A High-Selectivity D-Band Mixed-Mode Filter Based on the Coupled Over-Mode Cavities

Yi-Wen Wu, Student Member, IEEE, Zhang-Cheng Hao, Senior Member, IEEE, Rong Lu, Student Member, IEEE, and Jia-Sheng Hong, Fellow, IEEE

Abstract—A D-band low-loss mixed-mode filter with high selectivity is proposed and analyzed in this paper. The transverse quintuplet/triple topology has been employed in the design with coupled over-mode cavities using the TE_{2N,1,0} modes (N=2, 3, 4,...) and TE_{2N,1,0}-like modes. Two transmission zeros (TZs) are generated in the upper and lower stopbands. The fractional bandwidth (FBW) and positions of the TZs can be flexibly designed by properly selecting the geometries of the proposed over-mode cavity, which determine the frequencies of all resonating modes. To improve the frequency selectivity, multiple coupled over-mode cavities, which have different spurious responses and TZs distributions, are cascaded for the designed filter. As demonstrations, two types of filter architectures are proposed for two D-band mixed-mode bandpass filters, respectively, which shows the design flexibility of the proposed method. The first filter is realized by cascading multiple over-mode cavities through waveguide sections, and the second filter is realized by cascading over-mode cavities through slots. Experiments are carried out to verify the second filter with TZs. The measured FBW is 17.18% from 128.11 GHz to 152.19 GHz, the minimum insertion loss is around 0.33 dB, and the measured rectangle coefficient (BW_{40dB}) is about 1.38. The measured results agree well with the designed ones, which verifies the proposed method. The proposed filter can be a good candidate for millimeter wave and terahertz systems.

Index Terms—D-band, high selectivity, low insertion loss, mixed-mode filter, over-mode cavity, transverse quintuplet topology, transmission zeros (TZs).

I. INTRODUCTION

RECENTLY, the terahertz (THz) frequency region, loosely ranging from 0.1 to 10 THz, has drawn great attention for the potential applications in the security imaging, biological sensing, ultra-high speed communication, precision radars, and astronomy [1]-[10] due to its wideband spectrum, high spatial and temporal resolution. With the prosperous development of THz science and technology, the THz filter as an essential component in THz systems, has been extensively investigated [11]-[14]. Based on liquid crystals, photonic crystals, metamaterials and frequency-selective surfaces (FSS), a number of THz filters have been studied in [15]-[20]. These filters are exclusively for filtering free-space THz waves in the quasi-optical systems. With the advancement of low-temperature co-fired ceramic (LTCC) technology and micromachining technologies, THz filters based on coupling matrix theory have been reported [21]-[24]. Two 150 GHz LTCC filters with negative and positive couplings, which are realized by different coupling apertures, are illustrated in [21]. The insertion loss of five-pole Chebyshev filter is 8.4 dB with 1.31% FBW and the insertion loss of four-pole quasi-elliptic filter can be reduced to 5.5 dB with 1.35% FBW by removing a resonant cavity and introducing two transmission zeros. In [22], [23], 140 GHz fourth-order and third-order filters with cascaded nonuniform slotted-SIW-based electromagnetic bandgap (EBG) units are demonstrated. The measured minimum insertion losses are 2.44 dB and 1.91 dB, respectively. By adopting the quasi-TE_{111} mode of circular-SIW cavity and the TE_{130}, TE_{140} modes of the over-mode SIW cavity, a four-order filter with the minimum insertion loss of 1.9 dB at 174 GHz is investigated in [24]. The LTCC THz filter has a planar form and a low cost. However, its dramatically increased insertion loss is a challenge for the terahertz filter implementation.

