Polarization control of optical transmission of a periodic array of elliptical holes in a metal film

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Abstract

Spectral dependencies of polarized optical transmission of a metal film with a periodic array of elliptical nanoholes have been studied. Such nanostructured metal films exhibit the enhanced broadband optical transmission which can be controlled by selecting polarization of incident and/or transmitted light.

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Optical components for applications in extreme ambient conditions and high level of integration require novel design approaches. Recent progress in understanding of the optical properties of nanostructured metal films has allowed the design of spectral filters and devices which exploit surface plasmon polariton excitations (SPPs) in metal nanostructures. Such nanostructures could act as band-pass spectral filters or, if combined with nonlinear materials, could perform all-optical stitching and limiting functions at low control light intensities. Polarisation properties of light can also be controlled with metallic nanostructures.

Functionality of metallic nanostructures are determined by the interaction of photons with collective excitations of conduction electrons at a metal surface. The coupling and mutual transformations between photons and surface plasmons depend upon the frequencies and wave vectors of the excitations, as well as on the polarization state of incident electromagnetic field. The polarization state determines the excitation of SPPs in one or another generally non-equivalent directions of the Brillouin zone related to the periodic structure. By choosing the light polarization one could not only provide the optimal intensity transmittance through the structure but could also introduce various polarization-sensitive effects related to the chirality of the structure and non-locality of its electromagnetic response.

In this letter we report the studies of polarization properties of the enhanced light transmission through a metal film with a periodic arrangement of oriented elliptical nanoholes. Such metallic structure exhibits a broadband transmission stemming from the multiple SPP resonances permitted by the low-symmetry arrangement of elliptical holes in a square array. The transmission spectrum strongly depends on the polarization state of the incident light even at normal incidence, the property of striking contrast with a square array of circular holes where transmission spectrum has well-defined resonances independent on the polarization of the incident light. In the case of elliptical holes, the incident linearly polarized light is converted into elliptically polarized in transmission. Using this feature we can continuously tune the transmission spectrum of the structure from blue to red wavelengths by changing the polarization state of the incident light and selecting appropriate polarization component of the transmitted light.

The metallic nanostructures of overall size of 20 × 20 μ² studied here were fabricated in a 40 nm gold film on a glass substrate using ion beam milling. The structure consists of elliptical holes with the main axes of the ellipse of 250 and 500 nm (Fig. 1). The holes
are arranged in a square array with period $D = 500$ nm. The transmission spectra of the nanostructures were recorded using a spectrograph equipped with a CCD-camera coupled to a long-working-distance optical microscope. Collimated white light from a stabilized tungsten-halogen source passed through a polarizer and illuminated the sample at normal incidence. The light transmitted through the nanostructure was collected by an objective lens. The beam position at the nanostructure was monitored by an imaging CCD camera. The light exiting the structure passed through the analyzer and was launched into a fiber bundle connected to the spectrograph. Polarization mode scrambling in the fiber bundle ensured that polarization-related effects do not influence spectral measurements.

The transmission spectra of the structure obtained at normal incidence without polarization selectivity of the transmitted light are shown in Fig. 2 for different polarization states of the incident light with respect to the array orientation. For the incident light polarization parallel to the principal lattice axes ($x$ or $y$) the transmission spectrum is observed with broad features in the 450–550 nm and 750–800 nm spectral ranges. With the increase of the polarization azimuth $\phi$ up to about 20–25° the transmission increases in the 550–750 nm wavelength range, where the spectrum becomes rather flat. With further increase of $\phi$ when the light is polarized along the short principal axis of the elliptical holes, the transmission in the long-wavelength spectral range (750–800 nm) is significantly suppressed. For the polarization azimuth along the long principal axis of ellipse, the transmission at the far red
FIG. 2: Normal incidence transmission spectra of the array of elliptical holes for different polarizations of the incident light without polarization analysis of the transmitted light. Polarization angle $\phi$ is measured with respect to $y$-axis (Fig. 1).

part of the spectrum is enhanced, but becomes smaller at around 600–700 nm. Thus, with rotation of the polarization of the incident light, the intensity of the spectral components of the transmitted light exhibit complex, oscillatory behavior different in different spectral ranges. The relatively well-defined long-wavelength band at around 780–800 nm has transmission minimum for the polarization of light parallel to the short principal axis of an ellipse and maximum for the polarization along the long principal axis. For all wavelengths, the dependencies show a 2-fold symmetry corresponding to the symmetry of the array: a square lattice with basis elements of a 2-fold rotational symmetry.

