Extraordinary light transmission through opaque thin metal film with subwavelength holes blocked by metal disks

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Abstract: We observed that when subwavelength-sized holes in an optically opaque metal film are completely covered by opaque metal disks larger than the holes, the light transmission through the holes is not reduced, but rather enhanced. Particularly we report (i) the observation of light transmission through the holes blocked by the metal disks up to 70% larger than the unblocked holes; (ii) the observation of tuning the light transmission by varying the coupling strength between the blocking disks and the hole array, or by changing the size of the disks and holes; (iii) the observation and simulation that the metal disk blocker can improve light coupling from free space to a subwavelength hole; and (iv) the simulation that shows the light transmission through subwavelength holes can be enhanced, even though the gap between the disk and the metal film is partially connected with a metal. We believe these finding should have broad and significant impacts and applications to optical systems in many fields.

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References and links


1. Introduction

Many optical systems today, such as those in sensing, nanolithography, and many others [1–4], are built on a general belief: An optically opaque metal film would block light transmission even if the film has small holes, as long as the holes are covered with opaque metals which geometrically block the light path through the holes. For example, light transmission from one side of a glass to the other side is assumed to be blocked, when an opaque metal film is coated on one surface of the glass, even if the surface unavoidably has tiny dusts. This is because the coated metal covers the dust completely, hence blocking the light geometric path through the dust. Here, we report our experimental and theoretical study that demonstrates otherwise: Not only the light can transmit, but also the transmission is greatly enhanced, which is much better than an open hole. Furthermore, we found the transmission can be tuned by the metal blocker’s geometry and by the gap between the blockers and the metal film.

Before describing our work, we should point out that light transmission through a single or an array of open subwavelength-sized hole(s) in an opaque metal film has been studied extensively [5–9]. The “extraordinary transmission”, where the open subwavelength hole transmits more light than predicted by classical theory, has been experimentally observed [6]; and was found to be controllable by incorporating periodic structures surrounding the subwavelength holes [7,8], manipulating the array lattice of the holes [5], and loading the holes with different dielectric materials [10]. Furthermore, numerical simulations have predicted that covering the subwavelength holes or slits by cavity antennas [11] can also enhance the optical transmission; and that by properly placing periodic structures on both sides of a continuous metal film without any holes, the light can transmit through the film [8]. These predications are yet to be confirmed experimentally. At microwave wavelengths, split-ring antennas placed in front of subwavelength holes has been experimentally demonstrated to enhance the microwave transmission [12].

In developing a new plasmonic architecture, termed “disk-coupled dots on pillar antenna array” (D2PA) [13], for significantly enhancing Raman scattering signals, we needed to understand the effects of the metal disks (a key element in D2PA) on the light transmission through the subwavelength holes in a metal film, which were covered by these disks. We observed that even though the holes are fully blocked by the disks and there are no geometrically open light paths, the light transmission through the blocked holes is much larger than the holes unblocked [14]. We attributed this counterintuitive observation to the antenna effect of the blocking metal disks [14]. In this letter, we report the details of our experiments, observations, simulations and potential applications of enhancing and tuning the light transmission through subwavelength holes by blocking them with metal disks.
Fig. 1. Subwavelength metallic hole arrays with and without metal nanodisk blockers. 
(a) Schematic of a periodic hole array in Au film with and without Au nanodisks placed on top of each hole. The substrates are transparent fused silica with pillars which support the disks. The diameter of the disk is larger than the hole. The structure was fabricated by a self-aligned and self-limited process. And (b) Schematic drawing of light transmission through blocked holes and open holes.

