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Unequal Bandpass Filtering Power Divider Based on Hybrid HMSIW-SSPP Modes

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This letter presents a novel unequal bandpass filtering power divider based on hybrid-mode of half mode substrate integrated waveguide (HMSIW) and spoof surface plasmon polaritons (SSPPs). Bandpass response is achieved by combining the transmission properties of HMSIW and SSPPs simultaneously. The operating bandwidth can be designed in a wide range by simply optimizing the dimensions of HMSIW and SSPPs. In addition, defected ground structures (DGSs) are etched on the bottom of the substrate to improve out-of-band suppression. The power division ratio of the proposed unequal power divider is finally optimized to 1:3. The measured results agree with the simulated one. Such design provides a stable power division within wide frequency range from 6.5 to 9.5 GHz.

Keywords: unequal power divider, bandpass filtering, SSPPs, HMSIW, wide band

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INTRODUCTION

The rapid development of wireless communication systems proposes more and more requirements for functional devices. In order to meet the market demands, different kinds of well-performed functional devices have been widely studied. In the past decade, substrate integrated waveguide (SIW) has become one of the hotspots in researches [1]. Considering its perfect high-pass transmission with low-loss, high-efficient properties, functional devices such as filter [2], power divider [3–6] and coupler [7] have been proposed. Half-mode SIW (HMSIW) consists of only half of SIW structures, while keeping the same performance as SIW [8, 9]. Miniaturization can be realized. Spoof surface plasmon polaritons (SSPPs) are guiding surface modes along periodic metamaterial structures. Such modes have also received wide attention for its unique properties of perfect low-pass transmission and near-field confinement [10, 11]. SSPPs have been studies in field of different high-efficient designs such as bandpass filter [12, 13], power divider [14, 15], coupler [16], radiator [17].

Filters and power dividers are the most commonly-used functional devices in wireless communication systems. In certain applications, both kinds of devices are required to be integrated with each other to reduce the occupied space. And their performances are crucial for systems stability. In recent years, a series of filters and power dividers based SIW and SSPPs have been reported [18, 19]. In order to improve the integration and operating properties, parasitic structures like resonators [20], interdigital structures (ISs) [21], defected ground structures (DGSs) [22, 23] have also been studied. The combination of SIW and SSPP provides a new solution for the miniaturization designs, since the power dividers of SIW are usually narrow-band and those of SSPP have limits of bulky dimensions.

In this letter, we proposed a novel unequal bandpass filtering power divider based on the hybrid HMSIW-SSPP modes, which shows compact size and power division ratio of 1:3. The hybrid unit can

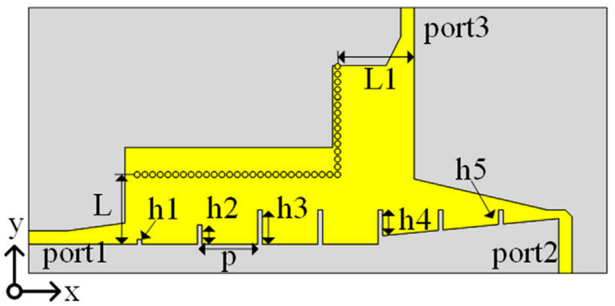

FIGURE 1 | Schematic of the proposed unequal filtering power divider.

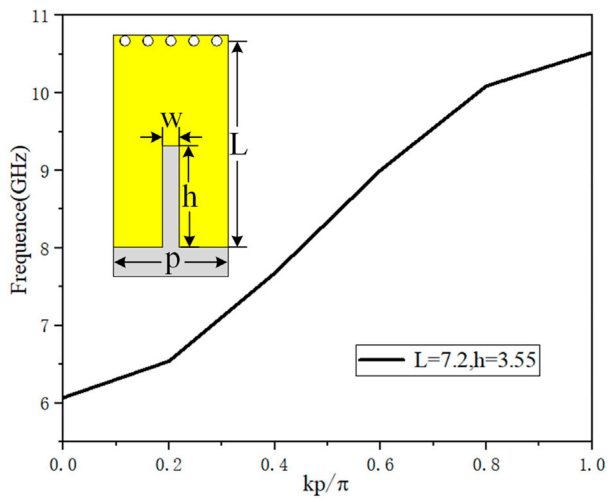

FIGURE 2 | The dispersion curves of the hybrid HMSIW-SSPP unit. Inset: the structure of the hybrid HMSIW-SSPP unit.

be compatible with the functional techniques of both HMSIW and SSPPs. The lower and upper edges of the passband can be controlled independently by changing the dimensions of HMSIW and SSPPs. Defected ground structure is also loaded aiming for improving out-of-band suppression.