To understand polarization sensitivity of transmission, the spectrum of the SPP Bloch waves on a periodically structured film should be considered. The strict consideration of the symmetry properties of the eigenstates of a periodic structure with an asymmetrical lattice basis would require the approach analogous to the linear combination of atomic orbitals (LCAO) method or the Wannier functions conventionally used in solid state physics. Nevertheless, it will be instructive to consider a simplified model using the SPP Bloch modes.

The field of SPP modes on a periodically structured surface can be described by

$$E(x, y) = U_{kSP}(\xi, \eta)exp[i(k_{SP}^{(x)}x + k_{SP}^{(y)}y)], \quad (1)$$

where $U_{kSP}(\xi, \eta)$ possesses the periodicity of the array and is the SPP Bloch function and
\( \mathbf{k}_{SP} \) is the wave vector of the Bloch wave. Here the coordinate systems \((\xi, \eta)\) of the basis and \((x, y)\) of the lattice are not generally independent and introduced to simplify symmetry considerations. At normal incidence of light, the allowed SPP wavevectors on the periodically structured surface are determined by

\[
\mathbf{k}_{SP} = \pm p \frac{2\pi}{D} \mathbf{u}_x \pm q \frac{2\pi}{D} \mathbf{u}_y,
\]

where \( \mathbf{u}_x \) and \( \mathbf{u}_y \) are the unit reciprocal lattice vectors of the periodic structure, \( D \) is its periodicity (assumed to be the same in both \( x \)- and \( y \)-directions), and \( p \) and \( q \) are integer numbers corresponding to the different directions of the SPP Brillouin zone. At normal incidence, SPP can be excited if the electric field of the incident light has a component in the direction of SPP propagation: \( \mathbf{E} \cdot \mathbf{k}_{SP} \neq 0 \). Thus, the polarization dependence of the coupling efficiency in different directions of the Brillouin zone is proportional to \(|pcos\phi + qsin\phi|\), where \( \phi \) is the polarization azimuth angle with respect to the \( x \) principal axis of the lattice. It is clear from this analysis that for a square lattice with basis elements of circular symmetry no polarization dependencies of the SPP excitation and, thus, of the enhanced transmission can be expected at normal incidence.

However, in the case of an elliptical basis of the lattice, polarization dependencies are significant. Taking into account different scattering properties of the ellipse in different directions, one can understand this by considering the mixing of the SPP Bloch states of the square lattice due to the lower symmetry of the basis elements. Elliptical holes with different size in the different directions modify the Brillouin zone structure by introducing size-dependent anisotropic scattering. This leads to the reduction of the Brillouin zone symmetry showing a 2-fold rotation axis instead of 4-fold, appropriate for a square lattice, effectively creating a medium with pronounced linear birefringence in dichroism. Linearly polarized waves with polarization azimuth along the main axes of the elliptical basis will be the polarization eigenstates of the structure. As a result of the anisotropic SPP Brillouin zone, the transmission spectrum of the structure is dependent on the polarization of the incident light.

Mixing and re-excitation of surface plasmon resonances in different directions of the Brillouin zone are responsible for anisotropic retardation and eventually for the elliptization of the polarization state of the transmitted light. Polarized transmission spectra show that the changes of the polarization state of the transmitted light are strongly wavelength de-
FIG. 3: Spectra of polarized transmission of the array measured for the incident light polarization (a) $\phi = 0^\circ$ and (b) $45^\circ$, (c) $100^\circ$. The spectra of the light transmitted without polarization state change ($P \parallel A$), with orthogonal polarization ($P \perp A$, $\psi = 0^\circ$), and close to orthogonal polarization $\psi = \pm 8^\circ$ and $15^\circ$ are shown.

This allows identification of transmission resonances contributing to the broad transmission spectrum. Several resonances can be identified by the different degree of elliptization at around 750, 650, and 550 nm. Thus, by controlling the polarization state of the incident and exercising polarization selection of the transmitted light, transmission spectrum of the elliptical hole array can be tuned at specific resonant band corresponding to one or another SPP mode of the system, quasi-continuously from blue to red wavelengths of the visible spectrum (Fig. 4).

In conclusion, we have studied polarization properties of the transmission spectra of a periodic array of elliptical holes in a metal film. Due to the reduced symmetry of the lattice, elliptical holes allow to achieve the enhanced broadband transmission which can be controlled by choosing the polarization of the incident and/or transmitted light, offering numerous applications in passive and active optical components. Combined with non-linear effects which are significantly enhanced in metallic structures due to surface plasmons, the observed polarization properties will allow further applications in integrated photonic circuits.
FIG. 4: True colour images of the nanostructure taken in transmission for different polarizations of the incident and transmitted light showing tuning of the dominating transmission wavelength.

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