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Miniaturized SIW Bandpass Filter Based on TSV Technology for THz Applications

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***Abstract*—A miniaturized substrate integrated waveguide (SIW) bandpass filter with an area of 0.682×0.210 mm^2 is proposed based on Through-Silicon Via (TSV) technology for terahertz (THz) applications. The design method of the THz cavity filter based on rectangular TSV is introduced and the filtering characteristics are investigated by the finite element method (FEM) and mode matching method (MMM). The rectangular TSV is substituted by cylindrical structures and the THz cavity filter is fabricated and measured in order to investigate the possibility of integration with typical 3D IC manufacturing processes. The cavity filter utilizing cylindrical TSV exhibits a bandwidth of 0.051 THz centered at 0.331 THz, an insertion loss of 1.5 dB, and a reflection of higher than 15 dB in the passband.**

***Index Terms*—Bandpass, cavity filter, substrate integrated waveguide (SIW), terahertz (THz), through-silicon via (TSV)**

I. Introduction

Terahertz (THz) frequencies are broadly applied in civil and military domains. For THz systems, rectangular waveguides remain an important transmission medium to realize passive components, such as filters, power dividers, and couplers [1]. Rectangular waveguide filters are always superior to the planar transmission line filters due to lower losses, higher *Q* factor, and higher power management capacities, as well as better physical robustness [2]. Unfortunately, the waveguide filter dimension decreases as the frequency increases. Although standard (micro)machining techniques can be used to fabricate these THz filters, accuracy and machining tolerances remain an issue [3]. On the other hand, the waveguide filter is usually not compatible with traditional planar silicon process for on-chip integration.

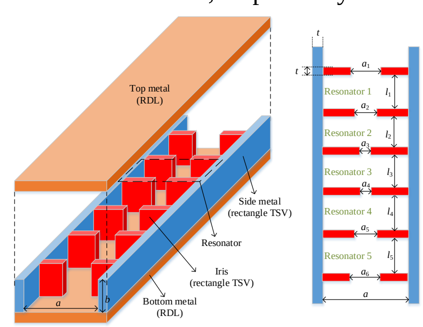
Substrate integrated waveguides (SIWs) have become an emerging transmission structure that attracts significant interest due to its advantages of high *Q* factor, high power handling capability, low loss, and low cost [4]. However, this waveguide is usually fabricated with a printed circuit board (PCB) or low temperature co-fired ceramic (LTCC) [5]-[7], which is not appropriate for on-chip integration. Meanwhile, operating traditional SIWs into THz frequencies is challenging due to the large physical dimension of these waveguides.

Alternatively, Through-Silicon Via (TSV), which is a key component for three-dimensional integrated circuits (3D ICs), demonstrates high-precision trench etching and metal filling on the order of micrometers, thereby raising significant research interest [8], [9]. Also, since TSV can interconnect other planar devices by re-distribution layers (RDLs) [10], these structures can be integrated with standard CMOS ICs. Therefore, these appealing characteristics make TSV technology a good candidate for miniaturization and integration of passive devices. Indeed, several TSV-based passive devices have been proposed [11]-[13].

In this paper, a miniaturized SIW cavity bandpass filter for THz applications utilizing TSV technology is proposed and verified. Firstly, the filter based on rectangular TSV with a simple structure is designed and analyzed in Section II. The rectangular TSV are substituted with cylindrical in order to be integrated with a typical 3D IC process and the filter is fabricated and measured in Section III. Some conclusions are drawn in Section IV.

II. THz Bandpass Filter Based on Rectangular TSV

The structure and design of the new TSV-based SIW are described in this section. The structure of THz bandpass cavity filter based on rectangular TSV is illustrated in Fig. 1. Here, the top metal is pulled up for the sake of observation. There are six pairs of rectangle TSV iris, forming five resonators. The proposed method for the design of SIW is discussed in subsection II-A and the resulting characteristics of the SIW are investigated in subsection II-B, respectively.



(a) (b)

Fig. 1. (a) Three-dimensional and (b) cross-sectional view of THz cavity bandpass filter based on rectangular TSV.

