# Tunable transmission at 100 THz through a metallic hole array with a varying hole channel shape

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**Abstract:** Extraordinary optical transmission spectrum for a two-dimensional metallic hole array (2D-MHA) changes with the hole channel shape. In this paper a new converging-diverging channel (CDC) shape is proposed. A three-dimensional (3D) finite element method is utilized to analyze the transmission characteristics of the 2D-MHA with CDC. The transmission peaks are blue-shifted when the gap at the throat of CDC is reduced. Similar blue-shift in the transmission peaks are observed for a straight channel MHA when the aperture size is reduced. The transmission for the straight channel MHA is not sensitive to the metal film thickness. But, for a CDC MHA the transmission varies with the metal film thickness. Also, the CDC shape gives an extra degree of geometrical variable to 2D-MHA for tuning the transmission peak location with potential applications in nanolithography, imaging and biosensing.



**OCIS codes:** (050.1220) Apertures; (050.0050) Diffraction and gratings; (120.2440) Filters; (240.6680) Surface plasmons; (040.2235) Far infrared or terahertz; (120.7000) Transmission.

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## 1. **Introduction**

The report of extraordinary transmission (EOT) phenomenon through subwavelength metallic hole arrays (MHAs) milled in opaque metal screen [1] generated considerable interest and promoted subwavelength apertures as a core element of new optical devices. This is because of the simplicity with which the spectral properties can be tuned and scaled. It is believed that the EOT phenomenon is mainly due to the surface plasmons polariton (SPP) modes trapped at the interface of metal and dielectric. But, not all agree on the same SPP mechanism for the enhanced transmission phenomena [2, 3]. Nevertheless, according to several other theoretical and experimental studies the enhanced transmission process through subwavelength MHA can be divided into three steps: the coupling of light to SPPs on the incident surface, transmission through the holes and then re-emission from the second surface [4]. EOT in THz region has been observed recently in both metallic [5-8] and semiconductor hole arrays [9-11]. In the millimeter wave and THz region the 2D MHAs act as band-pass filters also known as frequency-selective surfaces (FSSs). However, in those frequency regions the metal surfaces act as perfect conductors on which the SPPs excitation cannot be expected. But, it has been proved both theoretically [12] and experimentally [13] that the resonantly excited SPP-like mode plays an important role in the high transmission in the THz region.

The manipulation of light at the subwavelength scale using photonic structures have several geometric variables, such as hole shape, periodicity, interface media, film thickness, aperture size, etc. In previous work, different hole shapes like elliptical [14], rectangular [15], C-shaped [16, 17], X-shaped [18], coaxial [19] and so on have been studied. It was found that a hole shape change from circular to rectangular increases the normalized transmission by an order of magnitude with a large red-shift in the spectra [20]. But, it was noted that the influence of the hole shape is dramatically different in terahertz (THz) region from that in the optical region [5, 6]. Also, hole lattices with different symmetry were studied and it was found that the spectrum shape and transmission efficiency depended strongly on the rotational symmetry [21]. In addition, it was observed that when the index of refraction inside the metallic hole arrays was increased, then the peak transmission would have a red-shift [22, 23]. Similarly, when the surrounding dielectric constant was increased then a red-shift along with a reduction in the transmission amplitude was observed [9]. Furthermore, the thickness of the metal film strongly effects the coupling interaction of the SPPs on both incident and transmitted surfaces. It was found that when the hole depth is large then the SPPs on the two surfaces are uncoupled and the transmission increases exponentially with the decreasing depth [24]. It is observed in the THz region that the EOT can be achieved at an array thickness of only one third of the skin depth [25]. In mid-infrared region giant absorption and transmission is found through an optically thin silicon carbide (SiC) film perforated by an array of sub-wavelength holes [26]. It is also reported that a planar circular grating with the period of the rings matching the SPP wavelength can generate and have enhanced intensity at the focal point of the plasmonic lens [27]. Angle dependent transmission properties through a layered medium comprising of alternating negative and positive refractive index was found to have unusual band gap propertied independent on both angle and polarization [28].

However the effect of hole channel shape on the transmission characteristics has not received much attention. The hole size along with the channel shape will have significant impact on the transmission efficiency because the holes are expected to mediate the SPP coupling between both surfaces. Hence in the present study the subwavelength hole having converging diverging channel (CDC) is studied specifically along with the straight channel for transmission properties. This proposed CDC shape would still allow similar EOT effects but, would give an extra degree of freedom in a geometric variable to tune the transmission spectrum. This extra degree of freedom is the gap at the throat of the CDC channel (Fig. 1). A similar study [29] was performed on subwavelength metallic slits having a CDC and it was found that the transmission resonance bands would move close to each other in the spectrum locations when decreasing the throat size of CDC.

