Letter

Near-Field Enhancement and Polarization Selection of a Nano-System for He-Ne Laser Application

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Abstract: In this paper, we focus on transmission behavior based on the single aperture with a scatter. Both the near-field enhancement and polarization selection can be achieved numerically with a proposed nano-system under He-Ne laser wavelength. The nano-system consists of an Ag antenna, a wafer layer, an Ag film with an aperture and a dielectric substrate. Numerical results show that the near-field enhancement is related to the FP-like resonance base on surface plasmon polaritons (SPPs) in the metal–isolator–metal (MIM) waveguide for transverse magnetic (TM) polarization. The near-field optical spot is confined at the aperture export with a maximal electric intensity 20 times the value of the incident field for an antenna length of 430 nm. The transmission cutoff phenomenon for transverse electric (TE) polarization is because the transmission is forbidden for smaller aperture width. High extinction ratios of 9.6×10^{-8} (or 70.2 dB) and 4.4×10^{-8} (or 73.6 dB) with antenna lengths of 130 nm and 430 nm are achieved numerically with the nano-system. The polarization selective property has a good angular tolerance for oblique angles smaller than 15° . The spectral response is also investigated. We further demonstrate that the nano-system is applicable for another incident wavelength of 500 nm. Our investigation may be beneficial for the detection of polar molecules or local nano polarized nanosource.

Keywords: nano-system; extinction ratio; transmission; FDTD method

1. Introduction

The extraordinary optical transmission (EOT) has aroused great attention since it was first observed in the periodic aperture arrays in a metallic film by T. W. Ebbesen et al. in 1998 [1]. Many subsequent works have been conducted numerically and experimentally with different materials, film thickness, and aperture shapes, in order to understand the fundamental physics involved [2–6]. It is generally accepted that the surface plasmon polaritons (SPPs) play an important role in the EOT phenomenon with periodic aperture arrays. The SPPs are light coupled to collective oscillations of free electrons at a noble metal/dielectric interface. The unique surface nature of SPPs yields a wide range of applications, such as nanolithography [7,8], biosensing [9–12], enhanced spectroscopy [13–16], as well as solar cell [17–20].

Besides the EOT with periodic aperture arrays, the enhanced transmission through a single aperture is an important issue as it can achieve transmission enhancement in the optical near-field, which is useful for applications of nanofocusing, nanolithography and nanoimaging. A. Degiron et al. and F. J. Garcia-Vidal et al. investigated the EOT behavior through a single circular aperture [21] and a single rectangular aperture [22], respectively. Subsequently, ridge aperture with different shapes, such as C-shape, H-shape, and bowtie-shape, have aroused great interest as a key element for near-field optical enhancement. X. Shi et al. reported $\lambda/10$ resolution and resonant transmission with C-shaped

aperture [23]. N. C. Lindquist et al. demonstrated a plasmonic nanofocusing with a metallic pyramid and an integrated C-shaped aperture [24]. X. Xu's group studied the SPPs enhanced EOT of a C-shaped and an H-shaped nanoaperture in a silver film and the physical mechanism of the EOT was attributed to the waveguide mode and Fabry–Perot-like resonance [25]. Then, they experimentally demonstrated an enhanced optical near-field of a bowtie aperture in an aluminum film using near-field scanning optical microscopy [26]. They further experimentally performed a 66 nm linewidth for nanoimaging [27] and a 24 nm linewidth for nanolithography [28] on a positive photoresist coated sample, using near-field transmission enhancement with a bowtie aperture integrated on an NSOM probe.

Recently, another method of near-field transmission enhancement with a single aperture was found by introducing a scatter or meta-structure near the neighbourhood of the aperture. S. He's group reported an EOT through a vertical nanoslit by introducing an antenna over the slit opening [29]. P. Banzar et al. experimentally demonstrated an enhanced transmission through a single coaxial aperture when compared to a circular aperture with the same outer diameter [30]. F. J. Valdivia-Valero et al. studied the transmission enhancement of a subwavelength 2D slit by exciting the eigenmodes of plasmonic cylinders at the aperture entrance [31]. K. Bi's group reported an enhanced transmission by utilizing the Mie resonances of two high-permittivity low-loss ceramic particles located at either side of a metallic aperture [32]. Then, they experimentally and theoretically demonstrated the magnetically tunable dual-band transmission by placing two pairs of dielectric cubes and ferrite cuboids symmetrically on both sides of the single subwavelength aperture [33,34]. Thermally tunable enhanced transmission through a subwavelength metallic aperture was also realized by a dielectric-based metamaterial resonator with high temperature coefficient [35]. An enhanced transmission through a single subwavelength aperture incorporated with meta-structure was also reported by different research groups [36–40]. Afterwards, an enhanced electromagnetic transmission through a metallic aperture was realized with a dielectric meta-atom placed into the aperture at the meta-atom's resonant frequency [41]. All these works investigate the near-field enhanced transmission with a single aperture.

