

Article

Design of Filtering Magic-T with Wideband and Wide Stopband Based on HMSIW and Spoof Surface Plasmon Polaritons

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Abstract: A novel filtering magic-T (FMT) with a compact size, a broad bandwidth, and a wide stopband rejection based on the dielectric-covered L-shaped groove (DCLSG) half-mode substrate integrated waveguide and the spoof surface plasmon polariton (HMSIW-SSPP) structure is proposed for the first time. A HMSIW magic-T (HMT) based on dual-layer substrates is first designed. Then, we construct the proposed FMT by periodically etching the subwavelength DCLSG SSPP structure into the HMT. The proposed FMT achieves a bandpass filtering response and a nearly 50% reduction of longitudinal dimension attributed to the bandpass characteristics and strong slow-wave property of the DCLSG HMSIW-SSPP structure. In addition, beneficial from the regulable cut-off frequencies of the DCLSG HMSIW-SSPP structure, the proposed FMT provides a wide impedance bandwidth and independently adjustable lower and upper cut-off frequencies of the passband. Finally, a prototype of the proposed FMT is fabricated to validate this design idea. The measured results illustrate that the FMT has a 3-dB fractional bandwidth of 40.23% and a 20-dB stopband rejection up to $2.12 f_0$ (f_0 : center frequency of the passband).



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Keywords: filtering magic-T; spoof surface plasmon polaritons (SSPPs); half-mode substrate integrated waveguide (HMSIW); wide bandwidth; wide stopband; compact size

1. Introduction

The Magic-T is the vital four-port passive component in the RF front-end system. It has been used in various scenarios, such as mixer and monopulse antennas [1–3]. For a magic-T, the input port of the structure that operates as the power divider (PD) is named the sum port, while the input port of the structure that acts as the reverse-phase PD (balun) is called the difference port. Owing to the substrate integrated waveguide (SIW) with the advantages of easy integration with planar structures, high power capacity, and low insertion loss, researchers present multiple SIW and half mode SIW (HMSIW) magic-Ts by using slotline-to-SIW transition [4,5] and stripline-to-SIW transition techniques [6]. However, these SIW magic-Ts do not integrate with bandpass filters (BPFs), so it is hard to exclude unwanted signals. Since the direct link between the BPF and magic-T increases the footprint and the insertion loss [7], researchers propose filtering magic-T (FMT) by integrating magic-T and BPF into one joint-function component. To date, there are mainly two popular approaches to designing the SIW FMTs [8–14].

One approach is to use orthogonal degenerate modes of the SIW resonators to accomplish the input ports' isolations and the functions of filtering PD and balun [8–11]. Another approach is to design the two output channels of the filtering balun (PD) with opposite coupling coefficients while maintaining that of the filtering PD (balun) with identical coupling coefficients [12–14]. Nevertheless, the above papers have not discussed or optimized the stopband performance of the SIW FMTs, while the wide stopband rejection is often

necessary for microwave devices with filtering functions. Although researchers propose a frequency-tunable FMT using HMSIW evanescent-mode (EVA) cavity resonators [15], whose stopband rejection achieves $10.2 f_0$ (f_0 : center frequency of the passband), it operates at a relatively low frequency, and its insertion loss needs to improve. In addition, all the FMTs in [8–15] can only provide a fractional bandwidth (FBW) smaller than 8.62%, which is not appropriate for wideband applications. Moreover, using high-order resonators to meet wideband applications may lead to a large size [16]. A recent study in [17], reports an FMT based on hybrid SIW and coplanar waveguide (CPW) resonators to implement the compactness and 3rd-order filtering response, but its FBW is just 7.58%. Thus, designing a SIW FMT with compact size, wide bandwidth, and wide stopband rejection remains a challenge.

In recent years, spoof surface plasmon polaritons (SSPPs) have been proven to be a valuable technique in the designs of passive microwave devices, attributing to its merits of a slow-wave (SW) characteristic and strong field confinement [18–22]. These things considered, various filtering devices, including BPFs [23,24], dual-band BPFs [25,26], filtering power dividers [27,28], and duplexers [29,30], have been proposed by combining the high-pass property of SIW (or HMSIW) and the low-pass property of SSPP structure. Nevertheless, to the best of the authors' knowledge, the FMT based on the hybrid SIW and SSPP (SIW-SSPP) or HMSIW-SSPP structure has not been explored.

This paper proposes a novel FMT with a compact size, a wide bandwidth, and a wide stopband rejection using the dielectric-covered L-shaped groove (DCLSG) HMSIW-SSPP structure for the first time. The dispersion properties of the DCLSG HMSIW-SSPP unit cell are investigated first. Then, an HMSIW magic-T (HMT) based on dual-layer substrates is designed. Finally, we create the proposed FMT by periodically inserting the subwavelength DCLSG SSPP structure into the HMT. The DCLSG HMSIW-SSPP unit cell with gradient groove length is utilized to realize the momentum matching and mode conversion from the HMSIW to the required HMSIW-SSPP structure. The numerical simulations are conducted using the CST Microwave Studio [31].

The paper is organized as follows. In Section 2, the dispersion properties of the DCLSG HMSIW-SSPP unit cell are investigated. The detailed design procedures of the HMT and FMT are presented in Sections 3 and 4, respectively. The experimental results of the proposed FMT are discussed in Section 5. Section 6 gives the conclusions.

2. Dispersion Characteristics Analysis of Unit Cells

Figure 1a illustrates the configuration of the SIW, which consists of two copper layers (yellow part) and one dielectric layer (pink part). Two rows of vias connect the lower and upper copper layers. Figure 1b is the structure of the HMSIW, whose lateral size reduces by 50% compared to the SIW. Its lateral width is $w = 6.4$ mm. Figure 1c shows the configuration of the DCLSG SSPP unit cell. It is composed of two copper layers and two dielectric layers. The L-shape groove is inserted into the upper copper layer. The groove's lateral and longitudinal lengths are denoted as h and h_l , respectively, and the groove's width is denoted as g . Combining the DCLSG SSPP unit cell with the HMSIW, we obtain the proposed DCLSG HMSIW-SSPP unit cell, as illustrated in Figure 1d. The thickness of the copper layer is $t_0 = 0.018$ mm. The dielectric layer is selected as the Rogers 4350B substrate ($\epsilon_r = 3.48$ and $\tan\delta = 0.004$) with a thickness of $h_0 = 0.508$ mm. The detailed dimensions of the four models are given in Figure 1.

