Compact Half-Mode Substrate Integrated Waveguide Bandpass Filter Using Spoof Surface Plasmon Polaritons

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Abstract - *In this paper, a half-mode substrate integrated waveguide (HMSIW)-based bandpass filter (BPF) with a hollow bowtie-shaped spoof surface plasmon polariton (SSPP) structure is proposed. In the proposed design, the lower cut-off frequency is primarily determined by the HMSIW dimensions, while the upper cut-off frequency is effectively regulated by the hollow bowtie-shaped SSPP grooves. With a center frequency of 7.45 GHz and FBW of 51.3%, the filter operates from 5.54 to 9.36 GHz. It achieves a stopband rejection over 42.5 dB from 9.76 GHz to 14.42 GHz, a return loss greater than 12 dB across the passband, and an insertion loss of 0.34 dB at the center frequency (fc). The proposed BPF's overall size of 0.72λg × 2.32λg, makes it ideal for C- and X-band wireless applications.*

Key Words: **Half-mode substrate integrated waveguide, hollow bowtie-shaped spoof surface plasmon polaritons, bandpass filter and compact design.**

1. INTRODUCTION

In modern microwave and millimeter-wave communication systems, filters play a crucial role by allowing desired frequencies to pass while blocking unwanted and interfering signals improving signal integrity and the performance of an overall system in various applications such as radar, satellite communications, and high-frequency wireless systems. [1]. The spoof surface plasmon polaritons (SSPPs) are widely used in modern microstrip implementations to improve selectivity, reduce size, and increase out-of-band rejection [2]. Among all these microwave filters, band-pass filters are crucial to modern wireless communication systems because they allow only the desired frequency band to pass while rejecting undesired signals [3]. Many technologies such as metallic waveguides, coplanar waveguides (CPW), microstrip lines, coupled-line topologies, slot-based structures, and Substrate Integrated Waveguide (SIW) are used to implement Microwave filters. Among these many technologies, metallic waveguides require different design considerations in terms of size, selectivity, insertion loss, difficulty integrating with planar circuits, and overall system performance [4]. The SIW technology was introduced to address the limitations which effectively simulate the behavior of a conventional rectangular waveguide by using two parallel rows of metallic vias in a dielectric substrate [5]. The design equations and operational characteristics of SIW, including the calculations of effective widths, lengths, and cut-off frequencies were provided by recent research in this field [6] and [7], which provides an extensive analytical framework for SIW-based microwave component design. By successfully integrating SSPP and SIW in compact modern microwave filtering applications, recent hybrid SIW–SSPP bandpass filter designs have demonstrated enhanced performance by achieving wider bandwidth, improved selectivity, and superior out-of-band rejection [8]. The HMSIW can be created from a traditional SIW by dividing it in half through one of its magnetic walls, to achieve reduction in size and enhance integration with planar circuits, which will typically provide a reduction in the component's size of about 50% [9]. The dumbbell-shaped SSPP is integrated into a SIW structure. In addition to being compact, the carefully designed hybrid structure achieves a high level of mounting suppression [10]. The groove depth controls the cutoff frequency and field confinement of the SSPP structure. SSPP structures provide strong electromagnetic confinement and compact size, while SIW offers low loss and good power handling capability [11]. By combining the advantages of both structures, hybrid SIW-SSPP technology offers an effective method for realizing compact and high-performance microwave and millimeter-wave components [12]. The hybrid HMSIW-SSPP slow-wave structure approach successfully creates band-pass behavior with reduced size and strong confinement while improving effective electrical length without increasing physical size [13]. By adjusting the dispersion characteristics of periodic structures, compact SSPP-based bandpass filters have been developed to achieve wide bandwidth along with enhanced upper-band rejection [14]. Natural surface plasmon polaritons (SPPs) are limited to optical frequencies due to the negative permittivity of metals. At microwave frequencies, metals act as ideal electric conductors, preventing the natural spread of SPP. Spoof Surface Plasmon Polaritons (SSPPs) are used to overcome this issue. SSPPs are enabled by engineered periodic structures on metallic surfaces that enable SPP-like wave propagation at microwave frequencies [15].

