Tuning the extraordinary transmission in a metallic/dielectric CDC hole array by changing the temperature

Wei Wang[1], Yalin Lu[2], R. J. Knize[2], Kitt Reinhardt[3], and Shaochen Chen[1*]

[1]*Mechanical Engineering Department, The University of Texas at Austin, TX 78712 USA*
[2]*Laser Optics Research Center, Physics Department, USAF Academy, CO 80840 USA*
[3]*AFOSR/NE, 875 North Randolph Street, Suite 326, Arlington, VA 22203 USA*
**scchen@mail.utexas.edu*

Abstract: Tunable extraordinary transmission via changing temperature of a porous metallic layer on top of a thin layer of dielectric strontium titanate (STO) was studied. The metallic layer has a through-hole array and each hole has a circular converging-diverging channel (CDC) shape, which induces the excitation of surface plasmon polaritons (SPPs) and then results in a controllable extraordinary optical transmission in the terahertz (THz) frequency range. We used a three-dimensional (3D) finite element method to analyze the transmission characteristics of the structure. Location and magnitude of the transmission peaks can be adjusted by hole size, converging angle, and thicknesses of metal and STO layers. Remarkably, the suggested structure presents a strong transmission dependency on temperature, which offers a new approach to actively and externally tune the transmission. This new design could lead to a family of temperature-sensitive devices working in the THz frequency range, promising in many applications including photonics, nanolithography, imaging, and sensing.

OCIS codes: (000.2700) General science.

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1. Introduction

The terahertz (THz) frequency band, which lies between domains of microwave electronics and mid infrared optics, has received increasing attentions recently because of its possible applications in fundamental science, new imaging and sensing modalities, and high bandwidth signal processing [1]. Examples of such applications include communication [2], medical imaging [3], pharmaceutical quality control [4], and chemical and biochemical sensing [5]. Utilizing the light in the THz band, however, requires a precise control of the wave propagation as well as the electromagnetic field distribution. For example, in the applications as THz filters, photonic circuits, and sensors, control of the transmission spectrum, especially a capability of active and precise frequency tuning, is highly desirable.

The extraordinary optical transmission (EOT) phenomenon was first reported by T. W. Ebbesen *et. al.* in 1998 [6]. This work has generated considerable interests in recent years and led to the development of a new family of optical devices based on subwavelength hole arrays with extraordinary transmission spectra. This unique phenomenon is believed to be due to the SPPs excited at the metal/dielectric interface [7–9]. Although metal surfaces in the THz frequency region act as perfect conductors making SPPs excitation unexpected, EOT has been observed recently in both metallic [10–12] and semiconductor [13–15] hole arrays, and it has been proven both experimentally and theoretically that the resonantly-excited SPP-like mode plays an important role in the much enhanced transmissions [16,17]. Excited by Ebbesen's pioneer work, intensive studies were done to analyze the tunability of the transmission. By changing the geometric variables (film thickness, interface media, periodicity, hole shape, aperture size, channel shape, etc.), the transmission properties (magnitude, location of the peaks, the full width at half maximum (FWHM), and selectivity of different polarization) can be tuned correspondingly [10,11,18–24].

However, tuning by changing the geometry variables indicates either deforming or replacing the device will be required, and is not active. This actually limits their future

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applications in real-time systems. Previous work has shown that the transmission of light through a thin Ag film with a specifically designed periodic subwavelength hole array can be influenced by the presence of the externally applied magnetic field [25], which indeed indicates an initial move toward the active frequency tuning direction. Considering the fact that SPPs strongly rely on the metal/dielectric interface, modification of the interface would become an effective route for realizing the active tuning, and recent development of dielectric materials with a strong non-linear response [26] will actually support the idea. Here, the term "non-linear response" means their optical properties can be controlled by external parameters (temperature, electric or magnetic field, light pulse, etc.). Among these non-linear materials, so called incipient ferroelectric materials [27] such as strontium titanate (SrTiO3, STO) or potassium tantalate (KTaO3, KTO) exhibit a potential to realize the large frequency range and active tuning. For example, between 0.3 THz to 0.9 THz, i.e. wavelengths between 300 µm to 1 mm, both real and imaginary parts of permittivity of STO undergo an increase as temperature decreases [26]. This unique property offers a new way to design strong temperature-dependent devices working in the THz band.

