Light transmission through a circular metallic grating under broadband radial and azimuthal polarization illumination

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We studied the characteristics of a circular metallic grating illuminated by broadband radial and azimuthal polarizations. We demonstrated that this scenario is the cylindrical analogue of a one-dimensional Cartesian grating illuminated by TM and TE polarizations. We measured the transmission spectra of this structure and observed strong polarization selectivity and, specifically, a resonance for radial polarization excitation, indicating a strong coupling to surface plasmons. The structure may be attractive for applications where pure radial polarization is needed, such as tight focusing, material processing, and particle trapping. © 2011 Optical Society of America

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The transmission of light through nano apertures perforated in metallic films has been the subject of growing interest in recent years [1–3]. A large variety of structures, e.g,. single holes in a thin metallic film with a variety of shapes, periodic and quasi-periodic hole arrays with different shapes, and arrays of nanometallic structures, have been studied theoretically, numerically, and experimentally [4–6]. In many cases, the polarization of the excitation source was found to play a major role in controlling the transmission spectrum, due to the role of surface plasmons polaritons (SPPs) and their strong dependency on polarization [7,8]. A fundamental structure that was extensively studied over the years is the one-dimensional Cartesian metallic grating [9,10]. Intuitively, the equivalent of such a grating in a cylindrical coordinate system is the circular grating, i.e., a set of concentric circular slits or corrugations in a thin metallic film. This structure was studied recently and was found to be attractive for several applications, including the enhancement and beaming of transmitted light [11], plasmonic focusing [12,13], circular Bragg cavities [14], and for receiving and transmitting electromagnetic radiation in a plasmonic nanoantenna [15]. To measure the transmission spectrum of a circular grating under TM- and TE-polarization illumination, the generation of the equivalent polarizations in a cylindrical coordinate system is needed, i.e., radially and azimuthally polarized beams, respectively. These beams have been the subject of extensive recent research, primarily due to their interesting characteristics and their utilization in various applications, e.g., tight focusing, optical trapping, and material processing [16,17]. Following that, there is a need to develop a set of components, such as filters and polarizers, that operate in a cylindrical coordinate system. In this Letter, we use broadband radially and azimuthally polarized light to study the transmission spectrum of a circular grating under TM- and TE-polarization illumination.

The metallic circular grating was fabricated by evaporating a 5 nm layer of Ag on a glass substrate, followed by the evaporation of a 20 nm Au layer on top of the Ag film (Ag was used as an adhesion layer between the substrate and the Au layer because of its low ohmic loss compared to the commonly used adhesion layers of Cu or Ti, and its good adhesion to both the glass substrate and the Au). Next, a 40 nm thick Au circular grating with a period of 450 nm and a duty cycle of 50% was fabricated on top of the first Au layer by standard electron-beam lithography and liftoff procedures. The grating's diameter was chosen to be 90 μm, supporting 100 periods along the radial direction. Figure 1 shows a schematic representation and a scanning electron micrograph picture of the sample. Unlike other structures (e.g., "bull's eye," [11]), our structure has a thin uniform metal layer underneath the circular grating structure. Indeed, most of the absorption occurs in this uniform layer, whereas the role of the circular grating is mostly to perform coupling between propagating waves and SPPs.

To analyze the interaction of light with the structure, we assumed that a concentric circular grating illuminated by radially and azimuthally polarized beams can be approximated as the cylindrical analogue of a one-dimensional Cartesian metallic grating illuminated by TM and TE polarizations, respectively [18,19]. The accuracy of this assumption improves with the increase in sample size, due to the smaller curvatures. We thus can use rigorous coupled-wave analysis (RCWA) to calculate the transmission, reflection, and absorption of a one-dimensional Cartesian grating illuminated by either TM or TE polarizations [20]. The RCWA method assumes infinite periodicity of the structure and a plane-wave illumination. The radial axis in the cylindrical coordinate system is semi-infinite since it is always positive. Therefore, the periodicity of the circular grating is not well