2. Structures and fabrication of open and blocked metallic hole arrays

In our study, we compared the light transmission through a (or an array of) subwavelength hole(s) in an opaque metal film deposited on a transparent substrate (i.e. fused silica) with two different configurations: (A) the hole(s) are completely blocked by opaque metal disks of the diameter larger than the hole, and (B) the hole(s) are open without any blockers (Fig. 1a). A cartoon in Fig. 1b shows the conceptual drawing of the light transmission through the blocked and open hole arrays that we have studied experimentally and will be discussed in details later. To ensure accurate comparison of the light transmission, we fabricated the sample A (blocked holes) and performed the optical measurements first, and then removed the metal disks selectively without changing the rest of the structures, making it become the sample B (open holes) for the comparison measurements.

Specifically, the sample A has a transparent fused silica substrate with a nanopillar array on the surface, a gold film on the pillar foot, and a metal disk stack on the top of each pillar (Fig. 1a). The diameter of the disks is larger than the silica pillars, and also larger than the holes in the gold film. Each of the metal disk stacks consists of a thin chromium disk and a gold disk. The chromium disk plays three roles of: (i) etching mask for creating the SiO$_2$ pillar, (ii) good adhesion layer between the gold disks and the SiO$_2$ pillars, and (iii) selective removal of the gold disks. After the optical measurements of the sample A, the chromium disk was selectively etched away in a chemical etchant solution that etches only chromium not gold and SiO$_2$, and hence removing the gold disks but not the gold film and the rest of the structures, to make the sample A become the sample B.

The samples were fabricated on 4” fused silica wafers using nanoimprint [15, 16] with a 4” pillar mold fabricated by double imprinting and etching [17]. The fabricated samples have a 40 nm thickness in both top gold disks and bottom perforated gold film, and a 200 nm pitch between the holes. The chromium disks between the gold disks and the SiO$_2$ pillars are 10 nm thick. Each hole in the array has a diameter of 60 nm. The gold disks have a diameter of 85 nm (25 nm larger than the hole). The SiO$_2$ pillars are 52 nm high, and each of them protrudes from one individual hole in the gold film to support the gold disk that blocks the hole. The height of the SiO$_2$ pillar determines the gap between the gold disk and the hole and consequently the coupling strength between the two. For the particular pillar height and gold film thickness given above, the gap between the gold film and gold disk blocker is ~12 nm.
Fig. 2. SEM pictures of fabricated gold hole arrays (a) with and (b) without gold nanodisks, showing in tilted views (top) and zoom-in cross-sectional views (bottom).

Fig. 3. Schematic of self-aligned fabrication of subwavelength hole arrays with and without nano-disk blockers. (a) Chromium disks are patterned on transparent fused silica substrate by nanoimprint; (b) SiO₂ pillars are etched in fluorine-based RIE with the Cr masks; (c) Isotropic etching of SiO₂ in BOE solution creates an undercut beneath the chromium disks; (d) E-beam evaporation deposits gold from normal direction to the wafer, creating Au disks on top of the pillars and the gold film on pillar foot in a self-aligned manner; and (e) After the optical measurements of the blocked holes, a selective Cr etch dissolves the Cr layer and lifts-off the top gold nanodisks, while leaving the rest of the structures unchanged.

Figures 2a and b show the scanning electron micrographs (SEMs) of the blocked hole array and the open hole array, respectively. It is important to note that the hole arrays in our experiments, as shown in both Figs. 2a and b, are exactly the same except for the presence of the top gold disks, and hence the geometry of the hole array is kept unchanged to ensure a reliable optical transmission comparison.