In this work, we propose a new structure with a metallic layer on top of a thin layer of the STO. The metallic layer has a through-hole array with a circular, converging-diverging channel (CDC) shape. Use of the CDC shape has been proven with similar EOT effect, in addition, with an extra degree of freedom in a geometric variable to further fine-tune the transmission spectrum [23]. Simulations were performed to study the EOT properties under different temperature conditions. By careful design of the converging angle and STO layer thickness, the proposed structure can function well at certain THz bands with a realistic transmission spectrum profile. More importantly, the strong transmission dependency on temperature provides us the capability to modulate the transmission without using deformation or replacement—a true active frequency tuning.

2. Simulation considerations

Figure 1 shows a side view of the proposed structure used for the simulation where the incident light transmits through the thin layers of silver and STO. Their thicknesses are t_1 and t_2, respectively. There is a circular CDC hole array with a semi converging angle θ in the silver layer [23]. The radii of the holes at surface are fixed at 20µm. The transmission was calculated for different wavelengths, temperatures and geometric variables. Figure 2 shows the top view of the silver film. The circular hole array is periodic in both the x and y directions, and the periodicity for the two directions are the same (50µm). The inset shows the details of a single circular hole.

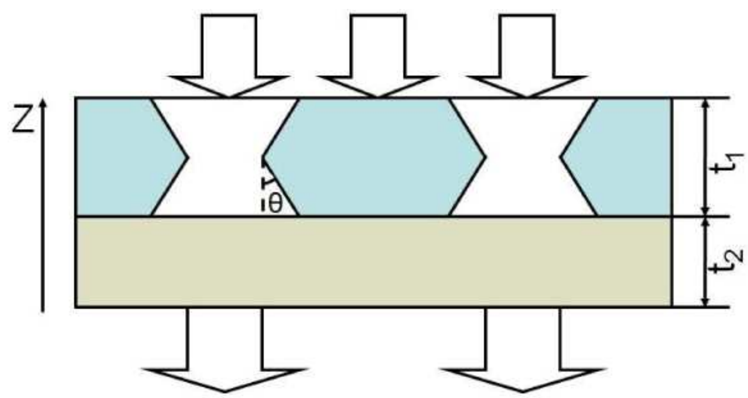

Fig. 1. The side view of the device structure. The thickness for the metallic layer is t_1, the thickness for the dielectric layer with a temperature dependent dielectric constant is t_2, and a circular CDC hole array with a semi-angle θ will be made inside the metallic layer.

The converging angle, θ, and the metal and STO thickness, t_1 and t_2, were changed accordingly in the simulation, while keeping all other parameters unchanged. The goal is to

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study the effect of such varying parameters on the relationship among transmission, wavelength, and temperature. For this study we considered the frequency to be around 0.6THz or 450μm wavelength and the temperature range to be from 270K to 305K. The dielectric constant of STO was described by a damped harmonic oscillator model: $\varepsilon = \varepsilon_\infty + f^2 / (\omega_0^2 - \omega^2 - i\gamma_t\omega)$, where $\omega_0(\mathrm{T})[\mathrm{cm}^{-1}]=\sqrt{31.2(\mathrm{T}-42.5)}$, $\gamma(\mathrm{T})[\mathrm{cm}^{-1}]=-3.3+0.094\mathrm{T}$, $f = 2.3 \times 10^6 \mathrm{cm}^{-2}$ [26]. The dielectric constant of silver used in the simulation was described by the Drude model $\varepsilon = \varepsilon_\infty - \omega_p^2 / (\omega^2 + i\gamma_s\omega)$, where $\varepsilon_\infty = 1$, $\omega_p = 1.44 \times 10^{16}\ \mathrm{s}^{-1}$, and $\gamma_s = 4 \times 10^{13}\ \mathrm{s}^{-1}$ [28]. Within the suggested temperature range in our calculation, the dielectric constant of silver is set to be temperature independent. The electromagnetic fields were assumed to be time harmonic and the resulting governing equations for the steady-state distribution was solved using commercially available three-dimensional (3D) finite element software (COMSOL 3.3). The computational domain considered is a single unit cell surrounded either by periodic boundary conditions or by perfectly matching layers (PML) [29]. The light is incident normal to the film surface and the transmittance is calculated from the obtained electromagnetic field distributions.