The dispersion curves of the models in Figure 1 are compared and plotted in Figure 2a, which are calculated using the eigenmode solver in CST Microwave Studio. The light's dispersion curve is also plotted in Figure 2a. As shown in Figure 2a, the lower cut-off frequencies of the HMSIW and SIW are approximately equal and exhibit high-pass properties. The DCLSG SSPP structure operates in the SW region and enables low-pass characteristics. The DCLSG HMSIW-SSPP structure features dispersion properties of both the HMSIW and SSPP structures. It provides a bandpass property with a lower frequency (6.3 GHz) and an upper cut-off frequency (10.91 GHz), which offers theoretical support to

the implementation of bandpass filtering devices. As illustrated by the red dash curve in Figure 2a, the normalized propagation constant of the DCLSG HMSIW-SSPP structure is larger than two times that of HMSIW at 8.7 GHz, which means that the proposed DCLSG HMSIW-SSPP structure has a >50% size reduction.

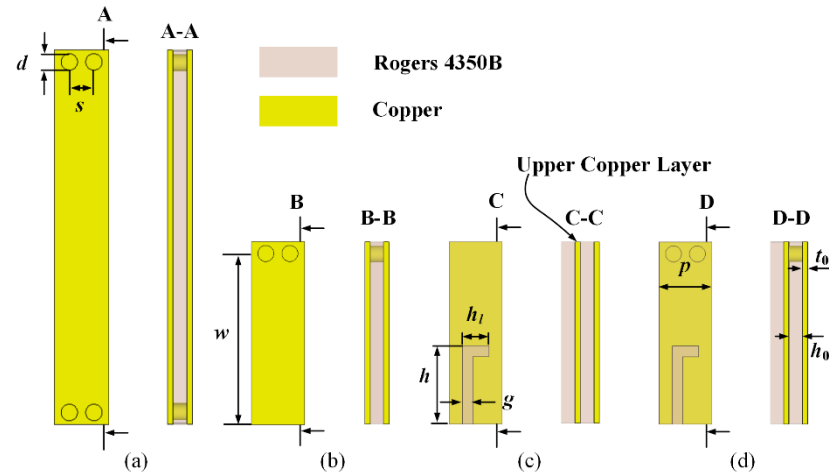


Figure 1. Configurations of (a) SIW, (b) HMSIW, (c) DCLSG SSPP unit cell, and (d) DCLSG HMSIW-SSPP unit cell. The detailed dimensions are $d = 0.6$ mm, $s = 0.9$ mm, $w = 6.4$ mm, $h = 2.94$ mm, $h_l = 1$ mm, $g = 0.4$ mm, $p = 2$ mm, $t_0 = 0.018$ mm, and $h_0 = 0.508$ mm.

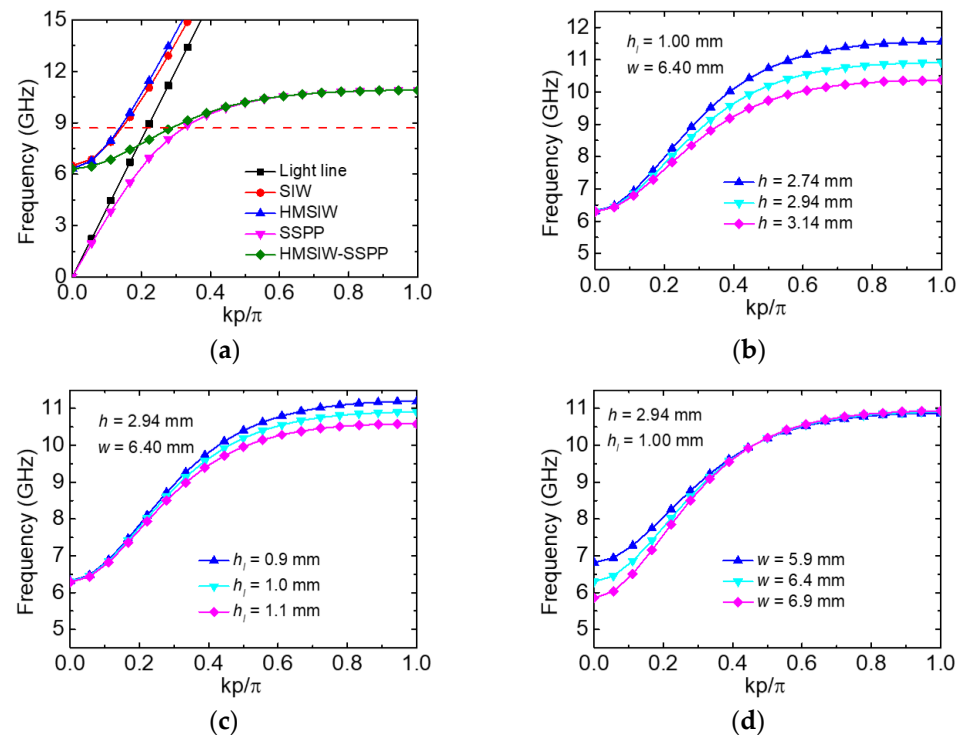


Figure 2. Simulated dispersion curves of (a) SIW, HMSIW, SSPP unit cell, and HMSIW-SSPP unit cell, (b) HMSIW-SSPP unit cell with different lateral groove length h , (c) HMSIW-SSPP unit cell with different longitudinal groove length h_l , and (d) HMSIW-SSPP unit cell with different width w .

Figure 2b,c illustrate the impacts of the transverse groove length (h) and longitudinal groove length (h_l) on the cut-off frequencies of the DCLSG HMSIW-SSPP structure. As the h (h_l) increases from 2.74 mm (0.9 mm) to 3.14 mm (1.1 mm), the upper cut-off frequency decreases from 11.55 GHz (11.20 GHz) to 10.36 GHz (10.59 GHz), while the lower one is almost unchanged, remaining at around 6.3 GHz (6.3 GHz). Figure 2d demonstrates the

dispersion curves of the DCLSG HMSIW-SSPP unit cell versus diverse values of w . As w increases from 5.9 to 6.9 mm, the lower cut-off frequency decreases from 6.82 to 5.86 GHz, while the upper one keeps almost constant, remaining at around 10.9 GHz. Thus, we can independently regulate the lower and upper cut-off frequencies of the DCLSG HMSIW-SSPP structure by altering its geometric dimensions, which offers the feasibility of designing the bandpass filtering device with an independently controllable wide bandwidth.