The schematic of the fabrication of the blocked and open gold subwavelength hole arrays is shown in Fig. 3. A fused silica wafer was used as the substrate for its optical transparency. First, a 2-D array of chromium disks was created on the surface of the fused silica substrate by nanoimprint lithography using a 2-D pillar mold and a chromium evaporation and lift-off (Fig. 3a). The 2-D pillar mold was fabricated using an orthogonal double nanoimprint patterning [17] with a 1-D grating mold made by optical interference lithography, plus a series of advanced fabrication techniques, such as the self-perfection methods [18], which can ensure the pillars have perfectly round shape and are uniform over wafer scale area. Using the chromium disks as etching masks, the SiO₂ pillars were etched into the silica substrate using fluorine-based reactive ion etching (RIE) (Fig. 3b). Then a brief (5 second) isotropic etching of SiO₂ in a buffered oxide etch (BOE) shrunk slightly the diameter of the SiO₂ pillars without changing the chromium disk masks, hence creating an overhang (Fig. 3c). Without
removing the chromium masks, a layer of gold was deposited by e-beam evaporation from the normal direction to the wafer surface, forming simultaneously the gold disks on top of each SiO₂ pillars and the gold film on the pillar foot with nanohole array defined by the pillars (Fig. 3d). A key novelty of this process is a self-aligned process, where each gold nanodisk is precisely aligned on the top of a hole with the disk diameter larger than the hole, hence completely covering the entire hole and completely blocking the geometric light path through the hole. The overhang of the chromium disks caused by the slight BOE shrinking of SiO₂ pillars provides a shield to protect SiO₂ pillar sidewall from gold deposition.

To remove the top gold nanodisk blockers, we simply immersed the sample A in a chromium etchant (Cr-7 from Cyantek, Inc.) for 5 minutes and then rinsed it by DI water. As the chromium layer between the gold nanodisks and SiO₂ pillars was dissolved by the etchant, the gold nanodisks were separated from the SiO₂ pillars. The chromium etchant does not etch the gold nor the SiO₂, therefore after the Cr etching, only the Cr and Au disks are removed while the rest of the structures remain unchanged (Fig. 3e), allowing an accurate comparison of light transmission between the blocked and open holes.

3. Enhanced transmission by blocking subwavelength metallic holes with opaque metal disks

The red curve in Fig. 4a shows the light transmission through an open hole array in the gold film. It has a minima at 550 nm due to the interaction between the propagating surface plasmon and gold hole array lattice [19]. The transmittance peak is at 600 nm wavelength and ~35% efficiency. However, when blocking the holes by the gold disks completely (i.e. with a zero projected open area), the light transmission (the black curve in Fig. 4a) has a peak of 47% (34% larger than the open holes) and the peak transmission wavelength shifts to 630 nm. Note that regardless open or blocked holes, their peak transmittances are much large than the ratio of the hole area to the total area of the Au film, which is only 7%.

For a better comparison, we also plotted the ratio of the transmission of blocked hole array to the open hole array for the full wavelength range (Fig. 4b). The key findings include: (i) for the wavelengths from 600 nm to 800 nm, this particular “blocked” hole array can transmit more light than the open hole array; (ii) the maximum transmission enhancement occurs not at 630 nm—the transmission peak of the blocked holes, but at a longer wavelength of 670 nm with a 70% larger transmission; and (iii) for the wavelengths shorter than 600 nm, the blocked hole array transmits less light than the open holes.

![Fig. 4](image-url)
The transmission on the samples was characterized in the visible wavelength range from 400 nm to 800 nm using an Oceanoptics USB-2000 compact spectrometer that has a built-in white light source. To calibrate the transmission spectra, a bare fused silica substrate was used as the reference.

As shown in Fig. 4, the measured transmission spectrum of the hole array blocked by metal disks is different from the open holes in several ways: (i) the blocked hole array can transmit more light than the same holes when they are open (unblocked); and for this particular sample tested, the blocked holes can transmit up to 70% more light than the open holes at the same wavelength, (ii) the transmittance peak of the blocked hole is shifted to longer wavelength than that of the open hole (e.g. from 600 nm to 630 nm), (iii) when comparing the peak transmittances of the blocked holes with the open holes, which are at two different wavelengths, the transmission by the blocked hole is still more than 34% higher.

4. Transmission symmetry in blocked holes

We also studied the light transmission through the blocked hole array by reversing the light propagation direction. In this case, the light was incident from the sample backside instead of the front side. We did not observe noticeable difference in the transmissions from both directions. This shows that the light transmission property through the blocked holes is independent of placing the metal blockers in front of or behind the holes, which is consistent with the reciprocal property of our optical structures.

