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2014 Appl. Phys. Express 7 032001
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Transmission of TE-polarized light through metallic nanoslit arrays assisted by a quasi surface wave

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Received November 4, 2013; accepted January 21, 2014; published online February 6, 2014

Optically thick metallic nanoslit arrays are opaque to TE-polarized light, in contrast to enhanced transmission of TM-polarized light. Here, we numerically show that, by introducing an ultrathin high-index dielectric coating on the metal surfaces, a quasi surface wave can be excited at the metasurfaces to enhance the transmission of TE-polarized light. The quasi surface wave is shown to behave like surface plasmon waves, and enhance the transmission in similar mechanisms as surface plasmon waves do for TM-polarized light. In this work, we suggest a way of manipulating TE-polarized light in metallic subwavelength structures.

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Optically thick metallic nanoslit arrays are opaque to TE-polarized light, in contrast to enhanced transmission of TM-polarized light. Here, we numerically show that, by introducing an ultrathin high-index dielectric coating on the metal surfaces, a quasi surface wave can be excited at the metasurfaces to enhance the transmission of TE-polarized light. The quasi surface wave is shown to behave like surface plasmon waves, and enhance the transmission in similar mechanisms as surface plasmon waves do for TM-polarized light. In this work, we suggest a way of manipulating TE-polarized light in metallic subwavelength structures.

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It is known that the transmission of light through nanopatterned thick metal films is due to the excitation of surface plasmons (SPs), which carry the coupled optical energy to propagate and oscillate in the nanoscale, resulting in enhanced transmission. However, SPs can be excited at metal surfaces with only transverse-magnetically (TM) polarized light; thus, the transverse-electrically (TE) polarized component of the light is usually excluded from mesoscopic optical interactions in metallic nanostructures. For example, metallic nanoslit arrays, to which purely TE or TM polarization states of incidence light can be de

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of the transverse magnetic field ($H_y$) of a TM-polarized SP wave mode. As such, we consider it as a quasi surface wave, locating at an HID-coated metasurface of metal. In Fig. 2(c), propagation of the quasi surface wave at the MDA metasurface is simulated, mimicking that of SP waves. In Fig. 2(d), the normalized complex propagation constant ($\beta/k_0$, $k_0 = 2\pi/\lambda_0$) or effective index ($N_{\text{eff}} = \beta/k_0$) of the TE-mode quasi surface wave is plotted as a function of the wavelength for HID layers of $n_c = 4$ and $t_c = 20$ and 30 nm. For a given set of the HID parameters, the cut-off wavelength is clearly indicated, e.g., at $\lambda_0 = 630$ nm for $n_c = 4$ and $t_c = 20$ nm. Thus, the quasi surface wave exists only below the cut-off wavelength, beyond which the field cannot be effectively confined near the metal surface. The results suggest that a medium of higher index is preferred for the HID layer, which allows a thinner HID layer and the existence of the quasi surface wave in a wider VIS–NIR spectrum range.

Moreover, the ultrasmall thickness of the dielectric layer allows its incorporation into subwavelength metal structures. For instance, a metallic subwavelength gap can be so modified to form the metal–dielectric–air–dielectric–metal (MDADM) gap structure shown in Fig. 3(a), whose fundamental TE mode also has a field distribution similar to that of an SP gap mode.\textsuperscript{13,14} This indicates the possibility of squeezing the TE-polarized light into metallic nanostructures for mesoscopic interactions. In Fig. 3(c), dependences of the normalized propagation constant on wavelength are shown for the guiding mode in an MDADM gap with HID layers of
Unlike the mode at an MDA surface, a cut-off wavelength is defined here corresponding to \( \text{Re}(\beta/k_0) = 1 \) for the MDADM gap mode. When \( \text{Re}(\beta/k_0) < 1 \) [shaded regimes in Fig. 3(c)], it becomes a leaky mode; the power is strongly attenuated as if propagating in a bulk metal. In Fig. 3(d), dependences of the normalized propagation constant on gap width are shown for the MDADM waveguides of \( n_c = 4 \) and \( t_c = 20 \) or 30 nm at \( \lambda_0 = 600 \) nm. These results show that the characteristics of the quasi surface wave mode at an MDA metasurface or in an MDADM gap are qualitatively similar to those of the SP modes in general. As for the existence of the cut-off, it exists also for the SP waves in fact—as we know, there are no SP waves in the long-wavelength range where noble metals are perfect conductors. That is how the terminology of “spoof surface plasmons” is used for the SP-like waves in microwave and terahertz regimes.\(^{15,16}\) Simply, the SP waves intrinsically exist in a relatively broad band.

