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Compact TSV-Based Hairpin Bandpass Filter for Thz Applications

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ABSTRACT A hairpin bandpass filter with compact feeder structure is proposed for terahertz (THz) applications by using the model of odd-even propagation mode. By employing the three-dimensional integrated through-silicon via (TSV) technology, the proposed filter exhibits an ultra-compact size of only 0.24×0.028 mm^2 ($1.38 \times 0.16\ \lambda_g^2$). The model of the proposed filter is established and optimized with the HFSS tool based on finite element method. The results of *S*-parameters reveal that the proposed filter with center frequency at 0.5 THz, exhibits a bandwidth of 0.08 THz with insertion loss of 1.5 dB and reflection loss over 13.4 dB in the passband.

INDEX TERMS Hairpin bandpass filter, terahertz applications, odd-even model, through-silicon via (TSV).

I. INTRODUCTION

The filter is the most important component for the radio-frequency (RF) communication front end [1]–[4]. A hairpin filter with resonators is the simplest structure used for microstrip filters exhibiting the appealing features of miniaturization, easy integration, and high-gain [5]–[13]. Presently, a great deal of researches on hairpin filters focus on microstrip planar hairpin units [5]–[16]. However, the microstrip line structure fails to operate normally at above 0.1 THz frequency due to excessive losses.

Fortunately, the through-silicon via (TSV) technology has been shown to be a good candidate for miniaturization and integration of passive devices [17]–[24]. TSV is a vital component of 3-D ICs [25], [26], [29], [32], which can extend Moore's law for several more technology nodes despite the bottleneck of physical size transistor scaling [29]. Based on these observations, a TSV-based hairpin bandpass filter has been proposed as a well-suited component for THz applications. However, this filter exhibits insertion loss of as much as 6.9 dB and, therefore, does not satisfy the basic performance index of the filter. The structure of hairpin filter needs to be more improved for operating at the THz frequency range.

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In this paper, a compact TSV-based hairpin bandpass filter for THz applications is proposed. In addition, as the traditional design method of the hairpin filter is based on microstrip structure in frequencies lower than THz, there is no prior work investigating the behavior and design process for TSV-based hairpin filters in THz band. To fill this gap, this paper proposes to design hairpin filter based on TSV in THz band following a structure that cannot be supported by traditional microstrip structures that incur considerably overhead in area and form factors.

This paper is organized as follows. The design method of the proposed filter with TSV and compact feeder is described in Section II. The results and a discussion around the *S*-parameter curves are presented in Section III. Conclusions are drawn in Section IV.

II. DESIGN OF TSV-BASED HAIRPIN BANDPASS FILTER

The proposed filter is based on the Chebyshev filter, adopting TSV and tailoring the feeder position to THz applications. The filtering function of the proposed filter is realized by the coupling action between hairpin units, which can be analyzed by using odd-even model. Each hairpin unit consists of two through-silicon vias (TSVs) as arms and one RDL segment as connection. The input-output feeder with compact size is the interface between the power supply and the proposed filter.

The proposed methodology is also applicable to other filters based on this geometry.

A. COMPACT FEEDER

The input and output design includes the same three parts, which are the TSV, RDL segment, and feeder described in Fig. 1.

The TSV has diameter D and length L_2, respectively. The RDL segment has length L_3, width W, and height H_2. Furthermore, the feeder has length L_1, width W, and height H_1. The feeder of hairpin filter is designed to obtain the maximum transmission efficiency. The feeder is a branch modulator that matches the impedance of the filter. As depicted in Fig. 1, l is the distance from the middle of RDL to the middle of feeder, while L is the distance from the middle of RDL to the top of TSV.

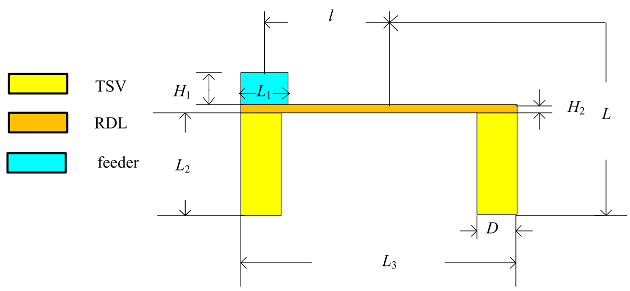

FIGURE 1. The structure of input design in hairpin filter and the related design parameters.

