding metal layers.

This work improves the mechanical stability of coupled-cavity-based AFSIW filters by proposing a staggered filter topology. The cavity resonators of the filter are coupled by staggering the neighboring cavities to create narrow coupling irises, hereby eliminating thin metal protrusions. Additionally, a transversal coupling slot is employed to suppress spurious modes present in the staggered filter topology, leading to high-performance, low-loss designs, suitable for implementation in low-cost platforms such as PCB. The topology is showcased in this work by designing, manufacturing and validating a 26.5 GHz-29.5 GHz filter prototype aiming to cover the 5G n257 band.

Section II outlines the topology of the staggered filter and its operating principle. In section III, a 6th order filter prototype is designed, constructed and measured to validate the staggered filter topology. Finally, section IV summarizes the findings of this article. All simulations are performed using CST Studio Suite.

II. Staggered Filter Topology with transversal coupling slot

When implementing AFSIW structures cost-effectively in standard PCB technology, air-filled cavities are constructed by judiciously milling cavities in a two-layer PCB and implementing sidewalls by edge-plating or via walls [6], [7] and closing the AFSIW structure by copper sheets or additional single-layer or two-layer PCBs. Directly translating the SIW-based iris-coupled filter topology [1], [2] to AFSIW technology leads to the milled and edge-plated PCB shown in Fig. 1a [3], [4]. Often, the protrusions that create the irises must be made thin to obtain the coupling required for a desired filter characteristic, leading to mechanical instability and breakage. Furthermore, good contact between the protrusions, and top and bottom cavity wall is not always ensured, leading to improper filter operation.

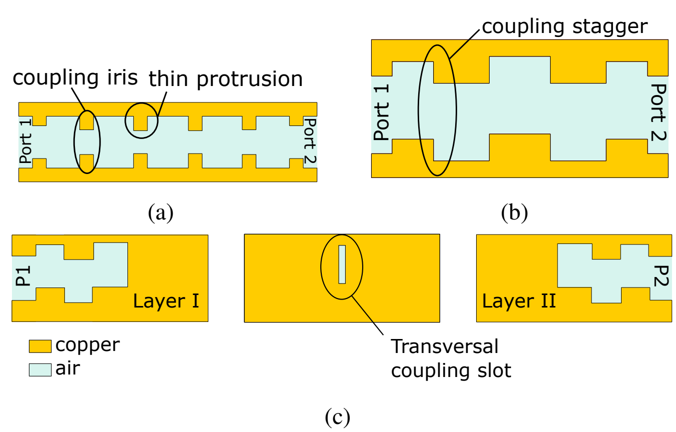


Fig. 1: (a) Non-produceable iris-coupled filter topology, (b) proposed solution with staggered coupling and (c) proposed staggered topology with staggered coupling and transversal coupling slot to enhance out-of-band rejection.

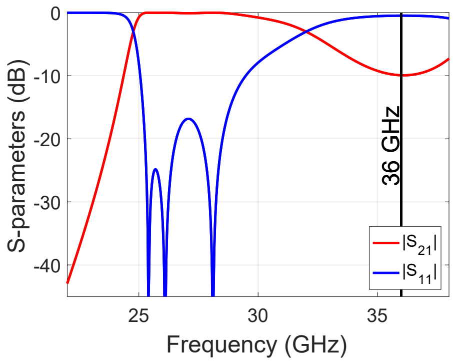
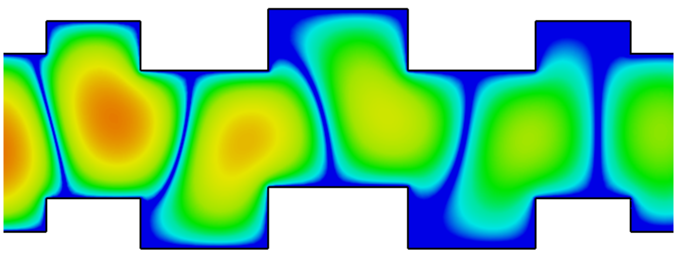
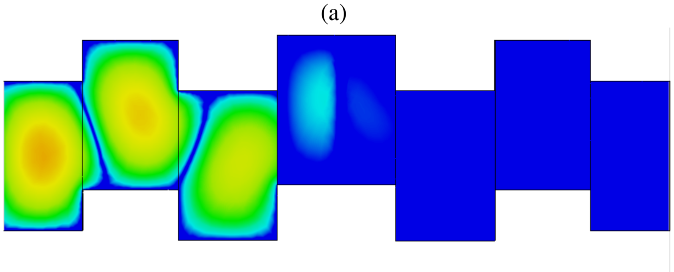


Fig. 2: Simulated results of a staggered filter design example.



