Spoof surface plasmon polariton based half-mode substrate integrated waveguide bandpass filter for x-band applications

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Abstract - *In this study, two bandpass filters designed for X-band applications are introduced, utilizing a combination of hybrid spoof surface plasmon polariton (SSPP) and half-mode substrate integrated waveguide (HMSIW). The transmission properties of these hybrid SSPP-SIW structures are examined, and the impact of changes in their structural parameters is explored. The dumbbell-shaped SSPP demonstrates greater slow-wave effects compared to the rectangle-shaped SSPP when the groove height is the same, making it an ideal option for creating compact, low-loss, and highly integrated microwave and terahertz devices. The lower and upper cut-off frequencies of the hybrid SSPP-HMSIW bandpass filters can be independently adjusted by altering the structural parameters of the SIW and SSPP units, respectively. Both proposed filters offer excellent passband performance, operating within the 7.4 to 13.7 GHz frequency range. The simulated results exhibit a low insertion loss of 0.53–0.65 dB and a stable return loss better than 10 dB across the entire operating bandwidth. Furthermore, they provide wide upper-band rejection exceeding 40 dB up to 20 GHz. The physical dimensions are highly compact, measuring approximately 2.1 × 0.5 λ_g^2 at the center frequency, ensuring suitability for modern integrated communication systems.*

Key Words: Bandpass filter, Spoof surface plasmon polariton, Half-mode substrate integrated waveguide, X-band applications.

1.INTRODUCTION

Modern communication systems, including radar and satellite applications, increasingly require microwave filters and transmission lines that are high-performing yet compact. While conventional metallic waveguides provide superior power-handling and minimal loss, their physical bulk and high cost make them difficult for planar circuit integration [1]. To address these challenges, Substrate Integrated Waveguide (SIW) technology has emerged as a preferred alternative, combining the benefits of planar transmission lines with the efficiency of metallic waveguides [1]. However, conventional SIW structures still face size limitations at lower frequencies [1], as they typically require dimensions on the order of a quarter wavelength.

Surface Plasmon Polaritons (SPPs) are electromagnetic excitations capable of confining energy at subwavelength scales along metal-dielectric interfaces [2]. While SPPs occur naturally at optical frequencies [1], metals behave as perfect electrical conductors at microwave frequencies [3], preventing natural SPP existence. To bridge this gap, Spoof Surface Plasmon Polaritons (SSPPs) were developed using artificial periodic structures, such as subwavelength grooves, to mimic the field confinement of natural SPPs. Previous investigations indicate that the dispersion characteristics of SSPPs are highly dependent on the periodic structural dimensions [4].

The Half-Mode Substrate Integrated Waveguide (HMSIW) represents a significant step in miniaturization by bisecting a standard SIW along a quasi-magnetic wall. This reduces the transverse width by approximately 50% while preserving the original field characteristics [1]. To achieve even greater longitudinal miniaturization, recent research has focused on integrating SSPP structures into the HMSIW framework to introduce "slow-wave effects" [1]. This hybrid approach combines the low-loss waveguiding of HMSIW with the tunable dispersion and field confinement of SSPPs.

Integrating corrugated grooves on the top metal layer of an HMSIW allows for the realization of hybrid structures that reduce both transverse and longitudinal dimensions significantly [1]. These hybrid designs naturally support bandpass filtering by combining the high-pass nature of the HMSIW with the low-pass behavior of the SSPP units [5]. Furthermore, adjusting structural parameters allows for independent control of the lower and upper cutoff frequencies [6]. This paper presents the design and analysis of a spoof surface plasmon polariton-based HMSIW optimized for X-band applications, aiming to achieve significant miniaturization compared to conventional approaches [7].