The ratio of l to L is related to the effect of impedance matching. There is a theoretical relation between l to L [27] given by

$$l = \frac{2L}{\pi} \cdot \arcsin\sqrt{\frac{\pi R}{2Z_0 Q_{e1}}}, \tag{1}$$

where R and Z_0 are the characteristic impedances of feeder and hairpin unit, respectively. These impedances have the same value of 50 Ω. Q_{e1} is external coupling coefficient, which can be obtained from [28]

$$Q_{e1} = \frac{g_0 g_1}{(\omega_{p2} - \omega_{p1}) \big/ \sqrt{\omega_{p2}\omega_{p1}}}, \tag{2}$$

where g_0 and g_1 can be obtained by the Chebyshev low pass filter element table [30]. ω_{p1} and ω_{p2} are, respectively, the predesigned lower passband frequency and upper passband frequency.

In this paper, l is made up of 0.5 W_1, W and 0.5 L_3, while L is made up of L_2, W and 0.5 L_3. L can be given by [6]

$$L = \frac{c}{4f_0\sqrt{\varepsilon_e}}, \tag{3}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\frac{h}{W}}}\right), \tag{4}$$

$$W = \frac{8he^A}{e^{2A} - 2}, \tag{5}$$

$$A = \frac{Z_0}{60}\sqrt{\left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\left(0.23 + \frac{0.11}{2}\right)}, \times \left(\frac{W}{h} < 2l\right), \tag{6}$$

where f_0 and c are, respectively, the center frequency and the speed of light in vacuum. ε_0 and h are, respectively, dielectric constant and height of substrate. The substrate of the proposed filter is a high-resistance silicon substrate with a dielectric constant of 11.9, dielectric tangent of 0.005 and resistivity of 1000 Ω·cm. In this paper, h is the distance between double conductors of the proposed filter.

L_2 as the length of TSV can be initial determined as

$$L_2 = \frac{c}{8f_0\sqrt{\varepsilon_e}}, \tag{7}$$

where ε_e can be obtained from Eqs.(4)-(6). In addition, L_1 as the length of feeder can be obtained from Eqs.(5)-(6).

The structure of feeder is compact due to the low height. In addition, the length of the RDL segment can be determined as

$$L_3 = 1.438\,(L_2 + H_2 + 1.429L_1)\,. \tag{8}$$

B. COUPLING OF TSV

The coupling between two types of hairpin units which comprise the length, the diameter, and the distance of adjacent TSVs in Fig. 2.

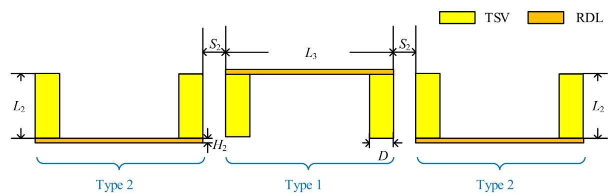

FIGURE 2. The structure of coupling of TSV in hairpin filter and the related design parameters.

As depicted in Fig. 2, S_2 is the distance between the Type 1 and Type 2 hairpin units. The impedances of adjacent TSVs can be obtained based on the impedance value analysis of odd-even propagation mode [27]. Furthermore, the diameter of TSV can be given by Eqs. (5)-(6). S_2 is inversely proportional to the coupling coefficient. The coupling coefficient is one of the decisive factors to determine the filter, which is given in theory as [28]

$$k_{i,i+1} = \frac{\omega_{p2} - \omega_{p1}}{\sqrt{\omega_{p2}\omega_{p1}g_i g_{i+1}}}\,(i = 1, 2, 3, 4)\,, \tag{9}$$

where $k_{i,i+1}$ is the specified interstage coupling coefficient related to electromagnetic hybrid coupling.