Design of Unequal Power Divider

The schematic configuration of the proposed unequal filtering power divider is shown in **Figure 1** with dimensions labelled. As it can be seen in the figure, periodic corrugated slots are etched on the top layer of HMSIW. Two slots with gradient groove depths of h1 and h2 are used to achieve broadband excitation of SSPP modes. Optimizing grooves' depths can help to improvement of the transmission efficiency. Two uniformed grooves of SSPP with depth of h3 are set as the transmission part. They collaborate with the HMSIW structures to provide the hybrid HMSIW-SSPP modes with unique transmission properties. The periodic interval of the SSPP units is p. At the output terminals, a SSPP channel of three unit matching structures with gradient grooves' depths and tapered edges are designed for momentum matching of SSPP at port 2. Meanwhile, another HMSIW channel is paralleled connected between the hybrid unit and the SSPP channel. The widths of both HMSIW structures are L and L1, respectively.

Figure 2 show the dispersion curves of the hybrid HMSIW-SSPP unit. And its structure is shown in the inset of **Figure 2**. It can be observed from the figure that the cutoff frequency of HMSIW modes is lower than that of SSPP modes. Thus, bandpass response can be obtained. The hybrid unit provides bandpass property from 6.1 to 10.5 GHz. As is introduced in literatures, the cutoff frequencies of SIW and SSPP modes can be controlled by changing the width of SIW and the depth of SSPP grooves. For the proposed design, reduction of L or h leads to upper shifting of the lower or upper cutoff frequencies, respectively. Limited by the space allocation, SSPP grooves are always smaller than HMSIW. So the cutoff frequencies of SIW are always lower than those of SSPPs.

The dispersion properties of the hybrid HMSIW-SSPP unit under different parameters are compared in **Figure 3**. The unit with dimensions of h = 3.5 mm, L = 7 mm, w = 0.5 mm and p = 6 mm is used as reference and shown as the red dashed lines in the figure. Then each dimension is optimized and compared. In **Figure 3A**, the groove's depth in HMSIW unit is examined. When the depth h3 increases from 3 to 4 mm, the upper cutoff frequencies shift from 11.2 to 9.4 GHz, while the lower cutoff frequencies keep at 6.1 GHz. Similarly, from **Figure 3B** it can be seen that when width L increases from 6 to 8 mm, the lower cutoff frequencies of the hybrid unit reduce from 6.8 GH to 5.5 GHz. Meanwhile, small range fluctuation between 10.1 and 10.3 GHz of the upper cutoff frequencies is observed. The width of the groove w and its interval p can also be used for the modulation of operating band (shown in **Figures 3C,D**). The groove width w can change the upper cutoff frequencies in a small range. And the interval p has a significant impact on the upper cutoff frequencies. Since the increasing interval would lead to excessive length of the device, depth L is usually used in modulation of operating band.

The simulated transmissions at port 3 of the unequal filtering power divider are illustrated in **Figure 4** to testify the bandwidth modulation of the hybrid unit. As is compared in **Figures 4A,B**, upper cutoff frequencies or lower cutoff frequencies of S_{31} shift to lower frequency band independently without apparently mutual influence. Based on the above analysis, a high-efficient passband from 6.5 to 9.5 GHz of unequal filtering power divider can be designed. The simulated S parameters are shown in **Figure 5**. In the whole passband, the reflection coefficient S_{11} keeps below −10 dB, while the transmission coefficient S_{21} and S_{31} are around −2.2 dB and −7 dB.

OPTIMIZATION AND MEASUREMENT

The DGS can disturb the current distribution on the metallic ground and introduce an extra transmission zero. In the optimized model, a two-element array of inverted T-shaped