In this paper, we also focus on the transmission behavior based on the single aperture with an antenna. Both the near-field enhancement and polarization selection can be achieved numerically with the proposed nano-system under He-Ne laser wavelength. The nano-system consists of an Ag antenna, a wafer layer, an Ag film with an aperture and a dielectric substrate. Numerical results show that the near-field enhancement is related to the FP-like resonance base on surface plasmon polaritons (SPPs) in the metal–isolator–metal (MIM) waveguide for transverse magnetic (TM) polarization. The near-field optical spot is confined at the aperture export with maximal electric intensity 20 times the value of the incident field for an antenna length of $l_a = 430$ nm. The transmission cutoff phenomenon for transverse electric (TE) polarization is because the transmission is forbidden for smaller aperture width w_b . High extinction ratios of 9.6×10^{-8} (or 70.2 dB) and 4.4×10^{-8} (or 73.6 dB) with antenna lengths of $l_a = 130$ nm and $l_a = 430$ nm are achieved numerically with the nano-system. The polarization selective property of the nano-system has a good angular tolerance for oblique angles smaller than 15° . The spectral response of the nano-system is also investigated. We demonstrate that the design of the nano-system is applicable for another incident wavelength of 500 nm. Our investigation may be beneficial for the detection of polar molecules or localized nano polarized source.

2. Structures and Methods

The proposed nano-system is composed of four parts: a silver (Ag) nano-antenna, a SiO₂ wafer layer, a silver (Ag) film with an aperture and a sustained SiO₂ substrate. The top and side views of the nano-system are shown in Figure 1a,b. The nano-antenna and the aperture are designed to be perpendicular to each other for different polarizations. The antenna is defined by its length of l_a and width of w_a . The aperture is described by its length of l_b and width of w_b . The thicknesses of the nano-antenna, the wafer layer and the silver film are represented as t_a , t_g and t_b , respectively. The electromagnetic wave injects from the top side with its wavenumber k and angle θ with respect to the z axis. The electric field component parallel to the x or y axis indicates a TM or TE polarization.

Figure 1. Schematic illustration of the high extinction ratio nano-system: (a) top view and (b) side view.

The complex permittivity of the noble metal (silver in this paper) depends on the incident frequency and can be described by the Drude model as

$$\varepsilon(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma_0}, \quad (1)$$

where ω is the angular frequency of incident wave, ε_{∞} represents the relative permittivity at infinite frequency, ω_p refers to the bulk plasma frequency and γ stands for the electron collision rate. In our simulation, these parameters are $\varepsilon_{\infty} = 5$, $\omega_p = 9.5$ eV and $\gamma_0 = 0.015$ eV, respectively. The refractive index of SiO_2 material is a constant of 1.45.

We used a finite-difference time-domain (FDTD) method for the investigation in this paper. The basic idea of the FDTD method is to use the central difference instead of the partial derivative of the field component in Maxwell's equations to simulate the wave propagation process in the time domain. The method was first proposed by K. S. Yee in 1966 [42]. He divided the computational space into individual cubes, called the Yee cell. In the Yee cell, the sampling nodes of electromagnetic field components are arranged alternately in time and space. Each electric (magnetic) field component is surrounded by four magnetic (electric) field components, which satisfies the requirement of Faraday's law and Ampere circuital theorem. The field distribution is finally obtained by solving the field component in Maxwell's equation step by step in time axis. The simulation space is $1200 \text{ nm} \times 1200 \text{ nm} \times 1400 \text{ nm}$ and the mesh size is $5 \text{ nm} \times 5 \text{ nm} \times 5 \text{ nm}$. The perfectly matched layers (PML) are applied on all the boundaries to fully absorb the outgoing wave of the simulation space.

3. Results and Discussions

We start with a fixed wavelength of 632.8 nm under normal incidence, as the He-Ne laser is the most common laser applied in the visible region. The complex permittivity of silver is $-18.35 + 0.48i$ under the wavelength. The parameters of the aperture are constant as $l_b = 200$ nm and $w_b = 30$ nm. The thicknesses of the nano-antenna, the wafer layer and the silver film are $t_a = 50$ nm, $t_g = 50$ nm and $t_b = 220$ nm. The electric intensity of incident field is 1 V/m. The width of the nano-antenna is $w_a = 50$ nm. The influence of the antenna length of l_a on transmission is investigated under TM-polarized light. Figure 2a shows the absolute transmission with various antenna lengths of l_a from 30 nm to 600 nm, every 20 nm. As the antenna length changes, two peaks with antenna lengths l_a of 130 nm and 430 nm appear in the transmission in Figure 2a.