A. Design method

The iris of TSV THz filter is equivalent to a *K* impedance transformer, and the *K* impedance transformer form of the equivalent circuit of the filter can be obtained from [14]. Each

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K impedance transformer is equivalent to a T-network, including a series inductance X_s, a shunt inductance X_p, and a phase $\phi/2$. According to the performance requirements, the theoretical impedance of K impedance transformer K/Z_0 can be obtained. By employing HFSS [15], the relationship of impedance K/Z_0 and the width of the iris window W is determined, according to which, W is obtained combined with the theoretical value of K/Z_0. The length of i^{th} resonator, l_i can be determined by the relationship between K and l_i [14]. Through these steps, all of the structure parameters of the filter are initially determined. Fine-tuning of the structural parameters based on the mode matching method (MMM) follows. MMM is a fast numerical method compared to computationally expensive FEM simulations with EM solvers.

Using the method described above, the structural parameters of the proposed THz filter are obtained. The internal cross-sectional area ($a \times b$) is 200 μm × 100 μm. The thickness of TSV iris and side metal (t) is 10 μm. The thickness of RDL is 5μm. The length of resonators (l_i, i=1-5) are 125 μm, 143 μm, 146 μm, 143 μm, and 125 μm, respectively. The width of the iris windows (a_i, i=1-6) are 115 μm, 85 μm, 78 μm, 78 μm, 85 μm, and 115 μm, respectively. Therefore, the core area occupied by the THz filter is only 0.682 mm × 0.210 mm.

B. Filtering characteristics

In this subsection, both FEM and MMM are used to investigate the filtering characteristics of the proposed THz filter. The *S*-parameters of the proposed THz cavity filter are shown in Fig. 2. The THz filter exhibits a bandwidth of 0.05 THz centered at 0.336 THz, and an insertion loss of 0.01 dB.

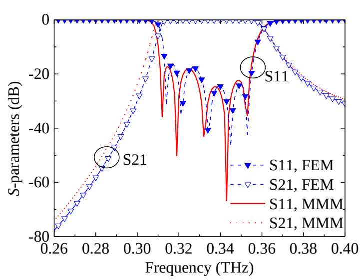


Fig. 2. *S*-parameters of the proposed THz filter based on rectangular TSV.

III. THz BANDPASS FILTER BASED ON CYLINDRICAL TSV

In order to integrate the proposed filter with conventional 3D ICs, common cylindrical TSVs are utilized instead of rectangular TSVs, as shown in Fig. 3. According to the design rules proposed in [4] where the electromagnetic leakage is considered and the requirements of the TSV fabrication process, the diameter and pitch of the cylindrical TSV are selected as 10 μm and 20 μm, respectively. In addition, the aspect ratio of cylindrical TSV is 10:1. The other structural parameters are the same as those used for the filter in Section II. In this section, the prototype filter based on cylindrical TSV is fabricated and measured as described in subsections III-A and III-B, respectively.

A. Fabrication and measurement

In this subsection, the THz cavity bandpass filter based on cylindrical TSV is fabricated in high-resistivity silicon substrate (dielectric constant of 11.9 and resistivity of 1000 Ω•cm) with standard TSV process, described in detail in [11]. The scanning electron microscope (SEM) photo of the cross-section view of the THz cavity filter is depicted in Fig. 4. The SEM photo of few TSVs is also provided.

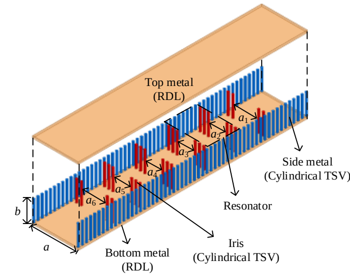


Fig. 3. Three-dimensional view of the THz cavity bandpass filter based on cylindrical TSV.

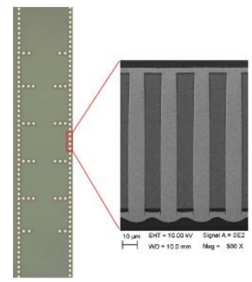
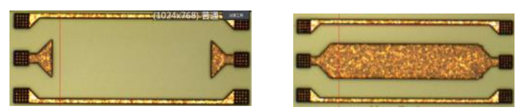


Fig. 4. SEM photographs of cross-section view of THz cavity filter and partial TSVs.



