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Abstract: Optical transmission through concentric circular nanoslits is studied in experiments and numerical simulations. Polarized optical microscopic imaging shows that the optical transmission through these apertures is spatially inhomogeneous, exhibiting colored fan texture patterns. Numerical simulations show that these colored fan texture patterns originate from the cylindrical vector polarization of the transmitted beam. Specifically, the transmitted light is in-phase radially polarized at long wavelengths due to the predominant transmission of the transverse magnetic (TM) waveguide modes; and in-phase azimuthally polarized at short wavelengths due to the increased optical transmission of the transverse electric (TE) waveguide modes. Additionally, the transmission shows a peak at the wavelength of Wood anomaly and a dip at the resonant wavelength of surface plasmon excitation; and the transmitted light at these wavelengths is a mixture of azimuthally and radially polarized fields. These interesting optical transmission behaviors of circular nanoslits provide a miniaturized way to generating radially and azimuthally polarized light.

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References and links
1. Introduction

The discovery of extraordinary optical transmission through periodic arrays of subwavelength apertures in metal films has inspired considerable research interest owing to both its intriguing underlying physics and potential applications in a variety of fields such as quantum optics, optical wavelength filtering, nanolithography and sensing [1–10]. Two different physical mechanisms have been identified responsible for the enhancements of optical transmission. The dependence of the enhanced transmission on the grating periodicity is primarily attributed to the Wood anomalies and the excitation of surface plasmons at the metal surfaces [11–16], while the effects of aperture shapes are due to the Fabry-Perot type of cavity mode resonances inside individual subwavelength apertures [17–21]. It has been shown that the coupling of surface plasmons with other diffraction orders may lead to the suppression of transmission in one-dimensional (1D) slit array [22]. It has also been shown that the enhanced transmission can be obtained through cavity resonances only [23,24].

One interesting aperture shape is related to circular slits [25,26]. Through arrays of subwavelength circular nanoslits, the total optical transmission could reach 80% in the visible wavelength range [27]. When its diameter is larger than the incident wavelengths, an individual circular nanoslit can be utilized to generate and focus surface plasmon waves, and thus was denoted as plasmonic lens [28]. By adding concentric nanoslits, generation and focusing of surface plasmons by plasmonic lenses can be optimized [29]. However, detailed characteristics of the optical transmission through such concentric circular nanoslits remain unexplored.

On the other hand, cylindrical vector beams, or laser beams with cylindrical symmetry in polarization have attracted considerable research recently due to their interesting properties and potential applications [30]. For example, radial polarization is optimal for laser machining [31,32]. The laser machining with a radially polarized beam can be about 2 times more efficient than with a linear polarized beam due to the polarization dependence of absorption of metal materials [32]. It has also been shown that a radially polarized light beam can be focused to a much sharper spot than a linearly polarized light, an effect that might find unique applications in various optical instruments and devices such as lithography, confocal microscopy, and optical data storage, as well as in particle trapping [33]. While a myriad of methods have been developed to generate cylindrical vector polarized light beams, most of these methods require complex and bulky optical setups [30]; and a miniaturized device for cylindrical beam generation is highly demanded.

In this paper, we present experimental and numerical studies on optical transmission through individual apertures composed of concentric circular nanoslits in Ag films. Polarized optical microscopic imaging shows that the optical transmission through these apertures is spatially inhomogeneous, exhibiting colored fan texture patterns; numerical simulations demonstrate that this spatial spectral inhomogeneity arises from the cylindrical vector polarization of the transmitted light. In particular, the transmitted light is in-phase radially polarized at long wavelengths due to the dominant transmission of transverse magnetic (TM) waveguide modes in the nanoslits; and in-phase azimuthally polarized at short wavelengths due to the increased optical transmission of transverse electric (TE) waveguide modes in nanoslits. Moreover, the transmission exhibits a peak at the wavelength of Wood anomaly and a dip at the wavelength of the surface plasmon wave excitation; and the transmitted light at the Wood anomaly peak contains a mixture of azimuthally and radially polarized components and surface waves. The concentric circular nanoslits make it possible to generate azimuthally and radially polarized light in a very compact way.

2. Experiment

The concentric circular nanoslits were perforated in a 100nm Ag film on a fused silica substrate by using a focused ion beam (FIB) (FEI Nova Nanolab Dual Beam Workstation). In order to promote the adhesion between the Ag film and the glass substrate, a 10nm Ti adhesion layer is evaporated on the glass substrate before the Ag film deposition. Three
different radial periods, 270nm, 320nm and 375nm, have been used in the experiments. The width of the circular slits is designed to be about one third of the radial period, which is approximately reproduced in the fabricated samples as can be seen from the scanning electron microscopic (SEM) pictures (Fig. 1a).