## 2. Computational method

Figure 1 shows a schematic view of the square array of holes having CDC shape in a metallic film with the definition of different parameters: the period of hole array (d), the aperture size (A), the thickness of the metallic film (t), the slope or angle of the CDC shape (θ) and the gap at the throat (g). Figure 1(b) shows a cross-sectional view of the CDC channel with an angle (θ), which would relate 'A' and 'g' by a simple equation $g = A - \tan(\theta)*t$. The metallic film considered is silver (Ag) and for most part of the current study we used a fixed value for the period (d = 19.0 μm) and thickness (t = 2.0 μm). Although the transmission resonances of the holes depend on their period and thickness, they are fixed in this study to explore the effect of different aperture dimension and throat size. Nevertheless, it should be pointed out that the effects discussed in this present study do appear for any other range of hole parameters provided that 'A' is very small in comparison to 'd'. Also the frequency of incident light has to be well below the plasma frequency of the metal and for the present study we considered the frequency to be around 100 THz or 20 μm wavelength. The silver dielectric constant was described by a Drude model $\varepsilon = \varepsilon_\infty - \omega^2_p / (\omega^2 + i\gamma\omega)$ by taking $\varepsilon_\infty = -175.0$, $\omega_p = 1.1 \times 10^{16}\ s^{-1}$, and $\gamma = 10.51 \times 10^{13}\ s^{-1}$ in order to fit the empirical data given by [30] in the 100 THz

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frequency region. The electromagnetic fields were assumed to be time harmonic and the resulting governing equation for the steady-state distribution is solved by using a commercially available 3-dimensional (3D) finite element software (COMSOL 3.2a) [31]. The computational domain considered is a single unit cell surrounded by either periodic boundary conditions or by perfectly matching layer (PML) as given in [32]. The light is incident normal to the film surface and the transmittance is calculated from the obtained electromagnetic field distributions.

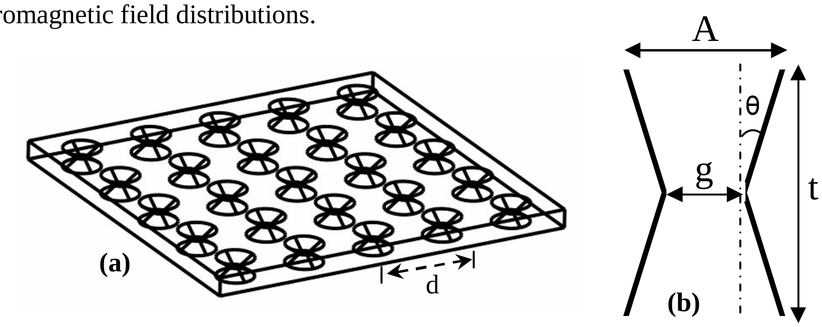


Fig. 1. (a). Schematic view of silver metallic hole array having periodicity ‘d’ with converging-diverging channels (CDC), (b) cross-sectional view of the CDC shape with aperture (A), thickness (t), slope or angle (θ) of CDC shape and gap at the throat (g).

### 3. Results and Discussion

Figure 2(a) shows the transmission spectrum for Ag MHAs having various aperture sizes. The transmission spectrum changes when the aperture size decreases. But, the magnitude of the transmission peak remains the same when the aperture size increases and this is unexpected according to the Bethe-Bouwkamp power law model [33, 34]. According to this model the transmissivity for a single hole should vary with $(A/\lambda)^4$, where ‘A’ is the aperture size and ‘λ’ is the wavelength of light. One possible reason is that the transmission through the holes might have reached saturation with respect to the open air fraction of the metallic film [35]. The full width at half maximum (FWHM) of the transmission peaks becomes smaller when the aperture size decreases. The peak of the transmission has a blue-shift when the aperture size decreases, which is in agreement with the result reported by [35]. Figure 2(b) shows the transmission spectrum for different MHAs having CDC shape or straight channel shape. For CDC shape smaller throat sizes ‘g’ are considered while the aperture size ‘A’ is fixed at 10 μm. It can be observed that the straight channel has a broader transmission peak. When the channel shape is changed to CDC then the transmittance peaks become narrower along with a blue-shift. The blue-shift is larger when the throat gets smaller. In addition the transmission on the red side of the peak decays faster for the CDC shape MHA with smaller throat when compared to the other cases. Also, it is to be noted that the transmission peak magnitudes do not decrease with the CDC shape.

