

Miniaturized Bandpass Filter Using the Metamaterial Half-Mode Technique for Substrate Integrated Waveguide

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Abstract – In this paper, a half-mode evanescent substrate integrated waveguide (SIW) bandpass filter is proposed. The proposed filter operates below the cutoff frequency of the conventional SIW by adopting the metamaterial technique. The operating frequency of the full-mode substrate integrated waveguide (FM-SIW) is 2.2 GHz, while the cutoff frequency of the conventional SIW structure is 5.2 GHz. Fractal slots are cut from the broad wall of the SIW. First-, second-, and third-order bandpass filters are designed, simulated, fabricated, and experimentally validated using a vector network analyzer. The metamaterial technique achieves a miniaturization of about 60% relative to the conventional SIW structure, and the responses are compared with those of its FM-SIW counterpart, with no obvious difference observed. The half-mode SIW (HM-SIW) technique is then used to achieve further miniaturization of about 50% relative to the original FM-SIW structure. The measured one-stage filter covers the 2.4 GHz ISM band with an insertion loss of about 1.2 dB and a return loss of about 40 dB, and cascading additional unit cells is shown to sharpen the filter's selectivity while preserving close agreement between simulation and measurement. Finally, the simulation and measurement results agree well with other work in the literature.

Keywords – bandpass filter, fractal slot, half-mode substrate integrated waveguide (HM-SIW), metamaterial, substrate integrated waveguide (SIW)

1. Introduction

Since the turn of the century, a transmission-line structure known as the full-mode substrate integrated waveguide (FM-SIW) has emerged. Over the last decade this concept has been widely adopted, since it enables fabrication of low-cost, highly efficient microwave and millimeter-wave circuits. By replacing the side walls of a conventional waveguide with two rows of metallic vias [1], this technique brings the capabilities of a traditional air-filled rectangular waveguide to a printed circuit board (PCB). FM-SIW combines several benefits of microstrip technology — small size, simple integration, low radiation loss, high quality factor (Q-factor), and high power handling. Well-known equations govern the physical structure of the FM-SIW as a transmission line, including the propagation mode, the transmission-line width, and the diameter of the copper vias, as detailed in [2]. The half-mode substrate integrated waveguide (HM-SIW) is obtained by dividing the FM-SIW structure into two halves; each half retains the same propagation characteristics as the FM-SIW. The HM-SIW structure has also been widely used to build microwave circuits [3]. Moreover, fabrication difficulty remains the same as for the FM-SIW, while retaining the same benefits of low loss, small size, and high Q-factor. Many filters have been reported based on the HM-SIW since its introduction [4, 5, 6]. Studies on the HM-SIW

show that this alternative to the FM-SIW can reduce the original width by around 50% while preserving the same cutoff frequency and propagation properties, and HM-SIW designs have been widely used to build filters and other microwave circuits [7]. In addition, composite right/left-handed (CRLH) transmission-line theory has been extended to FM-SIW and HM-SIW guides, enabling further miniaturization through operation below the cutoff frequency of either structure [8]; many microwave circuits based on CRLH FM-SIW and CRLH HM-SIW have since been successfully investigated [8]–[10]. In this paper, the FM-SIW structure is introduced first, operating as a highpass filter with a cutoff frequency of 5.2 GHz; its upper layer is then loaded with fractal slots so that it operates below the cutoff frequency of the original design. The overall structure is then divided horizontally in half to obtain an HM-SIW bandpass filter using the same metamaterial fractal slot, retaining the same cutoff frequency and the same advantages as the FM-SIW.

2. Design Procedure

2.1. Designing the FM-SIW

The design uses an FR4 substrate with a dielectric constant of 4.3. All three layers are drilled to accommodate copper vias, which pass through the structure and connect

electrically to the upper and lower layers on both sides. All dimensions of the design are determined using the parameters shown in Figure 1 and the five basic equations governing the FM-SIW structure, which depend on the material used and the required cutoff frequency; the target is a highpass filter with a cutoff frequency around 5.2 GHz.