![Fig. 1. (a) An SEM image of the circular nanoslit sample with 375nm radial period and 145nm slit width; (b) the experimental setup for imaging and spectral measurements.](image)

For optical measurements, the samples are illuminated from the metal film side with a tungsten halogen white light source, and the transmitted light is collected by using a 40 × objective (NA = 0.6) on an inverted optical microscope. Although the subwavelength radial periods of the nanoslits exclude the grating effects, the transmitted light beam is slightly divergent due to the Fraunhofer diffraction caused by the finite size of the nanoslits. Simple estimation can yield that the objective with 0.6 numerical aperture can collect more than 90% of the transmitted light for a 3 µm diameter aperture (~the smallest sample in our experiments). A circular pinhole of 300 µm in diameter located at the image plane of a side exit of the microscope is used to select the area of interest and block the background and stray light. The light transmitted through circular nanoslits is imaged into this pinhole and then coupled into the entrance slit of an imaging spectrograph for spectral measurements (Fig. 1b). Through a switchable mirror in the optical microscope, the light transmitted through those nanoslits can also be imaged on to a color CCD camera. With this setup, the measured optical spectra can be correlated with optical microscopic images of the samples.

In the experiments, the incident light is linearly polarized, and a polarization analyzer is placed after the microscope objective. Under the optical microscope, these circular nanoslits show vivid colors which are spatially inhomogeneous and vary with their radial periods (Fig. 2). When the analyzer is parallel to the polarization of the incident light (parallel polarized microscopy), the images of these circular slits exhibit color fan textures (Fig. 2a-c). When the analyzer is perpendicular to the incident polarization (cross polarized microscopy), the optical images exhibit a different type of fan texture patterns with black crosses (Fig. 2d-f). These black crosses indicate that the polarization of the transmitted light in these black regions is linear and parallel to the polarization of the incident light. It is important to note that these colors observed with the CCD camera are slightly different from the measured spectra because the spectrum of the illuminating halogen lamp cannot be properly normalized with the color CCD camera.
We measured the total transmission spectra without the polarization analyzer and the transmission spectra under parallel and cross polarized microscopic conditions (Fig. 3a-c). The results show that the transmission of the electrical field parallel to the incident polarization is much higher than that perpendicular to the incident polarization. A broad transmission peak can be observed in the total transmission spectra with the peak wavelength dependent on the radial period of the nanoslits. For the radial period decreased from 375nm to 270nm, the resonant wavelength decreases from 550nm to 400nm.
3. Simulation

In order to understand the relationship between the transmission spectra and the color fan textures in the optical microscopic images, we performed numerical calculations using finite-difference time domain (FDTD) simulations. The geometrical parameters of the circular gratings used in the simulations are obtained from SEM pictures of these samples. The Drude model: 

$$\varepsilon(\omega) = \varepsilon_\infty - \omega_p^2 / \omega(\omega - i\omega_c)$$

is used to describe the complex dielectric permittivity of Ag, where the parameters, \(\varepsilon_\infty = 3.57\), \(\omega_p = 1.388 \times 10^{16}\) rad/s and \(\omega_c = 1.064 \times 10^{14}\) Hz, are obtained by fitting to previously measured Ag permittivity [34].

![Fig. 4. FDTD calculated local field distributions of the transmitted light at a plane 350nm beneath the Ag film for the circular nanoslits of 375nm radial period at three representative free space wavelengths: 850nm (a, b and c), 550nm (d, e and f) and 400nm (g, h and i). The left column (a, d and g) depicts the amplitudes of the vertical components of the electric field; the middle column (b, e and h) depicts the amplitudes of the horizontal components of the electric field; and the right column (c, f and i) depicts the snapshots of the electric field vector distributions. The incident polarization is vertical for all simulations. The electric field amplitudes have been normalized by the incident field amplitude. In (c), (f) and (i), the arrow color represents the electric field amplitude; the arrow orientation represents the electric field direction.](image)