Figure 2. (a) Transmission with various antenna lengths of l_a for transverse magnetic (TM) polarization; electric and magnetic field distributions of (b) $l_a = 130$ nm and (c) $l_a = 430$ nm for TM polarization in the xz section; electric field distributions of (d) $l_a = 130$ nm and (e) $l_a = 430$ nm for TM polarization at the aperture export.

Figure 2b,c show detailed electric and magnetic field distributions of $l_a = 130$ nm and $l_a = 430$ nm for TM polarization in the xz section. From these two figures, we can see that the Ag antenna, wafer layer and Ag film form a horizontal MIM waveguide and the aperture can be taken as a disturbance of the waveguide. In the waveguide, the dispersion relationship of SPPs can be derived from Maxwell's equations and boundary conditions as [43]

$$e^{-2k_2 t_g} = \frac{\frac{k_2}{\varepsilon_2} + \frac{k_1}{\varepsilon_1}}{\frac{k_2}{\varepsilon_2} - \frac{k_1}{\varepsilon_1}} \cdot \frac{\frac{k_2}{\varepsilon_2} + \frac{k_3}{\varepsilon_3}}{\frac{k_2}{\varepsilon_2} - \frac{k_3}{\varepsilon_3}}, \quad (2)$$

where the quantities with subscripts of 1, 2 and 3 represent the corresponding wavenumber and permittivity of the Ag antenna, wafer layer and Ag film, respectively. An FP-like resonance base on SPPs appears in the MIM waveguide. The FP-like resonance is related to the slit thickness in an open FP cavity [44]. The condition of the FP-like resonance is written as [45]

$$\frac{4\pi l_a}{\lambda_{\text{spp}}} + \arg(\rho_1 \rho_2) = 2m\pi. \quad (3)$$

where λ_{spp} represents the SPPs wavelength in the MIM waveguide, m is an integer, ρ_1 and ρ_2 denote the reflective coefficients at the two ends of the nano-antenna, respectively. According to the equation, $l_a = 130$ nm and $l_a = 430$ nm correspond to the FP-like resonance with $m = 0$ and $m = 1$. When the antenna length l_a reaches the FP-like resonant condition, the transmission is maximal, i.e., 0.09 with $l_a = 130$ nm and 0.21 with $l_a = 430$ nm, because the antenna helps the energy focus on the aperture entrance and then transmit through the aperture. Figure 2d,e show the distribution of the spots at the aperture export for TM polarization in the xy section, which indicates that the electric field is localized at the near-field of the aperture export for both antenna lengths. The maximum electric intensity of these spots is 12 times and 20 times the value of the incident field for $l_a = 130$ nm and $l_a = 430$ nm, respectively.

Subsequently, the influence of polarization angle is investigated. The antenna length is chosen as $l_a = 130$ nm and $l_a = 430$ nm from Figure 2a. Figure 3a shows the transmission with polarization angles from 0° to 360° , every 5° . The polarization angle of 0° and 180° corresponds to the TM polarization, while the polarization angle of 90° and 270° stands for the TE polarization. For TM polarization, the transmission is 0.09 for $l_a = 130$ nm and 0.21 for $l_a = 430$ nm, as discussed in Figure 2a. For TE polarization, the transmission is 8.83×10^{-9} for $l_a = 130$ nm and 9.16×10^{-9} for $l_a = 430$ nm. Figure 3b,c show the detailed electric and magnetic field distributions of $l_a = 130$ nm and $l_a = 430$ nm for TE

polarization in the xz section. The two figures reveal that the energy is localized in the MIM waveguide and does not transmit through the aperture for both the antenna lengths. Figure 3d,e further give out the distributions at the aperture export for TE polarization in the xy section. This shows that there is no near-field spot at the aperture export for TE polarization with both antenna lengths. Note that the range of the color bar is from 0 to 1 in Figure 3d,e.

Figure 3. (a) Transmission with different polarization angles at $l_a = 130$ nm and $l_a = 430$ nm; electric and magnetic field distributions of (b) $l_a = 130$ nm and (c) $l_a = 430$ nm for transverse electric (TE) polarization in the xz section; electric field distributions of (d) $l_a = 130$ nm and (e) $l_a = 430$ nm for TE polarization at the aperture export.

