Design of Compact and Low-EMI Waveguide Structures based on Through Glass Vias

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***Abstract*—In this paper, two kinds of compact waveguide structures based on through glass vias (TGVs) technology are proposed. A full-wave simulator on the basis of finite element method is applied to analyze the transmission characteristics of these structures. The return loss S11, transmission S21 and electric field distribution results show that they have the similar signal transmission performance of the traditional full waveguide structures. The air filled TGVs are employed in the proposed waveguides. Simulation results show that these air filled vias can concentrate electromagnetic field within the waveguides, and hence reduce the electromagnetic interference.**

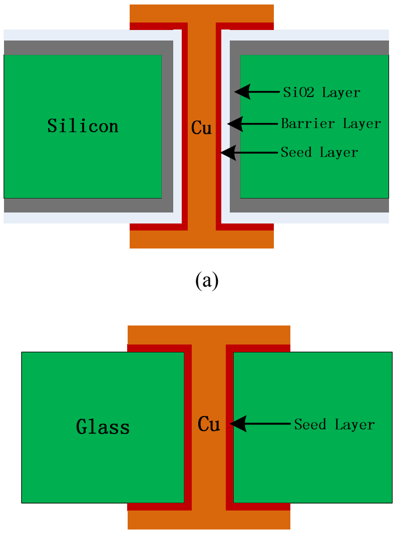
***Keywords*—Low-EMI; TGV; compact waveguide structure**

I. INTRODUCTION

With the fast growing of integrated circuit (IC) industry, traditional semiconductor device is suffering physical scaling limitations. Three dimensional (3D) system integration technology with increased packaging density and improved system performance is believed to be a promising solution to solve this problem[1]-[3]. As the core technology of three dimensional integrated circuit (3DIC), through substrate via instead of wire bonding is gaining tremendous attraction for its shorter interconnection length, reduced RC delay and parasitic effect, lower power consumption and flexibility to meet the design requirements.

Beside used for interconnects, through substrate vias also can be used for package-level substrate integrated waveguide, which has the fascinating advance in expanding communication and sensor applications towards millimeter-wave/THz circuits. Combining the advantage of planar technology with low loss characteristics intrinsic to the non-planar rectangular waveguide, substrate integrated waveguide technology allows the design of compact light-weight and low-cost devices fully integrated into the substrate[4]. Considerable effort has been devoted to the design and development of PCB-level substrate integrated waveguide in the past years [5][6]. However, for the package-level substrate integrated waveguide, due to the low resistivity of silicon substrate (ρ=10Ω·cm), waveguide structure integrated in silicon interposer always suffers larger transmission loss[4]. New materials and new waveguide structures are required to solve this problem.

Recently, a couple of glass companies have reported large, thin and low cost glass wafers with high quality and their usage for through glass via (TGV) [7]. Compared with silicon interposer, especially the expensive and complicated through silicon via (TSV) fabrication processes (BOSCH-process) [8], glass interposer and TGV have a lot of advantages including high electrical insulation, high optical transparency, great hermeticity, low warping and resistance to corrosion, ultra-flat surface, low material cost, and relatively simple TGV production processes [9]. Therefore, glass with TGV technology is a great potential alternative material of silicon to manufacture interposer for higher frequency 3D system integration applications.



(a)

(b)

Fig. 1 . Interposer structures with TSV and TGV technology. (a) Silicon interposer with TSV technology and (b) glass interposer with TGV technology.

Fig. 1 shows the schematic view of TSV and TGV structures. TGV interconnection designed in glass interposer, instead of TSV in silicon interposer, eliminates the need for barrier and oxide coating layers before copper filled processing, which results in reducing via capacitance between copper and interposer tremendously and lowering the electromagnetic interference (EMI) among vias, active and passive circuits. Also, this elimination provides the benefit of cost and complexity reduction. There even presents a new fabrication method of void-free copper filled TGV for wafer-lever RF MEMS packaging using glass reflow while without seed layer electroplating process in silicon interposer [10] to comprehensively utilize their advantages.

In this paper, compact waveguide structures which can be fabricated in glass interposer based on TGV technology instead

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of silicon interposer are designed so as to decrease the loss mainly caused by the low resistivity characteristic of silicon. Two kinds of waveguide structures are proposed, the TE mode waveguide which is formed by using copper filled TGV on one edge and air filled TGV on the other edge, the TEM mode waveguide which is formed by using air filled TGV on both edges. A full wave method is applied to analyze the propagation characteristics and electric field distribution of these structures up to 200GHz. Results demonstrate that the compact TE mode waveguide have the similar performance to the traditional fully integrated waveguide (where the copper filled vias are used on both edges), while cut down the waveguide spacing size almost by 50%. The TEM mode waveguide shows a low-EMI than the traditional planar waveguide structures. The results also show that drilling an array of vias without filling copper along the edge of these compact waveguide structures can concentrate electromagnetic field inside the waveguides, which leads to less electromagnetic interference consequently.