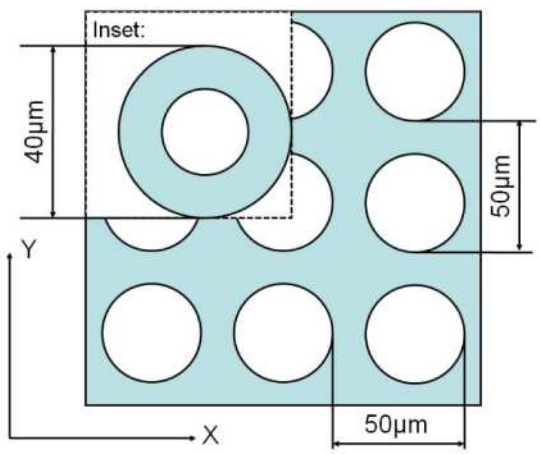

Fig. 2. The top view of the structure. The circular hole array is periodic in both the x and y directions, and the periodicity for the two directions are the same (50μm). The inset shows the top view of a single circular hole.

3. Results and discussion

Figure 3 shows the transmission vs. temperature and wavelength for the structure having various geometric variables. To better evaluate the transmission property, all figures in Fig. 3 were plotted at the same scale. All the figures shown are characterized by their strong transmission peaks which are much larger than $(A/\lambda)^4$, the Bethe-Bouwkamp power law model [30]. In this model, 'A' is the aperture size and 'λ' is the wavelength of the light. This indicates the existence of EOT inside the proposed structure. Further examination reveals that the transmission spectrum changes as both temperature and geometry change. Let's first look at the transmission's dependency on temperature. Each figure in Fig. 3 shows the full transmission spectrum under certain geometric conditions. Since a higher temperature results in both smaller imaginary and real parts of the dielectric constant of the STO material, the magnitude of the transmission peak increases and the peak blue-shifts as the temperature increases.

To better study the role of changing both temperature and converging angle, we compare Fig. 3a-c altogether. Responses from both CDC and the straight-hole array due to a temperature change of 36 K are re-plotted in Fig. 4. When changing the temperature 36 K around the room temperature as shown in Fig. 4a, the transmission peak's location and magnitude among all cases change about 33 μm, which is about 3% central to the

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transmission wavelength. This indicates a fairly large frequency tunable range, and is actually practical for many long wavelength photonics application. Another remarkable benefit is that these transmission properties are nearly linearly dependent on temperature. Moreover, the full width at half maximum (FWHM) is relatively independent of temperature change, which remains to be around 60 µm.

For the hole-arrayed metal/dielectric structure, an increase in the angle θ actually gives rise to a decrease in transmission, this is slightly different from the case without the dielectric layer [23]. However, it shows a blue-shifted transmission when increasing the angle θ, indicating an additional manipulation over the transmission by changing the angle is possible. Figure 4b shows the different transmission spectra at different converging angles at 269 K. As the apertures in the metal layer change from straight-channel to the CDC shape with a converging angle of 60°, the peak transmission reduces from 20.1% to 15.8% with a blue shift of ~32 µm, and the FWHM of those peaks is actually becoming narrower too. The results here indicate, for the suggested metal/dielectric structure, introducing CDC to the design is not beneficial to the transmission amplitude, but does add a freedom in fine-adjusting the peak position and in modifying the FWHM of the transmission.