Nowadays, metallic waveguides are popularly adopted for designing high performance THz filter due to its merits of high quality factor and simple fabrication. Based on different micromachining techniques, such as Si deep reactive ion etching (DRIE) [25]-[27], SU-8 photoresist technology [28]-[31], and computer numerical control (CNC) metal-milling technology [32]-[36], a few THz filters have been reported with a low insertion loss. For example, the insertion loss of a D-band 5-pole filter is 0.61 dB with 10.39% FBW in [25], the measured insertion loss of a 400 GHz silicon micromachined filter with elliptic cavities is up to 2.84 dB with 7.52% FBW in [26], and a 570 GHz silicon micromachined three-pole waveguide filter has a 0.9-dB insertion loss in [27]. The SU-8 photoresist technology shows promising advantages for the implementation of the THz filter [28]-[31]. For example, the measured minimum insertion loss of a 300GHz fifth-order waveguide filter is around 1 dB with 8% FBW in [30]. Apart from the above two technologies, the precision CNC machining technology is also a promising candidate for realizing high performance THz waveguide devices [32]-[36]. Following rapid
development of the precision CNC machining technology, CNC machined waveguide components with high performance have been developed. For example, the insertion loss of the 257.7 GHz filter based on cross coupling is about 0.7 dB with 8.77% FBW at 34, while the 256.3 GHz filter based on modal bypass coupling has an insertion loss of around 0.5 dB with 9.83% FBW [34]. In [35], a 220-GHz fourth-order quasi-elliptic filter fabricated by CNC metal-milling technology exhibits a 0.6-dB insertion loss and 9.8% FBW at 3dB. By utilizing mode cancellation technology between the spurious mode and dominant mode, a 140 GHz fifth-order filter with two TZs has a 0.52-dB insertion loss and 9.29% FBW3dB [36]. Generally, a good insertion loss is achieved in [33]-[36]. However, their design becomes much complex if a wide stopband suppression and a high selectivity are desired, which also leads to an increased cost. Moreover, different to the DRIE and SU-8 technologies which can afford a fabrication tolerance up to a few micrometers, special considerations still have to be taken for the CNC machining technology due to its cost and fabrication tolerance limitation. For example, a simple filter topology and a relative large coupling slot would be helpful to improve the CNC implementation quality.

In this paper, we proposed a high selective THz mixed-mode filter with simple structure and design process. And higher order filters are realized by cascading multiple over-mode cavities through waveguide sections or slots [37]-[39]. The FBW and the TZs’ distributions can be flexibly adjusted by properly selecting the geometries of the over-mode cavity, which determine the distributions of corresponding resonating modes. Section II describes the operating mechanism of the basic over-mode filter block. The determination of the positions of TZs and FBW are presented, and some empirical formulas are given for determining the initial geometries of the basic filter block. In Section III, two 140 GHz bandpass prototypes with high selectivity are designed for validations. Section IV presents experimental results for verifications, as well as comparisons between the proposed filter and relative works in literatures. Finally, Section V draws a conclusion.

II. MECHANISM OF THE PROPOSED OVER-MODE CAVITY

A. Basic Configuration and Topology

As indicated in Fig. 1, the basic building block for the proposed filter is the coupled over-mode cavity, which consists of two cavities and a few slots. The input/output is the standard WR06 waveguide for 140 GHz applications, and feeding slots are etched at the top/bottom center of two cavities. Those resonant cavities are designed with an even-order mode, i.e. TE2N,1,0 (N=2,3,4,…), at the center frequency of the bandpass filter by properly turning the dimensions of the cavities (L1 and W1). The height of the cavities is 0.78mm, which is similar to the standard WR06 waveguide. Between those two cavities, two slots are used for implementing the inter-coupling. Fig. 2 shows the electromagnetic field distributions for different resonant modes of the proposed cavity. Different from the conventional low frequency applications, relatively large electrical sizes have to be adopted for coupling slots to ensure the CNC fabrication quality. Thus, two degenerated even-order modes, shown in Fig. 2b and 2d, appear near the conventional even-order mode shown in Fig. 2c. Since the proposed resonator is composed by two slot-coupled rectangular cavities, those three even-order modes have very similar electromagnetic field distribution, as shown in Fig. 2(b)-(d).