C. THE PROPOSED TSV-BASED HAIRPIN FILTER

As depicted in Fig. 3, the hairpin units consist of the input feeder, output feeder, and hairpin coupling line. S_1 is the space between Type 1 and Type 2 hairpin units. The value of S_1 is set equal to the radius of the TSV. In addition, the value of

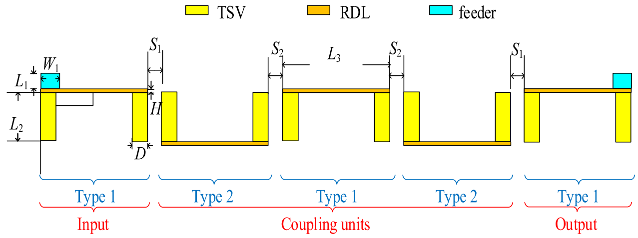

FIGURE 3. The 2D structure diagram of TSV-based hairpin bandpass filter.

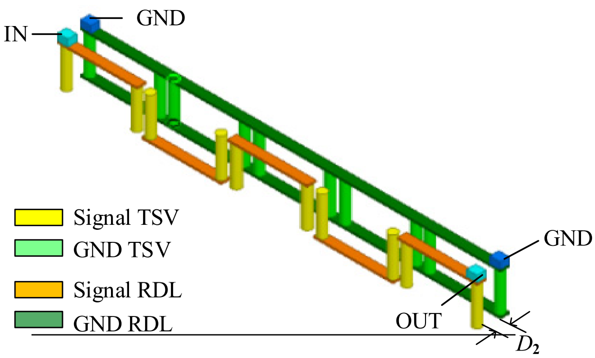

FIGURE 4. The 3D structure diagram of a TSV-based hairpin bandpass filter.

S_2 is determined by the ratio of S_2 and S_1. In this paper, S_2 is 1.4 times as much as S_1. For example, the value of S_2 is 7 μm while the value of S_1 is 5 μm.

The distance between the ground plane and the hairpin units is D_2, illustrated in Fig. 4. D_2 can be on the order of the dielectric layer thickness of the microstrip filter.

III. RESULTS AND DISCUSSION

The proposed filter is verified by the HFSS software and a comparison with prior THz filters is presented in this section. HFSS is used to verify the S-parameters in microwave frequencies, due to the high precision of HFSS [17], [32].

A. RESULTS

The physical size of the filter can be obtained following the design method presented in Section II.

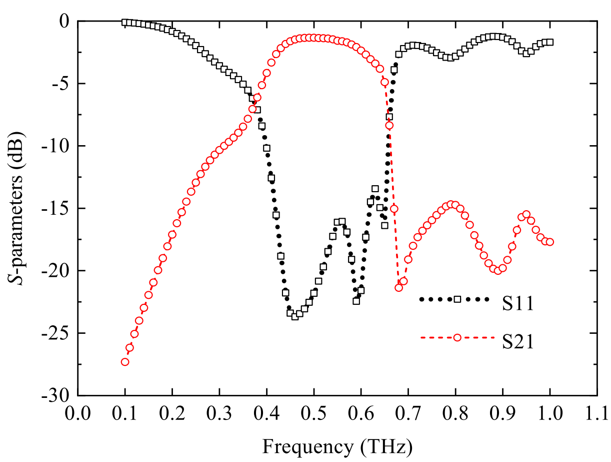

FIGURE 5. S-parameters of the proposed filter.

The TSV has D of 5 μm and L_2 of 22 μm, respectively. The RDL segment has L_3 of 45 μm, W of 5 μm, and H_2 of 1 μm. Furthermore, the feeder has L_1 of 5.8 μm, W of 5 μm, and H_1 of 4 μm. The distances between the Type 1 and Type 2 hairpin units are S_1 of 2.5 μm and S_2 of 3.5 μm. In addition, the distance between the ground plane and the hairpin units is D_2 of 8 μm.

