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An Ultra-high Quality Factor Terahertz Photonic Crystal Cavity

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Abstract– **High quality factor Terahertz (THz) cavities are highly desired for many THz applications. This paper presents an ultra-high quality factor terahertz planar photonic crystal cavity at 315 GHz. Two approaches are employed to reduce the losses in the cavity, increasing the quality factor of the cavity. Firstly, short embedded photonic crystal waveguides are employed to reduce the in-plane loss. Secondly, a novel way of hole displacement is adopted for four edged holes of the L3-type photonic crystal cavity to decrease the radiation loss. An ultra-high quality factor of 65000 at a resonant frequency of 315.3 GHz was achieved for the designed cavity. This result could enable promising applications such as THz sensing.**

Keywords– **Terahertz waves, photonic crystal, high quality factor cavity.**

1 Introduction

Terahertz (THz) waves are electromagnetic radiations with frequencies ranging from 100 GHz to 10 THz. Such waves have attracted interest from research groups worldwide owing to their promising applications including high-data-rate wireless communications [1–3], high-resolution imaging [4–6], radars [4, 7], spectroscopy [8, 9], and sensing [10, 11]. These applications originate from unique features of THz waves such as extremely wide available bandwidth, short wavelength, ability to penetrate through non-conducting materials, and exhibiting "fingerprints" to living tissues and various chemical substances.

Sensing applications were demonstrated using THz cavities [12, 13]. For sensing applications, high quality factor cavities are always desired for high sensitivity detection [12]. Recently, high quality factor cavities were demonstrated based on silicon photonic crystal and effective medium materials [12–17]. THz cavities can be divided into two groups which are cavities with a suspended structure and planar cavities. THz cavities with a suspended structure eliminate the requirement of a lossy substrate, thus reducing the material loss. A suspended THz cavity with a loaded quality factor of 18300 at the resonant frequency of 640 GHz was reported in [14]. In another work, a suspended THz cavity exhibited a loaded quality factor of 11900 at 100 GHz [15]. Such cavities, however, require anchors to hold the suspended structure, hindering the system integration and complicating the fabrication process as well. Planar photonic crystal cavities exhibited relatively high-quality factors and can be fabricated easily using standard technologies such as deep reactive-ion-etching (RIE) with a low-cost photolithographic mask [17]. In general, a photonic crystal cavity is formed by removing one or several holes in the lattice of air holes. Yu *et.al.*, reported a so-called L1 cavity integrated with a resonant-tunneling-diode (RTD) oscillator to narrow the spectral linewidth of the RTD oscillation [16]. The cavity has the resonant frequency of 318 GHz. Yee *et.al.*, reported so-called L3 cavities resonating near 1 THz [18]. The loaded quality factors of the L1 and L3 cavities mentioned above were 1700 and 1000, respectively. In those studies, the loaded quality factors were low because of the strong coupling between the cavity and the waveguides. Otter's group reported L3 THz cavities which operated at about 100 GHz. These cavities exhibited loaded quality factors of less than 10000 [17]. In [12] a L3 cavity resonating at 318 GHz with a loaded quality factor of 12000 was reported. To date, this is the highest reported quality factor of planar THz photonic crystal cavity resonating at 300 GHz range. In this structure, the coupling between the waveguides and the cavity was weak because the waveguides were moved far from the cavity line. In the two latest works mentioned above, edged holes next to the cavity were dislocated to obtain a high-quality factor. Nevertheless, the mechanism of the high-quality factor has not been explained clearly.

In this study, we proposed a novel method to reduce losses of the planar photonic crystal cavity structure in Reference [12] for obtaining an ultra-high-quality factor at around 300 GHz. The high-quality factor can be obtainable by optimizing both losses in the in-plane direction and out-plane direction. By mitigating the effect of the waveguide, the reflection from the walls of the air holes is improved. This helps to reduce the in-plane loss. The low out-plane loss component was achieved by dislocating the two edged holes in the both sides of the cavity, where adjacent holes are shifted in opposite directions. This novel way to dislocate air holes has not been investigated in any previous work. We utilized the frequency domain simulation method with an adaptive meshing of the powerful full-wave electromagnetic (EM) simulator 3D CST Microwave Studio 2019. The simulated results show that a high loaded quality factor of 65000 was obtained. Because the coupling efficiency between the waveguides and the cavity is weak, the unloaded quality factor is similar to the loaded quality factor. To the best of our knowledge, this is the highest calculated quality factor of a THz cavity operating at around 300 GHz.