To quantitatively describe the polarization selective characteristic of the system, we introduce the concept of extinction ratio γ as

$$\gamma = T_{\text{TE}}/T_{\text{TM}}, \quad (4)$$

or

$$\gamma = -10 \times \lg(T_{\text{TE}}/T_{\text{TM}}) \text{ (dB)}, \quad (5)$$

where T_{TE} and T_{TM} are the transmissions for the TE and TM polarizations. The extinction ratio of γ is 9.6×10^{-8} (or 70.2 dB) for $l_a = 130$ nm and 4.4×10^{-8} (or 73.6 dB) for $l_a = 430$ nm according to Equation (4). A system with a high extinction ratio can be realized for the both antenna lengths.

To reveal the physics mechanism of the proposed perfect system, we further examine the transmission with different aperture parameters. Figure 4a,b show the transmission with different aperture widths and lengths for the TE and TM polarizations. The antenna is defined as $l_a = 430$ nm and $w_a = 50$ nm. The thicknesses of the nano-antenna, the wafer layer and the silver film are $t_a = 50$ nm, $t_g = 50$ nm and $t_b = 220$ nm. The aperture length remains at $l_b = 200$ nm as the aperture width w_b changes in Figure 4a, while aperture width is constant at $w_b = 30$ nm with different aperture lengths l_b in Figure 4b. Figure 4a shows that the aperture width w_b plays a critical role in the transmission cutoff phenomenon for TE polarization of the nano-system. When $w_b \leq 100$ nm, the transmission for TE polarization is smaller than 0.03. This is because the light transmission with an electric field parallel to the y axis is forbidden for smaller w_b . A similar transmission cutoff at half wavelength has been reported for a nano-slit with an electric field parallel to the slit in reference [46]. The difference between the critical values of the transmission cutoff in our system and the reference is probably due to the structural difference between the two works. In our system, it is a rectangle aperture, while only a grating slit is presented in the reference. When w_b exceeds 100 nm, the transmission cutoff disappears for TE polarization and the nano-system is not suitable for a nano-system. The transmission for TM polarization decreases dramatically as w_b increases. Therefore, one should keep the width of the aperture below 100 nm when designing such a nano-system. As Figure 4b illustrates, the transmission remains below 1.2×10^{-8} for TE polarization, as l_b changes from 30 nm to 600 nm. The transmission for TM polarization peaks at 200 nm and the full width at half maximum (FWHM) is about 80 nm.

Consequently, the l_b should be chosen from 160 nm to 240 nm, and the best value of l_b is 200 nm for the nano-system.

Figure 4. Transmissions with different (a) w_b and (b) l_b of the aperture for TM and TE polarizations; extinction ratio with different (c) w_b and (d) l_b .

Figure 4c,d show the corresponding extinction ratios with different w_b and l_b . The extinction ratio is smaller than 1% with $w_b \leq 100$ nm. The transmissions for the TM and TE polarizations are comparable with large w_b , thus the extinction ratio increases. The extinction ratio drops dramatically as l_b increases because transmissions for the TM and TE polarizations are comparable with small l_b and transmission is cut off for the TE polarization with large l_b .

To make explicit that the transmission cutoff is not related to the nano-antenna, we also compare the transmission of different w_b and l_b with and without antenna for the TE polarization in Figure 5. Figure 5a shows that with or without antenna, the transmission curves with w_b have a similar trend, i.e., transmission cutoff remains with $w_b \leq 100$ nm and disappears with $w_b > 100$ nm. Figure 5b illustrates the same transmission trend for the TE polarization as l_b changes. The results exclude the influence of nano-antenna and support our explanation that the aperture width w_b is the critical reason for the generation of the transmission cutoff for the TE polarization on another aspect.

Figure 5. Transmission of different (a) w_b and (b) l_b with and without antenna for TE polarization.

Since all previous discussions are based on normal incidence, we then study the nano-system with oblique incidence for practical applications. The antenna width is defined as $w_a = 50$ nm. The aperture size is $l_b = 200$ nm and $w_b = 30$ nm. The thicknesses of the nano-antenna, the wafer layer and the silver film are $t_a = 50$ nm, $t_g = 50$ nm and $t_b = 220$ nm. Figure 6a clearly illustrates the gradual decrease of transmission as θ increases with $l_a = 130$ nm and $l_a = 430$ nm for TM polarization. The magnitude of transmission is on the order of 10^{-9} or 10^{-8} with θ from 0° to 30° at $l_a = 130$ nm and $l_a = 430$ nm for the TE polarization. The transmission is larger than its half maximum for $\theta < 15^\circ$, indicating that the proposed nano-system is suitable for oblique angles smaller than 15° . Figure 6b shows the transmission with different polarization angles for oblique angles θ from 0° to 30° , every 5° . The larger the θ is, the smaller transmission received.