The comparison of Fig. 3b and 3d reveals the transmission dependency on the metal film thickness. With the same converging angle and temperature, the magnitude of the transmission peak is much lower for a thicker metal layer. Also, as the metal layer thickness increases, the location of the transmission peak red-shifts at the same time. It is important to point out that Fig. 3c (using a larger converging angle) and 3d (using a thicker metal layer thickness) show very closed transmission spectrum, which indicates that adding the CDC design to the structure can provide not only an extra degree of freedom to fine-tune the transmission properties, but also as an important substitution to change other geometric variables, for example, here to use less amount of metallic material.

The thickness of STO the layer also plays an important role in the transmission properties. Figure 3b, 3e and 3f show the transmission spectrum with a same converging angle of 45° for different STO thicknesses. Although all the transmission peaks in the three plots are still much larger than those predicted by the Bethe-Bouwkamp power law model, the magnitude of each peak is much lower for a thicker layer of STO. Along with magnitude reduction, the location of the transmission peak red-shifts at the same time. Since STO is not a lossless material, the reduction of transmission results from the increased energy loss in longer travel distance in the absorbing material. In the case of our simulation, as shown in Fig. 3, when the STO layer thickness increases from 1.5 µm to 2.5 µm, a steep magnitude drop of the transmission peaks of around 10% with a red shift of nearly 100 µm is observed. The dramatic transmission change suggests that the STO layer thickness is a crucial parameter on which special attention is needed to meet the desired performance requirement. A further investigation over the case having holes all the way through the metal/dielectric structure will be also interesting, and this is an ongoing effort.

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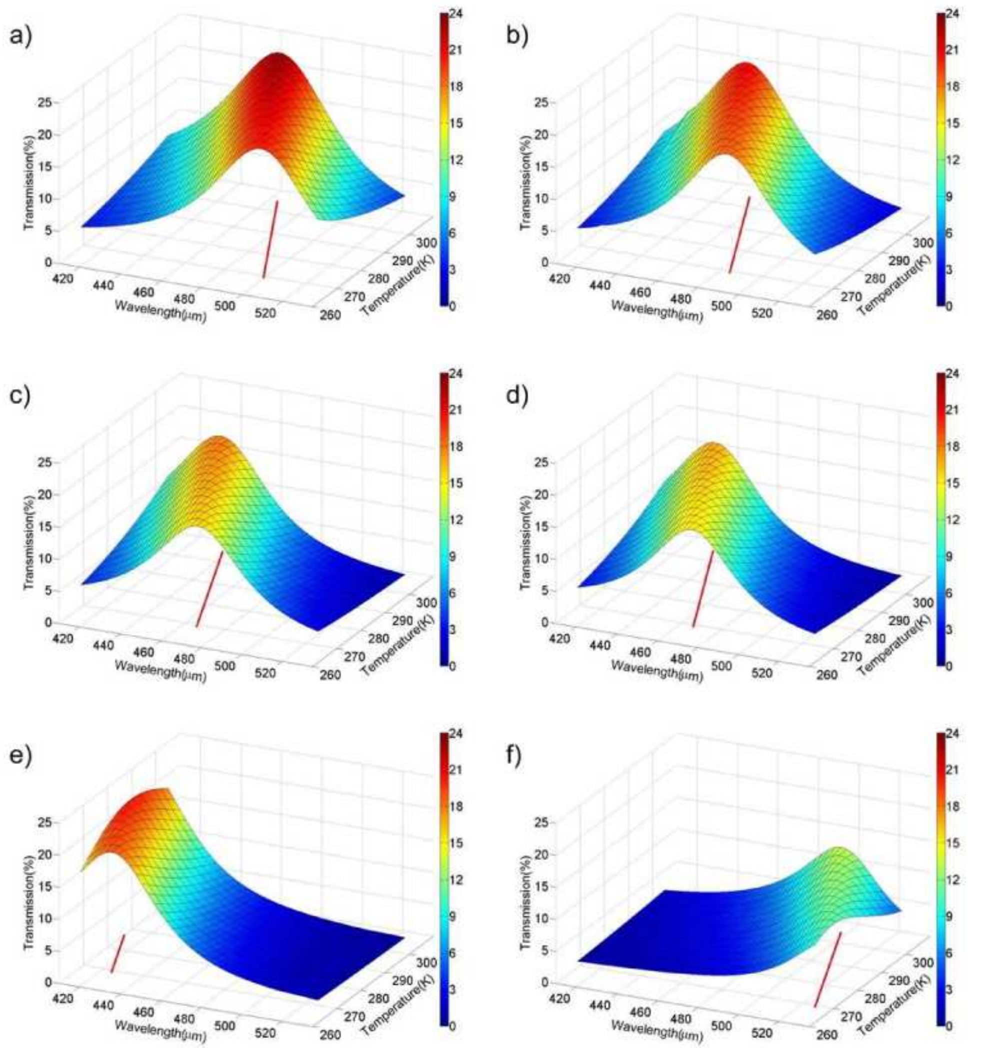