2 Structure of the Proposed THz Photonic Crystal Cavity

The proposed cavity structure is constructed based on a silicon photonic crystal slab. The slab thickness is 200 µm. The L3 cavity is formed by defecting three holes at the center of a perforated slab as depicted in Figure 1. The lattice of air holes has periods in the x-direction and the y-direction are a = 240 µm and $\sqrt{3}a/2$, respectively. The periodic air holes guarantee the in-plane total internal reflection. To increase the quality factor of the cavity, the four air holes near the edge of the cavity are shifted from their original positions as indicated in Figure 1. The detailed discussions of this are given in Section 3. We call s_1 and s_2 the shift distances of the A and B holes from their original positions, respectively. Here, we assume the signs of s_1 and s_2 are positive when A and B holes are shifted far away from the cavity center, and they are negative if A and B holes are shifted toward the cavity center.

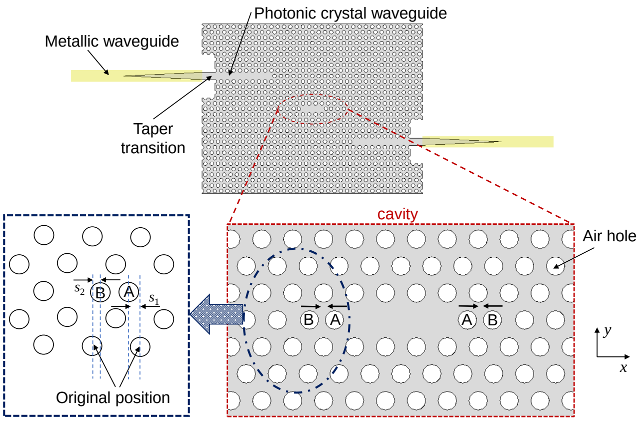

Figure 1. Structure of the proposed THz planar photonic crystal cavity.

The cavity is excited using embedded photonic crystal waveguides. The embedded waveguides are constructed by removing several adjacent air holes in a line parallel to the cavity. The excitation signal is input to a WR3 metallic waveguide. To mitigate the reflection, a taper transition is employed to efficiently couple the excitation signal to the embedded photonic crystal waveguide [12]. The taper transition converts the TE_{10} mode of the metallic waveguide into the fundamental mode of the embedded photonic waveguide and vice versa. The excitation signal is weakly coupled to the cavity, where the photons corresponding to the resonant frequency are strongly confined. The photon energy is then slowly released. The output signal is detected at the output of the metallic waveguide on the other side. In the simulation, the excitation and output signals are introduced and captured using waveguide ports. By analyzing the resulting scattering parameters, one can determine the resonant frequency, as well as the quality factor of the cavity.

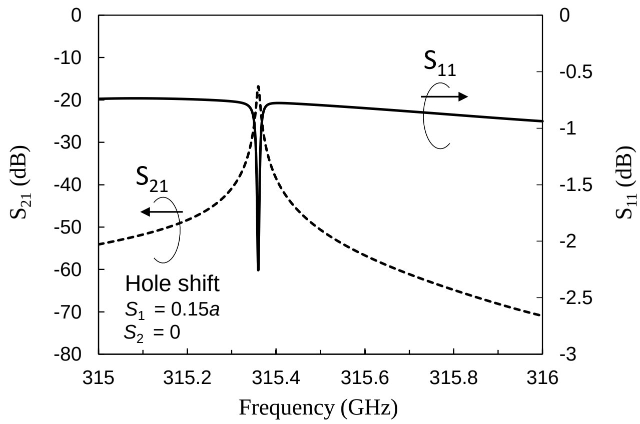

Figure 2. S – parameters of the proposed structure.

We modeled and simulated the proposed structure shown in Figure 1 with shifted distances of air holes A and B from their original positions $s_1 = 0.15a$ and $s_2 = 0$, respectively. The scattering parameters of the simulated structure are given in Figure 2. By analyzing the S_{11} and S_{21} -parameters, it can be seen that the obtained resonant frequency is 315.36 GHz. At a resonant mode, the S_{11} has a minimum, whereas the S_{21} gets peaked as shown in Figure 2. This behavior implies a correct resonant mode of the cavity. Figure 3(a) and (b) describes the electric field distribution of the simulated structure at resonant and off-resonant modes. It can be clearly seen that at resonance the confinement of the photon within the cavity is stronger than that of the case when the cavity is off-resonance.