The transmission spectra were calculated by integrating the Poynting vectors on a plane placed at 350nm away from the metal surface. Similar calculations for a few representative cases were also performed for planes placed at 300nm, 350nm, 400nm and 450nm from the metal surface; all calculations yield the same transmission spectra, excluding near field effects. The calculated transmission spectra (in Fig. 3d-f) agree qualitatively with the experimental results in terms of their overall trend and the occurrence of the resonance peak.
The electric field distributions were calculated at representative wavelength also at a plane placed 350nm beneath the Ag film. Exemplary results for the 375nm radial period are shown in Fig. 4. Clearly, the electric field of the transmitted light is not linearly polarized. Instead, the transmitted light is in-phase radially polarized at long wavelengths (e.g., 850nm in Fig. 4a-c), while in-phase azimuthally polarized at short wavelengths (e.g., 400nm in Fig. 4g-i). When the incident wavelength is close to the resonant peak (~550nm), the transmitted electrical field is oriented primarily perpendicular to the metal surface (Fig. 4f), indicating the propagation of electromagnetic waves along the metal surfaces. Though so, it can be seen that the transmitted light contains a mixture of azimuthally and radially polarized components as well (Fig. 4d-f).

This wavelength dependence of the polarization of the transmitted light explains the colored fan textures observed under the optical microscope (Fig. 4a-b, d-e and g-h). For the fan textures observed under the parallel polarization condition, the radially polarized transmission at long wavelengths is responsible for the two vertical quadrants (Fig. 4a), while the azimuthally polarized transmission is responsible for the two horizontal quadrants (Fig. 4g). In contrast, under cross-polarization condition, both the radially polarized transmission and the azimuthally polarized transmission contribute to the transmission in these four quadrants (Fig. 4b and 4h), since they all have the electric field components along the crossed polarization.

4. Discussion

The generation of cylindrical vector polarized light at long and short wavelengths can be understood as a result of the interplay between the transmission of the TM and TE waves through the nanoslit arrays. A straight nanoslit can be considered as a planar metal-insulator-metal (MIM) waveguide. For a circular nanoslit, the electrical field of the incident light can be projected into a component tangential to the slit (TE mode) and a component normal to the slit (TM mode).

In an MIM waveguide, there exist a symmetric and an anti-symmetric mode for both TE and TM modes [35,36]. Because the symmetric TM mode has much higher propagation loss than the anti-symmetric TM mode and the symmetric TE mode has much lower cutoff wavelength than the anti-symmetric TE mode, only the anti-symmetric TM and anti-symmetric TE modes contribute to the optical transmission through nanoslits. For example, for a 250nm wide nanoslit, the propagation length of light with 600nm free space wavelength is around 0.26\(\mu\)m for the symmetric TM mode, while is 19\(\mu\)m for the anti-symmetric TM mode; and the cutoff wavelength is about 600nm for the anti-symmetric TE mode, while is about 315nm for the symmetric TE mode.

The dispersion relations can be expressed as:

\[ \varepsilon_r k_m - i\varepsilon_r k_d \tan(k_d d / 2) = 0 \]  
(1)

for the anti-symmetric TM mode; and expressed as:

\[ k_m - ik_d \tan(k_d d / 2) = 0 \]  
(2)

for the anti-symmetric TE mode [35,36]. Here, \( k_m = \sqrt{\varepsilon_r \omega^2 / c^2 - k_{wg}^2} \) and \( k_d = \sqrt{\varepsilon_r \omega^2 / c^2 - k_{wg}^2} \), and \( k_{wg} \) is the wave vector for the MIM waveguide modes. The propagation length of these waveguide modes can be obtained by \( L_p = \left| 2 \Im(k_{wg}) \right|^{-1} \).

From these equations, the dispersion curves and propagation lengths can be calculated for these modes in the vacuum nanoslits of 90nm, 120nm and 145nm widths in Ag films (Fig. 5). It can be seen that the anti-symmetric TE mode has a cutoff wavelength above 400nm and that the anti-symmetric TM mode has no cutoff wavelength. This indicates that the transmission of the anti-symmetric TM mode is much higher than that of the anti-symmetric TE mode at long

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wavelengths; and as a result, the transmitted light should be radially polarized at these wavelengths.

On the contrary, the anti-symmetric TE mode plays an important role at short wavelengths. The propagation length $L_p$ of the anti-symmetric TE mode increase with decreasing wavelength and becomes comparable to the Ag film thickness when the incident wavelength is below 500nm. As a result, the TE mode has a finite transmission at short wavelengths [37]. It was previously shown that the transmission enhanced by the Fabry-Perot type of cavity resonances necessitates $2k_{sp}h \sim 2n\pi$ with $n$ being an integer [38]. For the anti-symmetric TM mode at short wavelengths in our experiments, $2k_{sp}h \sim \pi$ (for 429nm wavelength), therefore its transmission is minimal due to the destructive interference. These imply that the transmitted light at short wavelengths should be azimuthally polarized.