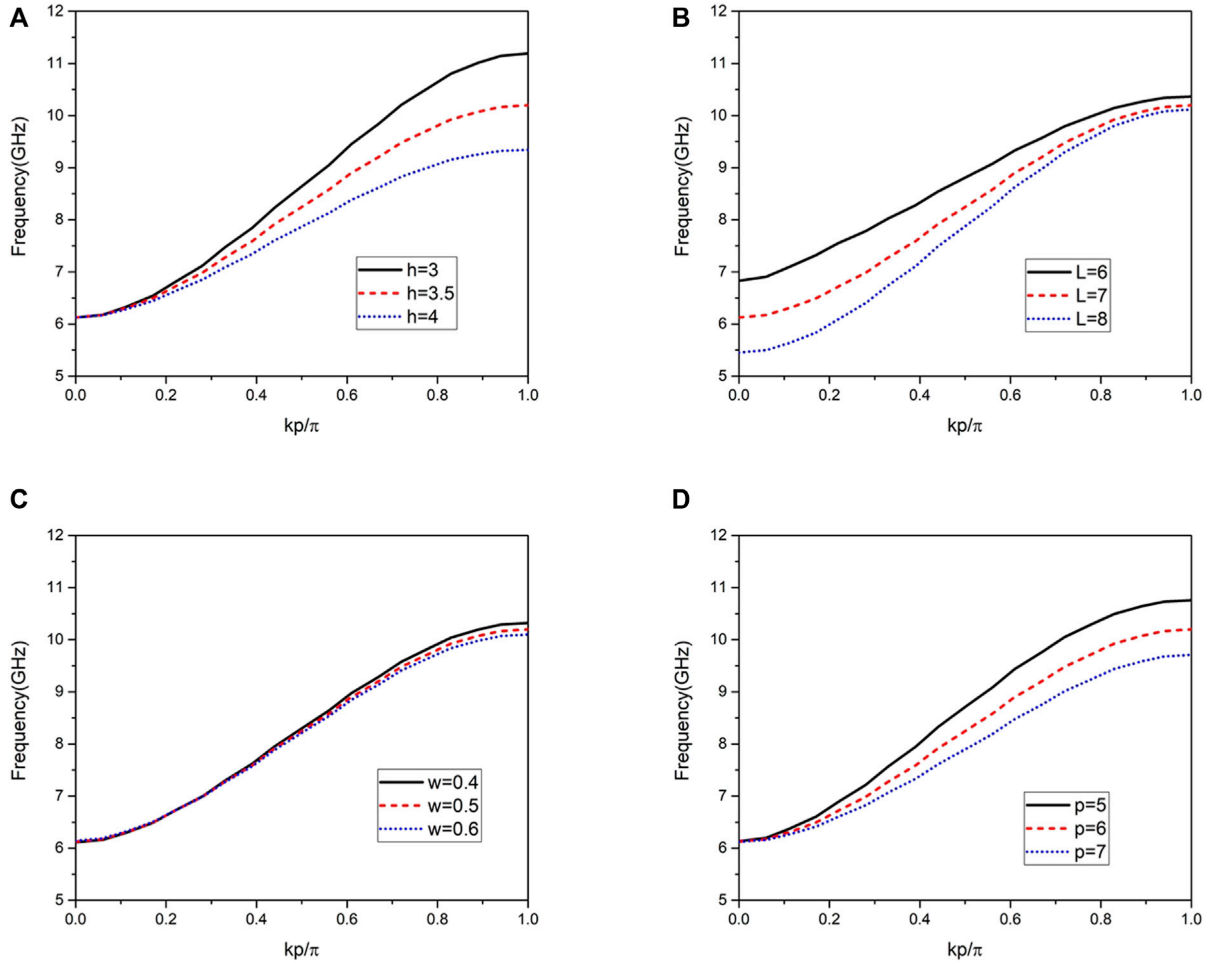

FIGURE 3 | The dispersion properties of the hybrid unit under different parameters of **(A)** depth of SSPP grooves h, **(B)** width of HMSIW L, **(C)** width of SSPP grooves w, and **(D)** interval of SSPPs p.