3. Design of HMT

Figure 3a,b show that we first designed an HMT based on dual-layer Rogers 4350B substrates and three copper layers. In this design, Port 4 on substrate 2 is served as the sum port and excites SIW through the tapered microstrip line (ML). Then, the longitudinal slot with a width of $g_1 = 1.8$ mm divides the SIW into two symmetrical HMSIW. The tapered MLs with a length of l_2 realize the mode and impedance transition from the HMSIW to the output uniform MLs ports. Figure 3c shows the simulated S-parameters of the sum port driven. It exhibits a high-pass transmission response from 6.9 to 10.5 GHz, and the $|S_{24}|$ is approximately equal to the $|S_{34}|$. Figure 3d is the simulated phases of the S_{24} and S_{34} , showing a maximum phase difference of 2.4° between Ports 2 and 3 within 6 to 10.5 GHz. Thus, the function of PD is achieved.

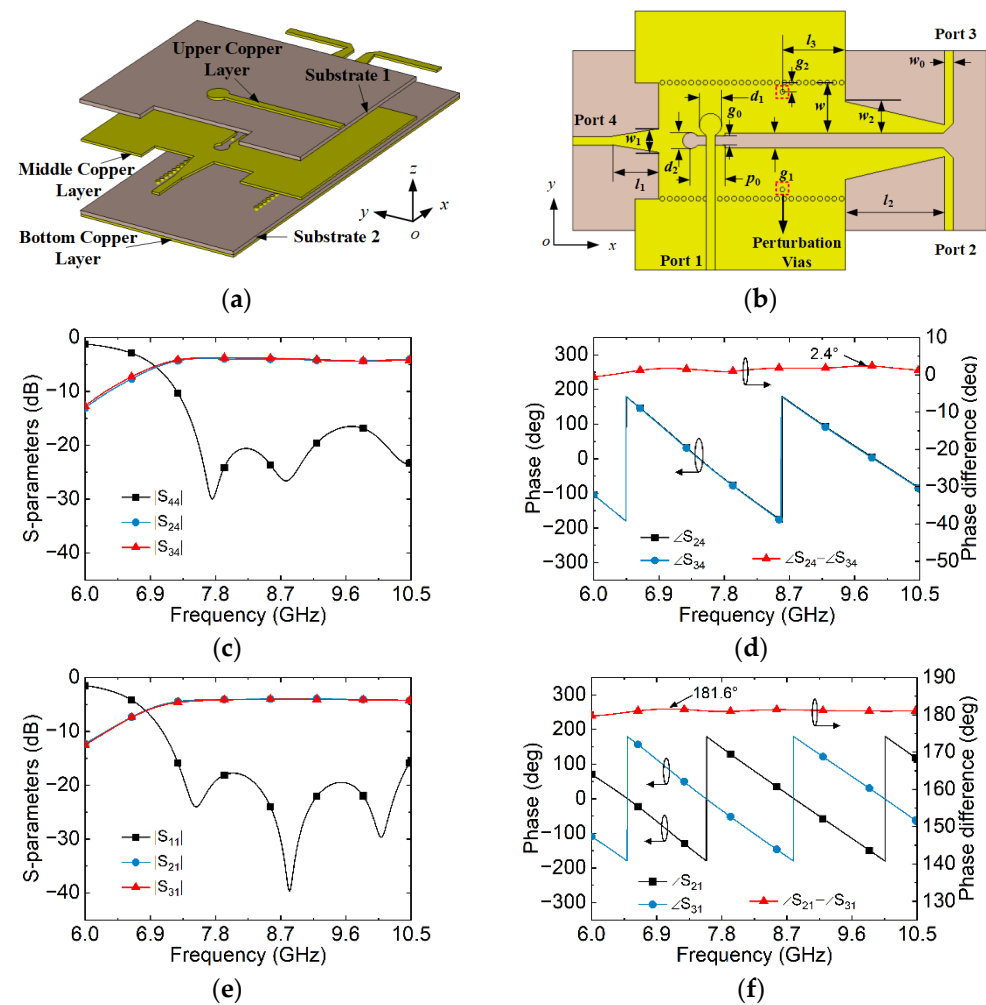


Figure 3. Configurations and simulated results of HMT. (a) Exploded view. (b) Top view (Substrate 1 is set as transparent to show intuitively). (c) S-parameters of sum port driven. (d) The phase of sum port driven. (e) S-parameters of difference port driven. (f) The phase of difference port driven. The detailed dimensions are $w_1 = 3$ mm, $l_1 = 5.82$ mm, $d_2 = 2$ mm, $d_1 = 2.8$ mm, $g_0 = 1.2$ mm, $p_0 = 4.31$ mm, $g_1 = 1.8$ mm, $g_2 = 1.16$ mm, $w = 6.4$ mm, $w_2 = 4$ mm, $l_2 = 12.5$ mm, $l_3 = 7.9$ mm, and $w_0 = 1.1$ mm.

Port 1 on substrate 1 is served as the difference port and excites symmetric HMSIW through the slot coupling. Herein, the width of the slot under Port 1's feed line is reduced to $g_0 = 1.2$ mm, which improves the impedance matching of input and the isolation between the sum and difference ports. Substrate 1 is extended along the x -axis direction to cover the HMSIW parts. Figure 3e shows the simulated S-parameters of the difference port driven. It achieves the high-pass transmission response from 6.85 to 10.5 GHz, and the input power is equally divided at Ports 2 and 3. Figure 3f illustrates the simulated phases of the S_{21} and S_{31} , which demonstrate that Ports 2 and 3 achieve a maximum phase difference of 181.6° from 6 to 10.5 GHz. Therefore, the balun function is obtained. The structures in the HMT served as the PD and balun functions share the output ports. Moreover, the results in Figure 3d,f indicate that the fields excited by the sum and difference ports possess different symmetry, which enables the natural physical isolation between the sum and difference ports [32].