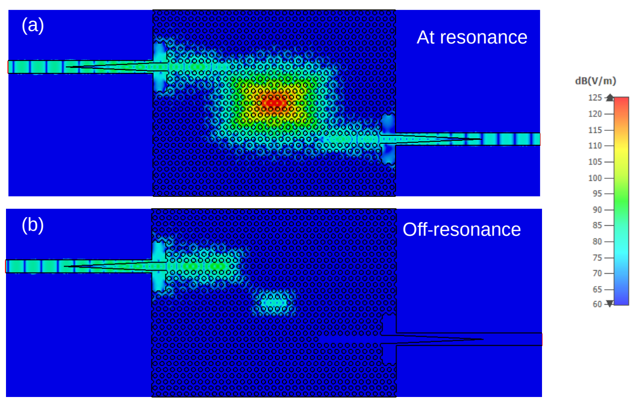

Figure 3. Electric field distribution of the proposed structure (a) at resonant and (b) off-resonance.

Generally, the stronger the confinement of the photon within the cavity, the higher the quality factor. In this article, we utilize the electric field distribution at resonance to analyze loss components and the quality factor of photonic crystal cavities. In the loss term, a strong confinement is equivalent to the low loss. The total loss includes the in-plane loss and the out-plane loss. The former relates to the reflection at the walls of the air holes. In the ideal case, in-plane loss is zero if the photons are perfectly reflected by the walls of the air holes. We also modeled again and simulated the photonic crystal cavity structure reported in Reference [12] to investigate its loss components. The electric field distribution of this structure is depicted in Figure 4.

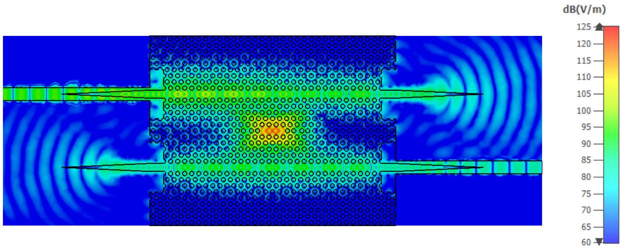

Figure 4. Electric field distribution of the structure in Reference [12].

2.1 In – Plane Loss Reduction

We found that for the structure reported in Reference [12], due to the long embedded photonic crystal waveguides, which destroy the periodicity of the lattice of the air holes, the reflection worsens. This leads to higher in-plane loss as can be seen from comparing the electric field distribution between Figure 4 and Figure 3(a). The confinement area in Figure 4 is larger than that in Figure 3(a), implying the confinement in Figure 4 is weaker. In the proposed structure shown in Figure 1, we recovered a number of air holes, which were omitted to form the long embedded waveguides in Figure 4, to make the embedded waveguides shorter. As a result, the structure shown in Figure 1 exhibits better reflection, and consequently, lower in-plane loss component. The proposed structure, however, has lower transmittance compared to that of the previous structure because of weaker coupling. This would lead to a few difficulties related to measurements. Nevertheless, this issue can be overcome by using the excitation source with higher output power.

2.2 Out - Plane Loss Reduction

In this subsection, we investigate a method for reducing the out-plane loss component. Generally, because the reflective index of the air is smaller than that of the silicon, which is 3.4, the total internal reflection condition takes place and in the ideal case the photon energy will not leak in the out-plane direction. The out-plane loss is therefore quite small. Previous studies show that this loss component is mostly caused by an abrupt change in the electric field near the edges of the cavity [19]. Noda's group has pointed out that an electric field profile having a Gaussian envelope function is necessary to avoid an abrupt change of the electric field near the edges of the cavity, resulting in a high-quality factor. A common way to achieve an electric field profile with an envelope function similar to the Gaussian one is to dislocate edged holes. All previous studies shifted only one hole or shifted adjacent edged holes in the same direction. In this study, we proposed to shift two adjacent edged holes in opposite directions to improve the electric field profile as indicated by arrows in Figure 1. We simulated the proposed structure with various the shifted distance s_2 of the air holes B from their original positions. It should be noticed that a negative value of s_2 means the air B are shifted toward the cavity center. For all cases, the shifted distance s_1 of the air holes A is unchanged and equal to $0.15a$. The y-direction electric field, E_y profile along the centerline of the cavity in the x direction for various values of the shift distance of the B holes is plotted in Figure 5.

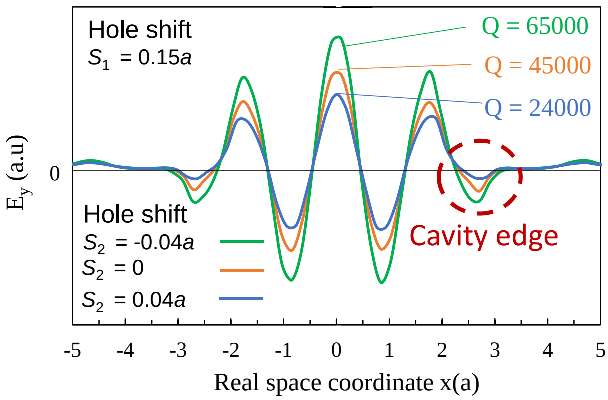

Figure 5. Ey profile along the centerline of the cavity in the x-direction for various values of the shift distance of the B holes.