(a)



(b)

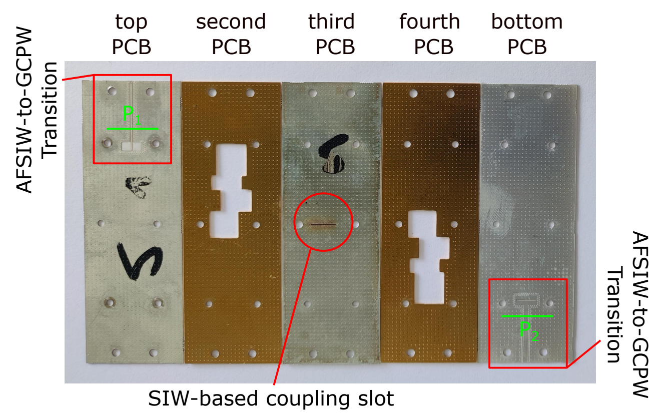
Fig. 3: (a) Staggered filter example as in Fig. 2 and (b) slot-enhanced staggered filter prototype excited by a TE_{10}-mode at 36 GHz.

An initial solution to this problem is presented by the topology shown in Fig. 1b. Here, the coupling irises are replaced by a stagger between adjacent cavities. This topology requires no protrusions or small features, making it much more robust and ideal for cost-effective implementation in standard PCB technology. Yet, the simulated S-parameters of the staggered filter prototype in Fig. 2 indicate that the high-pass behavior of the staggered filter topology is rather poor. Since the staggered filter structure starts resembling that of a regular bent waveguide structure as the operating frequency increases, undesired transmission of spurious modes occurs. As such, the topology shown in Fig. 1b cannot be used effectively as a bandpass filter.

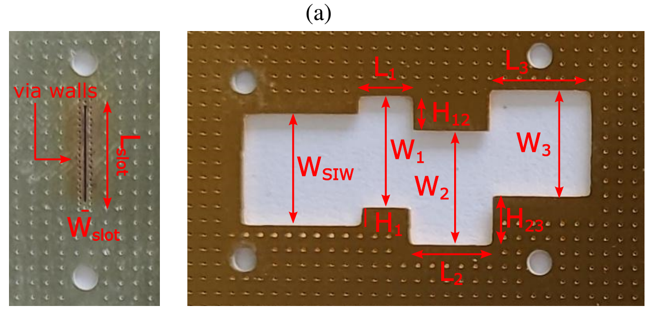
This problem is eliminated by including a single coupling slot, which is implemented vertically in the top/bottom walls of adjacent cavities, leading to a dual-layer filter topology as shown in Fig. 1c. This inclusion effectively suppresses the spurious mode of the staggered filter resulting in the improvement illustrated in Fig. 3. No small metalized protrusions are required to manufacture this enhanced topology, such that it can be easily produced in standard PCB technology and scaled to higher operating frequencies.

III. Design and Results

The slot-enhanced staggered filter topology is validated by a prototype filter that is designed, optimized and manufactured for a target bandwidth of 26.5 GHz-29.5 GHz, covering the n257 mmWave-band [8]. The filter is constructed by stacking five two-layer PCBs with a 254-μm-thick ROGERS 4350B laminate patterned using standard PCB processes. The fabricated prototype is shown in Fig. 4.



(a)



(b)

Fig. 4: Slot-enhanced staggered filter prototype realized in PCB technology.: (a) PCB layers of the prototype and (b) inset of the coupling slot and milled cavities.