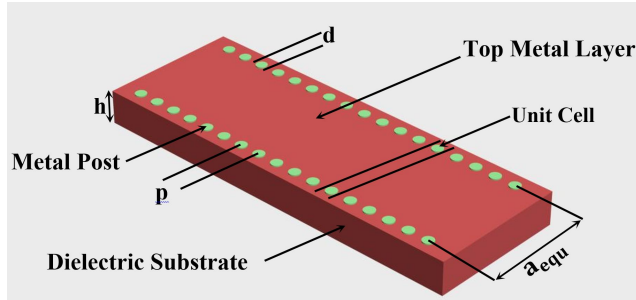


Fig. 1 SIW structure.

Here, h is the thickness of the substrate, d is the diameter of the copper vias, p is the center-to-center distance between adjacent vias, and a_{equ} is the center-to-center distance between the two rows of vias on either side of the FM-SIW unit cell.

$$f_c = c / (2 a_{equ} \sqrt{\epsilon_r}) \quad (1)$$

The resulting cutoff frequency is the same as that of the equivalent conventional rectangular waveguide. Equation (1) can be rewritten as follows to calculate a_{equ} :

$$a_{equ} = c / (2 f_c \sqrt{\epsilon_r}) \quad (2)$$

The via diameter d and the via pitch should be chosen according to Equation (3) to reduce leakage losses in the SIW and ensure physical reliability [11]:

$$d < p \quad (3)$$

Considering fabrication constraints — manufacturing time, feasibility, and complexity, which depend on the number of vias — the via pitch should satisfy the following condition, where the pitch should not exceed 20% of the guided wavelength [11]:

$$0.05 < p / \lambda_c < 0.25 \quad (4)$$

The center-to-center distance between the vias on the side rows, a , can be found from Equation (5) [11]:

$$a = a_{equ} + d^2 / (0.95 p) \quad (5)$$

After the overall calculation, the proposed design was obtained using the Advanced Design System (ADS) solver, as shown in Figure 2.

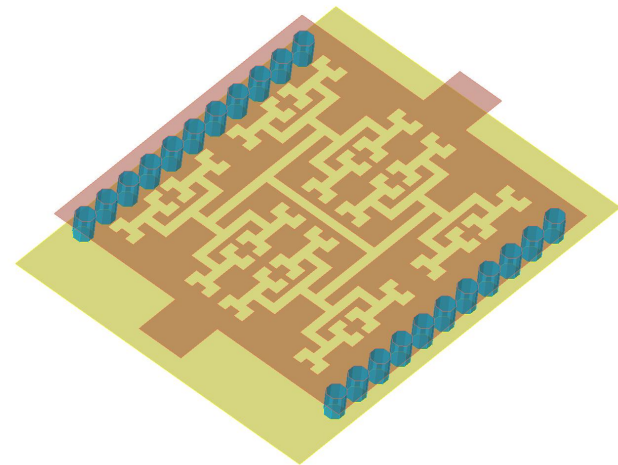


Fig. 2 Simulated FM-SIW layout (length 22 mm, width 17 mm; via diameter $d = 1$ mm, via pitch $p = 1.5$ mm, row-to-row spacing $a_{equ} = 15$ mm).

2.2. Fractal-Slot Loading

The fractal slot is etched into the top metal layer of the FM-SIW to achieve the first stage of miniaturization using the metamaterial technique, as shown in Figures 2 and 3. The filter then behaves as a bandpass filter, operating below the cutoff frequency, with the center frequency reduced to about 60% of the original SIW cutoff frequency prior to loading the metamaterial fractal slot.