Figure 6. (a) Transmissions with different θ at $l_a = 130$ nm and $l_a = 430$ nm for TM and TE polarizations; (b) transmission with different polarization angles for different θ at $l_a = 430$ nm.

To reveal the gradual decrease of transmissions for TM polarization as θ increases, we illustrate the electric and magnetic field distributions with $\theta = 10^\circ$, 20° and 30° for the TM polarization in Figure 7. This shows that the energy localizations shift to the left side of the aperture entrance with an increasing oblique angle of θ . As a result, the transmission decreases gradually.

Figure 7. Electric and magnetic field distributions with θ of (a) 10° , (b) 20° and (c) 30° for TM polarization.

The spectral responses of the nano-system with $l_a = 130$ nm and $l_a = 430$ nm for the TM and TE polarizations are shown in Figure 8a. The magnitude of transmission is on the order from 10^{-10} to 10^{-7} for both antenna lengths for TE polarization, while there are three peaks in spectrum for both antenna lengths for the TM polarization. For the TM polarization with $l_a = 430$ nm, the second and third peaks of the transmission are not obvious, so the spectral FWHM of the nano-system is mainly determined by the first peak and is about 40 nm. For the TM polarization with $l_a = 130$ nm, the three peaks are shown clearly and the spectral FWHM contains two bands. The first narrow band is from 620 nm to 660 nm, and the second, wide band is from 730 nm to 970 nm. Then, we focus on the physical mechanism of the three peaks with $l_a = 130$ nm because they are more obvious. The first peak is related to FP-like resonance with $m = 0$ in the MIM waveguide, as shown in Figure 2b. Figure 8b,c show the electric and magnetic field distributions of the second peak, with $\lambda = 790$ nm and third peak, with $\lambda = 936$ nm. Comparing the field distribution in Figures 2b and 3b, it is found that the second peak is related to the resonance of the aperture. At the third peak, the nano-antenna can be viewed as a particle that concentrates light energy at the aperture entrance to help transmission.

Figure 8. (a) Spectral responses of the nano-system with $l_a = 130$ nm and $l_a = 430$ nm for TM and TE polarizations; electric and magnetic field distributions of (b) $\lambda = 790$ nm and (c) $\lambda = 936$ nm with $l_a = 130$ nm for TM polarization.

Finally, we have tested the wavelength of 500 nm to identify whether the proposed nano-system is suitable for another wavelength. Figure 9a shows the transmission with various antenna lengths of l_a from 30 nm to 600 nm for the TM polarization. The parameters of the aperture are $l_b = 200$ nm and $w_b = 30$ nm. The thicknesses of the nano-antenna, the wafer layer and the silver film are $t_a = 50$ nm,

$t_g = 50$ nm and $t_b = 200$ nm. The width of the nano-antenna is $w_a = 50$ nm. The antenna length $l_a = 230$ nm corresponds to the FP-like resonance $m = 1$ in the MIM waveguide for $\lambda = 500$ nm. With the fixed antenna length, the transmission with various polarization angles from 0° to 360° , every 5° is shown in Figure 9b. This shows that the polarization-selective phenomenon can also be realized for $\lambda = 500$ nm with a high extinction ratio of 9.8×10^{-7} (or 60.1 dB), which demonstrates the proposed nano-system for another wavelength.

Figure 9. (a) Transmission with various antenna lengths of l_a under $\lambda = 500$ nm for TM polarization; (b) transmission with different polarization angles at $l_a = 230$ nm under $\lambda = 500$ nm.

4. Conclusions

In summary, we propose a nano-system consisting of an Ag antenna, a wafer layer, an Ag film with an aperture and a dielectric substrate. Numerical results show that both near-field enhancement and polarization selection can be achieved with the nano-system under He-Ne laser wavelength. The near-field enhancement is related to the FP-like resonance base on surface plasmon polaritons (SPPs) in the metal-isolator-metal (MIM) waveguide for TM polarization. The near-field optical spots are confined at the aperture exports with maximal electric intensities 12 times and 20 times the value of the incident field for antenna lengths of $l_a = 130$ nm and $l_a = 430$ nm. The transmission cutoff phenomenon for TE polarization is because the transmission is forbidden for smaller aperture width w_b . High extinction ratios of 9.6×10^{-8} (or 70.2 dB) and 4.4×10^{-8} (or 73.6 dB) with antenna lengths of $l_a = 130$ nm and $l_a = 430$ nm are achieved numerically with the nano-system. The nano-system has a good angular tolerance for oblique angles smaller than 15° , although the transmission for the TM polarization gradually decreases as oblique angle θ increases. The decrease in transmission results from the shifting of energy localization with an increasing θ . The spectral FWHM of the nano-system with $l_a = 430$ nm is about 40 nm, while it contains two bands of 620–660 nm and 730–970 nm with $l_a = 130$ nm. The design of the nano-system is also applicable to another incident wavelength of 500 nm.