Fig. 3. Transmittance spectrum with different geometric variables and temperatures. (a)-(c) are plots of transmission versus wavelength and temperature with converging angle (a) 0°, (b) 45°, and (c) 60°. Thickness of the metal and STO layer are both fixed at 2μm. (d) shows the case at which the thickness of the metal and STO are 3μm and 2μm, respectively. The converging angle is 45°. (e) and (f) show the transmittance spectrums with the same metal film thicknesses (2μm) and converging angle (45°), but with different STO layer thicknesses: (e) t_2 = 1μm and (f) t_2 = 2.5μm. For all cases above, the hole area is unchanged. The transmission peak vs. temperature curve is shown at the bottom in each figure (red curve).

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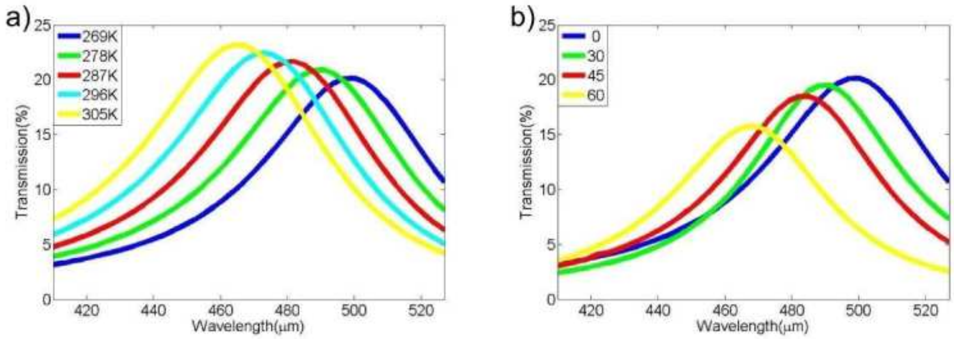

Fig. 4. Transmittance spectrum curves. (a) shows transmission spectrum with different temperatures. The converging angles are fixed at 0° (straight hole) for all cases. (b) shows transmission spectrum with different converging angles. The temperatures are fixed at 269 K for all cases.

4. Conclusion

We have investigated the transmission spectra of metallic hole arrays with different converging-diverging channels combined with a layer of STO. Besides extraordinarily-high subwavelength transmission, the simulation results also show strong tunable transmission characteristics. Both the location and magnitude of the transmission peak can be tuned by temperature, converging angle, and both of the metal and STO film thickness. Moreover, adding a STO layer offers a new approach to actively control the transmission without mechanically changing the optical device. As a result, this proposed structure could lead to extraordinary transmission at different wavelengths and can be used to develop temperature-tuning THz filters.

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