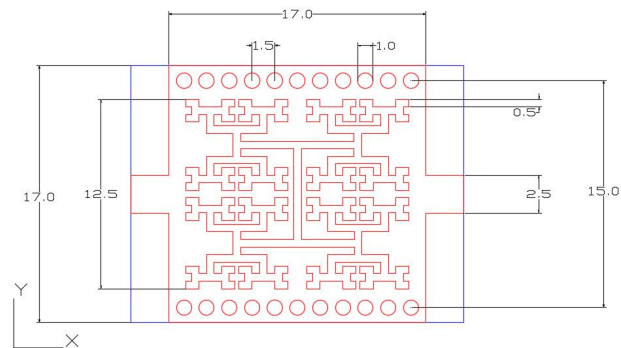


Fig. 3 Dimensions of the SIW fractal unit cell for the required cutoff frequency.

2.3. HM-SIW

The overall structure is divided exactly in half to achieve a second stage of miniaturization, reducing the size to 50% of the original FM-SIW size, as shown in Figure 4; no obvious difference in cutoff frequency is observed between the FM-SIW and the HM-SIW. The filter is then loaded with the fractal slot, as shown in Figure 5, so that it operates below the cutoff frequency and achieves a bandpass response at the required frequency band, excited by the TE_{0.5,0} mode, while retaining the same characteristics as the FM-SIW filter before partitioning.

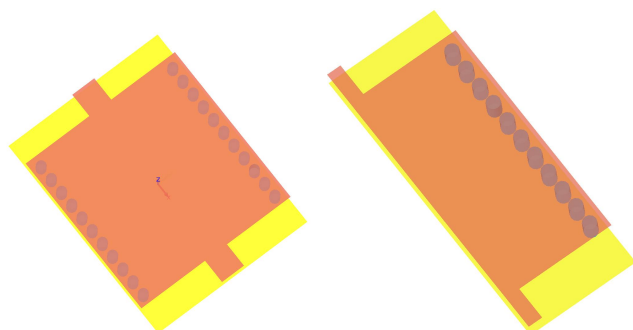


Fig. 4 Conventional FM-SIW and HM-SIW structures.

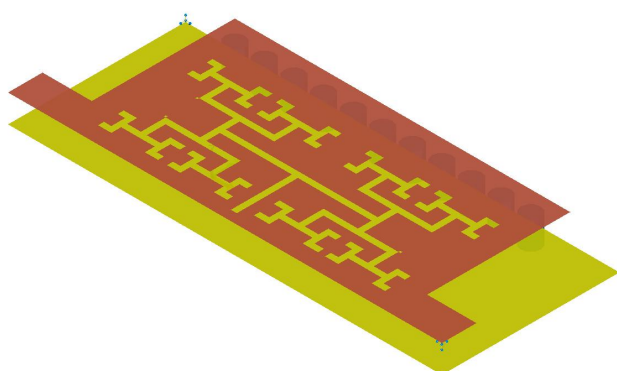


Fig. 5 Fractal curve loaded on the HM-SIW.

3. Results and Discussion

The simulation results, extracted using the Advanced Design System (ADS) solver, give a cutoff frequency of 5.2 GHz, as shown in the scattering-parameter plot (S11 and S21) in Figure 6, where the cutoff frequency lies in the same region for both the FM-SIW and the HM-SIW, confirming a size reduction of about 50% relative to the original FM-SIW structure.

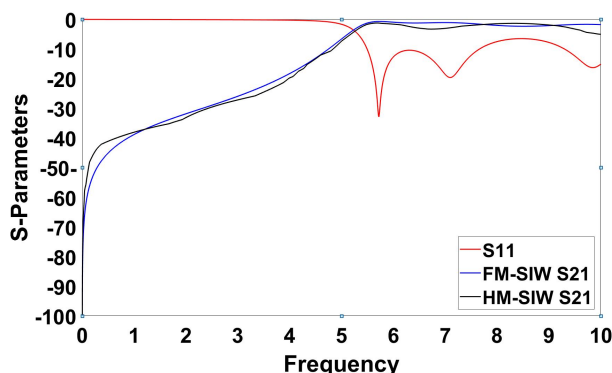


Fig. 6 Comparison of the frequency response of the FM-SIW and the HM-SIW.