In this work, a compact hybrid HMSIW-SSPP BPF integrated with a hollow bowtie-type SSPP geometry is proposed. The upper cutoff frequency is effectively controlled by the hollow bowtie-shaped SSPP geometry, resulting in an enhanced wideband BPF response and improved selectivity. This configuration supports SSPP propagation and enables flexible frequency tuning primarily through the outer bowtie length (b1) and inner bowtie length (b2). By appropriately adjusting these parameters, an improved and controllable frequency response is obtained. A comprehensive parametric analysis is carried out to guide the design process. The proposed filter exhibits enhanced compactness, sharp selectivity, strong stopband suppression, and improved insertion and return loss characteristics, making it a promising candidate for C-band and X-band wireless communication applications.

2. DESIGN AND ANALYSIS OF PROPOSED FILTER

2.1 Design of standard HMSIW structure

The design process begins with the design of a standard HMSIW as shown in Fig. 1.

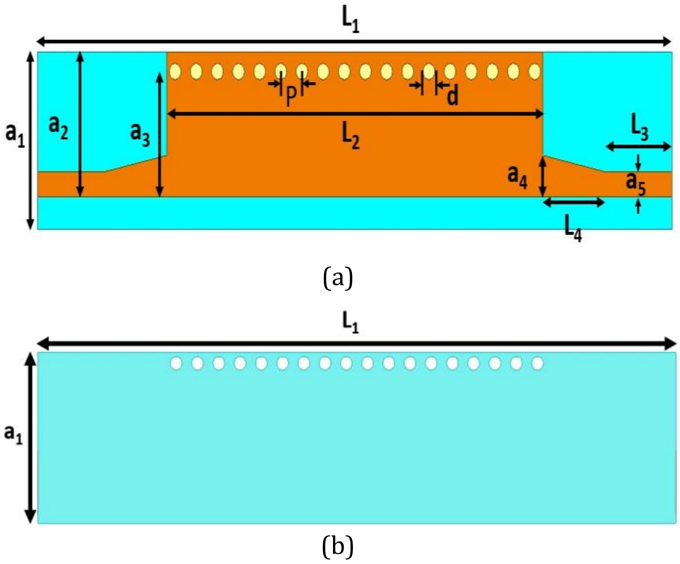

Fig. 1. The structure of the HMSIW filter (a) top view (b) bottom view

The electrical characteristics of the SIW structure are comparable to those of a standard rectangular waveguide. The key design parameters, including the effective width, length, and cutoff frequency, are determined using the following equations (1), (2), and (3) in [6] and [7].

$$a_{eff} = a_{SIW} - \left(\frac{d^2}{0.95p}\right) \quad (1)$$

$$L_{eff} = L_{SIW} - \left(\frac{d^2}{0.95p}\right) \quad (2)$$

$$f_c = \frac{c}{2\sqrt{\varepsilon_r}}\left(a_{SIW} - \frac{d^2}{0.95p}\right)^{-1} \quad (3)$$

Equations (1), (2), and (3), a_{eff} and L_{eff} indicates that the effective width and length of the SIW. While a_{SIW} and L_{SIW} represents the physical width and length of the SIW, c denotes the velocity of light in free space, d indicates the diameter of the metallic via holes, and p defines the periodic interval between vias. Substrate width a_1, patch width a_2, effective width a_3, tapered transition width a_4, feed width a_5, substrate length L_1, patch length L_2, feed length L_3, and tapered transition length L_4 are the physical variables of the HMSIW filter. The filter's optimum geometrical parameters of the filter are a_1=12.5 mm, a_2=10.5 mm, a_3=9.7 mm, a_4=2.8 mm, a_5=2 mm, p=1.8 mm, L_1=54 mm, L_2=32 mm, L_3=6.65 mm, L_4=4.35 mm, and d=1 mm. The simulated S-parameter response of the HMSIW filter is illustrated in Fig. 2. It shows that the operating frequency of HMSIW at 5.54 GHz exhibits good return loss and low insertion loss.