2. DEMONSTRATION OF HYBRID SSPP-HMSIW BANDPASS FILTERS

2.1 Conventional HMSIW

The proposed HMSIW structures are designed using Rogers RT/duroid 5880 substrate with a dielectric constant (ϵ_r) of

2.2, a loss tangent of 0.0009, and a thickness of 0.508 mm. The copper metallization thickness is maintained at 0.018 mm. As illustrated in Fig. 1a, the conventional HMSIW configuration is implemented based on the optimized parameters detailed in Table 1. By precisely tuning the geometric parameters, particularly the width(a) of the HMSIW, the structure is configured to operate as a high-pass filter. The simulated S-parameters (S_{11} and S_{21}), as presented in Fig. 3a, demonstrate the filter's performance with significant insertion and return loss characteristics. This behavior is attributed to the efficient conversion of the TE_{10} mode of the HMSIW into the transition mode. It is observed that the lower cutoff frequency is primarily governed by the HMSIW width; hence, for X-band applications, the width was optimized to achieve a specific cutoff frequency of 8 GHz.

Table -1: Design parameters of rectangle-shaped hybrid SSPP SIW filter

Parameter	Dimension (mm)	parameter	Dimension (mm)
a	7.2	L_1	6.6
W	10	L_2	3.4
W_1	1.6	L_3	28
W_2	2.32		

2.2 HMSIW Loaded with Rectangular-shaped SSPP'S

Initially, the hybrid SSPP-HMSIW structure, as shown in Figure 1b, is investigated by varying the graded rectangular slots heights of h (i = 1, 2, 3, 4). The simulated S-parameters are plotted in Figure 3b, It is clear that the value of performance can be improved when the graded slots are linear and matched to the microstrip taper slope with a good conversion of the SSPP TE_{10} mode in the HMSIW to the required mode.

The configurations of the hybrid SSPP-HMSIW filters are shown in Figure 1b. These configurations are divided into three parts: the microstrip to HMSIW transition part (Region I), the HMSIW to SSPP transition part (Region II), and the hybrid SSPP-HMSIW part (Region III). In Region I, the broadband impedance matching element is constructed using a linearly tapered microstrip line [13-15] to allow for an efficient transition between the 50 Ω input/output feedline and HMSIW, as well as enable a smooth transition from the quasi-TEM mode of the microstrip directly to fundamental TE_{10} mode of HMSIW. In order to align the momentum of a traditional HMSIW with that of a hybrid SSPP-HMSIW, we propose using linearly graded rectangular slots transitioning from the region I boundary (Si) in terms of their transverse dimensions, as shown in Region II, thus providing gradient momentum. And also, the rectangular slots at end are tapered and they all aligned with the same slope as that of microstrip taper. Such a structure guarantees minimum reflections [14], achieving broadband impedance matching and provides a gradual transition between the lower TE mode of HMSIW to SSPP. The width and length of 50 Ω microstrip lines are W_1 = 1.6 mm and L_1 = 6.6 mm. The initial width and length of linearly tapered microstrip lines are calculated from [13].

(a)

(b)

(c)