Figure 7 shows how the bandpass response is achieved below the cutoff frequency, at an operating frequency of 2.2 GHz, with low radiation losses — the second-stage miniaturization of about 60% relative to the original size, achieved through

the metamaterial effect of the fractal slots together with the modified dielectric characteristics.

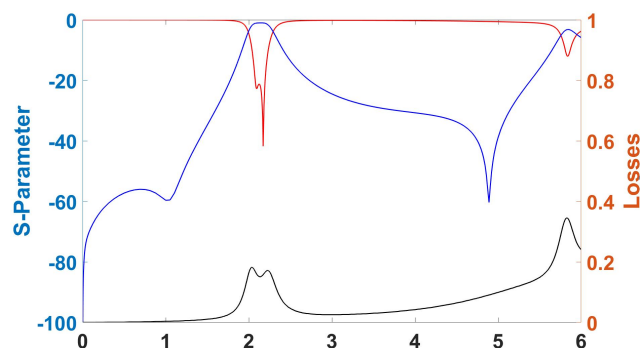


Fig. 7 Frequency response of the FM-SIW metamaterial filter (red and blue lines) together with the losses (black line).

Figure 8 shows that both forward and backward propagation are achieved: in the left-highlighted region both permittivity and permeability become positive, and in the right-highlighted region both become negative, whereas before the fractal loading the permittivity was negative — characteristic of the SIW — and the permeability was positive.

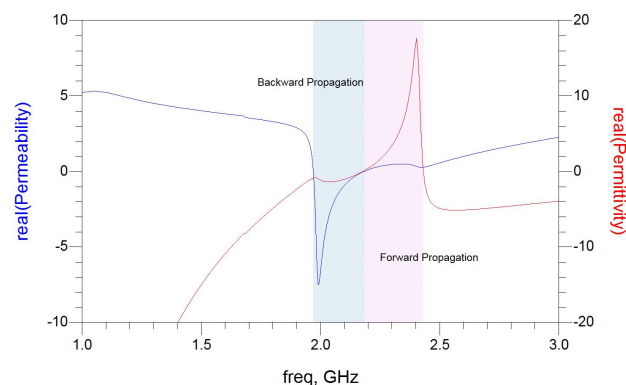


Fig. 8 Permittivity and permeability of the FM-SIW metamaterial filter, showing the propagation regions.

Figure 10 shows the frequency response of the HM-SIW structure shown in Figure 9, demonstrating that it remains at the same cutoff frequency while the filter size is reduced to half that of the original FM-SIW metamaterial filter.

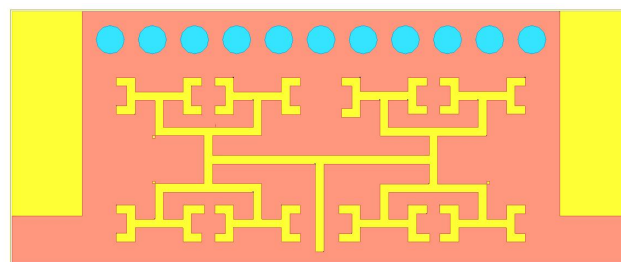


Fig. 9 HM-SIW structure.

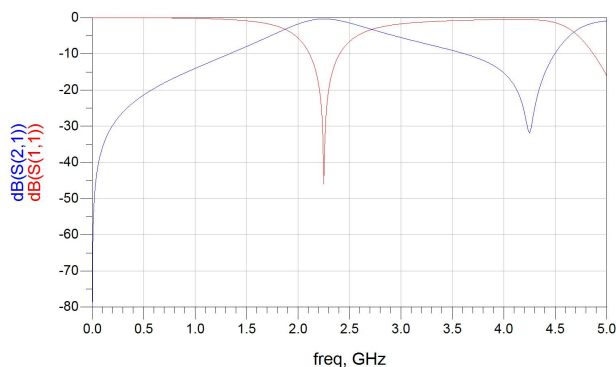


Fig. 10 Frequency response of the HM-SIW structure.