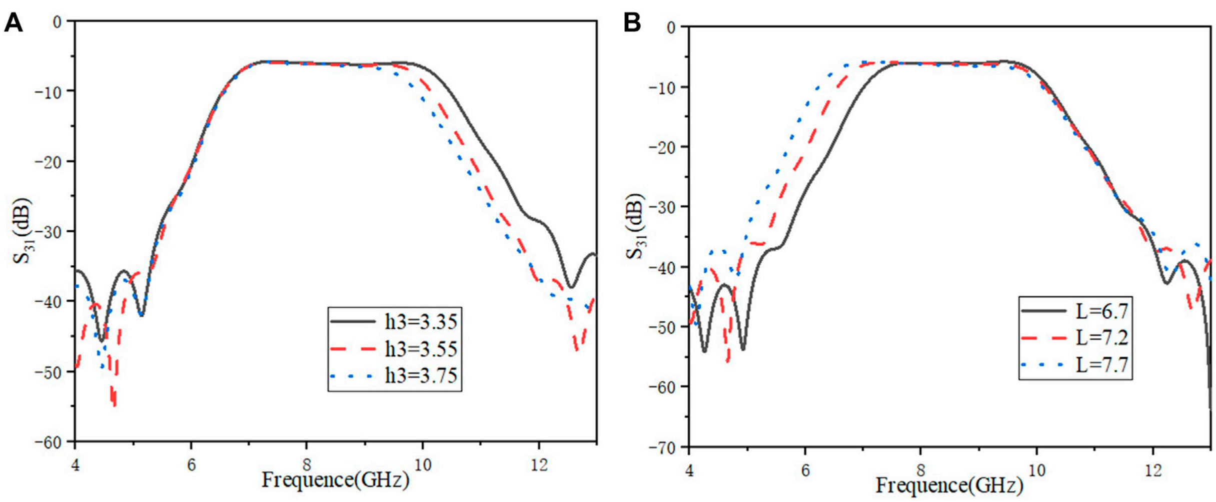

FIGURE 4 | Simulated transmission coefficients (S_{31}) with different dimensions of **(A)** h3 and **(B)** L.

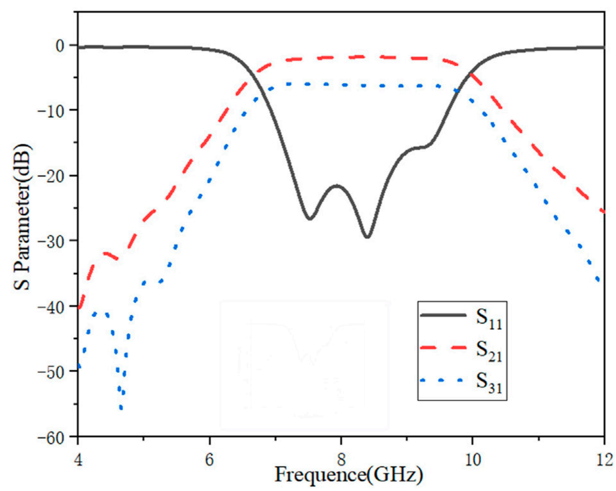

FIGURE 5 | Simulated S parameters of unequal filtering power divider.

DGSs is introduced. The DGSs are loaded on the bottom layer of the hybrid HMSIW-SSPP units to improve the upper stopband rejection. The structure of the DGS unit is shown in the inset of **Figure 6A**, in which the red line represents the contour of the grooves on the top layer. The DGS is etched on the bottom layer and it is in the middle of two adjacent grooves. The dimensions of the DGS decide the frequency of its transmission zero. And the optimized dimensions are a1 = 1.9 mm, a2 = 4.4 mm, a3 = 3.8 m, t = 0.6 mm, s = 0.45 mm, g = 0.25 mm. The comparison of S_{21} of the design with and without the DGSs is shown in **Figure 6A**. The transmission with two-element array of DGSs provides an extra transmission zero, providing better out-of-band suppression. The cut-off efficiency of transmission zero of DGS at 10 GHz can be improved by increasing the number of DGSs used in the model. A small shift of the cutoff frequency of SSPPs is observed due to the coupling between DGSs and SSPPs. The transmission of the proposed design loaded with DGSs are shown in **Figure 6B**. An unequal power divider with bandpass filtering effect is observed within band from 6.5 to 9.5 GHz. The simulated S_{11}