II. TE-MODE COMPACT WAVEGUIDE STRUCTURES

A. Proposed Compact Waveguide Structures

A compact TE mode waveguide is proposed and its performance is compared with the full TE mode waveguide structure.

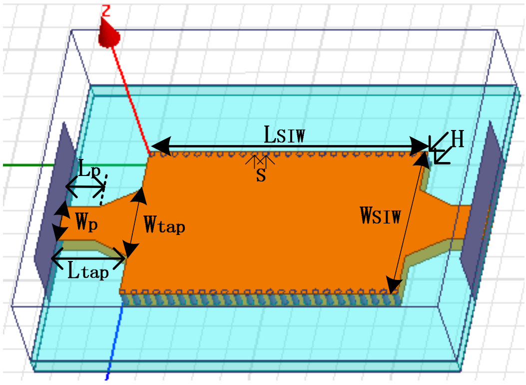


Fig. 2. 3D view of full waveguide structure

Firstly, a full waveguide structure with planar waveguide transition is illustrated in Fig. 2, by means of drilling via arrays fully filled with copper. These vias serve as the perfect electric conductor (PEC) as in the rectangular metal waveguide. This waveguide is integrated in a glass interposer with the relative dielectric constant ε_r=6.7, and the loss tangent tanδ=0.006. Each TGV along the waveguide sidewalls has a diameter of d=30um and a center to center spacing of s=40um between two TGVs. Other dimensions of the waveguide include its height H=50um, external width W_{SIW}=600um and internal width W=W_{SIW}-2d, width W_{tap}=W/2 and W_P=W_{tap}/2, length L_{SIW}=990um, L_{tap}=256.5um and L_P=L_{tap}/2.

This full waveguide structure can be equivalent to a glass-filled rectangular waveguide with its metallic sidewalls replaced by arrays of TGVs sufficiently close to each other. Due to the discrete TGV walls, vertical currents can flow through them while longitudinal surface currents of TM modes are unable to propagate into this waveguide. Therefore, it only supports the vertically directed currents of TE waveguide modes and presents a broadband feature for the discrete conducting vias along the sidewalls, while do not allow the propagation of TM modes[11]. In this paper, we just consider the transmission characteristics of the fundamental TE_{10} mode. According to the rectangular waveguide theory, the cutoff frequency of the TE_{10} mode is

$$f = \frac{1}{2W\sqrt{\varepsilon\mu}} = 107.3\text{GHz}\cdot \qquad (1)$$

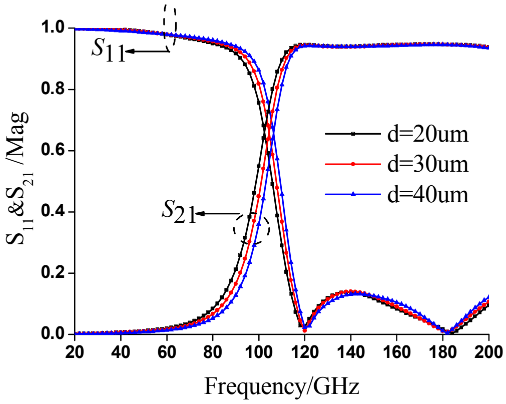
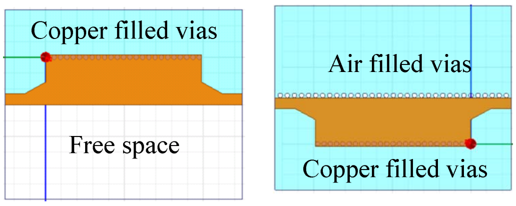


Fig. 3. The S parameter with the variation of TGV diameter.

According to Fig. 3, we can see that increasing TGV diameter will decrease the waveguide internal width W leading to the cutoff frequency shifting a little towards higher frequency on the basis of equation (1). However, if we keep the center spacing s=40um between TGVs unchanged, the magnitude of S_{11} and S_{21} parameters won't change too much with the variation of TGV diameter. Therefore, there is unnecessary to pursuit small size TGV processing, and it makes this waveguide structure more applicable.