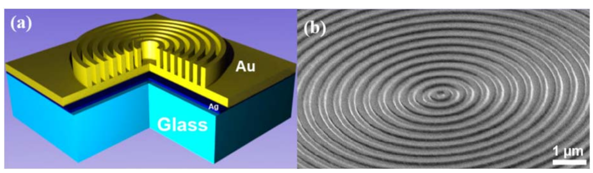

Fig. 1. (Color online) (a) Schematic representation of the sample and (b) a scanning electron micrograph of the fabricated sample.

defined at the center. However, the illumination intensity of radially and azimuthally polarized beams is nearly zero at the center of the beam and, thus, light diffracting from the center of the structure has a negligible effect on the results.

To verify our assumption, we also simulated the resonances of a circular grating having a radius of 15 μm with a finite-difference time-domain simulation, and obtained very similar results compared with the RCWA simulation. The RCWA simulation results are shown in Fig. 2. The values of the measured spectra are normalized to the corresponding values obtained for a flat sample (zero grating height). The normalized absorption peak is a clear indication for the strong excitation of SPPs under radially polarized excitation. Moreover, for radially polarized light, higher energy density is obtained at the center of the structure compared with linearly/circularly polarized light [12,15] and, thus, the local absorption is maximized at the center.

The transmission spectra measurements were carried out using the following experimental setup: linearly polarized, 100 fs pulses with average power of 300 mW emerging from a mode-locked Ti:sapphire laser (Tsunami, Spectra-Physics, $\lambda = 800$ nm) were focused onto a photonic crystal fiber (SCG 800, Newport) to generate a supercontinuum spectrum. The generated linearly polarized supercontinuum mode was then cleaned by a spatial filter and transmitted through a polarization converter (ARCoptix, Switzerland) to convert it into radially/azimuthally polarized light. An additional broadband liquid crystal π phase compensator was used to compensate for the π phase error generated by the polarization converter in half of the beam's cross section.

The radially/azimuthally polarized light is then weakly focused onto the circular metallic grating (the sample plane is imaged onto a CCD camera for alignment purposes) and the transmitted light is collected by a second objective lens to a spectrometer (MicroHR, Horiba Jobin Yvon). Figure 3 shows the experimental setup.

Figure 4(a) shows the measured transmission spectra obtained by illuminating the circular grating with radially and azimuthally polarized beams. These spectra are accompanied by the corresponding calculated spectra for the one-dimensional Cartesian grating illuminated by TM- and TE-polarized beams shown in Fig. 4(b). In accordance with our assumptions, the transmission spectra

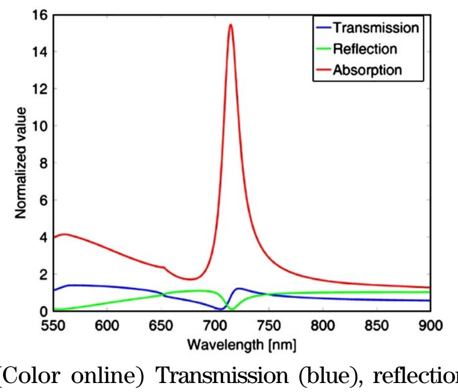

Fig. 2. (Color online) Transmission (blue), reflection (green), and absorption (red) spectra, calculated using RCWA, of a one-dimensional Cartesian grating, having the same parameters as the fabricated sample and illuminated by a TM-polarized light.

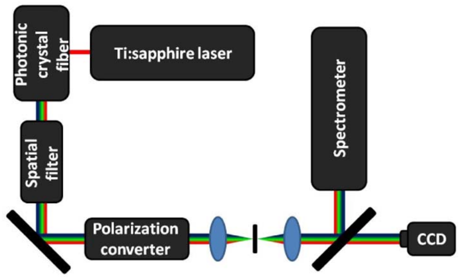

Fig. 3. (Color online) Experimental setup used for measuring the transmission spectra. The sample is illuminated from the grating side.