Specifically, when the metal nanodisks are in the front, the incident light first sees the metal nanodisks, which act as receiving antennas. Therefore, the enhanced transmission is due to an enhanced receiving efficiency induced by the metal disk antennas. If the light is incident from the backside, the nanodisk antennas play a role of transmitting antennas, and hence the enhanced transmission is due to an enhanced emission efficiency of the metal disks through the localized plasmons excited by the light.

5. Tuning transmission by varying the gap between blocking disks and holes

Our study also shows that the enhanced transmission through the blocked metallic holes strongly depends on the coupling efficiency between the metal disks and the perforated metal film. To study this effect, we fabricated a series of samples with different SiO₂ pillar heights, varying from 33 nm to 68 nm. For the pillar heights larger than the thickness of the deposited gold, which was 40 nm in our structures, the vertical gap from the bottom of the intermediate chromium layer and the top surface of the perforated gold film is roughly equal to the pillar height minus the film thickness. However when the pillar heights are less than the gold film thickness, it does not mean there is no gap between the metallic disks and the metal film. In fact, a gap still exists, as evident in the SEMs in the Fig. 5a (e.g. pillar height H = 33 nm). This is due to the self-alignment and self-blocking (hence self-limiting) during the metal deposition: The deposited gold disk will limit the gold deposition behind the disk.

Figure 5b shows the transmission spectra of nanodisks blocked hole arrays with different pillar heights (hence different gap sizes between the disks and holes). We observed that with decreasing pillar heights, which result in stronger coupling between the disks and the hole arrays, the peak transmittances occurred at longer wavelengths, as plotted by the red dots in Fig. 5e. For example, at 68 nm pillar height, the transmission peak was observed at 610 nm, while at 33 nm pillar height, this peak wavelength shifted to 750 nm.

On the other hand, the transmission efficiency, illustrated by the blue triangles in Fig. 5e, is more or less constant at 45% to 50% for the pillar height from 43 nm to 61 nm; but drops when the pillar height becomes less than the Au thickness or higher than 68 nm (the normal gap 28 nm). The transmission drop at high pillar height (large nominal gap) is due to a weak coupling between gold disks and the perforated gold film, making the antenna effect of the Au disk less effective. When the pillar height is less than the Au film thickness, certain part of the gap can be shorted by Au, hence causing a reduction of light transmission (more discussions are given in the simulation section).
The relationship between the nominal gap and the resonant transmission peak wavelength can be understood by treating the coupled disk-hole system as an optical circuit [20]: The smaller coupling gap, the larger capacitance induced between the disks and the holes; hence giving a lower resonant frequency, i.e. a longer resonant transmission wavelength, as we observed in the experimental measurement.

![Fig. 5. Experimental demonstration of tuning the optical properties through the blocked hole arrays by varying the coupling gap between the nanodisks and holes. (a) A schematic and SEMs of gold subwavelength hole arrays coupled to gold nanodisks with different gaps. (b) Measured transmittance and (c) measured reflectance spectra on the structures in (a). (d) Calculated absorbance spectra based on the measured reflectance and transmittance. (e) Plot of measured peak wavelengths (red) and peak transmission efficiencies (blue) versus the heights of the central SiO₂ pillars.](image)

Furthermore, we found that once the disk blockers are removed, the optical transmission spectra of all the above five samples, which are different with the presence of the gold disk blockers (due to different gap and hence different coupling), become virtually identical. This shows that the transmission peak wavelength shift in Fig. 5b is primarily caused by the metal blocker and its coupling to the perforated metallic film, and has nothing to do with the dielectric medium provided by the SiO₂ pillars of different heights.