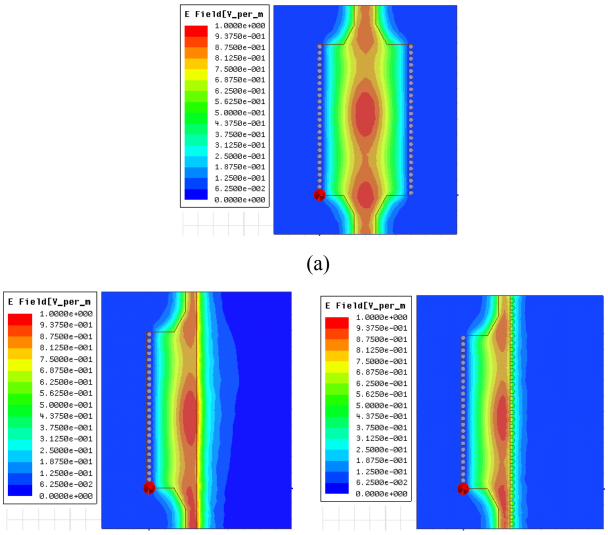
(a) (b)

Fig. 4. Proposed compact TE mode waveguide structures: (a) Half-Air-waveguide and (b) Half-AirVia-waveguide

The above full waveguide is expensive since it covers a little larger area of the interposer. If we reduce the full waveguide dimension, the cutoff frequency of its fundamental mode will increase, which will eliminate the propagation of low frequency signals. To solve this problem, we propose the compact half waveguide structures as shown in Fig. 4, where the width of the compact waveguide is one half of the width of their corresponding full waveguide. In Fig. 4 (a) the Half-Air-waveguide structure is integrated along the edge of interposer, and in Fig. 4 (b) a Half-AirVia-waveguide structure is obtained by drilling an array of free vias without filling copper along one edge of the half waveguide, and an array of copper filled vias along another edge. For both of these half waveguides, one edge of which can be taken as the perfect electric conductor and another edge can be taken as the perfect magnetic conductor (PMC). Therefore, they can support the same TE_{10} mode as that of their corresponding full waveguide in Fig. 2.

B. Propagation Characteristics and Electric Field Distribution

Fig. 5 and Fig. 6 present the full wave simulation results about electric field distribution, reflection and propagation characteristics of the full waveguide and proposed compact half waveguides respectively.



(a)

(b) (c)

Fig. 5. Electric field distribution results at 140GHz for (a) Full waveguide structure, (b) Half-Air-waveguide, and (c) Half-AirVia-waveguide structure.

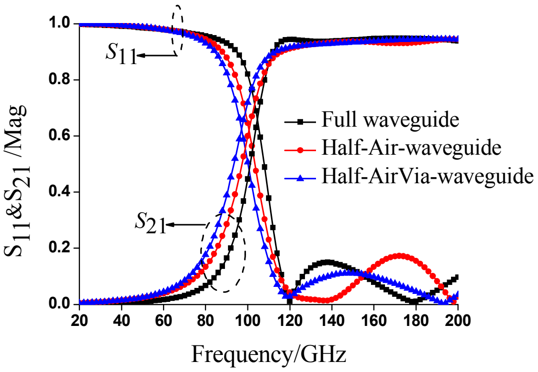


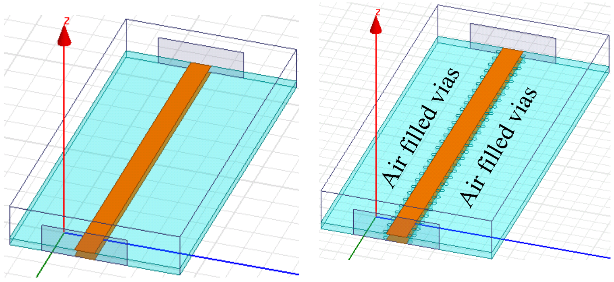
Fig. 6. Reflection and propagation characteristics

The S parameters and electric field distribution results demonstrate that these two compact half waveguide structures have similar performance to their corresponding full waveguide structures, however, they only occupy 50% area of the full waveguide. Due to the fringing effect (which can be seen from Fig. 5), part of electric field leaks into the glass or air medium, this results in that the cutoff frequencies of these compact waveguides all shift towards lower frequency.

The electric field leaking into the medium outside of the waveguide will bring about substantial offset of the cutoff frequency. By comparing the S parameter curves in Fig. 6 and electric field distribution in Fig. 5 of Half-Air-waveguide structure and Half-AirVia-waveguide structure, it shows free vias filled with air located along the edge of the Half-Air Via-waveguide structure can concentrate the electric field within the waveguide structure and decrease electromagnetic radiation as a result.