Fig. 3 illustrates the full-wave simulated S-parameters of the basic structure in Fig. 2 for the proposed filter with weak excitations. Five resonance points can be founded in Fig. 3, which indicates five resonate modes are involved in the filter design. To clearly describe those resonate modes, we name those resonate modes as R1 (at 129.4 GHz), R2 (at 135.1 GHz), R3 (at 137.6 GHz), R4 (at 142.3 GHz), and R5 (at 149.8 GHz), respectively. In addition, the electric field distributions of those resonate modes are presented in Fig. 4. Obviously, two more resonant modes are obtained under weakly coupled excitation. Moreover, the signs of the vector electric field distributions of the R1, R2, R3 modes at the input (S) and output (L) ports are the same in Fig. 4(a) and (c) and (e). Hence, the input and output couplings have the same amplitude and sign (MS = M2L, M3 = M3L, and M5 = M5L). On the contrary, the input and output couplings of the R4 and R5 modes have different signs (M4 = -M4L, M5 = -M5L) according to the vector electric field distributions in Fig. 4(b) and (d). Consequently, the transversal quintuplet topology in Fig. 5 can be implemented by these five resonators.

B. Study of the Coupling Coefficients

The transversal quintuplet topology based on the quintuplet modes cavity can generate five poles within the passband as well as TZs in the upper and lower stopbands. What can be clearly seen in Fig. 3 is: f1 < f2 < f5 < f3 < f5. Hence, the resonant frequencies (f1 and f5) of the R1 and R5 modes determine the bandwidth (BW) of the proposed filter. In addition, a TZ located in the lower stopband is generated when M2 > M1 (and M3 > M4), and a TZ located in the upper stopband is generated when M4 > M5 (and M4 > M5) [38]. Fig. 6 reveals the extracted coupling coefficients M1, M2, M3, M4, and M5 versus different geometries of feeding slot. Apparently, the coupling coefficients have a steady fall as the height (t1) of feeding slot increases. In addition, the coupling coefficients M2, M3, and M4 are similar, and so are the coupling coefficients M1 and M5. Furthermore, the input and output couplings satisfy the following relation: M2 ≈
$M_3 \approx M_4 > M_1 \approx M_5$. Hence, the TZs located in the upper and lower stopbands respectively are generated based on the characters of the transverse quintuplet topology.

As depicted in Fig. 4, since the field distribution in each cavity is similar to that of the TE$_{4,1,0}$ mode, the resonant frequencies can be estimated by using a few formulas. Supposing the proposed filter is operated with a center frequency of $f_0$, the length ($L_1$) of the over-mode cavity is designed as $N \lambda_{g0}$ at $f_0$ to keep the dominant TE$_{2N,1,0}$ ($N=2,3,4,...$) mode resonating at center frequency when the width ($W_1$) of the over-mode cavity is chosen, which can be calculated by (1)-(3).

For example, if $W_1$ is chosen as 1.64 mm, $L_1$ should be $2 \lambda_{g0}$, i.e. 5.64 mm, for obtaining the TE$_{4,1,0}$ resonating mode at 140 GHz.

$$\lambda_g = \frac{c_0}{f_0}, \quad \lambda_{g0} = \frac{\lambda_g}{1 - \left(\frac{c_0}{\lambda_g}\right)^2}$$  \hspace{2cm} (1)

$$L_1 = N \lambda_{g0}, \quad N=2,3,4,...$$  \hspace{2cm} (2)

$$L_s = \frac{\lambda_{g0}}{2}$$  \hspace{2cm} (3)

where $c_0$ is the speed of light in vacuum, $f_0$ is the center frequency, $\lambda_{g0}$ is the guide wavelength at the center frequency $f_0$.

Due to the limitation of the available CNC metal-milling technology, wide coupling slots have to be adopted in the design to relax manufacturing tolerances, which have a width of 0.5 mm, i.e. around one third of the width of the cavity. Consequently, degenerated TE$_{2N+1,1,0}$-like ($N=2,3,4,...$) modes are generated inside each cavity, of which the resonant frequencies determine the BW of the proposed filter. Due to the large thickness of the feeding slot, it works like a waveguide. Therefore, the cut-off frequency determined by the length ($L_s$) of the feeding slot should be lower than the passband of the filter.