The tuning of light transmission and the resonant coupling between the metal disks and the holes can be further seen from the reflection and absorption spectra (Figs. 5c and d). The reflection spectra were measured using a microscope-based spectrometer with a silver mirror used as the reference to calculate the reflectance. A 10x objective lens with a numerical aperture of 0.25 was used in the reflection measurement, corresponding to a full collection angle of 28°. Figure 5c shows the measured reflection spectra on the blocked hole arrays with
different pillar heights corresponding to Fig. 5a. Dips in the reflection spectra are observed at the positions close to the peaks in the transmission spectra in Fig. 5b.

Using the measured light transmittance, $T$, and reflectance, $R$, we are able to calculate the absorbance, $A$, of the blocked hole arrays as $A = 1 - T - R$. The absorption spectra are given in Fig. 5d. We observed for the blocked holes, there are enhanced absorptions, which have their own resonance peaks that are at wavelengths slightly shorter than the transmission resonant peak wavelengths. We attribute the absorption resonance to (a) the cavity effect due to the coupled disks and perforated metal film, and (b) a significantly enhanced local electrical field, which results in significant ohmic losses in the metals. This absorption is similar to the results reported on flat gold films coupled with nanodisks [21, 22]. However, an important and unique observation in our unique coupled disk-hole structure is that our structures not only enhance the absorption at certain wavelength, but also enhance the transmission at other wavelengths.

6. Tuning transmission by varying the diameter of the disks and holes

Another important geometric parameter in our blocked hole array is the diameter of the holes and the nanodisks, which is predominantly determined during the fabrication by the diameter of the SiO$_2$ pillars and the self-aligned gold deposition. By varying the SiO$_2$ pillar diameters between 40 nm to 120 nm, we fabricated the blocked holes with different sizes of the hole and the metal disk blocker. The height of the pillars was fixed at 58 nm, the gold thickness was 40 nm, and the period of the hole array was maintained at 200 nm.

The transmission spectra measured from the above fabricated blocked hole arrays of different pillar diameters, and their transmission peak wavelengths versus the pillar diameter are shown in Figs. 6a and b, respectively. It is observed from Fig. 6 that the transmission peak red-shift from 626 nm at a 40 nm pillar diameter to nearly 760 nm at a 120 nm pillar diameter. We attribute this wavelength shift to a longer plasmonic resonant wavelength in a larger gold disk blocker – consistent with previous observation: the larger the nanoparticle diameter, the longer the plasmonic resonant wavelength.

7. Numerical simulation analysis and further discussions

To verify and further understand the enhanced transmission in the blocked hole array, we carried out numerical simulation using a Lumerical software which is based on finite difference time domain algorithms. Figures 7a and b show the simulated transmission spectra and enhancement ratio on a blocked hole array of 90 nm antenna diameter, 80 nm SiO$_2$ pillar height, 80 nm SiO$_2$ pillar diameter and 50 nm gold thickness. The bottom gold hole array has a hole diameter of 80 nm and a pitch of 200 nm. The simulated structure does not include the 10 nm thick intermediate chromium layer for modeling simplicity.

![Fig. 6. Tuning of the transmission properties of the nanodisk-coupled hole arrays by varying the hole diameter. (a) Measured transmission spectra on the blocked hole arrays with different hole diameters and a fixed gold thickness of 40 nm. (b) Measured peak transmission wavelength versus the diameters of the pillars as measured in (a).](image)
The numerical simulation results qualitatively reproduce major features in the experimental observation, including the enhanced absolute optical transmission and red-shifted transmission peak on blocked gold hole arrays coupled with gold nanodisks. The structure used in the numerical simulation is simplified from the actual fabricated structure, but a numerical study on the electrical field distribution at transmission peak wavelengths confirms that the role of the metal disk blocker acting as a nano-antenna, which although blocks the geometric light path through the holes, actually enhances the surface plasmon coupling and light transmission.