Herein, we introduce two perturbation vias to enhance the reflection performance of the difference and sum ports. The diameter of the perturbation via is 0.6 mm. Figure 4 shows the simulated S-parameters of the HMT with or without perturbation vias. The lower end of the $|S_{11}|$ at 7.8 GHz decreases from -12.16 to -19.22 dB, and that of $|S_{44}|$ reduces from -13.90 to -28.85 dB, indicating the perturbation vias can effectively enhance the reflection performance of the HMT's two input ports. The role of the perturbation vias is equivalent to the narrow-to-wide SIW transition in [33]. The perturbation vias reduce the width of the HMSIW, raising the lower cut-off frequency of the HMT's passband. In addition, the widths of input and output MLs in the HMT are set as 1.1 mm (corresponding to the characteristic impedance of 50Ω), which facilitates connecting with the SMA connectors to test.

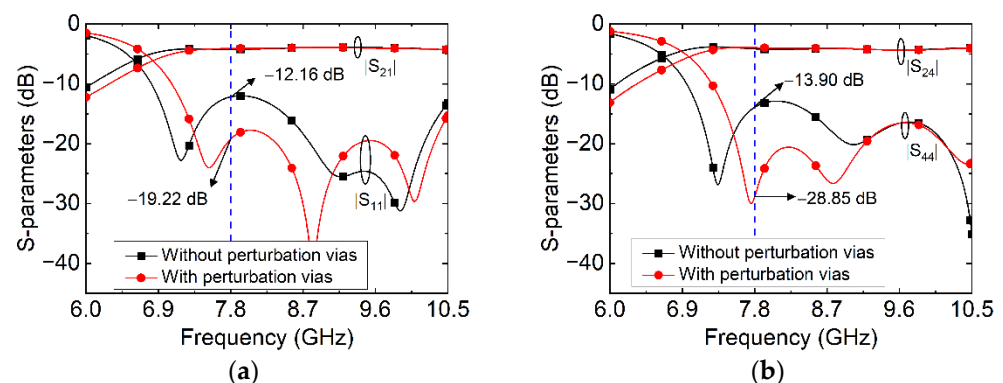


Figure 4. Simulated S-parameters of HMT with or without perturbation vias. (a) Difference port is driven. (b) Sum port is driven.

4. Design of FMT

As shown in Figure 5, the proposed FMT is constructed by symmetrically inserting the subwavelength DCLSG SSPP structures into each branch of HMT's HMSIW without altering other dimensions. The proposed FMT's structural parameters are given in Figure 5. The HMSIW-SSPP structures in the proposed FMT are mainly divided into three parts.

Part I consists of three HMSIW-SSPP unit cells (M1, M2, and M3) with different groove lengths. Part II comprises two identical HMSIW-SSPP unit cells (M4) whose dimensions are identical to that in Figure 1a. The role of Part I is to implement the mode conversion and momentum matching from the HMSIW to the HMSIW-SSPP structures in Part II. Its operating principle can be explicated by the matching theory [34]. The dispersion curves of the HMSIW and the HMSIW-SSPP unit cells in Part I and Part II are analyzed and portrayed in Figure 6. As the unit cell changes from M1 to M3, the dispersion curve of the HMSIW-SSPP unit cell is far away from the HMSIW and approximates the unit cell M4. Thus, good momentum matching is achieved. Part II can determine the desired passband with lower and upper cut-off frequencies. The role of Part III is inverse to that of Part I. Figure 7 illustrates the simulated S-parameters of the proposed FMT. The 3-dB FBW of the

difference port driven is 36.44% (7.07–10.22 GHz), and that of the sum port driven is 35.16% (7.15–10.20 GHz). Thus, a wideband FMT based on the HMSIW-SSPP structure is obtained.

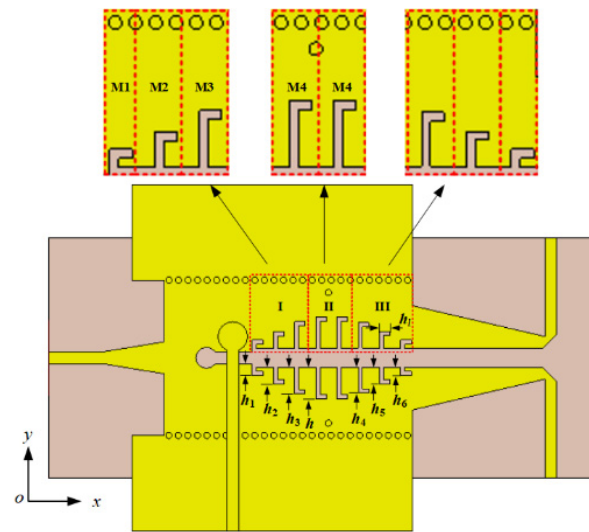


Figure 5. Configurations of FMT. The detailed dimensions are $h = 2.94$ mm, $h_l = 1$ mm, $h_l = 0.77$ mm, $h_2 = 1.55$ mm, $h_3 = 2.50$ mm, $h_4 = 2.42$ mm, $h_5 = 1.58$ mm, and $h_6 = 0.77$ mm.

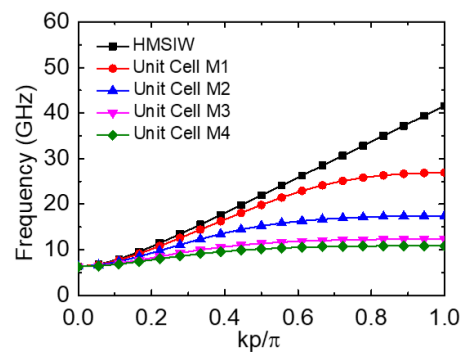


Figure 6. Dispersion curves of HMSIW and HMSIW-SSPP unit cells in Part I and Part II.

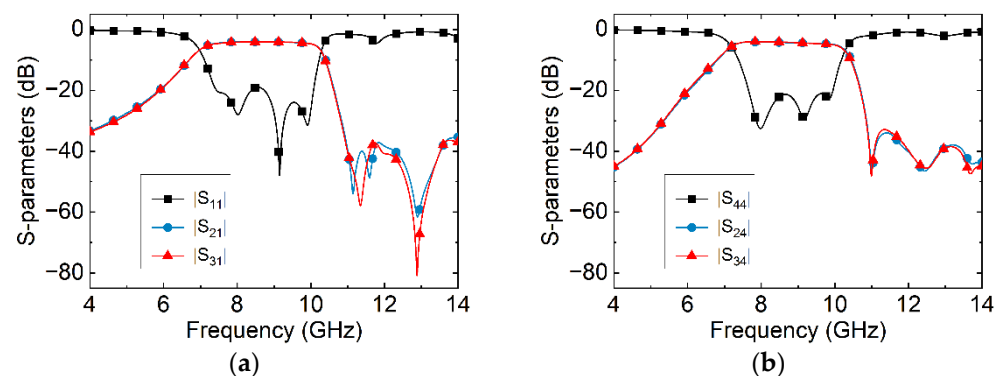


Figure 7. Simulated S-parameters of the proposed FMT. (a) The difference port is driven. (b) The sum port is driven.