4. Fabrication, Measurement, and Extension to Higher-Order Filters

To validate the design and to demonstrate its scalability, the proposed HM-SIW bandpass filter concept was fabricated in three configurations — a one-stage, a two-stage, and a three-stage cascaded unit-cell filter — using the conventional PCB process on an FR4 substrate with a relative permittivity of 4.3 and a thickness of 1.5 mm, and tested using a vector network analyzer (VNA). Figure 11 shows the fabricated prototypes.

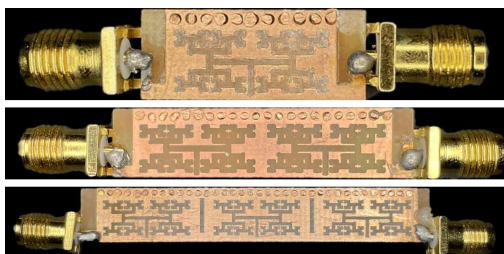


Fig. 11 Fabricated prototypes of the proposed HM-SIW bandpass filters: one-stage (top), two-stage (middle), and three-stage (bottom).

Figure 12 compares the measured and simulated S-parameters for each configuration. For the one-stage filter, shown in Figure 12(a), the passband extends from about 1.9 GHz to 2.7 GHz, covering the 2.4 GHz ISM band, with a measured insertion loss of about 1.2 dB and a return loss of about 40 dB at resonance, in close agreement between simulation and measurement; the rejection improves to better than 40 dB beyond 4 GHz.

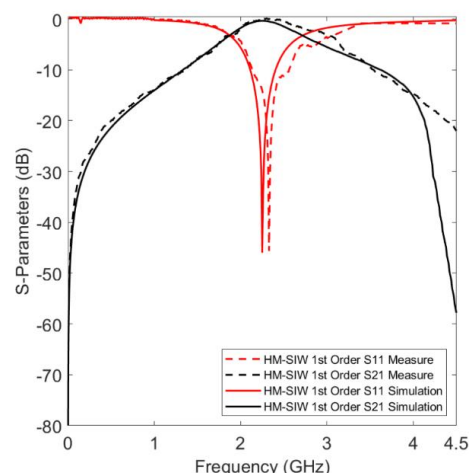


Fig. 12(a) Measured and simulated S-parameters of the one-stage HM-SIW filter.

Cascading two and three of the same HM-SIW metamaterial unit cells, shown in Figure 12(b) and Figure 12(c), introduces additional transmission zeros close to the passband edges, which sharpens the rejection skirts and improves selectivity while keeping a similar center frequency and comparable insertion and return losses. As the filter order increases, the passband becomes flatter and the roll-off becomes sharper, at the expense of a longer physical structure.

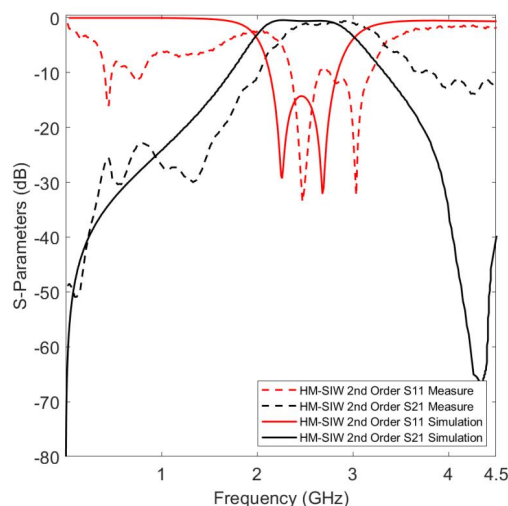


Fig. 12(b) Measured and simulated S-parameters of the two-stage HM-SIW filter.