Two possible physical processes, i.e., surface plasmon excitation and Wood anomaly may be responsible for the transmission peaks and the generation of surface waves. The excitation of surface plasmons at the metal-dielectric surfaces have been considered to play a key role in the enhanced transmission through subwavelength apertures; and its resonant condition is that for a perpendicular incident light, the wave vector of surface plasmon $k_{sp} = k_0\sqrt{\varepsilon_m \varepsilon_d / (\varepsilon_d + \varepsilon_m)}$ should be matched by the reciprocal vector $(2\pi/d)$ of the grating. Here $k_0$ is the wave vector of a light wave in vacuum; $\varepsilon_m$ and $\varepsilon_d$ are the permittivity for the metal (Ag) and the dielectric materials (air or SiO$_2$). For the grating period $d = 375$nm, 320nm and 270nm, it can be calculated that the plasmon resonant wavelength is at 413nm, 371nm and 340nm respectively for the air/metal interface, and 590nm, 520nm and 460nm respectively for the substrate/metal interface. Comparisons with the simulated and measured transmission spectra indicate that the resonance wavelengths for plasmons at the glass/Ag interface actually correspond to the dips in the transmission spectra.

The Wood anomaly occurs when a diffraction order disappears, or $2\pi/d = k_0\sqrt{\varepsilon_d}$ for perpendicular illumination [14,15,39]. As a result, the resonant wavelength of the Wood anomaly at the substrate/metal interface should be at 548nm, 467nm and 394nm for $d = 375$nm, 320nm and 270nm. These Wood anomaly resonant wavelengths, though obtained for 1D gratings, are in good agreement with these transmission peaks in the measured and simulated spectra. Again, the resonant wavelengths of the Wood anomaly at the air/metal interface are below 400nm and outside the wavelength range of the measurements. For a 1D grating, one signature of the Wood anomaly is a sharp edge in the transmission spectrum [15,39]. This distinctive feature of Wood anomaly is smeared out in our structures, which can
be attributed to the curvature and the finite size of the nanoslits. It can be expected that 1D grating of nanoslits can be used as a good approximation when the diameter of the circular nanoslit is larger than the incident wavelength. While for these circular nanoslits of wavelength size or smaller in the middle of the samples, more rigorous models should be employed [26,40].

The suppression of transmission at the resonance of surface plasmon excitation, which seems in contradiction with the common belief of the critical role played by surface plasmons, actually agrees with a number of recent numerical, experimental and theoretical studies in 1D array of subwavelength slits [12,15,22,41]. This discrepancy has been resolved by considering the coupling between surface plasmons and other diffraction orders or a background radiation [19,22,42,43]. One clear physical picture is based on the equipartition of diffraction orders.

![Fig. 6. A vector distribution snapshot of the calculated local electrical field for the transmitted light at a plane 350nm beneath the Ag film for 270nm radial period and 400nm incident wavelength.](image)

Considering the surface plasmons as one diffraction order, a resonant excitation of surface plasmons suppresses other diffraction orders including the zeroth order transmission [22]. Similarly, a disappearance of a diffraction order means enhancing other diffraction orders including the zeroth order transmission, or enhanced transmission at Wood anomaly frequencies.

When the radial period of the nanoslits is decreased, the resonance of the Wood anomaly shifts to shorter wavelength. Therefore, it can be expected that a mixture of surface waves and azimuthally polarized light should exist at short wavelengths. This is actually the case for the nanoslits with small periods. For example, the resonant peak of the Wood anomaly for the 270nm radial period is located around 400nm; and thus the calculated electrical field contains both the azimuthally polarized components and surface wave components (Fig. 6).

5. Conclusion

To summarize, we have studied the optical transmission through single apertures composed of concentric circular nanoslits in Ag films. Experimental and numerical results show that the light transmitted through these apertures is in-phase radially polarized at long wavelengths and in-phase azimuthally polarized at short wavelengths due to the interplay between the TE and TM transmission through the nanoslits. Also, the transmission exhibits a peak at the wavelength of Wood anomaly and a dip at the wavelength of the surface plasmon wave excitation, and the wavelengths of these peaks and dips vary with the radial period of the slits.

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