As shown in Fig. 2, according to the eigenmode simulation in the HFSS, the $R_1$ mode appears between TE$_{1,1,0}$ ($N=2,3,4,...$); (b) the given bandwidth is equal to the frequency interval of two degenerated modes, i.e. $BW = f_{R_5} - f_{R_1}$. A few empirical formulas have been developed to speed up the initial design.

$$f_{TE_{m,1,0}} = \frac{c_0}{2} \sqrt{\left(\frac{m^2}{W_1}\right)^2 + \left(\frac{1}{W_2}\right)^2}, \quad m=1,2,...$$  \hspace{2cm} (4)
where \( c_0 \) is the speed of light in vacuum, \( W_i \) and \( L_1 \) are the width and length of the cavities. \( f_{R_1} \), \( f_{R_2} \), and \( f_{R_3} \) are the resonating frequencies of the standard modes, i.e. \( R_1 \) and \( R_2 \) modes, respectively. And FBW is the fractional bandwidth of the bandpass filter.

Although the bandwidth of the proposed filter is mainly determined by the length \( L_i \) and width \( W_i \) of the resonators, the dimensions of coupling slots \((dy, L_c)\) can be used to adjust the self-coupling coefficients of each mode, which affects the filter bandwidth as well.

To demonstrate this, the self-coupling coefficients of each mode have been investigated by using full-wave parameter studies, as shown in Fig. 7. As clearly indicated in Fig. 7(a), a larger offset \((dy)\) of the coupling slots leads to larger \([M_{11}]\) and \([M_{55}]\), which results in a larger resonance frequency separation and wider passband. On the other side, a larger length \((L_c)\) of the coupling slots causes the increase of \([M_{11}]\), \([M_{33}]\), and \([M_{55}]\), as shown in Fig. 7(b). As a result, the passband shifts to a lower frequency. In addition, \(M_{22}\) and \(M_{44}\) keep nearly unchanged in Fig. 7(a)-(b). Unfortunately, the coupling of each mode can not be tuned independently to the others, as shown in Fig. 7. A non-independent control of self-coupling limits the degrees of freedom of the design a little bit. However, the selection of the desired band is still possible by designing the mode resonance frequency. Hence, the proposed structure provides a simple and efficient way for the THz filter design. Moreover, the implement of relatively large cavities and slots reduces the fabrication difficulty at THz band and improves the fabrication reliability.

To verify the proposed method, three filters with different FBW, are illustrated in Figs. 8-10 and Tables I-III by properly selecting the

\[
\begin{align*}
  f_{R_1} &= \frac{c_0}{2} \left( \frac{2N+0.5}{L_1} \right)^2 + \frac{1}{W_i^2}, \quad N=2, 3, 4, \ldots \tag{5} \\
  f_{R_2} &= \frac{c_0}{2} \left( \frac{2N+0.5}{L_2} \right)^2 + \frac{1}{W_i^2}, \quad N=2, 3, 4, \ldots \tag{6} \\
  \text{FBW} &= \frac{f_{R_2} - f_{R_1}}{f_{R_2}} \times 100\% \tag{7}
\end{align*}
\]

width \((W)\) and the standard even-order resonating mode \((\text{TE}_{2N,1,0})\) mode. Generally, a larger \(N\) or narrower width \((W)\) leads to a

![Fig. 7. Influence of (a) \(dy\) and (b) \(L_c\) of the coupling slots on the resonant frequencies: \(M_{11}, M_{22}\) and \(M_{55}\).](image)

![Fig. 8. First filter block.](image)

![Fig. 9. Second filter block.](image)
narrower bandwidth. It can be seen that the evaluated bandwidth and spurious passbands from (4)-(7) well predicts those of the designed filter.

C. Field Analysis of the Transmission Zeros (TZs)

As mentioned in part B, the proposed filter with the transversal quintuplet topology can generate two TZs in the upper and lower stopbands respectively, and the locations of TZs can be adjusted appropriately by changing the coupling coefficients of the transversal quintuplet topology. In this design, five resonant modes are excited by the same feeding slot, the adjustable range of ratio $M_2/M_1$ is limited, as revealed in Fig. 6. Hence, the positions of TZs varies within a certain range when the geometries ($W_1$ and $L_1$) of the over-mode cavity are determined. On this occasion, the approximate positions of TZs can be estimated according to the geometries of the over-mode cavity.

