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Modelling and Study of a THz Hollow Photonic Crystal Integrated Waveguide

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***Abstract*—We present a novel design of low-loss single-mode flat hollow photonic crystal integrated waveguide (HPCIW). The simulated propagation loss is below 1 dB/cm over the operating frequency range between 0.93 THz and 1.06 THz, with an averaged minimum loss of 0.78 dB/cm at 0.972 THz. Compared with substrate integrated waveguide (SIW) and photonic crystal waveguide, the proposed HPCIW requires no via and can be easily integrated vertically, which make the HPCIW a strong candidate for multilayer THz system in package (TSiP) applications.**

I. INTRODUCTION

THz waveguides are fundamental and key components for functional THz devices and systems. For multilayer TSiP applications, THz waveguides are highly preferable to be low loss, single mode, and easy to be integrated vertically. The traditional planar transmission lines, such as microstrip, coplanar waveguide and stripline, suffer from high loss due to the lossy dielectric substrate and strong frequency dependent loss due to Cherenkov-like radiation especially at THz frequency range [1]-[3]. Reported propagation loss results at 1THz are approximately α_{ms}=43.3 dB/cm, α_{cpw}=65.1 dB/cm, and α_{st}=26 dB/cm for microstrip, coplanar waveguide, and stripline, respectively [1]-[3]. SIWs [4] and hollow SIWs [5] encounter fabrication challenges at high THz frequencies as vias become too small and difficult to metallize. Photonic crystal waveguides [6], [7] support slow wave and can be extremely low loss and low GVD when using low-loss materials as the host material, e.g. high-resistivity silicon. But, photonic crystal waveguides can be greatly affected by the properties of the substrate and superstrate, which makes multilayer packaging challenging. In this paper, we propose a novel HPCIW which avoids the use of metallic vias and offers various functionalities as photonic crystal waveguide does.

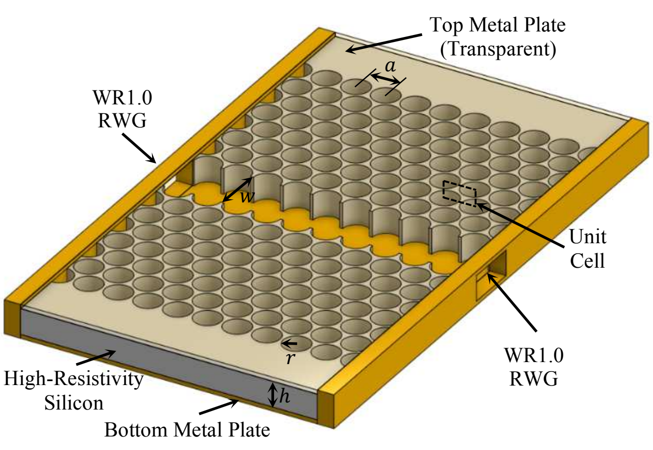

Fig. 1. Schematic of the HPCIW. The inner surfaces of the WR1.0 RWGs, top metal plate and bottom metal plate are set to be plated by thin gold film with thicknesses greater than 5 times of the skin depth at the longest operating wavelength point. The constant of lattice $a = 122\ \mu m$. The radius of the air holes $r = 0.45a = 54.9\ \mu m$. The width of the line defect in the center $w = 254\ \mu m$. The height of the high-resistivity silicon layer $h = 127\ \mu m$.