The S-parameter curves are the simulation results of the proposed filter, which are depicted in Fig. 5. It is shown that the proposed filter with center frequency at 0.5 THz, exhibits a bandwidth of 0.08 THz with insertion loss of 1.5 dB and reflection loss over 13.4 dB in the passband.

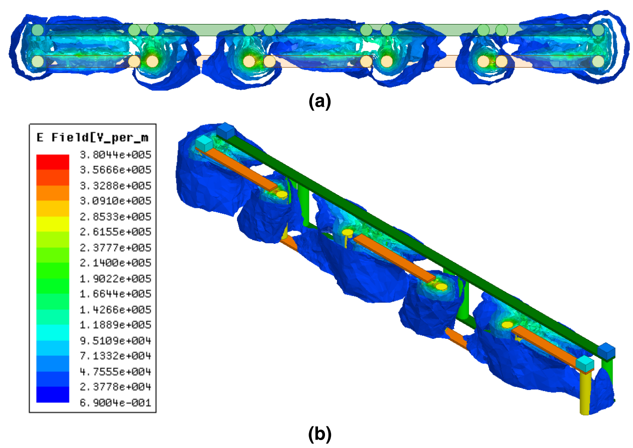

FIGURE 6. a) 2D and b) 3D E field of the proposed hairpin filter.

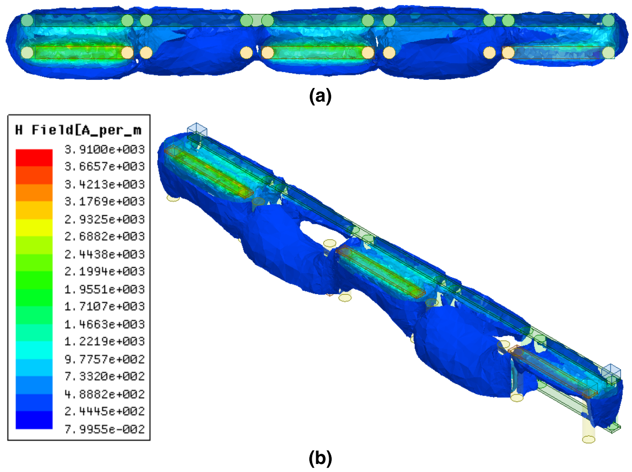

FIGURE 7. a) 2D and b) 3D H field of the proposed hairpin filter.

And the E field and H field of the proposed hairpin filter are presented in Fig. 6 and Fig. 7, which show the coupling paths. After the signal passes through the Type 1 hairpin unit and Type2 hairpin unit, the signal phase is opposite and the energy is offset, thus generating transmission zeros. The coupling path consists of input, coupling units, and output, which are five hairpin units to transmit a quasi - TEM mode.

The proposed filter adopts direct-coupled mode, which consists of three Type 1 hairpin units and two Type 2 hairpin units. Each Type 1 hairpin unit structure can implement the circuit function of a series connection between an inductor and a capacitor, while each Type 2 hairpin unit structure can implement the circuit function of an inductor and a capacitor in parallel. The five hairpin units realize the topological circuit with five-order coupling.

A comparison among the proposed filter and four related THz filters is performed in Table 1. Due to the introduction of TSV, the proposed filter exhibits a better coupling effect than the other filters. The 0.08 THz bandwidth of the proposed filter (listed in the fourth column of Table 1) is about 2.67×, 4.00×, 3.48×, and 1.57× higher as compared to the THz filters presented in [25], [26], [31], and [32], respectively. The size of the four related THz filters (listed in the last two columns of Table 1) is, respectively, about 8.93× [25], 87.1× [26], 211.6× [31] and 21.3× [32] greater than this work.

Because the proposed filter adopts a compact feeder structure, the size of the proposed filter is greatly miniaturized. Consequently, it can be concluded that the proposed filter has excellent performance and extremely low form factor.

TABLE 1. The comparison of the THz filters.