Figure 8 demonstrates the simulated S-parameters of the proposed FMT under the impacts of geometric parameters h , h_l , and w in Part II. Owing to the structural symmetry between Ports 2 and 3, we only give the simulated results of S_{21} and S_{24} . As illustrated in Figure 8a–d, as the h (h_l) increases from 2.74 mm (0.9 mm) to 3.14 mm (1.1 mm), the upper cut-off frequency of the $|S_{21}|$ decreases from 10.75 GHz (10.47 GHz) to 9.64 GHz (9.95 GHz)

and that of the $|S_{24}|$ decreases from 10.85 GHz (10.44 GHz) to 9.61 GHz (9.93 GHz). However, the lower cut-off frequencies of the $|S_{21}|$ and $|S_{24}|$ remain unchanged. As illustrated in Figure 8e,f, as the w increases from 5.9 to 6.9 mm, the lower cut-off frequency of the $|S_{21}|$ ($|S_{24}|$) decreases from 7.62 GHz (7.68 GHz) to 6.6 GHz (6.74 GHz). Nevertheless, the lower cut-off frequencies of the $|S_{21}|$ and $|S_{24}|$ are almost unchanged. The rule of the simulated S-parameters affected by h , h_l , and w coincides well with the dispersion analysis in Figure 2b–d. Thus, we can independently control the lower and upper cut-off frequencies of the proposed FMT's passband by tuning several structural parameters.

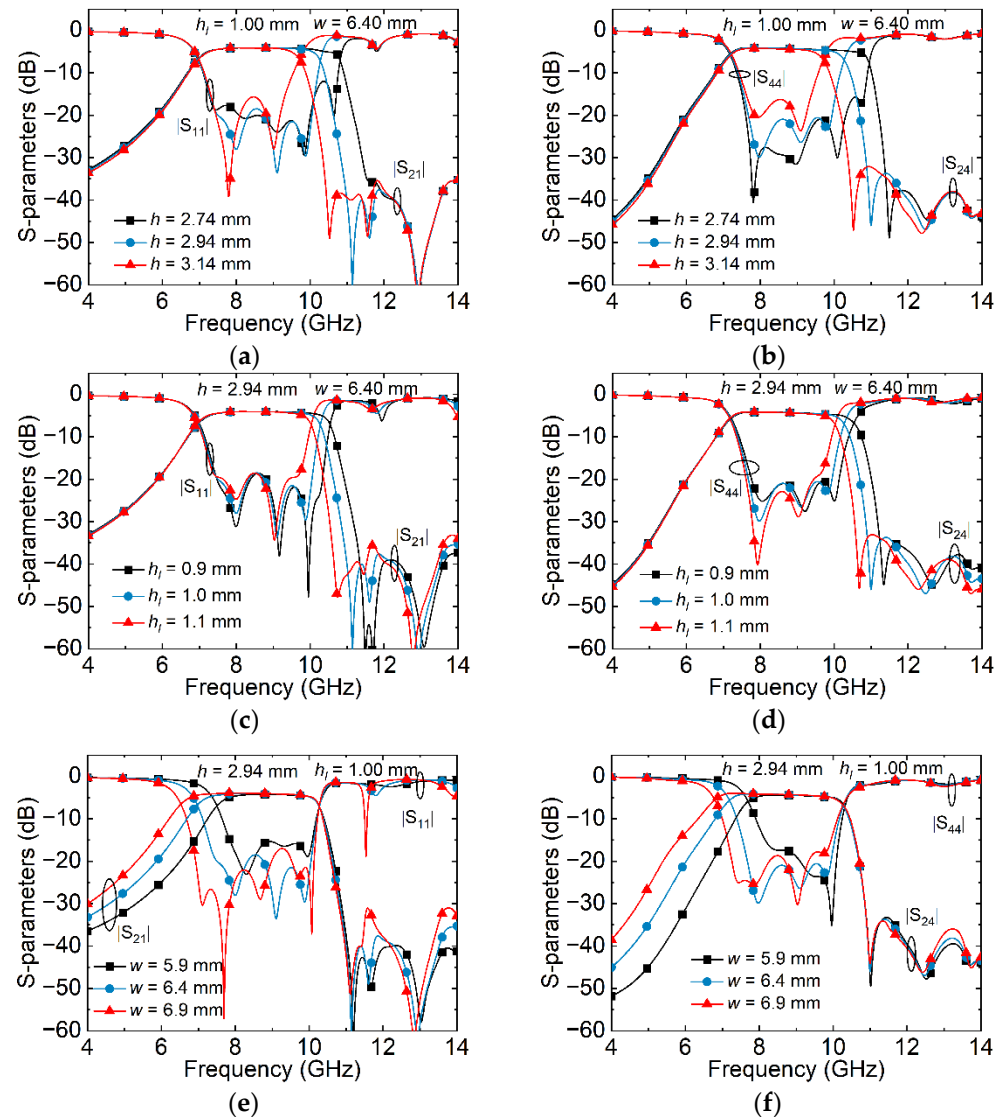


Figure 8. Passband controllability analysis of the FMT. (a) $|S_{11}|$ and $|S_{21}|$ with different values of h . (b) $|S_{44}|$ and $|S_{24}|$ with varying values of h . (c) $|S_{11}|$ and $|S_{21}|$ with different values of h_l . (d) $|S_{44}|$ and $|S_{24}|$ with varying values of h_l . (e) $|S_{11}|$ and $|S_{21}|$ with different values of w . (f) $|S_{44}|$ and $|S_{24}|$ with varying values of w .

Figure 9a,b demonstrate the configurations of proposed FMT with three and four HMSIW-SSPP unit cells in Part II, respectively. The perturbation vias are located in the middle of Part II. Their simulated S-parameters of difference and sum ports driven are shown in Figure 10a,b, respectively. The increase of the unit cells in Part II slightly improves the selectivity and bandwidth of the FMT.