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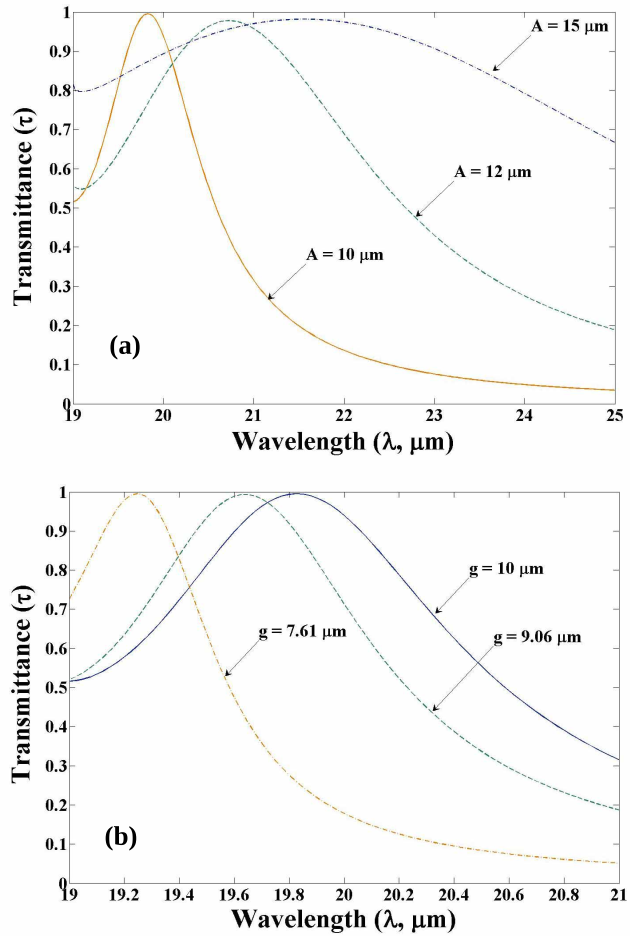


Fig. 2. (a). Transmission spectrum for a silver metallic hole array with a straight channel shape having period 'd' = 19 μm, thickness 't' = 2 μm and different aperture sizes 'A', (b) Transmission spectrum for silver metallic hole array with converging-diverging channel having period 'd' = 19 μm, thickness 't' = 2 μm, aperture 'A' = 10 μm and different gaps at the throat 'g'.

Figure 3(a) shows the transmittance of MHAs at λ = 20 μm for two different aperture sizes with varying 'g'. For A = 10 μm the MHA with a straight channel (g = 10 μm) has higher transmission when compared to the CDC shape with different throat sizes. The transmission decreases exponentially with the decrease in the throat size and reaches '0' value asymptotically. For A = 12 μm the transmission for the straight channel (g = 12 μm) is not the highest. But, the CDC shape with approximately g = 9.75 μm has near unity transmittance. Hence, it can be seen that when A = 12 μm the transmittance increases as the throat size reduces until it reaches a maximum transmission and then decreases exponentially with the decrease in the 'g'. This suggests that the CDC shape with a particular 'g' aids the mediation of SPP mode coupling between the incident and transmitted surfaces. Similar kind of behavior was observed previously in gold metallic gratings having CDC shape [29]. It is to be noted that the small variation in transmittance for A = 12 μm near the peak is due to the numerical calculations with different mesh densities.

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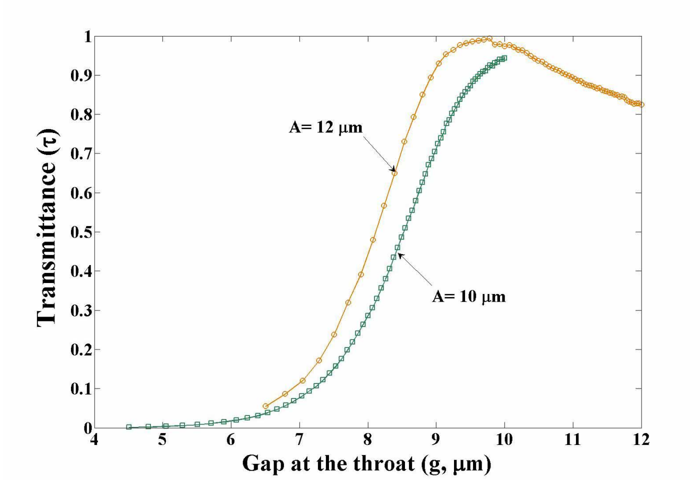


Fig. 3. Transmittance at wavelength ‘λ’ = 20 μm for silver metallic hole array with converging-diverging channel having period ‘d’ = 19 μm, thickness ‘t’ = 2 μm, different aperture sizes ‘A’ and varying gaps at the throat ‘g’.