In addition, the proposed nano-system may be fabricated using modern processing technologies, including focused ion beam (FIB) etching, vacuum evaporation, plasma-enhanced chemical vapour deposition (PECVD), wet etching, joining and adhesion technology. The possible preparation process is explained as follows: firstly, an Ag film is deposited on a polished SiO_2 substrate by the vacuum evaporation method. Then a rectangular hole is fabricated using FIB. Simultaneously, a SiO_2 film is deposited on a polished silicon substrate through PECVD. Subsequently, an Ag film is evaporated on the SiO_2 film, and then an Ag antenna is fabricated with FIB. Afterwards, the silicon substrate is removed by wet etching. Finally, the two structures are bonded with thermal adhesives. Close attention should be paid to the amount of adhesive to ensure that the aperture is not blocked.

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References

1. Ebbesen, T.W.; Lezec, H.J.; Ghaemi, H.F.; Thio, T.; Wolff, P.A. Extraordinary optical transmission through sub-wavelength hole arrays. *Nature* **1998**, *391*, 667–669. [[CrossRef](#)]
2. Martin-Moreno, L.; Garcia-Vidal, F.; Lezec, H.; Pellerin, K.; Thio, T.; Pendry, J.; Ebbesen, T.W. Theory of extraordinary optical transmission through subwavelength hole arrays. *Phys. Rev. Lett.* **2001**, *86*, 1114. [[CrossRef](#)] [[PubMed](#)]
3. Lezec, H.J.; Degiron, A.; Devaux, E.; Linke, R.; Martin-Moreno, L.; Garcia-Vidal, F.; Ebbesen, T.W. Beaming light from a subwavelength aperture. *Science* **2002**, *297*, 820–822. [[CrossRef](#)] [[PubMed](#)]
4. Barnes, W.L.; Murray, W.A.; Dintinger, J.; Devaux, E.; Ebbesen, T.W. Surface plasmon polaritons and their role in the enhanced transmission of light through periodic arrays of subwavelength holes in a metal film. *Phys. Rev. Lett.* **2004**, *92*, 107401. [[CrossRef](#)]
5. Gordon, R.; Brolo, A.; McKinnon, A.; Rajora, A.; Leathem, B.; Kavanagh, K. Strong polarization in the optical transmission through elliptical nanohole arrays. *Phys. Rev. Lett.* **2004**, *92*, 037401. [[CrossRef](#)]
6. Garcia-Vidal, F.J.; Martin-Moreno, L.; Ebbesen, T.; Kuipers, L. Light passing through subwavelength apertures. *Rev. Mod. Phys.* **2010**, *82*, 729. [[CrossRef](#)]
7. Srituravanich, W.; Pan, L.; Wang, Y.; Sun, C.; Bogy, D.B.; Zhang, X. Flying plasmonic lens in the near field for high-speed nanolithography. *Nat. Nanotechnol.* **2008**, *3*, 733. [[CrossRef](#)]
8. Xie, Z.; Yu, W.; Wang, T.; Zhang, H.; Fu, Y.; Liu, H.; Li, F.; Lu, Z.; Sun, Q. Plasmonic nanolithography: A review. *Plasmonics* **2011**, *6*, 565. [[CrossRef](#)]
9. Sreekanth, K.V.; Alapan, Y.; ElKabbash, M.; Ilker, E.; Hinczewski, M.; Gurkan, U.A.; De Luca, A.; Strangi, G. Extreme sensitivity biosensing platform based on hyperbolic metamaterials. *Nat. Mater.* **2016**, *15*, 621. [[CrossRef](#)]
10. Aristov, A.I.; Manousidaki, M.; Danilov, A.; Terzaki, K.; Fotakis, C.; Farsari, M.; Kabashin, A.V. 3D plasmonic crystal metamaterials for ultra-sensitive biosensing. *Sci. Rep.* **2016**, *6*, 25380. [[CrossRef](#)]
11. Li, M.; Cushing, S.K.; Wu, N. Plasmon-enhanced optical sensors: A review. *Analyst* **2015**, *140*, 386–406. [[CrossRef](#)] [[PubMed](#)]
12. Zhang, T.; Xu, J.; Deng, Z.L.; Hu, D.; Qin, F.; Li, X. Unidirectional enhanced dipolar emission with an individual dielectric nanoantenna. *Nanomaterials* **2019**, *9*, 629. [[CrossRef](#)] [[PubMed](#)]
13. Matricardi, C.; Hanske, C.; Garcia-Pomar, J.L.; Langer, J.; Mihi, A.; Liz-Marzan, L.M. Gold nanoparticle plasmonic superlattices as surface-enhanced Raman spectroscopy substrates. *ACS Nano* **2018**, *12*, 8531–8539. [[CrossRef](#)] [[PubMed](#)]
14. Chen, S.; Zhang, Y.; Shih, T.M.; Yang, W.; Hu, S.; Hu, X.; Li, J.; Ren, B.; Mao, B.; Yang, Z. Plasmon-induced magnetic resonance enhanced Raman spectroscopy. *Nano Lett.* **2018**, *18*, 2209–2216. [[CrossRef](#)] [[PubMed](#)]
15. Liu, Y.; Zhang, N.; Li, P.; Yu, L.; Chen, S.; Zhang, Y.; Jing, Z.; Peng, W. Low-Cost Localized surface plasmon resonance biosensing platform with a response enhancement for protein detection. *Nanomaterials* **2019**, *9*, 1019. [[CrossRef](#)] [[PubMed](#)]
16. Chang, Y.C.; Lu, Y.C.; Hung, Y.J. Controlling the nanoscale gaps on silver Island film for efficient surface-enhanced Raman spectroscopy. *Nanomaterials* **2019**, *9*, 470. [[CrossRef](#)] [[PubMed](#)]
17. Jang, Y.H.; Jang, Y.J.; Kim, S.; Quan, L.N.; Chung, K.; Kim, D.H. Plasmonic solar cells: From rational design to mechanism overview. *Chem. Rev.* **2016**, *116*, 14982–15034. [[CrossRef](#)]
18. Mandal, P.; Sharma, S. Progress in plasmonic solar cell efficiency improvement: A status review. *Renew. Sust. Energ. Rev.* **2016**, *65*, 537–552. [[CrossRef](#)]
19. Kluczyk, K.; David, C.; Jacak, J.; Jacak, W. On modeling of plasmon-induced enhancement of the efficiency of solar cells modified by metallic nano-particles. *Nanomaterials* **2019**, *9*, 3. [[CrossRef](#)]