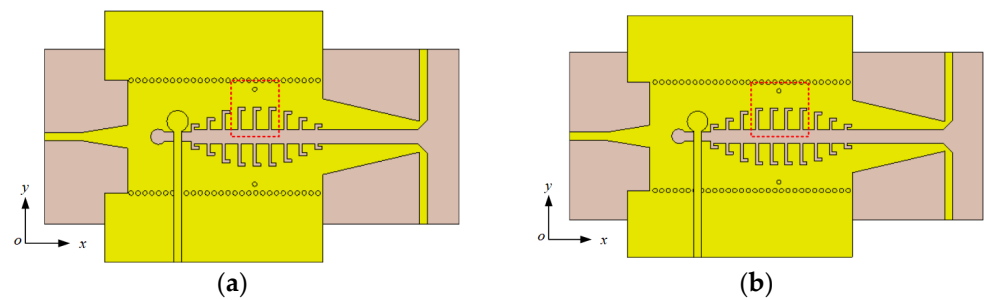


Figure 9. Configurations of the proposed FMT with (a) three-unit cells in Part II and (b) four-unit cells in Part II.

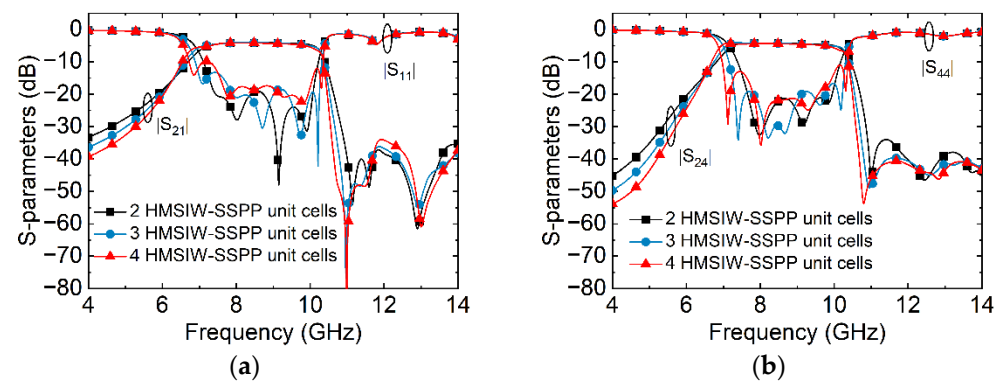


Figure 10. Simulated S-parameters of the proposed FMT with different unit cells in Part II of (a) difference port driven and (b) sum port driven.

5. Measurement and Discussion

To validate the above analysis, the FMT prototype with two-unit cells in Part II is fabricated, and its photograph is displayed in Figure 11. Its dual-layer substrates are fabricated separately using the printed circuit board (PCB) process. Then, seven screws are utilized to fix the dual-layer substrates. The SMA connectors are welded to the four MLs ports before testing by the Agilent Technologies E8363B network analyzer. Figure 12a illustrates the simulated and measured S-parameters of the difference port driven. It exhibits a measured 3-dB FBW of 40.23% from 6.95 to 10.45 GHz. In the passband, the measured minimum insertion loss (IL) is 1.09 dB (excluding intrinsic 3 dB loss of the balun), and the measured return loss (RL) is higher than 11.35 dB. In addition, its measured 20-dB stopband rejection reaches $2.12 f_0$.

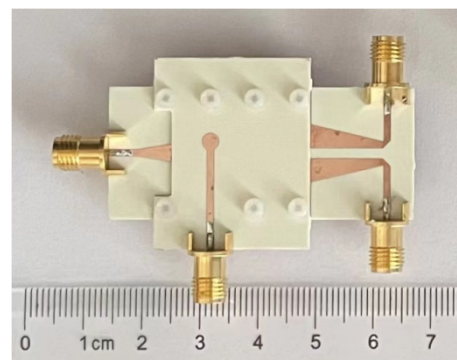


Figure 11. Photograph of the proposed HMSIW-SSPP FMT.

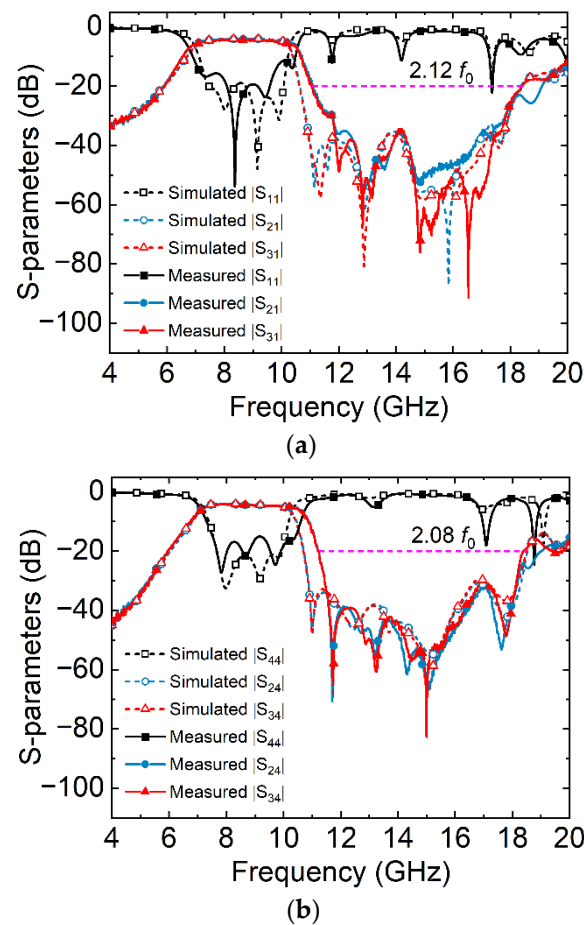


Figure 12. Simulated and measured results of the FMT. (a) $|S_{11}|$, $|S_{21}|$, and $|S_{31}|$. (b) $|S_{44}|$, $|S_{24}|$, and $|S_{34}|$.