Figure 4 shows the transmittance of different MHAs with respect to wavelength and aperture size ‘A’ or throat size ‘g’ ($g = A - \tan(\theta)*t$) where ‘θ’ [Fig. 1(b)] and the thickness are held fixed. Figure 4(a) shows the transmittance for MHAs with straight channel or $\theta = 0^o$. It can be seen that at a large aperture the transmittance is high at large wavelengths and decreases very slowly as the wavelength is reduced. But, when the aperture is small the transmittance is high at lower wavelengths and it decreases very sharply as the wavelength increases. Also, it can be noted from Fig. 4(a) is that the location of the transmittance peak spectrum changes linearly as the ‘A’ or ‘g’ decreases. In addition, the full width at half maximum (FWHM) of the transmittance peaks is large when the aperture is big and it becomes very narrow as the aperture is reduced. Similar kind of transmittance variation [Fig. 4(b)] is observed for the CDC MHA having $\theta = 50^o$. But, this time transmission suffers a cut-off aperture size where there is no transmittance below a particular aperture size. Furthermore the location of the transmittance peak spectrum with respect to the aperture or throat size is not exactly linear. When the ‘θ’ in CDC MHA increases to $65^o$ [Fig. 4(c)] and $72^o$ [Fig. 4(d)] the cut-off aperture for zero transmittance increases.

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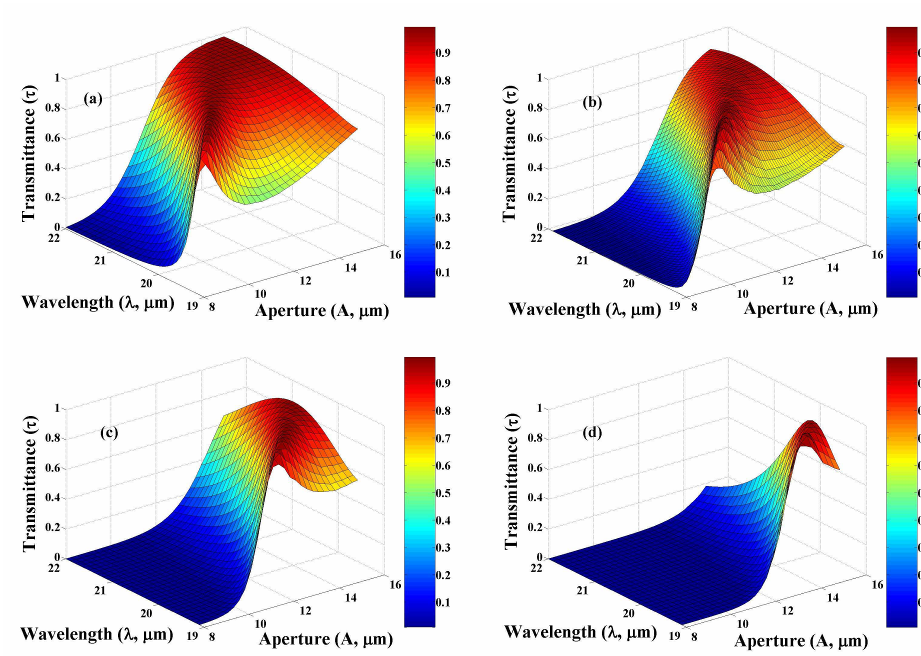


Fig. 4. Transmittance spectrum of silver metallic hole array with period ‘d’ = 19 μm, thickness ‘t’ = 2 μm for varying aperture sizes ‘A’ and hole channel shapes as (a) straight, (b) CDC shape with angle ‘θ’ = 50$^{o}$, (c) CDC shape with angle ‘θ’ = 65$^{o}$, and (d) CDC shape with angle ‘θ’ = 72$^{o}$.

## 4. Conclusion

It has been shown that the transmission spectrum of metallic hole arrays (MHAs) with converging-diverging channel (CDC) changes with the gap at the throat. The transmission peaks are blue-shifted when the throat size is reduced. Whereas, MHAs with a straight channel and a large aperture have broad transmission peaks at longer wavelengths. But, when the aperture size decreases, the transmission peak shifts to a lower wavelength and become narrower. It is also shown that the transmittance can be increased when the MHA channel changes from straight to CDC. But, the transmittance of MHAs with CDC shape suffers a cut-off aperture size below which there will be no transmission. The cut-off aperture size increases as the angle (θ) of the CDC shape increases. Also, it has been shown that the transmittance of MHAs with straight channel does not change much with the thickness of the film. But, for the MHA with CDC shape the transmittance is very sensitive to the thickness of the film. The proposed CDC shape in MHAs could lead to extraordinary transmission at different wavelengths and can be used to develop THz filters. This could lead to a wide range of potential applications in integrated photonic circuits, tunable filters, near-field optics, imaging, nanolithography, and biological sensors.

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