20. Wang, B.; Zhu, X.; Li, S.; Chen, M.; Lu, H.; Yang, Y. Ag@SiO₂ core-shell nanoparticles embedded in a TiO₂ mesoporous layer substantially improve the performance of perovskite solar cells. *Nanomaterials* **2018**, *8*, 701. [\[CrossRef\]](#)
21. Degiron, A.; Lezec, H.; Yamamoto, N.; Ebbesen, T.W. Optical transmission properties of a single subwavelength aperture in a real metal. *Opt. Commun.* **2004**, *239*, 61–66. [\[CrossRef\]](#)
22. Garcia-Vidal, F.; Moreno, E.; Porto, J.; Martin-Moreno, L. Transmission of light through a single rectangular hole. *Phys. Rev. Lett.* **2005**, *95*, 103901. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Shi, X.; Hesselink, L. Design of a C aperture to achieve $\lambda/10$ resolution and resonant transmission. *J. Opt. Soc. Am. B* **2004**, *21*, 1305–1317. [\[CrossRef\]](#)
24. Lindquist, N.C.; Johnson, T.W.; Nagpal, P.; Norris, D.J.; Oh, S.H. Plasmonic nanofocusing with a metallic pyramid and an integrated C-shaped aperture. *Sci. Rep.* **2013**, *3*, 1857. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Jin, E.X.; Xu, X. Obtaining super resolution light spot using surface plasmon assisted sharp ridge nanoaperture. *Appl. Phys. Lett.* **2005**, *86*, 111106. [\[CrossRef\]](#)
26. Jin, E.X.; Xu, X. Enhanced optical near field from a bowtie aperture. *Appl. Phys. Lett.* **2006**, *88*, 153110. [\[CrossRef\]](#)
27. Wang, L.; Xu, X. High transmission nanoscale bowtie-shaped aperture probe for near-field optical imaging. *Appl. Phys. Lett.* **2007**, *90*, 261105. [\[CrossRef\]](#)
28. Murphy-DuBay, N.; Wang, L.; Kinzel, E.C.; Uppuluri, S.M.; Xu, X. Nanopatterning using NSOM probes integrated with high transmission nanoscale bowtie aperture. *Opt. Express* **2008**, *16*, 2584–2589. [\[CrossRef\]](#)
29. Cui, Y.; He, S. Enhancing extraordinary transmission of light through a metallic nanoslit with a nanocavity antenna. *Opt. Lett.* **2009**, *34*, 16–18. [\[CrossRef\]](#)
30. Banzer, P.; Kindler, J.; Quabis, S.; Peschel, U.; Leuchs, G. Extraordinary transmission through a single coaxial aperture in a thin metal film. *Opt. Express* **2010**, *18*, 10896–10904. [\[CrossRef\]](#)
31. Valdivia-Valero, F.; Nieto-Vesperinas, M. Enhanced transmission through subwavelength apertures by excitation of particle localized plasmons and nanojets. *Opt. Express* **2011**, *19*, 11545–11557. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Guo, Y.S.; Zhou, J.; Lan, C.W.; Wu, H.Y.; Bi, K. Mie-resonance-coupled total broadband transmission through a single subwavelength aperture. *Appl. Phys. Lett.* **2014**, *104*, 204103.