The simulated and measured S-parameters of the sum port driven are demonstrated in Figure 12b. As can be observed, it exhibits a 3-dB FBW of 38.96% from 7.11 to 10.55 GHz, a minimum IL of 1.27 dB (excluding the 3-dB PD loss), and an RL of better than 15.01 dB. It produces a wide stopband rejection of 20 dB up to $2.08 f_0$. The measured 3-dB FBW of the sum and difference ports driven are wider than their simulated ones, which are mainly caused by the air gap between the two layers of PCBs from machining and assembling tolerance. Although three resonances at 11.78, 14.2, and 17.36 GHz and two resonances at 13.15 and 17.09 GHz are observed in the stopband of the difference and sum ports driven, respectively, which radiate power to the space, their bandwidth is very narrow. They hardly affect the overall stopband performance of the FMT.

The isolation performances of the FMT are shown in Figure 13. In the operating band, the measured isolation between Ports 2 and 3 is >15.87 dB, and that between Ports 1 and 4 is >27.17 dB. Moreover, the FMT's simulated and measured balance performances are demonstrated in Figure 14. When the sum port is driven, the measured worst amplitude imbalance (AI) and phase imbalance (PI) between Ports 2 and 3 are 0.25 dB and 3.5° , respectively. When the difference port is driven, the measured worst AI and PI between Ports 2 and 3 are 0.39 dB and 4.7° , respectively. The measured performance is in good consistency with the simulated ones.

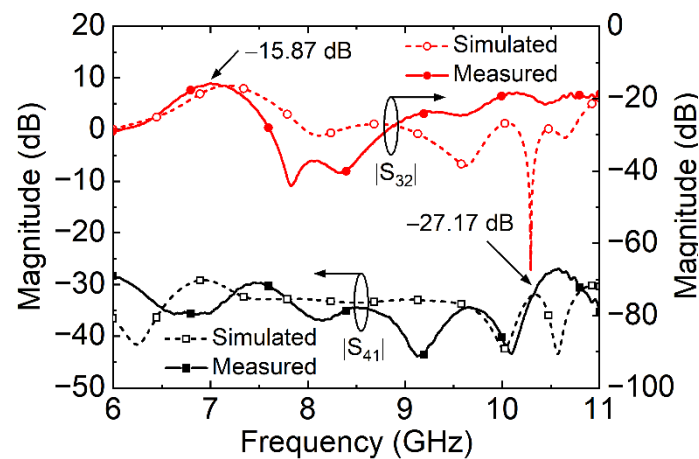
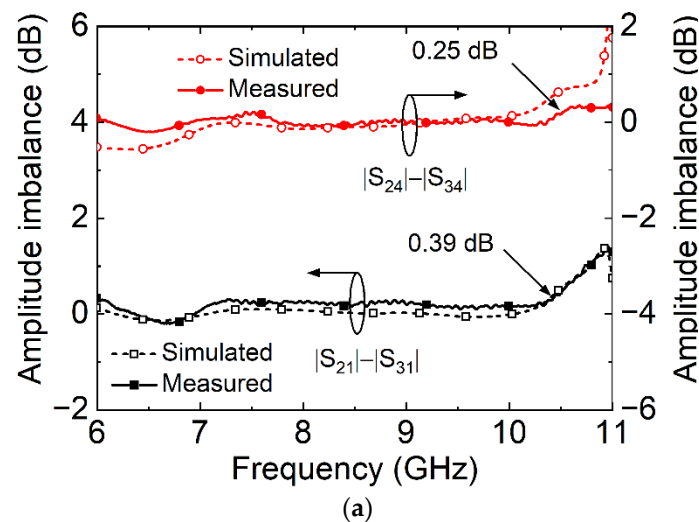
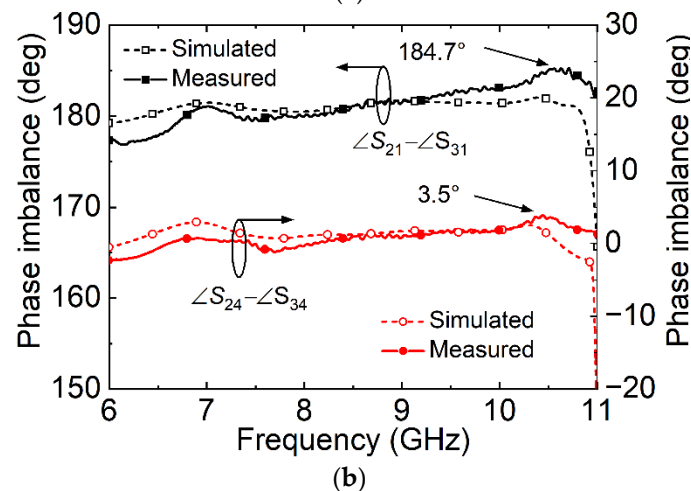


Figure 13. Simulated and measured isolation performances of the proposed FMT.



(a)



(b)

Figure 14. Simulated and measured balance performances of the FMT. (a) Amplitude imbalance. (b) Phase difference.

Figure 15a,b show the simulated electric-field distributions of the proposed FMT at various frequencies. When the difference port is driven, the two-channel reverse-phase signals equally transmit to Ports 2 and 3 at 8.7 GHz because it operates within the dual cut-off frequencies of the HMSIW-SSPP's passband. The signals at 5.4 GHz and 11 GHz are prohibited since they are below the HMSIW-SSPP's lower cut-off frequency and above

the HMSIW-SSPP's upper one, respectively. On the other hand, the two-channel in-phase signals are efficiently guided to the output ports in the passband (8.7 GHz) when the sum port is driven. However, the signals operating at the out-of-band, such as 5.4 and 11 GHz, are blocked gradually. The simulated electric-field distributions in Figure 15a,b exhibit a good consistency with the simulated S-parameters of the FMT shown in Figure 7. Moreover, the simulated electric-field distributions of the HMT at 8.7 GHz are plotted in Figure 16a,b. At 8.7 GHz, the FMT achieves a nearly 50% longitudinal size reduction and higher electric-field constraints than the HMT, which verifies the propagation constant's properties of the HMSIW and DCLSG HMSIW-SSPP structure described in Figure 2a.