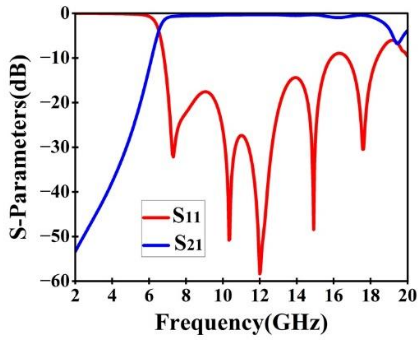

Fig. 2. Simulated output of the HMSIW filter

The effect of HMSIW width (a_3) on the filter response is analyzed, as shown in Fig. 3. It is observed that a_3 is mostly controls the lower cutoff frequency. The lower cut-off frequency shifts toward lower frequencies when a_3 increases from 8.7 mm to 10.7 mm. For instance, the lower cutoff frequency is considered at a_3=9.7 mm. Meanwhile, the upper cutoff frequency remains nearly unchanged. Therefore, HMSIW width is an important parameter for independently adjusting tuning.

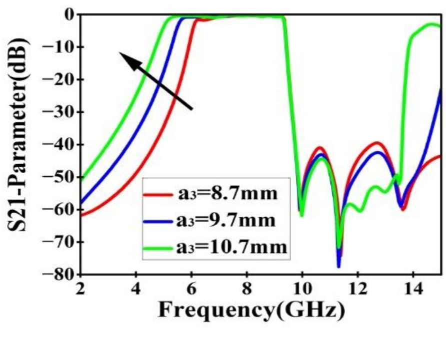

Fig.3. Simulated output for different values of a_3

2.2 Design Methodology of the Proposed HMSIW–SSPP-Based BPF

To achieve bandpass characteristics in the C- and X-band frequency ranges, the proposed compact microwave BPF is designed by combining both HMSIW and SSPP units, which is realized by integrating hollow bowtie-shaped SSPP structures into the HMSIW configuration, as plotted in Fig. 4.

The integration of hollow bowtie-shaped SSPP elements into the conventional HMSIW filter results in a bandpass response because both HMSIW and SSPP structures are known to exhibit high-pass and low-pass characteristics.

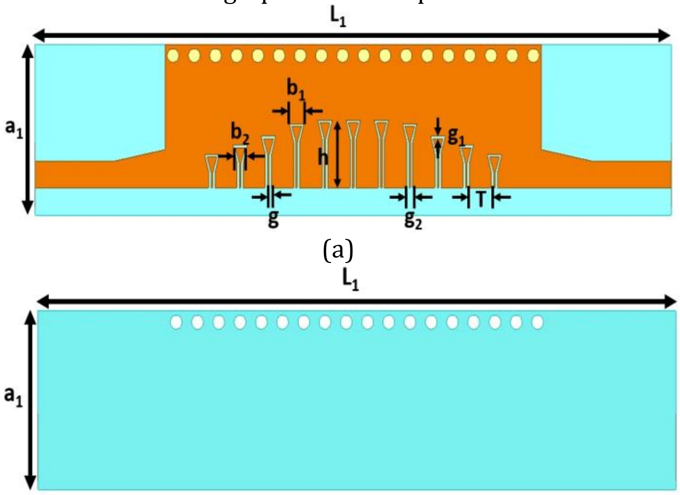

Fig. 4. Layout of proposed HMSIW-SSPP bandpass filter (a) Top view (b) Bottom view

The slow-wave effect is achieved by integrating sub-wavelength periodic SSPP structures onto the HMSIW's upper surface. As shown in the Fig. 4, the physical variables of the proposed hollow bowtie-shaped SSPP elements are outer bowtie length b_1, inner bowtie length b_2, height of SSPP h, width of the rectangular SSPP slot g, inner spacing of the bowtie-shaped slot g_1, spacing between adjacent rectangular slots g_2, and spacing between SSPP unit cells T. The filter's optimized geometrical parameters of the filter are b_1=1.2 mm, b-=0.82 mm, h=4.96 mm, g=0.2 mm, g_1=0.2 mm, g_2=0.52 mm, T=1.88 mm.