33. Bi, K.; Liu, W.; Guo, Y.; Dong, G.; Lei, M. Magnetically tunable broadband transmission through a single small aperture. *Sci. Rep.* **2015**, *5*, 12489. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Wang, Q.; Bi, K.; Lei, M. Magnetically tunable dual-band transmission through a single subwavelength aperture. *Appl. Phys. Lett.* **2015**, *106*, 194102. [\[CrossRef\]](#)
35. Guo, Y.; Liang, H.; Hou, X.; Lv, X.; Li, L.; Li, J.; Bi, K.; Lei, M.; Zhou, J. Thermally tunable enhanced transmission of microwaves through a subwavelength aperture by a dielectric metamaterial resonator. *Appl. Phys. Lett.* **2016**, *108*, 051906. [\[CrossRef\]](#)
36. Cakmak, A.O.; Aydin, K.; Colak, E.; Li, Z.; Bilotti, F.; Vegni, L.; Ozbay, E. Enhanced transmission through a subwavelength aperture using metamaterials. *Appl. Phys. Lett.* **2009**, *95*, 052103. [\[CrossRef\]](#)
37. Aydin, K.; Cakmak, A.O.; Sahin, L.; Li, Z.; Bilotti, F.; Vegni, L.; Ozbay, E. Split-ring-resonator-coupled enhanced transmission through a single subwavelength aperture. *Phys. Rev. Lett.* **2009**, *102*, 013904. [\[CrossRef\]](#)
38. Ates, D.; Cakmak, A.O.; Colak, E.; Zhao, R.; Soukoulis, C.M.; Ozbay, E. Transmission enhancement through deep subwavelength apertures using connected split ring resonators. *Opt. Express* **2010**, *18*, 3952–3966. [\[CrossRef\]](#)
39. Guo, Y.; Zhou, J. Total broadband transmission of microwaves through a subwavelength aperture by localized E-field coupling of split-ring resonators. *Opt. Express* **2014**, *22*, 27136–27143. [\[CrossRef\]](#)
40. Guo, Y.; Zhou, J. Dual-band-enhanced transmission through a subwavelength aperture by coupled metamaterial resonators. *Sci. Rep.* **2015**, *5*, 8144. [\[CrossRef\]](#)
41. Guo, Y.; Liu, S.; Bi, K.; Lei, M.; Zhou, J. Low-power nonlinear enhanced electromagnetic transmission of a subwavelength metallic aperture. *Photonics Res.* **2018**, *6*, 1102–1106. [\[CrossRef\]](#)
42. Yee, K. Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Trans. Antenn. Propag.* **1966**, *14*, 302–307.

43. Wang, Q.; Wang, X.; Wu, S. Interaction between two perpendicular Fabry–Perot-like resonances of the antenna–dielectric–slit structure and their influences on the transmission enhancement. *Plasmonics* **2013**, *8*, 669–676. [[CrossRef](#)]
44. Astilean, S.; Lalanne, P.; Palamaru, M. Light transmission through metallic channels much smaller than the wavelength. *Opt. Commun.* **2000**, *175*, 265–273. [[CrossRef](#)]
45. Li, Z.B.; Yang, Y.H.; Kong, X.T.; Zhou, W.Y.; Tian, J.G. Fabry-Perot resonance in slit and grooves to enhance the transmission through a single subwavelength slit. *J. Opt. A Pure Appl. Opt.* **2009**, *11*, 105002. [[CrossRef](#)]
46. Xie, Y.; Zakharian, A.R.; Moloney, J.V.; Mansuripur, M. Transmission of light through slit apertures in metallic films. *Opt. Express* **2004**, *12*, 6106–6121. [[CrossRef](#)]

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