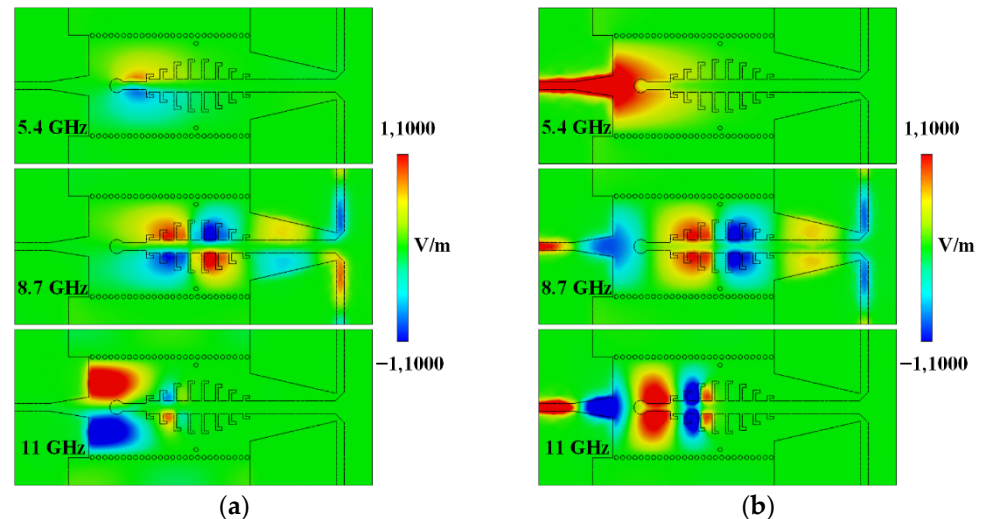


Figure 15. Simulated z -component electric-field distributions of the proposed FMT on the plane of $z = 0.526$ mm. (a) The difference port is driven. (b) The sum port is driven.

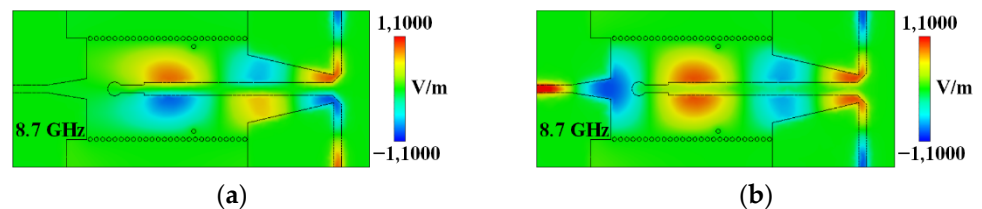


Figure 16. Simulated z -component electric-field distributions of the HMT on the plane of $z = 0.526$ mm. (a) The difference port is driven. (b) The sum port is driven.

Table 1 compares our design with other reported SIW magic-Ts and FMTs. Compared to the designs in [4,5], the proposed FMT realizes bandpass filtering response and miniaturization attributed to the bandpass characteristic and SW effect of the HMSIW-SSPP structure, and we can easily control the upper and lower cut-off frequencies of the passband by altering the structural parameters. Moreover, compared to the reported state-of-the-art FMT based on SIW technology [8–10,12–14,17], our proposed FMT exhibits the unique advantages of the wide operating bandwidth and wide stopband performance while maintaining a relatively compact size.

Table 1. Comparisons with previously reported SIW magic-Ts and FMTs.

Ref.	f_0 (GHz)	FBW (%)	IL (dB)	AI. (dB) /PI. (°)	FR	Rej. (dB) /S.B. (f_0)	Size ($\lambda_g \times \lambda_g$)	Tech. Type.
[4]	8.9	11.24	0.7	0.2/1.5	No	-	3.98×2.46	SIW
[5]	14.5	17.93	0.43	0.23/1.5	No	-	4.64×2.99	SIW
[8] *	24.1	8.59	2.24	0.25/6	Yes	No.	1.19×1.26	LTCC
[8] ‡	24.25	8.62	2.2	0.25/6	Yes	No	1.20×1.27	LTCC
[9] *	9	0.78	1.91	0.35/5	Yes	No	2.44×2.44	SIW
[9] ‡	9.01	0.78	1.91	0.35/5	Yes	No	2.44×2.44	SIW
[10]-1	11.8	3.4	1.3	0.1/2.5	Yes	No	1.18×1.18	SIW
[10]-2	10.94	3.1	1.3	0.05/2.5	Yes	No	0.88×1.64	SIW
[12]	7.75	2.6	1.45	0.56/5	Yes	20/1.48	0.79×0.42	SIW
[13]	11	1.4	2	0.8/9	Yes	No	1.36×1.28	SIW
[14]-1	10.3	2.7	1.4	0.05/3	Yes	No	1.21×1.21	SIW
[14]-2	10.2	3.1	1.35	0.1/3	Yes	No	1.19×1.19	SIW
[17]	10.02	7.58	0.89	0.48/4.8	Yes	No	1.22×1.22	SIW-CPW
T.W. *	8.7	40.23	1.09	0.39/4.7	Yes	20/2.12	2.81×1.76	HMSIW-SSPP
T.W. ‡	8.83	38.96	1.27	0.39/4.7	Yes	20/2.08	2.85×1.79	HMSIW-SSPP

Ref.: Reference; f_0 : Center frequency; FBW: Fractional bandwidth; IL: Insertion loss (without including intrinsic 3-dB insertion loss of the PD); AI: Amplitude imbalance; PI: Phase imbalance; FR: Filtering response; Rej./S.B.: Rejection/Stopband. λ_g : Guided wavelength at the frequency of f_0 ; Tech. Type.: Technology type; T.W. This work; *: Results of difference port driven.; ‡: Results of sum port driven.

6. Conclusions

This paper proposes a novel FMT based on the DCLSG HMSIW-SSPP structure for the first time. First, the dispersion properties of the DCLSG HMSIW-SSPP unit cell were investigated. The results show that the DCLSG HMSIW-SSPP structure has a >50% size reduction than HMSIW and we can independently regulate its lower and upper cut-off frequencies by changing structural dimensions. Then, an HMT based on dual-layer substrates was designed, and the proposed FMT was constructed by inserting the DCLSG SSPP structures into the HMT. The proposed FMT exhibits independently adjustable lower and upper cut-off frequencies of the passband. Finally, a prototype of the proposed FMT was fabricated to verify this design idea. The experimental results are in good consistency with the simulated ones. Compared with SIW magic-Ts in [4,5] and FMTs in [8–10,12–14,17], this design achieves the superiorities of compactness, wide filtering bandwidth, wide stopband rejection, and ease to design. It could be a capable candidate for future wireless communication systems.

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