The electric field distributions of the TZs are depicted in Fig. 11. As presented in Fig. 11(a), the lower cavity is excited by the feeding slot. However, the upper cavity can not be excited through coupling slots. It can be clearly seen from the vector electric field distribution in Fig. 11(b) that the coupling slot is placed on the right top of the out-of-phase part of the two neighboring standing waves. Therefore, the coupling electromagnetic fields are cancelled, which leads to a TZ at lower stopband. This kind of field distribution is caused by the mode cancelling between $R_1$ mode at $f_1$ and $R_2$ mode at $f_2$ in the transversal quintuplet topology. In the same way, the field distribution of the TZ at upper stopband results from the mode cancelling between $R_1$ mode at $f_1$ and $R_1$ mode at $f_2$ in the transversal quintuplet topology.

To initially determine the positions of TZs, empirical formulas have been concluded as (8)-(10) according to the field distribution of TZs.

$$L_0 = \frac{L_1 - L_2}{2} = \frac{(2N-1)\lambda_m}{4}, \quad N = 2, 3, 4, \ldots \quad (8)$$

$$f_{TZ\text{-lower}} = \frac{c_0}{2} \sqrt{(\frac{1}{L_0})^2 + (\frac{1}{W_1})^2}, \quad N = 2, 3, 4, \ldots \quad (9)$$

$$f_{TZ\text{-upper}} = \frac{c_0}{2} \sqrt{(\frac{2}{L_0})^2 + (\frac{1}{W_1})^2}, \quad N = 2, 3, 4, \ldots \quad (10)$$

where $L_0$ is the distance from the center of coupling slot-1 to the edge of the over-mode cavity, and $W_1$ is the width of the cavities. $f_{TZ\text{-lower}}$ and $f_{TZ\text{-upper}}$ are the frequencies of the TZs.

Based on the initial geometries, designed filters have the similar TZ distributions in the Tables I-III, which shows that those empirical formulas are good enough for obtaining the initial geometries of the proposed filter.

III. DESIGN EXAMPLES

As shown in Figs. 8-10 and Table I-III, although the basic block of the proposed filter can provide a good passband and selectivity, there are spurious passbands appeared near the lower or upper passband. That decreases the filter performance. To solve this problem, two basic blocks which have different spurious passbands can be integrated to design the proposed bandpass filter for achieving a wide stopband with high rejection level. For a given specification, the design procedure of the proposed filter can be summarized as following:

According to the selected CNC machining process, the miniature width of the feeding slots and coupling slots are chosen to ensure that a good fabrication quality can be achieved. In this design, it is 0.5mm. (i) According to the given specifications, one can built the first filter block whose geometries, including cavity size, locations of the coupling slots, can be initially obtained from (1)-(10) by properly choosing the fundamental resonating modes and the locations of TZs. As introduced in part B of Section II, the geometries are tuned according to the coupling matrix for achieving a good in-band response. (ii) Following (i), one can built the second filter block whose initial geometries are obtained from (1)-(10). In this step, to extend the stopband, the spurious response and TZs’ locations are different to those of the first filter block, and the coupling control and practical tuning based on the coupling matrix are repeated as well. If higher
selectivity and wider stopband are desired, this step can be repeated for more filter blocks.

(iii) Cascaded filter blocks built above for the proposed filter. And the full-wave simulator is used to adjust or optimize the filter structure to achieve a good in-band return loss, high selectivity and wide stopband for given specifications.

To show the design process in detail, two filter examples operated with a center frequency of 140 GHz are illustrated in the following with different cascaded topologies.

A. Filter-I

The first filter adopts a series topology using two basic filter blocks, as shown in Fig. 12(a), and its side view and top view are presented in Fig. 12(b) and (c), respectively. The specifications of this filter are:

1. Center frequency: $f_0 = 140$ GHz;
2. FBW$_{1dB} = 11.5\%$;
3. In-band reflection coefficient: better than -20 dB;
4. $|S_{21}| \leq -40$ dB within 110-120 GHz and 160-170 GHz.