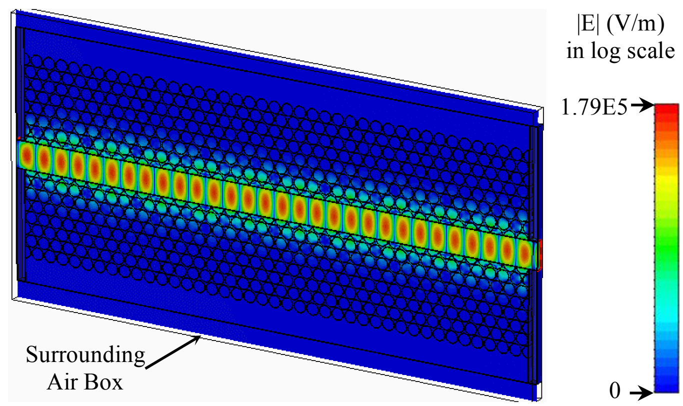

Fig. 2. Absolute electric field in the long HPCIW at 1 THz. Open boundaries are applied to all directions in the simulation.

II. RESULTS

Fig. 1 shows the schematic of the proposed HPCIW which is comprised of a line-defect hexagonal photonic crystal structure sandwiched between two parallel metal plates. The photonic crystal structure consists of hexagonal arrays of air holes in the high-resistivity silicon slab. The unit cell of the photonic crystal structure is indicated by the black dashed parallelogram. Two rows of unit cells are removed from the central part of the photonic crystal structure. In the horizontal direction, the EM wave is strongly confined in the air core owing to the photonic bandgap effect, while in the vertical direction, the EM wave bounces between the two parallel metal plates. The operating mode in the HPCIW is HE_{10} mode, which is the fundamental mode of the HPCIW. The similar polarization between HPCIW and rectangular waveguide (RWG) makes the HPCIW easy to measure with standard waveguide metrology techniques. Besides, the guided wave in HPCIW is fast wave, which differentiates the HPCIW from conventional photonic crystal waveguide.

Two HPCIWs with different lengths have been designed and simulated by using CST. Two Standard WR1.0 RWGs are used at both ends to feed the HPCIW. The period number of the photonic crystal lattice along the defect line, P, for the short and the long HPCIWs are 20 and 40, respectively. The frequency-dependent complex permittivity of the high-resistivity silicon used in the simulation is extracted and 2nd-order fitted from [8]. The expressions for the real and imaginary parts of the permittivity are $\varepsilon' = 0.00013\times f_{THz}^2 - 0.0004\times f_{THz}^1 + 11.68$ and $\varepsilon'' = 0.00053\times f_{THz}^2 - 0.0016\times f_{THz}^1 + 0.0017$, respectively, where f_{THz} is the frequency in THz unit. The mode pattern in the long HPCIW at 1 THz is shown in Fig. 2, which shows the electromagnetic field can be tightly confined in the air line-defect region and guided over the waveguide in single-mode pattern.