Figures 7c and d plot the simulated electrical field distribution for both blocked and open hole arrays at 650 nm wavelength, corresponding to the maximum transmission wavelength of the nanodisk coupled hole array. It is clearly shown that the gold nanodisk collects the incident light like an antenna and induces a significantly enhanced electrical field, which is further coupled to the hole array and results in an enhanced surface plasmon inside the hole. On the other side of the hole array, this enhanced surface plasmon couples back into free-space optical wave and contributes to an enhanced light transmission through the holes.

Fig. 7. Simulation of enhanced transmission through blocked and open gold hole arrays. (a) Simulated transmittance spectra of both structures with a nanodisk diameter of 90 nm, a SiO$_2$ pillar height of 80 nm, a hole diameter of 80 nm and a gold thickness of 50 nm. (b) Calculated enhancement ratio from transmission spectra in (a). (c)(d) Simulated electrical field distributions of the blocked and open hole arrays at 650 nm wavelength, corresponding to the peak transmission of the blocked hole array. Locally enhanced electrical field resulted from the antenna effect of the coupling nanodisks is responsible for the enhanced transmission through the blocked holes. (e)(f) Simulated Poyting vectors of the blocked and open metallic hole array.
The energy flows within the open holes and the blocked holes are further illustrated by the plots of the Poyting vector obtained in the simulation (Figs. 7e and f). The distribution of the simulated Poyting vector clearly shows that the energy flow is highly concentrated within the gap between the metal disk blockers and the holes, and more energy flows through the blocked holes (due to the coupling from the blocking disks) than the open holes. It is worth to note that although both the experimental measurements and numerical simulations shown in this paper use a periodic hole structure, our simulation (not shown) suggests that the enhanced transmission can also occur on a blocked single hole, in which the blocking disk plays the same role as a receiving or emitting antenna to enhance the overall transmission through the blocked hole.

Besides the nanodisk antenna induced transmission enhancement as studied in this work, other previously reported mechanisms also contribute to the overall transmission enhancement in both the blocked and open hole arrays. The periodic array lattice in our samples plays an important role in the conversion of the light in free space and surface plasmons on both surfaces of the hole array [8, 21]. The waveguide modes of individual circular holes also affect the light transmission through the subwavelength holes, and both mechanisms have been numerically and theoretically studied extensively [9, 23]. The nanodisk antenna’s enhanced coupling effect represents another enhancement in addition to these two mechanisms.

Finally we studied the case that the blocking disks and the blocked hole array are partially connected by a piece of metal, which might be found as defects in actual fabricated structures. Figure 8a shows the schematic structure used in this numerical simulation. The blocking gold disk is connected to the gold metal film at the edge of the hole by a gold cylinder of a diameter, d, ranging from 10 to 50 nm. The corresponding transmission spectra (Fig. 8b) shows that as the partial metallic connection between the gold blocking disk and the metal film increases, the light transmission is initially similar to that without the connection, then reduces gradually.

8. Summary

In summary, we report the study of the enhanced optical transmission through a periodically perforated metallic film with each subwavelength hole blocked by an opaque metal disk. We developed a novel self-aligned fabrication procedure to ensure precisely controlled vertical coupling between the blocking disks and blocked holes, and a novel structure that allows the
removal of the blockers and a reliable comparison of the transmission behavior in blocked and open hole arrays. Although the nanodisk antenna coupled hole array has a zero projected open area (completely blocked), we observed that this blocked hole array can transmit 70% more light than an open hole array. We attributed this enhancement to the antenna effect and plasmonic coupling. We also experimentally varied the coupling between the nanodisk antennas and the subwavelength hole array by changing the gap between the disks and the Au film, and we found the transmission spectrum has a strong dependence on the coupling strength. We fabricated different diameters of the disks and the holes and found that they also can be used to control the light transmission. The study presented here may find potential applications in various areas, including design of high efficiency optical probe for near field optical microscope, design of high performance chemical sensing devices, novel optical filters, etc.

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