According to the design procedure mentioned above, the TE$_{4,1,0}$ mode is chosen as the fundamental resonating mode at 140 GHz, which ensures that the cavity has a relatively large size for the CNC machining technology. Due to the same reason, the width of the coupling and feeding slots are chosen as 0.5 mm and the length of slots are 1.25 mm when the cut-off frequency is chosen as 120 GHz. Then, the width and length of the over-mode cavity of the first filter block are determined by using (1)-(10) as 1.64 mm and 5.64 mm, respectively, which indicates that the TZs are located at 115.6 GHz and 168.3 GHz, and the spurious passbands appear at 105.7 GHz and 183.4 GHz, respectively. The length and offset of the coupling slots are optimized with the HFSS software as $L_{c1} = 1.22$ mm and $dy_1 = 0.50$ mm for a good in-band response of the first filter block, as shown in Fig. 8.

To suppress the spurious passbands of the first filter block, the width and length of the second filter block are chosen as 1.41 mm and 6.6 mm by using (1)-(10), which means that the spurious passbands of the second filter block appear at 115.7 GHz and 173 GHz, and the locations of the TZs are 122.5 GHz and 161.4 GHz. The length and offset of the coupling slots are then optimized as $L_{c2} = 1.21$ mm and $dy_2 = 0.27$ mm for a good in-band response of the second filter block, as shown in Fig. 9.

As illustrated in Fig. 13, the two designed filter blocks are cascaded together by a WR06 waveguide. By properly adjusting the geometries of slots and WR06 waveguide section in Fig. 12, the filter-I is designed with a high selectivity, and its final geometries are listed in Table IV. The full-wave simulated results for the filter-I are depicted in Fig. 14. It can be seen that the spurious passband of the first and second filter block are well suppressed, and the frequency selectivity is significantly improved. The simulated FBW$_{1dB}$ is about 11.7%, the in-band reflection coefficient is better than -20 dB, the insert loss is around 0.25 dB at 140 GHz, and the rectangle coefficient ($BW_{40\%}$/$BW_{3\%}$) is around 1.44, where $BW_{40\%}$ and $BW_{3\%}$ are the 40-dB and 3-dB bandwidths, respectively. From 100-120 GHz and 160-180 GHz, the rejection level is higher than 40 dB.

B. Filter-II

The second filter is realized by cascading two basic single over-mode cavities through TE$_{4,4,0}$ mode cavities, as shown in Fig. 15. The specifications of this filter are:

1. Center frequency: $f_0 = 140$ GHz;
2. FBW$_{1dB} = 16\%$;
3. In-band reflection coefficient: better than -10 dB;
4. $|S_{21}| \leq -40$ dB within 110-120 GHz and 160-170 GHz.
The basic block in Fig. 1 is composed of two over-mode cavities and coupling slots, which has five resonant modes and can be represented by the transverse quintuplet topology. However, the basic filter block in Fig. 16(a) consists of only one over-mode cavity, a high-order mode (TE440 mode) cavity, and coupling slots. The implementation of these higher-mode cavities helps to reduce the insertion loss of the proposed filter, especially for THz applications. It should be mentioned that since the coupling slots on the top of the over-mode cavity have the same offsets, the electromagnetic-fields of the neighboring coupling slots have an out-of-phase. Hence, the single over-mode cavity can provide same-amplitude but alternative-phase excitation for the TE40 mode cavity, which ensures only the TE40 mode can be resonated inside the high-order mode cavity. To investigate the number of resonate mode of the over-mode cavity, a TE40 mode transmission line is connected with the single over-mode cavity as output port, as shown in Fig. 16(a). Then the full-wave simulated reflection coefficient is studied and presented in Fig. 16(b). Apparently, three resonate modes can be observed in Fig. 16(b). The vector electric field distributions of those three modes are depicted in Fig. 17. The signs of vector electric field of the $R_1'$ and $R_3'$ modes at the coupling slots are the same, but opposite to that of the $R_2'$ mode. Hence, it can be represented by a transverse triplet topology, which can generate two TZs.