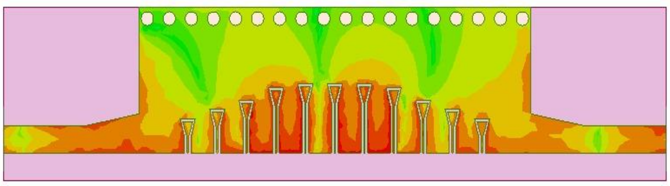

Fig. 5. The field distribution in the filter at 7.45 GHz

The field propagation across the compact hybrid HMSIW–SSPP BPF with a hollow bowtie-type SSPP geometry at center frequency 7.45 GHz as shown in Fig. 5. It is evident that the electric field is tightly confined within the SSPP units, with confirming effective field confinement and localization. The impact of bowtie structural dimensions on the frequency response filter was evaluated by the parametric studies as illustrated in Fig. 6. It shows, height of SSPP (h), the outer bowtie length (b_1), inner bowtie length (b_2), offer significant design flexibility to adjust passband's upper cutoff frequency. The S21 parameters shows that when the inner bowtie length (b_2) from 0.72 mm to 0.92 mm, the upper cut-off frequency value to shift downward as shown in Fig.6 (b). The parametric analysis also indicates that, whereas b_1 and h have a significant impact on the upper limit of the passband, variations in b_2 provide a more moderate effect as shown in Fig. 6, which makes it an ideal parameter for the fine-tuning the filter response.

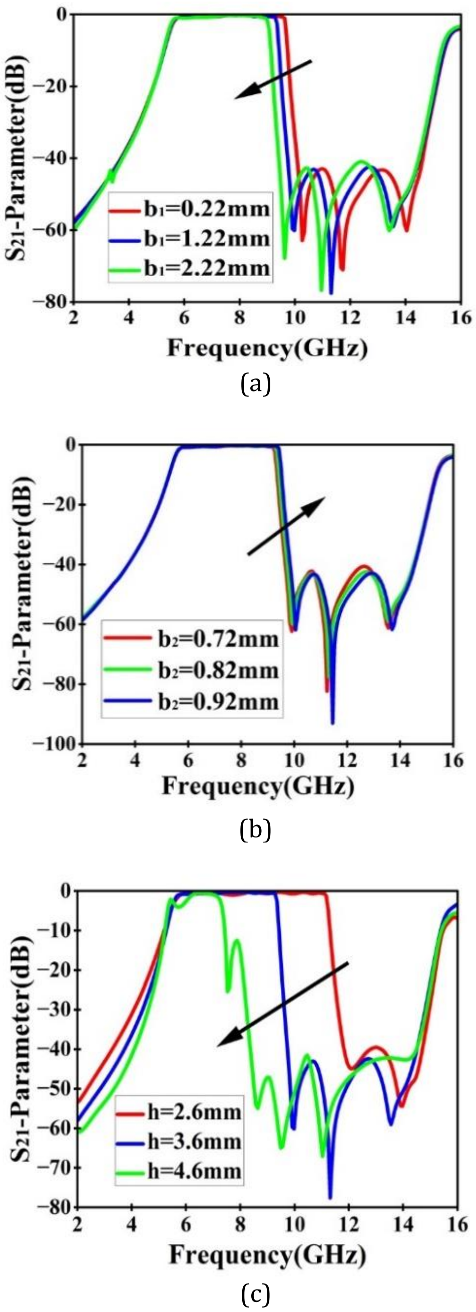

Fig. 6. Simulated output under variations in (a) b_1 (b) b_2 (c) h

The simulated output of the proposed filter is illustrated in Fig. 7. The filter exhibits a passband from 5.54 GHz to 9.36 GHz with a center frequency of 7.45 GHz. The higher-order modes may become slightly active in an HMSIW-SSPP-based filter just beyond the passband region.