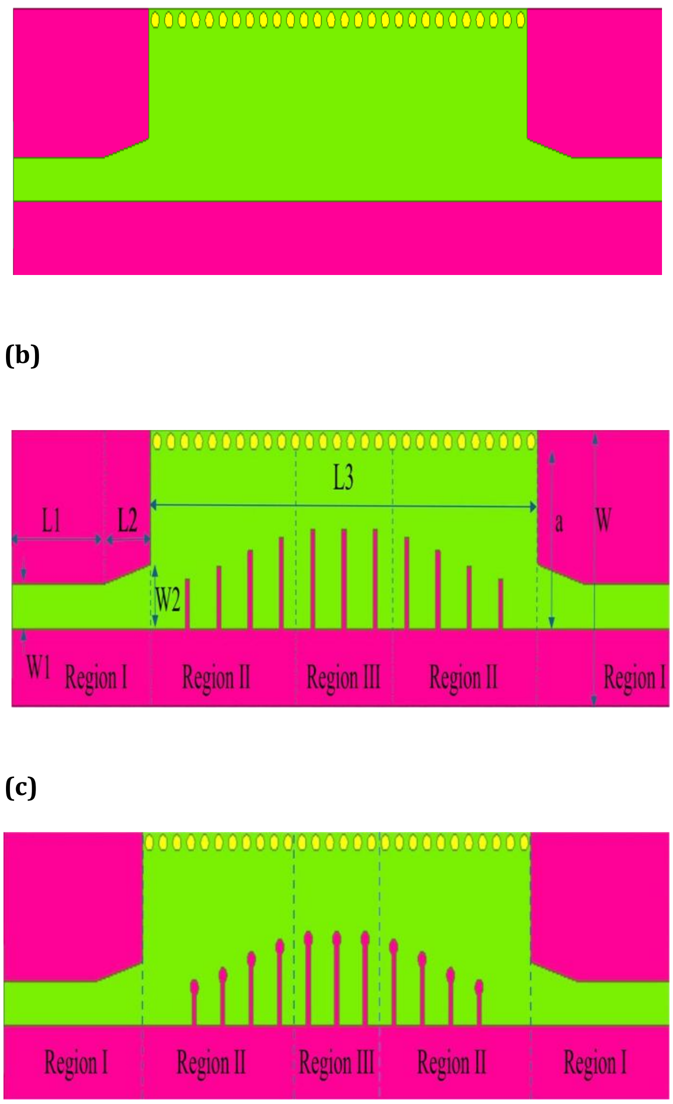


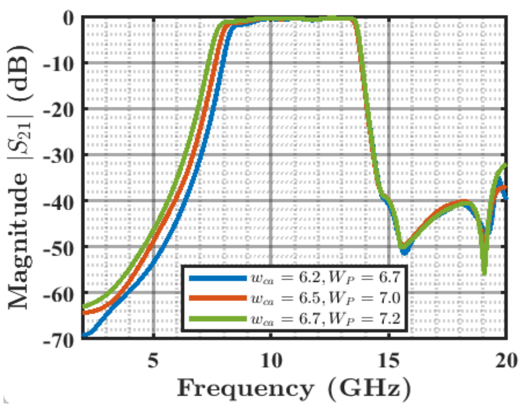
Figure-1: (a)configuration of conventional HMSIW, (b) Rectangle shaped (top view, filter I), (c) Dumbbell-shaped (top view, filter II)

They are optimized using EM simulations, and the parameters are set as W_2= 2.32 mm and L_2=3.4mm.The length of the HMSIW section L_3 is 28 mm. The variation in the width of HMSIW of a rectangle-shaped SSPP-HMSIW structure with the groove height of 3.5mm is depicted in Figure 2a, It is clear that the lower cut-off frequency of the passband can be adjusted independently with minimal or no effect on the upper cut-off frequency. Figure 2b demonstrates that the upper cut-off frequency can be modified independently by changing the periodicity of the rectangular grooves while maintaining the HMSIW width at 7.2mm, although this has a slight impact on the lower cut-off frequency, primarily due to the reduced coupling between the HMSIW and SSPP units.

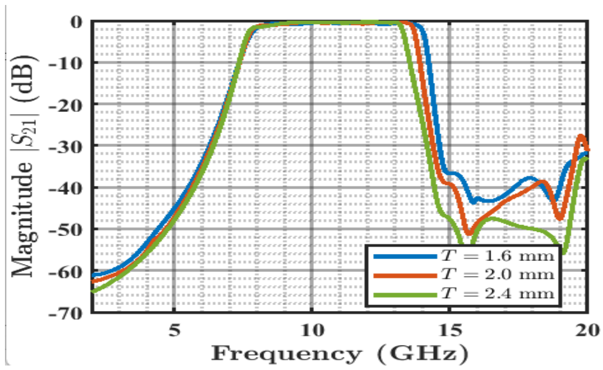
2.3 HMSIW Loaded with Dumbbell-shaped SSPP'S

The consistent features for different HMSIW widths and the grooves periodicity in a dumbbell-shaped SSPP-HMSIW scenario can be determined. Figure 2c illustrates the transmission coefficients for various radii of a dumbbell-shaped hybrid SSPP-HMSIW structure, maintaining a constant groove height of 3.5 mm. Increasing the radius of the dumbbell allows the upper cut-off frequency to shift to the right independently, without affecting the lower cut-off frequency. The material parameters for the filters are the same as mentioned above. The design parameters of the rectangle shaped hybrid SSPP-HMSIW filter are given in Table 1. For dumbbell-shaped hybrid SSPP-HMSIW filter, the design parameters are the same as for rectangle-shaped case, only the height of groove h is changed to 3.2 mm and the radius of dumbbell r is chosen as 0.3 mm.