As demonstrated in Fig. 15, two basic filter blocks are cascaded together with 16 slots to improve the frequency selectivity. The topology based on the transverse triplet is displayed in Fig. 18. In order to suppress the unwanted high-order resonating modes within the passband and keep the same resonating characteristics as the conventional over-mode cavity, eight tiny metal pins are placed along

![Image](image-url)
the black dash lines in Fig. 15(b). Similar design procedure is adopted to design the proposed filter-II. The geometries of over-mode cavities and TE440 mode cavities can be determined by using (1)-(10). The coupling matrix in Fig. 18 is used to guide the geometric tuning in the design. As depicted in Fig. 19, the input coupling coefficients monotonically decrease as the height ($t_1$) of feeding slot increases. For the given center frequency and the bandwidth of a passband filter, the width ($W_1$) and length ($L_1$) of the single over-mode cavity should satisfy the formulas (1)-(3) to keep the TE4,1,0 ($R_2'$) mode resonating at center frequency. Then the resonating frequencies of the $R_1'$ and $R_3'$ modes can be calculated by formulas (5) and (6) respectively. The self-coupling coefficients of $M_{1'1'}$, $M_{2'2'}$ and $M_{3'3'}$ are investigated with
the pins and screw holes of the UG-387/U flange are fabricated with minimum radius of the drill is 0.1 mm. For the accuracy of assembly, photographs are illustrated in Fig. 24. In the fabrication process, the CNC metal milling technology due to the relatively high cost. And its OML WR-06 frequency extension modules, and a TRL calibration by the Agilent Technologies PNA-X Network Analyzer N5245A, two um thickness gold. The measurement of the filter-II is carried out with high precision. Moreover, the fabricated structures are plated with 2

\( \text{IV. FABRICATION AND MEASUREMENT} \)

To verify the design, only the proposed filter-II is fabricated by CNC metal milling technology due to the relatively high cost. And its photographs are illustrated in Fig. 24. In the fabrication process, the minimum radius of the drill is 0.1 mm. For the accuracy of assembly, the pins and screw holes of the UG-387/U flange are fabricated with high precision. Moreover, the fabricated structures are plated with 2 um thickness gold. The measurement of the filter-II is carried out with the Agilent Technologies PNA-X Network Analyzer N5245A, two OML WR-06 frequency extension modules, and a TRL calibration by the V06-AL-371 CalKit.

The simulated and measured results of the proposed filter-II are compared in Fig. 25. The measured FBW \( 0.01 \) is 16.3% \( (128.58-151.5 \text{ GHz}) \). The in-band reflection coefficient is better than -12.5 dB, the minimum insertion loss is around 0.33 dB, and the measured rectangle coefficient \( (\text{BW}_{\text{40dB}}/\text{BW}_{\text{3dB}}) \) is around 1.38. Experimental results agree well with the simulated results in general. It verifies that the frequency selectivity can be improved by cascading multiple over-mode cavities, and the insertion loss can be reduced by utilizing higher-mode cavities.

Table VI lists comparisons between the proposed filters and other high frequency filters. A good performance, including a wide bandwidth, a low insertion loss, and high selectivity, has been achieved by the proposed filters. The bandwidth and positions of TZs can be flexibly designed by properly selecting size of the proposed over-mode cavities and its operating modes. In addition, the implement of these higher-mode cavities helps to reduce the insertion loss and fabrication difficulty of the proposed filter, especially for THz applications. In general, the proposed filter-II has a simple structure, and exhibits a low insertion loss and high selectivity.

Table VI: Comparisons of performances among the reported THz filters.