of the radial and azimuthal polarizations through the circular grating show characteristics similar to the case of TM and TE polarizations propagating through a one-dimensional Cartesian grating, respectively. Nevertheless, there is a difference in the numerical values of the transmission spectra between the measurements and the simulations. We attribute this difference to several reasons. (1) The absorption of the metals constructing the sample may increase during the fabrication process [21] and can no longer be accurately estimated by the correspondence values for metallic films that appear in literature. (2) The need for accurate alignment between the center of the radially polarized beam and the center of the circular grating. If the illumination light and the sample are not perfectly aligned, the sample will not be illuminated by a pure TM polarization, leading to a lower transmission. (3) Nonperfect polarization conversion. The location of the peak in the radial polarization case

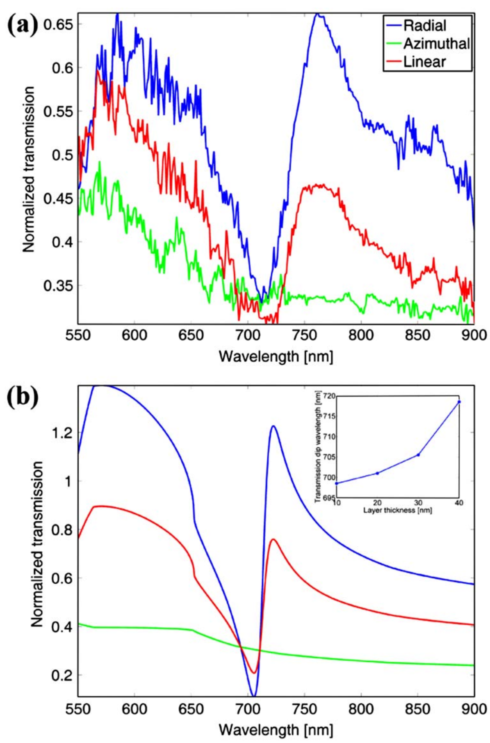

Fig. 4. (Color online) (a) Measured and (b) calculated transmission spectra obtained by illuminating the sample with radially (blue), azimuthally (green), and linearly (red) polarized beams. The inset shows the dependency of the resonant wavelength on the thickness of the uniform metal layer.

is very close to the predicted peak for the case of TM illumination, indicating the strong excitation of SPPs by the radially polarized light. Because of the use of a relatively thin metal layer, we excite SPPs on both ends of the metal layer. As a result, the resonant wavelength depends on the metal thickness, as shown in the inset of Fig. 4(b). In the long wavelength regime, the circular grating is effectively a wire grid polarizer, reflecting the azimuthal polarization that is parallel to the grating lines, and transmitting the radially polarized light.

The extinction ratio of this wire grid polarizer can be improved significantly by increasing the depth of the grating, similar to the design of standard wire grid polarizers. Figure 4(a) also shows the transmission spectrum obtained by illuminating the sample with linear polarization, and it can be seen that this spectrum lies between the spectra of the radial and azimuthal polarizations. A first approximation calculation of the transmission spectrum for this case can be obtained by decomposing the linearly polarized beam into its radial and azimuthal components as $E_{\text{linear}} = \cos(\theta)E_{\text{radial}} + \sin(\theta)E_{\text{azimuthal}}$, where θ is the azimuthal angle along the cross section of the beam. Averaging the intensity over all angles, we get $I_{\text{linear}} = 0.5(I_{\text{radial}} + I_{\text{azimuthal}})$. The calculated spectrum based on this linear decomposition is also shown in Fig. 4(b), giving a very good approximation to the measured spectrum.

In summary, we measured the transmission spectra of a circular metallic grating illuminated by broadband radially and azimuthally polarized light. We demonstrated that this grating is the cylindrical analogue of the one-dimensional Cartesian grating illuminated by TM and TE polarizations, respectively. We notice a strong resonance for the radially polarized excitation, indicating a strong coupling of light to SPPs. With an improved design, this grating can also act as a wire grid polarizer by reflecting the azimuthally polarized light while transmitting the radially polarized light. This structure may be attractive for spectral filtering of radially polarized light and in applications where a pure radial polarization is needed, such as tight focusing of light for lithography and memory, material processing, and particle trapping.

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