The simulated S-parameters of the two HPCIWs are

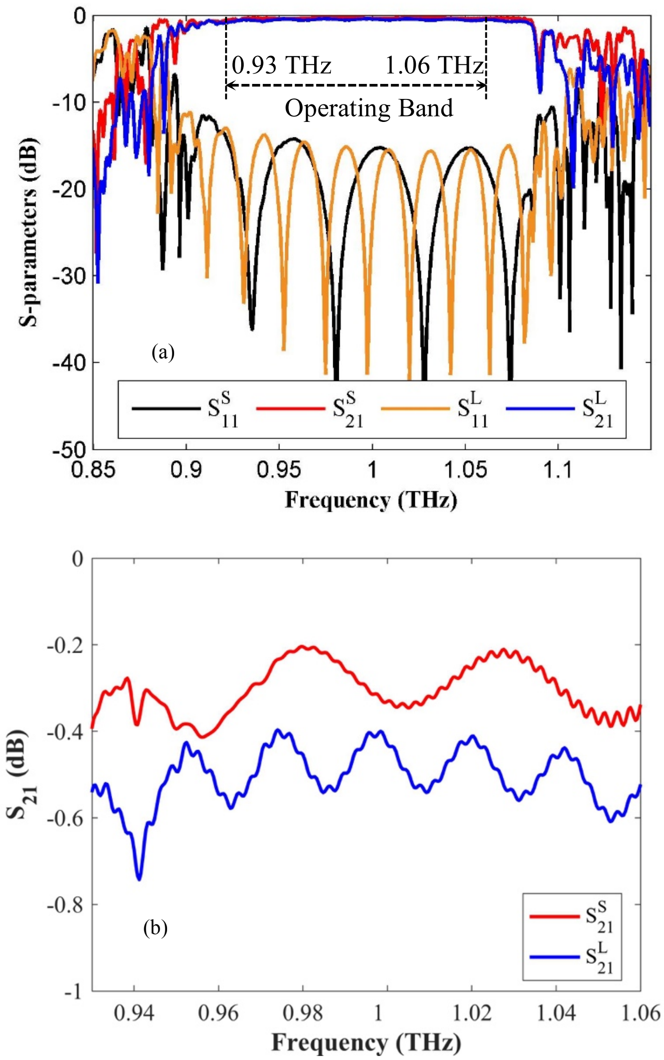

Fig. 3. (a) Simulated S-parameters of the short (S_{11}^{S} and S_{21}^{S}) and lone HPCIW (S_{11}^{L} and S_{21}^{L}). (b) Zoomed view of S_{21} parameters between 0.93 THz and 1.06 THz.

presented in Fig. 3(a). From the transmission coefficients, S_{21}, a transmission window between 0.93 THz and 1.06 THz can be obviously observed. The reflection coefficients, S_{11}, for both the short and the long HPCIWs are basically below -15 dB, indicating the coupling between the feeding WR1.0 RWG and the proposed HPCIW is effective and efficient. To distinguish the difference of the transmission coefficients of the short and the long HPCIWs better, the results within the frequency range from 0.93 THz to 1.06 THz are zoomed and shown in Fig. 3(b). From Fig. 3(b), we can see that difference between the S_{21} of the short and the long HPCIWs is significant. The ripples of the S_{21} over the transmission window are mainly caused by the impedance mismatch between the WR1.0 RWG and the HPCIW, as well as the slight impedance changes across the unit cell of the photonic crystal structure in the HPCIW.

Using multiline calibration method [9], the propagation loss of the HPCIW is calculated, as shown in Fig. 4. It is less than 1 dB/cm over the operating band from 0.93 THz to 1.06 THz, with an averaged minimum loss of 0.76 dB/cm at around 0.972 THz.

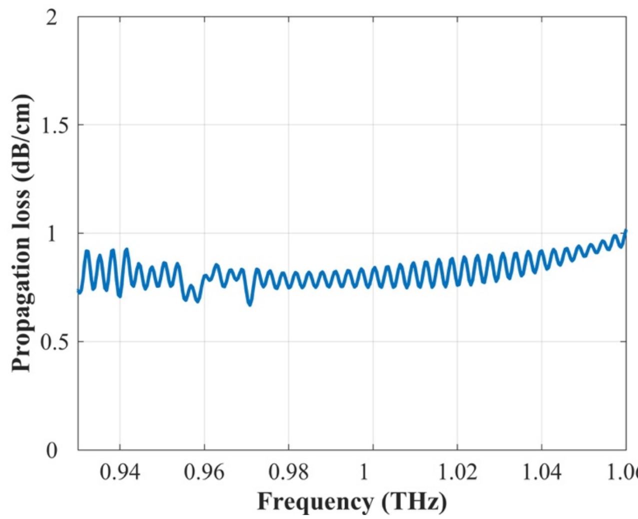

Fig. 4. Simulated Propagation loss of the HPCIW.

III. SUMMARY

This paper presents a novel hollow photonic crystal integrated waveguide (HPCIW) which combines the advantages of substrate integrated waveguide and photonic crystal waveguide, and avoids their drawbacks. The proposed HPCIW supports single-HE_{10}-mode propagation with propagation loss less than 1 dB/m from 0.93 to 1.06 THz. It can be a promising functional platform for TSiP applications.

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