Filters	Type	Method	CF (THz)	BW (THz)	IL (dB)	RL (dB)	Size (mm^2)	Size λ_g^2
[25]	Hairpin	Sim.	0.125	0.03	6.9	8	0.3×0.2	0.43×0.29
[26]	SIW	Sim.	0.16	0.02	1.5	10	0.9×0.325	2.25×0.81
[31]	SIW	Meas.	0.14	0.023	2.4	11	1.8×0.79	2.90×1.27
[32]	SIW	Meas.	0.331	0.051	1.5	15	0.68× 0.21	2.60×0.80
This work	Hairpin	Sim.	0.5	0.08	1.5	13.4	0.24×0.028	1.38×0.16

B. DISCUSSION

In order to investigate the association between parameters of TSV and the performance of the proposed filter, two another comparison about three groups of *D*, three groups of L_2, and three groups of L_3 (based on L_2 groups) are presented in Fig. 8, Fig. 9, and Fig. 10, respectively.

As depicted in Fig. 8, the sizes of *D* are 5 μm, 10 μm, and 15 μm, respectively, while the other physical size are constant. It is shown that the filter with *D* of 10 μm has the bandwidth of 0.1305 THz with insertion loss of 1.5 dB and reflection loss over 14.4 dB in the passband, while the filter with *D* of 15 μm has the bandwidth of 0.134 THz with insertion loss of 1.5 dB and reflection loss over 15.9 dB in the passband. Compare the three *S*-parameter curves in Fig. 8, it can be easily concluded that the in-band performance would increase a little as *D* increases, meanwhile the bandwidth increase.

Fig. 9 gives the *S*-parameters as L_2 are 22 μm, 27 μm, and 32 μm, respectively, while the other physical size are constant. It can be shown that the center frequency decreases as the L_2 of TSV increases, while the in-band performance decreases a lot. It is speculated that the performance loss

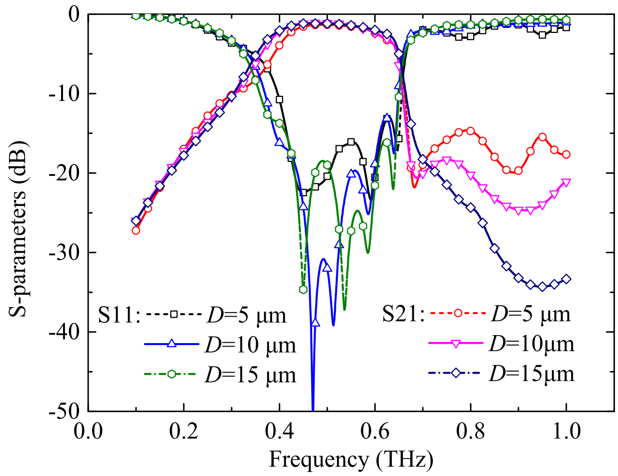

FIGURE 8. S-parameters vs. different *D*.