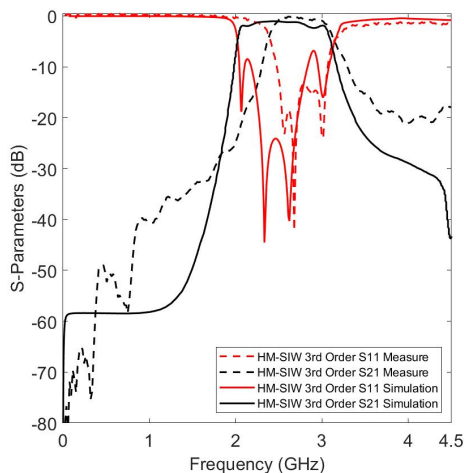


Fig. 12(c) Measured and simulated S-parameters of the three-stage HM-SIW filter.

Figure 13 compares the simulated responses of the one-, two-, three-, and five-stage HM-SIW filters together, confirming that the proposed unit cell is readily scalable to higher orders: the reflection coefficient develops additional ripples and the transmission skirt steepens progressively with order, while the center frequency remains close to 2.2–2.5 GHz across all configurations.

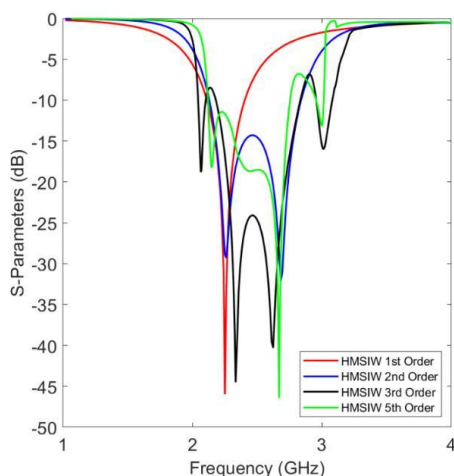


Fig. 13(a) Simulated reflection coefficient (S11) of the 1st-, 2nd-, 3rd-, and 5th-order HM-SIW filters.

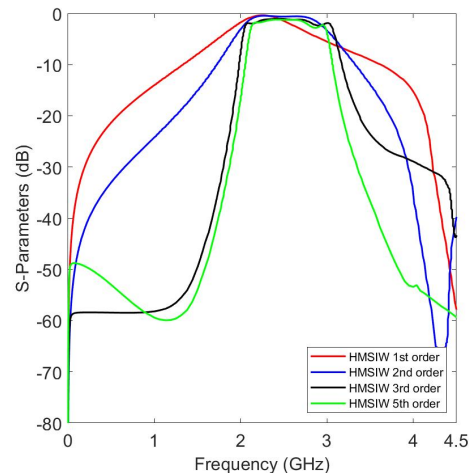


Fig. 13(b) Simulated transmission coefficient (S21) of the 1st-, 2nd-, 3rd-, and 5th-order HM-SIW filters.

5. Conclusion

This work demonstrated a compact bandpass filter built on a half-mode substrate integrated waveguide loaded with metamaterial fractal slots. The slots allow the guide to pass a band well below its natural 5.2 GHz cutoff, and halving the structure reduces its footprint by a further 50% without degrading the response. Extracted permittivity and permeability confirm the metamaterial behavior, with forward- and backward-wave regions appearing next to each other. Prototypes of one, two, and three cascaded stages were built on FR4 and measured; their responses match the simulations closely, and adding stages steepens the band edges while leaving the center frequency and losses nearly unchanged. Combining a small size, a simple single-layer PCB process, and low loss, the proposed filters are well suited to compact wireless front ends.

Conflicts of Interest

The authors declare no competing interests related to this work.

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