(a)



(b)



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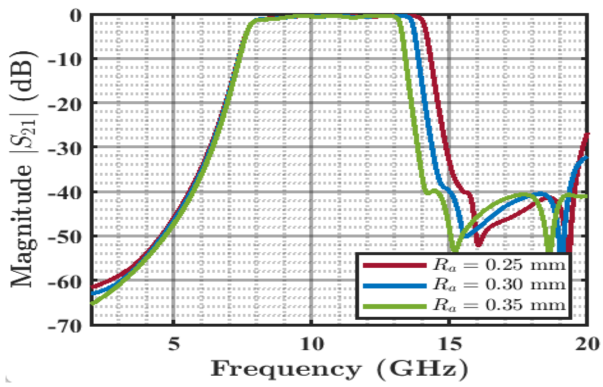
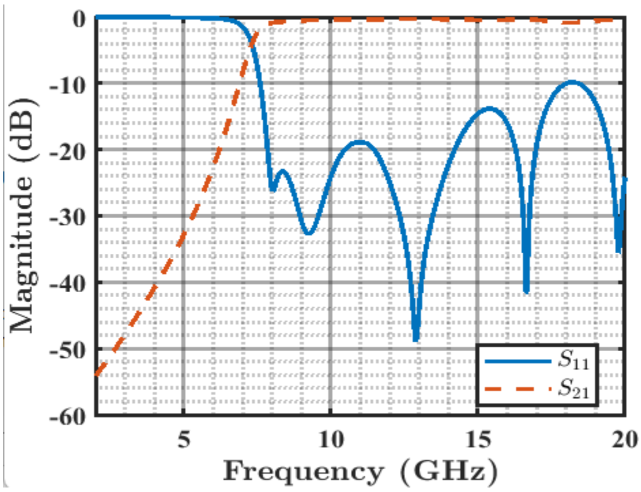


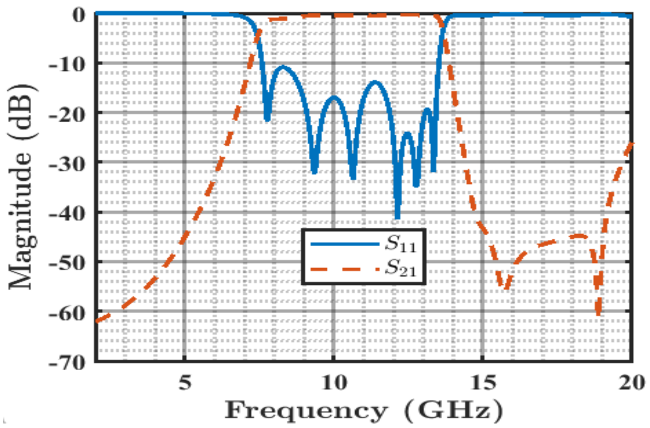
Figure-2: Simulated transmission coefficients of the proposed hybrid SSPP-HMSIW structures. (a) Different widths of HMSIW with rectangular shaped SSPP, (b) Different periodicities of rectangular-shaped SSPP, (c) Different radii of dumbbell-shaped SSPP with fixed h = 3.5 mm

The simulated and measured S-parameters of the rectangle-shaped hybrid SSPP-HMSIW bandpass filter are plotted in Figure 3b. The BW ranges from 7.4 to 13.7 GHz for $|S_{11}| < -10$ dB and $|S_{21}| > -1$ dB, covering the whole X-band of 8–12 GHz. A very good return loss (RL) of more than 10 dB in the whole passband has been achieved. The upper out-of-band rejection is better than 42.5 dB from 15.6 to 20 GHz. Figure 3c shows the simulated and measured S-parameters of the dumbbell-shaped SSPP-HMSIW filter. Its 10-dB passband ranges from 7.4 to13.7 GHz with a return loss of greater than 10 dB and insertion loss (IL) less than 1 dB in the whole passband. The upper stopband attenuation is more than 41 dB from 15.6 to 20 GHz. The roll-off rate of the filters is also very high.