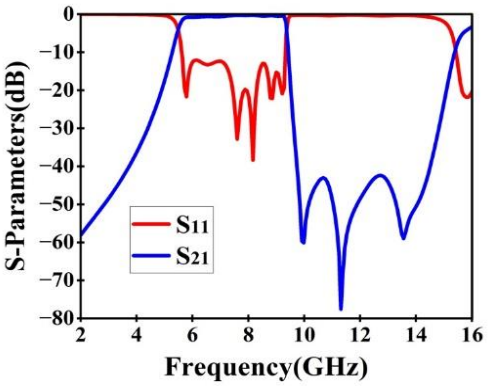

Fig. 7. Simulated output of proposed filter

3. Results and Discussion

The proposed HMSIW-SSPP based BPF shows a passband from 5.54 GHz to 9.36 GHz with an FBW of 51.3%. The insertion loss is approximately 0.34 dB at the center frequency and remains within 0.73 dB across the passband, and the return loss is better than 12.5 dB across the entire passband. In addition, a suppression level of more than 42.5 dB is observed from 9.76 GHz to 14.42 GHz, indicating effective stopband performance, and significant attenuation outside the passband. The proposed filter overall size is 0.72 λg × 2.32 λg, where λg is the guide wavelength. The proposed BPF performance is compared with a few published SSPP based BPFs as tabulated in Table I. The comparison clearly highlights that the proposed filter offers significant improvements in terms of size and insertion loss.

Table -1: Comparison of Proposed HMSIW–SSPP Bandpass Filter with Existing Designs

Ref.	Unit type	FBW (%)	RL (dB)	IL (dB)	Size $(\lambda_g)^2$	Out-of-band Rejection
[7]	SIW - SSPP	45.8	>10	<1.0 8	1.63 X 0.74	22.5–30 GHz @40 dB
[8]	SIW- SSPP	44	>12	2	4.57 X 0.25	11.8-19.8GHz @40 dB
[9]	HMSIW -SSPP	69.2 2	>10	<0.8	4.23 X 0.25	35-40GHz @40 dB
[10]	SIW- SSPP	51.2	>12	<1	1.03 X 0.71	14.2-19.5GHz @41dB
[12]	HMSIW -SSPP	50	>10	<1.2	1.2 X 0.6	NG
[14]	HMSIW - SSPP	59.2 5	>9.0 1	NG	2.69 X 0.42	8.6-16GHz@31.6 dB
This wor k	**HMSI W-SSPP**	**51.3**	**>12. 5**	**<0.7 3**	**0.72 X 2.32**	**9.76-14.42GHz @42.46dB**

4. CONCLUSION

A compact HMSIW-based bandpass filter integrated with a hollow bowtie-shaped SSPP structure has been successfully presented. The proposed structure effectively combines the advantages of HMSIW and SSPP technologies, where the lower cutoff frequency is primarily determined by the HMSIW dimensions and the upper cut-off frequency is effectively regulated by the hollow bowtie-shaped SSPP grooves. In particular, the key structural parameters of the hollow bowtie-shaped SSPP, b_1 and b_2, can be changed to further adjust the upper cutoff frequency. The hollow bowtie-shaped SSPP design effectively overcoming spacing constraints while achieving improved insertion and return loss performance. With a fractional bandwidth of 51.3%, low insertion loss, and good return loss across the operating band, the proposed filter provides wideband performance. In addition, strong out-of-band suppression exceeding 42.5 dB highlights its excellent selectivity. With its compact size, wide bandwidth, and excellent frequency response, the proposed filter is a promising candidate for modern C- and X-band applications.

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