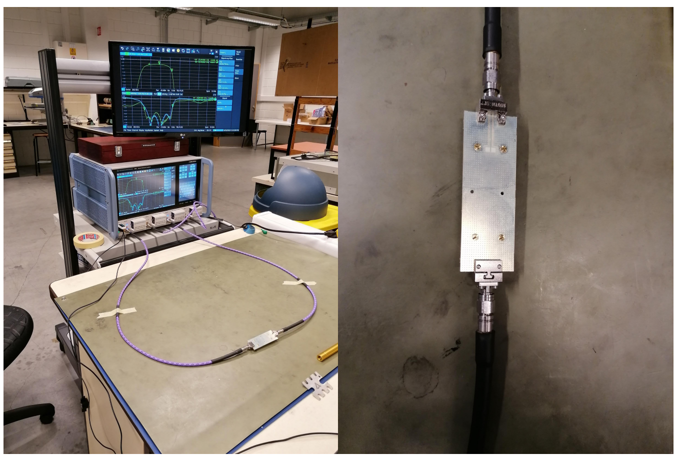
TABLE I: Dimensions of the prototype filter as shown in Fig. 4

parameter	[mm]	parameter	[mm]
L_1	3.6	W_{SIW}	7.5
W_1	7.5	H_1	1.3
L_2	5.5	H_{12}	2.375
W_2	7.65	H_{23}	3.425
L_3	6.8	L_{slot}	6.65
W_3	7.1	W_{slot}	0.2

The top and bottom PCB close the waveguide and contain the feed structure of the AFSIW filter, including a grounded co-planar waveguide (GCPW)-to-AFSIW transition, enabling connectorized measurements. The second and fourth PCB contain the milled cavities, which are edge plated after milling. Finally, the middle PCB contains the slot. The slot in the third PCB (Fig. 4) is enclosed by an SIW via cavity and the dielectric is removed by a laser. The dimensions of the filter are given in Table I. For the measurements, Southwest $1.85\,\mathrm{mm}$ connectors and a TRL calibration up to the port planes annotated in green on Fig. 4 are employed. The external loading vector and coupling matrix are given by

$$Q_e = \begin{bmatrix} 3.9 \\ 3.9 \end{bmatrix}, \tag{1}$$

$$M = \begin{bmatrix} 0 & 0.443 & 0 & 0 & 0 & 0 \\ 0.443 & 0 & 0.206 & 0 & 0 & 0 \\ 0 & 0.206 & 0 & 0.471 & 0 & 0 \\ 0 & 0 & 0.471 & 0 & 0.206 & 0 \\ 0 & 0 & 0 & 0.206 & 0 & 0.443 \\ 0 & 0 & 0 & 0 & 0.443 & 0 \end{bmatrix}. \tag{2}$$

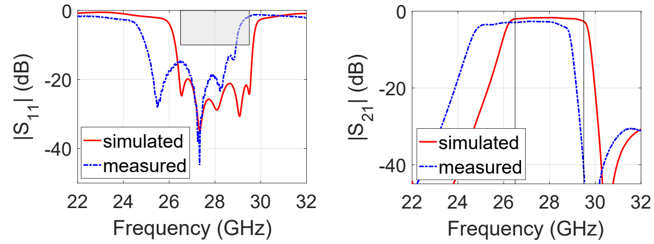


(a) (b)

Fig. 5: (a) Measurement setup and (b) assembled and connectorized prototype.

The simulation and measurement results are shown in Fig. 6. The simulated filter indeed operates with a -10 dB-impedance match from 26.5 GHz-29.5 GHz with an in-band insertion loss of 1.7 dB, illustrating the validity of the proposed filter topology. Additionally, note the steep roll-off behind the passband, which is present only when the coupling slot is included in the design.

The measured results agree well with simulation, albeit with a slight downward shift in frequency. The frequency shift is caused by overmilling, resulting in longer cavities than designed, which can be compensated for in the next production run. The measured in-band insertion loss is 2.7 dB, which is also slightly higher compared to simulation. This is caused by undesired leakage through the air gaps between the stacked PCB layers. This can be solved by including electromagnetic bandgap structures [9], which will further improve the efficiency of the proposed filter in the next production run.



(a) (b)

Fig. 6: Simulated and measured scattering parameters of the staggered filter prototype: (a) reflection coefficient and (b) transmission coefficient.

IV. Conclusion

In this paper, a new air-filled substrate-integrated-waveguide filter topology for millimeterwave applications is presented. The topology enables cost-effective manufacturing by employing a novel staggered filter cavity coupling technique, leading to excellent mechanical stability. The filter topology is validated with a 6th order mmWave prototype, which is designed and fabricated showing good filtering properties, a measured insertion loss of 2.7 dB and out-of-band rejection of over 30 dB ensured by the inclusion of the coupling slot. Additional results and design insights regarding the staggered cavity coupling will be presented during the conference.

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