(a)



(b)



(c)

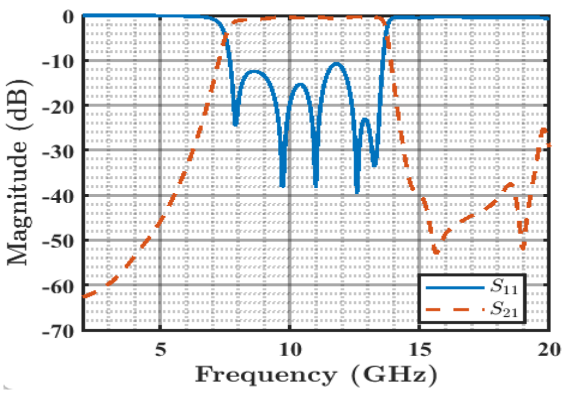


Figure-3: (a) S-parameters of the conventional HMSIW, (b)S-parameters of the rectangle-shaped SSPP-HMSIW bandpass filter, (c) S-parameters of the dumbbell- shaped SSPP-HMSIW bandpass filter.

Table -2: Performance comparison with the existing hybrid SSPP-HMSIW filters

Ref. No.	***Unit type***	***PB range (GHz)***	***FBW (%)***	***IL (dB)***	***RL (dB)***	***Size (Length × Width)* (λg×λg)**
[8]	Hybrid SSPP-SIW	11.92-21.54	57.5	<1	>10	10.3 × 0.74
[9]	Hybrid SSPP-SIW	11.8–18.3	43.2	<1	>10	7.88 × 0.67
[10]	Hybrid HMSIW-SSPP	8–16	67.0	<1.5	>12	2.64 × 0.29
[11]	Hybrid SSPP-SIW	7.3–11.2	42.2	<2	>12	2.85 × 0.67
[12]	Hybrid HMSIW-SSPP	15.6–32.1	69.2	<0.8	>10	4.23 × 0.25
This work	HMSIW-Rect. SSPP	7.4 – 13.7	59.05	0.5–0.65	>10	2.1 × 0.5
	HMSIW-Dumbbell-SSPP	74.–13.7	58.49	0.5–0.65	>10	2.1 × 0.5

Table 2 illustrates a comparison of the performance between the newly developed hybrid SSPP-HMSIW filters and the existing models. The newly designed filters exhibit remarkable efficiency both in the pass band and beyond. They excel in nearly all parameters when compared to the current hybrid SSPP-HMSIW filters. By incorporating the fewest possible SSPP units (only three) and implementing linearly graded slots for the optimal transition from HMSIW to SSPP mode, the resulting designs are notably compact.

3. CONCLUSION

In this study, two advanced hybrid SSPP-HMSIW bandpass filters, incorporating rectangle- and dumbbell-shaped SSPPs, have been successfully designed and analyzed for X-band applications. The investigation reveals that the dumbbell-shaped SSPP exhibits more significant slow-wave effects compared to the rectangle-shaped SSPP for an identical groove height, making it an ideal candidate for compact, low-loss, and highly integrated microwave and THz devices. The proposed design allows for the independent adjustment of lower and upper cut-off frequencies by tuning the structural parameters of the HMSIW and SSPP units, respectively. By employing linearly graded slots, an optimal mode conversion from HMSIW to SSPP was achieved. Both filters demonstrate superior passband performance within the 7.4–13.7 GHz range, characterized by a remarkably low insertion loss of 0.53–0.65 dB and a consistent return loss exceeding 10 dB. Furthermore, the filters provide substantial upper-band rejection (over 42.5 dB for Filter I and 41 dB for Filter II) up to 20 GHz. With a highly compact footprint of approximately 2.1 × 0.5 λ_g^2 , these filters are significantly shorter than existing hybrid SSPP-HMSIW designs, ensuring their suitability for modern communication systems. Future research will focus on the Bloch analysis of these SSPP-SIW structures to further explore their periodic properties.

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