<table>
<thead>
<tr>
<th>Reference</th>
<th>( f_0 ) (GHz)</th>
<th>FBW ( 0.3 )</th>
<th>IL (dB)</th>
<th>( \frac{\text{BW}<em>{\text{40dB}}}{\text{BW}</em>{\text{3dB}}} )</th>
<th>Technology</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>[21]</td>
<td>149.7</td>
<td>1.35%</td>
<td>-5.5</td>
<td>N.A.</td>
<td>LTCC</td>
<td>4-pole quasi-elliptic</td>
</tr>
<tr>
<td>[22]</td>
<td>140</td>
<td>14.28%</td>
<td>-2.44</td>
<td>-2.33</td>
<td>LTCC</td>
<td>Synthesis method based on electric coupling</td>
</tr>
<tr>
<td>[23]</td>
<td>140.45</td>
<td>13.03%</td>
<td>-1.91</td>
<td>-2.86</td>
<td>LTCC</td>
<td>Electromagnetic bandgap (EBG) Unit</td>
</tr>
<tr>
<td>[24]</td>
<td>174</td>
<td>13.8</td>
<td>-1.9</td>
<td>N.A.</td>
<td>LTCC</td>
<td>SICW resonant cavity</td>
</tr>
<tr>
<td>[25]</td>
<td>141.9</td>
<td>10.22%</td>
<td>-0.61</td>
<td>-3.24</td>
<td>DRIE</td>
<td>5-pole Chebyshev</td>
</tr>
<tr>
<td>[28]</td>
<td>88.47</td>
<td>9.73%</td>
<td>-0.97</td>
<td>N.A.</td>
<td>SU-8</td>
<td>H-plane bends</td>
</tr>
<tr>
<td>[29]</td>
<td>102</td>
<td>5%</td>
<td>-1.2</td>
<td>N.A.</td>
<td>SU-8</td>
<td>Extracted pole resonator</td>
</tr>
<tr>
<td>[30]</td>
<td>300</td>
<td>8%</td>
<td>-1</td>
<td>N.A.</td>
<td>SU-8</td>
<td>5-pole Chebyshev</td>
</tr>
<tr>
<td>[31]</td>
<td>298.6</td>
<td>5.36%</td>
<td>-0.45</td>
<td>N.A.</td>
<td>SU-8</td>
<td>Extracted pole resonator</td>
</tr>
<tr>
<td>[32]</td>
<td>286.6</td>
<td>5.58%</td>
<td>-0.41</td>
<td>-3.21</td>
<td>CNC</td>
<td>Extracted pole resonator</td>
</tr>
<tr>
<td>[33]</td>
<td>100</td>
<td>10%</td>
<td>-0.6</td>
<td>-1.9</td>
<td>CNC</td>
<td>Extracted pole resonator</td>
</tr>
<tr>
<td>[34]</td>
<td>258</td>
<td>8.8%</td>
<td>-0.7</td>
<td>-1.86</td>
<td>CNC</td>
<td>Higher order mode cavity</td>
</tr>
<tr>
<td>[35]</td>
<td>256</td>
<td>9.8%</td>
<td>-0.5</td>
<td>-1.62</td>
<td>CNC</td>
<td>Higher order mode cavity</td>
</tr>
<tr>
<td>[36]</td>
<td>140</td>
<td>9.29%</td>
<td>-0.52</td>
<td>-1.47</td>
<td>CNC</td>
<td>TE (_{031}) mode resonant cavity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>( f_0 ) (GHz)</th>
<th>FBW ( 0.01 )</th>
<th>IL (dB)</th>
<th>( \frac{\text{BW}<em>{\text{40dB}}}{\text{BW}</em>{\text{3dB}}} )</th>
<th>Technology</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter-I (Simulated)</td>
<td>140</td>
<td>13.35%</td>
<td>-0.25</td>
<td>-1.44</td>
<td>N.A.</td>
<td>Over-mode cavities</td>
</tr>
<tr>
<td>Filter-II</td>
<td>140</td>
<td>17.18%</td>
<td>-0.33</td>
<td>-1.38</td>
<td>CNC</td>
<td>Over-mode cavities</td>
</tr>
</tbody>
</table>

Authors appreciate the SynMatrix Support Team [40] for their technical support in this work. Authors are very grateful of the help from Prof. Luca Perregrini from University of Pavia, Italy and Prof.
Cristiano Tomassoni from University of Perugia, Italy. They gave many valuable suggestions to explain clearly the operating principle of the proposed filter, which are very important to improve the quality of this work. In addition, authors also appreciate anonymous reviewers for their helpful comments.

REFERENCES