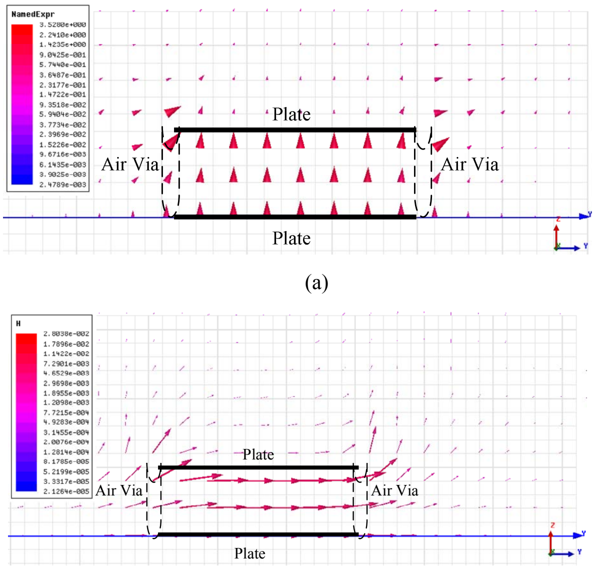
III. QUASI-TEM MODE COMPACT WAVEGUIDE STRUCTURES

Because the TE mode waveguide structures proposed in section II all have cutoff frequencies, they cannot support the propagation of DC and lower frequency signals. In this section, we propose another quasi-TEM mode compact waveguide as shown in Fig. 7(b), where the planar waveguide is employed and the air filled vias are placed along its both edges. These air filled vias serve as the PMC boundary as they do in Fig. 4 (b), therefore, the proposed waveguide can support quasi-TEM mode and hence DC and lower frequency signal propagation along it.



(a) (b)

Fig. 7. (a) Traditional planar waveguide without air filled vias and (b) planar waveguide with air filled vias.

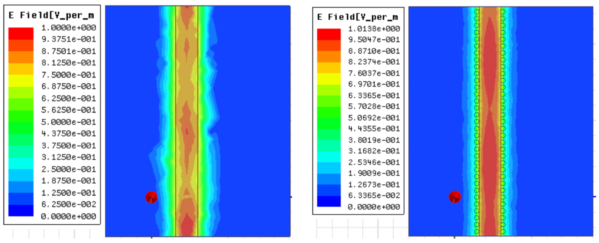


(a)

(b)

Fig. 8. (a) Electric and (b) magnetic field vectors distribution within planar waveguide with air vias at 100GHz.

Fig. 8 plots the electric and magnetic fields distribution on the cross section of the proposed planar waveguide with air vias. For both electric field and magnetic fields, their transverse components are quite larger than their longitudinal components. This verifies that such waveguide works at the quasi-TEM mode.



(a) (b)

Fig. 9. The electric field distribution results at 100GHz for (a) traditional planar waveguide without air filled vias and (b) planar waveguide with air filled vias

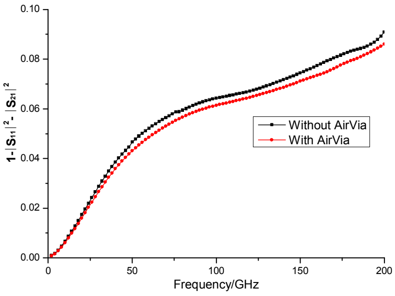


Fig. 10. The comparison of electromagnetic radiation losses.

Fig. 9(a) and (b) show the electric field propagation along the planar waveguides without and with air filled vias respectively, where the traditional planar waveguide without air vias has the same dimension as that of the proposed planar waveguide with air vias. From Fig. 9 we can see that the electric field of the planar waveguide with air vias is more concentrated within the waveguide region compared with that of the planar waveguide without air vias. This verifies again that the air filled vias can be used as PMC boundary to concentrate the electromagnetic fields inside the waveguide.

In Fig. 10, we study and compare the electromagnetic radiation losses inside the glass interposer. For this purpose, we calculate $1-(|S_{11}|^2+|S_{21}|^2)$ of these two planar waveguides. As we all know, $|S_{11}|^2+|S_{21}|^2=1$ is always true for a lossless medium and nonradiative system. To study their EMI property, the dielectric loss of the glass substrate is ignored during the simulation. Therefore, the value of expression $1-(|S_{11}|^2+|S_{21}|^2)$ presents the radiation loss. The results shown in Fig. 10 demonstrate that the electromagnetic radiation of planar waveguide with air vias dilled along the both edges is smaller than that of planar waveguide without air vias, which results in lowering EMI especially at high frequency.

IV. CONCLUSION

In this paper, we proposed two kinds of compact waveguide structures which can be integrated with glass interposer for millimeter-wave/THz application. Compared with silicon interposer waveguides, they have lower insertion loss. The transmission characteristics represented by S parameters and electric field distribution results of the proposed TE mode compact waveguide obtained by a 3D full-wave simulator indicate that they behave similarly to their equivalent full waveguides. In addition, they cut down the occupied spacing size almost by 50% and make them more appropriate for high-density integrated 3DIC system. It also shows that air filled TGVs can make the electromagnetic field more concentrated within the waveguide structure leading to lower EMI. Meanwhile, the fabrication of air filled TGVs is easy by using the available TGVs process.

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