It can be seen that a Gaussian-like envelope was observed for all cases. The quality factor corresponding to the hole shift $s_2 = -0.04a$ (which means the shift direction of the B holes is opposite to that of the A holes) is higher than that of other cases. This can be explained by the fact that the out-plane loss in this case is the smallest. The out-plane loss or radiation loss, in turn, can be adjusted by the damping level of the E_y component near the cavity edges [19]. As shown in Figure 5, near the cavity edge, E_y corresponding to the hole shift $s_2 = -0.04a$ decreases slower than that of other cases. This implies the out-plane loss is smallest in this case.

2.3 Quality Factor Analysis

The quality factors shown in Figure 5 are extracted from S_{21} parameters shown in Figure 2 and Figure 6. Figure 6 shows the resonant spectrum of the proposed cavity for the shift distance $s_2 = 0.04a$ and $s_2 = -0.04a$ of the B holes. The shift distance of the A holes is fixed at $s_1 = 0.15a$.

As indicated in Figure 6, a narrow 3 dB bandwidth of 5 MHz was achieved for shift distance $s_2 = -0.04a$, which corresponds to a high-quality factor of 65000 as shown above in Figure 5. This bandwidth is almost

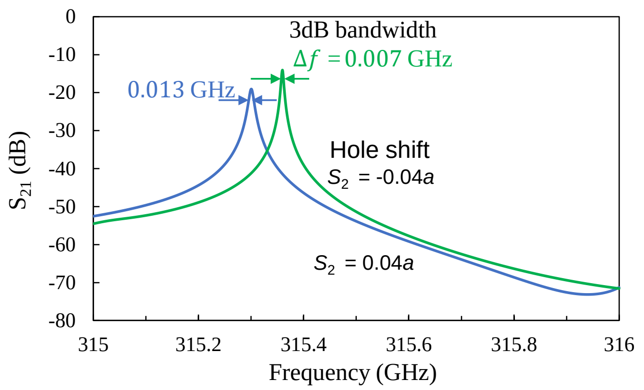

Figure 6. Resonant spectrum for various value of the shift distance of the B holes.

triple narrower than that of the case when the B holes move far away from the cavity center at the same distance. This result again confirms that a shift of the B holes toward the cavity center is effective in obtaining a cavity with a narrow resonant spectrum and high-quality factor.

The quality factor as a function of the shift distances of the A and B holes is presented in Figure 7. As the A holes and B holes are shifted simultaneously, Figure 7 shows that shifting the B holes toward the cavity center is efficient in increasing the quality factor. The highest quality factor of 67000 is achieved with $s_1 = 0.15a$ and $s_2 = -0.05a$ as can be seen in Figure 7. A more detailed study on the quality factor as a function of the shift distances of the A and B holes will be carried out and published elsewhere.

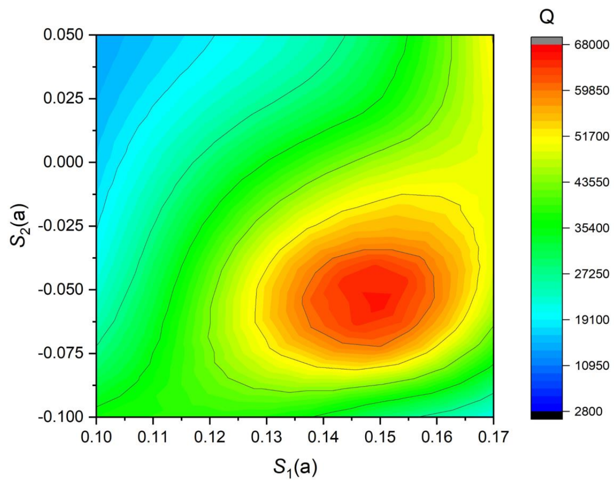

Figure 7. The quality factor as a function of the shift distances of the A and B holes.

3 Conclusion

In this article, we proposed methods to reduce in-plane and out-plane losses for obtaining the high-quality factor in THz planar photonic crystal cavities. The in-plane loss was reduced by employing short embedded photonic crystal waveguides to excite the cavity. This results in good reflection from the walls of the air holes, thus low in-plane loss can be achieved. We also proposed dislocating B holes toward the cavity center, which is opposite to the shift direction of the A holes. This helps to result in the low out-plane loss. We achieved an ultra-high calculated quality factor of 65000 at a resonant frequency of 315.3 GHz. The calculated results were supported by analyzing electromagnetic fields and theoretical analysis. This high-quality factor cavity would pave the way for various promising THz sensing applications.

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