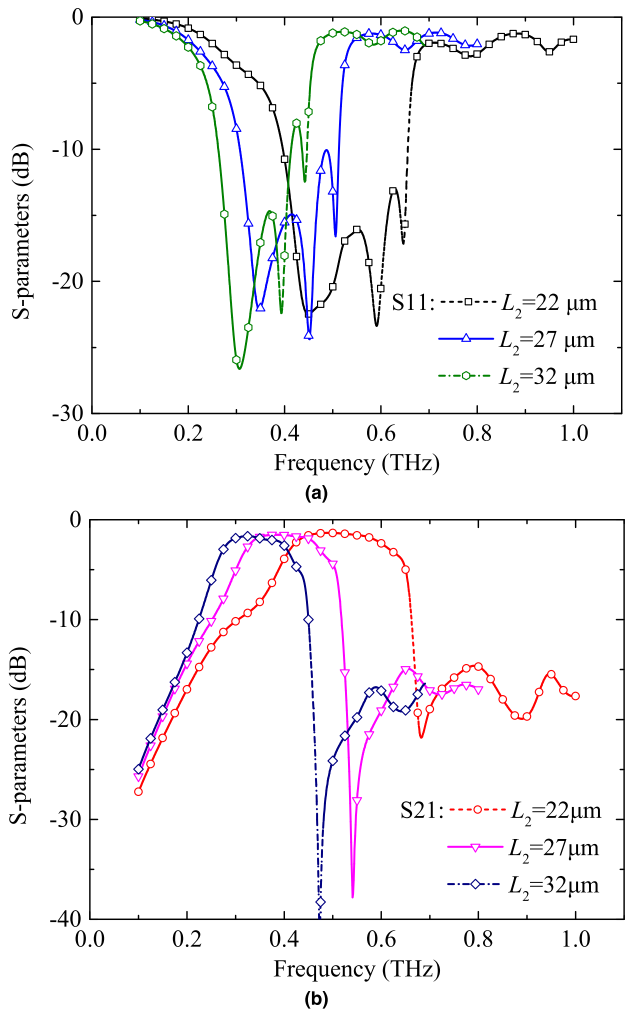

FIGURE 9. S-parameters vs. different L_2.

reason is that the physical size of the proposed filter in Fig. 9 is not in accordance with the impedance matching characteristics.

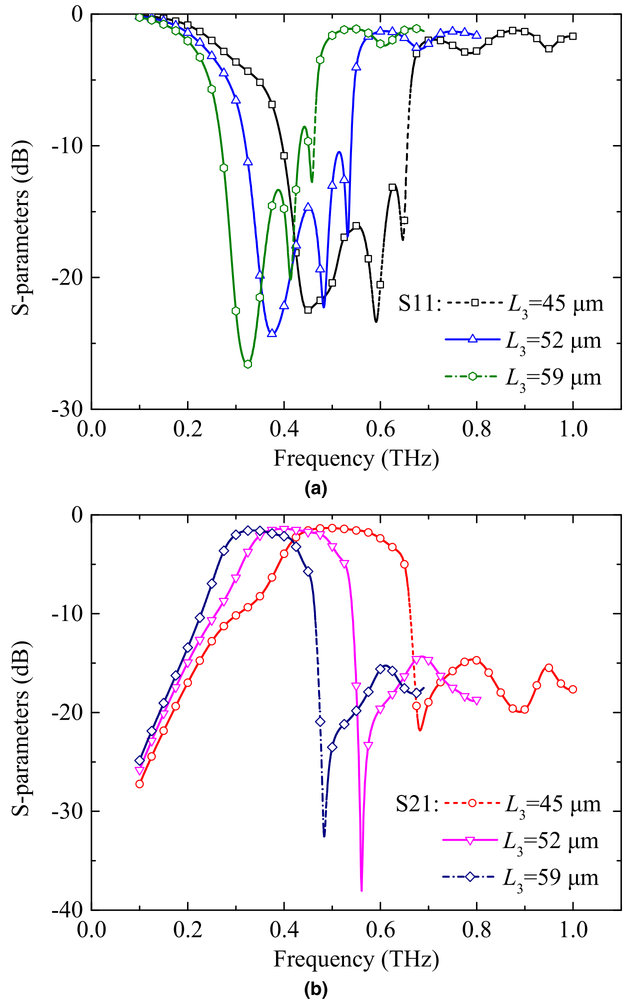

FIGURE 10. S-parameters vs. different L_3.

As depicted in Fig. 10, the simulation results of the proposed filter with of L_3 of 45 μm, 52 μm, and 59 μm, respectively, while the other physical size are constant. Compared to the S-parameters curves in Fig. 9, the in-band performance improves a lot, because $L_3$is adjusted as L_2 increases according to Eq. (8) for impedance matching.

IV. CONCLUSION

A compact TSV-based hairpin bandpass filter for THz applications is proposed and verified in the paper. The proposed filter exhibits 0.08 THz bandwidth at 0.5 THz center frequency, which can provide unprecedented data transmission rate and channel capacity for future mobile communication systems.

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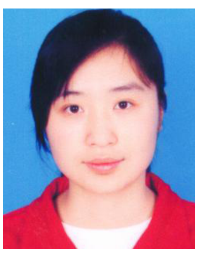

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