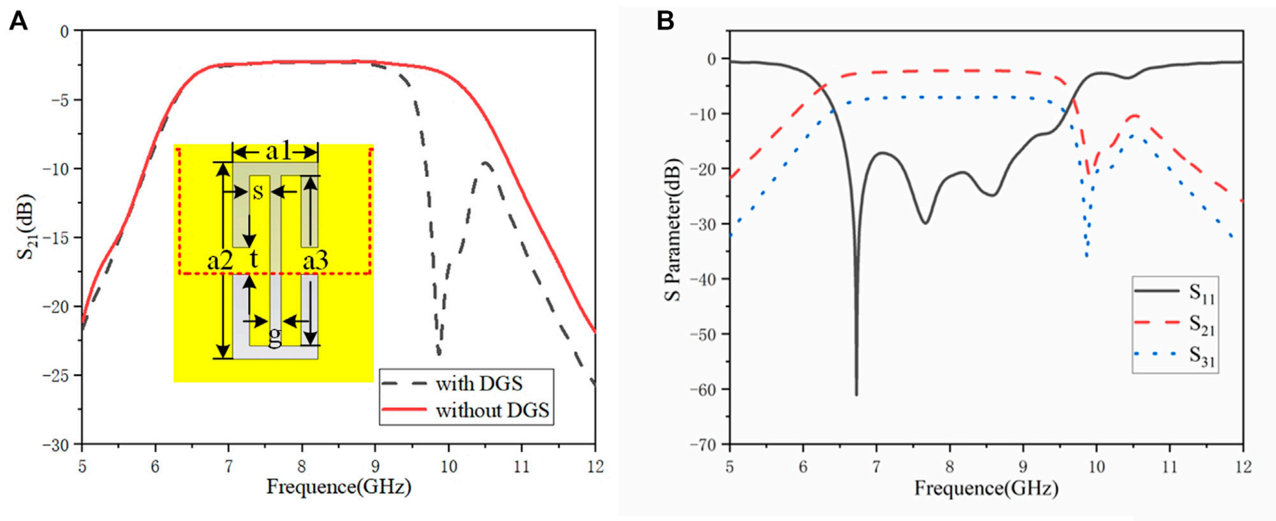

FIGURE 6 | (A) the comparison of S_{21} of the designs with and without DGSs. **(B)** Simulated S-parameters of the design with DGS.

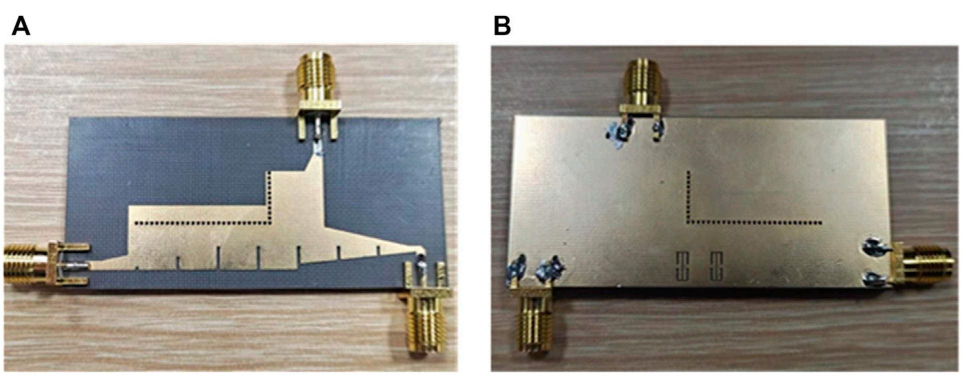

FIGURE 7 | (A) Top view and **(B)** back view of the prototype.

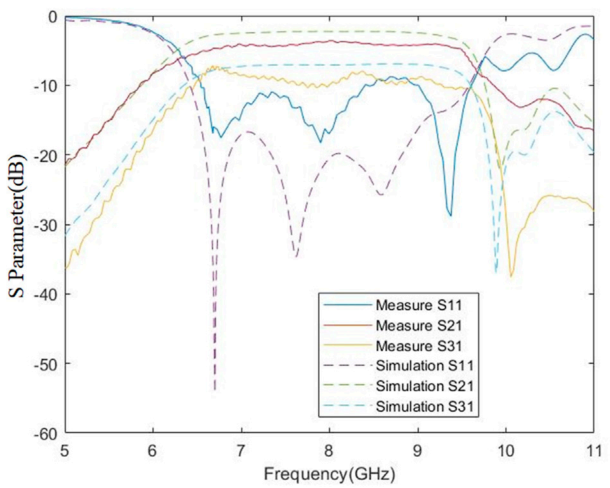

FIGURE 8 | Comparison of simulated and measured S-parameters.

is lower than −20 dB in the passband. S_{21} and S_{31} are −2.2 dB and −7 dB, respectively. Within the whole operating band, S21 undulates between −2.6 dB and −2.3 dB, and S31 undulates between −7.4 dB and −7 dB. The simulations indicate a stable power division. The power division ratio of port 2 and port 3 is 3:1.

A prototype of the proposed unequal filtering power divider is fabricated and measured. The substrate is F4B board with relative permittivity of 2.65 and thickness of 1 mm. Photographs of the prototype are shown in **Figure 7**. The total dimensions of the proposed design are 45 mm × 25 mm × 1 mm. **Figure 8** shows the compared of the simulated and measured S-parameters. The measured transmissions are about 1 dB lower than the simulated ones, because of the machining accuracy of the sample and the unskilled welding of SMA connectors in the experiments. The operating bandwidth and power division effect keeps steady.

CONCLUSION

In this paper, an unequal filtering power divider based on hybrid HMSIW-SSPP mode is proposed. The passband can be controlled independently by changing the dimensions of HMSIW and SSPPs. DGSs are introduced on the bottom layer of the device to improve the out-of-band suppression. A prototype working from 6.5 to 9.5 GHz is designed and fabricated. And power division ratio of 1:3 is obtained. Such design provides solutions for miniaturized multi-functional devices, and could be used in wireless communication systems.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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