(a) (b)

Fig. 5. Measurement structure of the proposed THz cavity filter. (a) Open structure and (b) short or device-under-test structure.

The test method in [16] is utilized to measure the *S*-parameters of the THz cavity bandpass filter based on cylindrical TSV. Since the measurement system is restricted above circa 100 GHz, the *S*-parameters of the proposed THz filter based on cylindrical TSV are investigated with the simplified power-loss method, which is adequate for the functional evaluation and inexpensive [16]. In order to eliminate the effect of the non-ideal factors in the measurement procedure, the open-short de-embedding method is utilized [17]. The measurement structure for the proposed THz cavity filter, including the open, short, and device-under-test structures are illustrated in Fig. 5. As the short and device-under-test structures are similar, only one figure for both cases is shown (see Fig. 5 (b)). An Agilent N5244A vector network analyzer is employed to evaluate the *S*-parameters of THz cavity filter.

B. Results and discussion

Fig. 6 shows the measured and simulated responses of the proposed THz cavity filter based on cylindrical TSV between 0.26 THz and 0.40 THz. The non-ideal fabrication process, such as the non-uniform thickness of RDL and the roughness of TSV sidewalls, leads to scattering during signal transmission. So the measurement results have some performance deviation compared with the ideal simulation results. However, as shown in Table I, the errors of IL and RL between the results of FEM and measurement are less than 1dB, which is acceptable. The cavity filter based on cylindrical TSV exhibits a real bandwidth of 0.051 THz centered at 0.331 THz with an insertion loss of 1.5 dB, and a reflection higher than 15 dB in the passband. The *S*-parameters of the filter based on rectangular TSV are also given in Fig.6 for comparison. The filter based on cylindrical TSV demonstrates worse filtering characteristics than the rectangular TSV due to the phenomenon of electromagnetic leakage from the gaps between cylindrical TSVs due to the required TSV pitch determined by the TSV fabrication process.

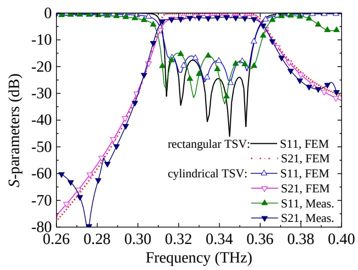


Fig. 6. *S*-parameters of the proposed THz filter based on rectangular and cylindrical TSVs.

The characteristics of the proposed THz filter are compared with related works as listed in Table I. Note that the proposed filter exhibits ultra-compact size and superior filtering characteristics. The reason is given as follows. The TSV-based hairpin filter in [18] has higher electromagnetic leakage since the operation of this filter is based on the electromagnetic coupling between TSVs, while the TSV-based SIW filter utilizes the electromagnetic fields propagating in the filter. The two-layer Through-Dielectric Via (TDV)-based SIW filter in [19] is of third order, while the filter in this work is of fifth order. The fourth-order SIW filter in [20] is based on LTCC, which is inherently larger than TSV and operates in lower frequencies.

TABLE I. COMPARISON WITH RELATED THZ FILTERS

Filters	Method	CF (THz)	BW (THz)	IL (dB)	RL (dB)	Size	
						(mm^2)	λ_g^2
[18]	FEM	0.125	0.04	6.8	8	0.3×0.2	0.43×0.29
[19]	FEM	0.16	0.02	1.5	10	0.9×0.325×2	2.25×0.81
[20]	Meas.	0.14	0.023	2.4	11	1.8×0.79	2.90×1.27
This work 1*	FEM	0.336	0.050	0.01	16	0.682× 0.21	2.60×0.80
This work 2**	FEM	0.337	0.046	0.7	16		
	Meas.	0.331	0.051	1.5	15		

*This work 1 represents the filter based on rectangular TSV.
**This work 2 represents the filter based on cylindrical TSV.

IV. CONCLUSION

The SIW cavity THz bandpass filters based on rectangular and cylindrical TSVs are proposed. For the filter based on rectangular TSV, the FEM and MMM techniques are used to investigate the filtering characteristics. The filter based on cylindrical TSV is fabricated and measured demonstrating the integration of this filter with conventional 3D ICs. The results show that the proposed filters demonstrate higher performance over state-of-the-art SIWs.

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