Next, we study the coupling of TE-polarized light into an HID-modified metallic nanoslit, as illustrated in Fig. 4(a), by FDTD simulations. To exclude the effects of cavity resonances in the slit, the slit is assumed to have a semi-infinite length. As neighboring slits may optically interact, we treated two cases of the slit being either in a periodic array or just a single one to see the effect of periodicity. For them, the periodic or perfect matching layer (PML) boundary conditions (BCs) are applied in lateral directions of the simulation region. Note that, under periodic BC, the width of the simulation region is the period; however, under the PML BC for a single slit, the simulation region width is set to be large enough so that the power “funneled” into the slit from the top surface can all be counted. Here, a coupling coefficient is defined for evaluation as the ratio of the power coupled into the slit to the power of the incident plane wave light within a width corresponding to the metal slit \( (s + 2t_c) \).

Figure 4(b) shows the calculated coupling coefficients as a function of wavelength, together with those when the top or all parts of the HID layers are removed.

\( n_c = 4, \ t_c = 20 \) or 30 nm, and a slit width of \( s = 60 \) nm. Unlike the mode at an MDA surface, a cut-off wavelength is defined here corresponding to \( \text{Re}(\beta/k_0) = 1 \) for the MDADM gap mode. When \( \text{Re}(\beta/k_0) < 1 \) [shaded regimes in Fig. 3(c)], it becomes a leaky mode; the power is strongly attenuated as if propagating in a bulk metal. In Fig. 3(d), dependences of the normalized propagation constant on gap width are shown for the MDADM waveguides of \( n_c = 4 \) and \( t_c = 20 \) or 30 nm at \( \lambda_0 = 600 \) nm. These results show that the characteristics of the quasi surface wave mode at an MDA metasurface or in an MDADM gap are qualitatively similar to those of the SP modes in general. As for the existence of the cut-off, it exists also for the SP waves in fact—as we know, there are no SP waves in the long-wavelength range where noble metals are perfect conductors. That is how the terminology of “spoof surface plasmons” is used for the SP-like waves in microwave and terahertz regimes.\(^{15,16}\) Simply, the SP waves intrinsically exist in a relatively broad band.

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Figure 4(b) shows the calculated coupling coefficients as a function of wavelength, together with those when the top or all parts of the HID layers are removed.
coupling coefficients decrease sharply to near zero for all cases of the HID-modified slits. It is found that, for the slit in a periodic array (p = 400 nm), there is a distinct dip of the coupling coefficient at \( \lambda_0 = 512 \) nm, corresponding to in-plane resonances of the quasi surface waves at the top MDA metasurface, as also shown in the transmission spectra in Fig. 1(b). Otherwise, the slit in a periodic array has a much higher coupling coefficient than the single slit in general; moreover, at its maximum (at around \( \lambda_0 = 587 \) nm), the coefficient is even larger than one. We think that the presence of the slits in periodicity prohibits long propagation of the nonresonant quasi surface waves at the top MDA surface, which renders more flow of the surface wave power into the slits, resulting in a larger coupling coefficient. It is also observed that, for the slit in a periodic array, removal of the top surface HID layer results in the disappearance of the dip, as the corresponding in-plane resonance mode is not supported without the HID layer. However, in the single-slit case, when the top HID layer is removed, the coupling coefficient is enhanced below the cut-off. This is thought to be attributable to the reduction of other channels (coupling into the surface mode at the top surface) upon scattering of incident light at the slit entrance.

The analyses above show that modification of metallic nanoslit arrays with an HID coating layer provides a basis for the transmission of TE-polarized light via excitation of the quasi surface waves. However, the transmission is also subject to resonances in the metallic nanostructures, which can be considered in reference to the SP-enhanced transmission of TM-polarized light. In-plane resonance of the quasi surface wave at the periodically structured top MDA surface has been mentioned above, corresponding to the transmission dip at \( \lambda_0 = 512 \) nm in Fig. 1(b). This is further verified with the field distributions in Fig. 5(a), in which the resonant quasi surface wave locates at the top MDA surface like standing waves, and there is nearly no transmission of light. Positions of the in-plane resonance modes can usually be estimated with the equation: 
\[
\lambda_0^{res} \approx \frac{N_{eff} \cdot \delta}{p / m},
\]
where \( \lambda_0^{res} \) is the resonance wavelength, \( N_{eff} \) is the effective index of the quasi surface wave, \( p \) is the period, and \( m \) is the resonance order. It is verified that, as \( p = 400 \) nm and \( m = 1 \), the above equation is satisfied at \( \lambda_0 = 519 \) nm for \( N_{eff} = 1.297 \), close to the position of the transmission dip. Note that the deviation is due to the neglect of the Bloch-mode nature of the slit cavities, respectively.

Additionally, resonances in the slit cavities are also identified, which result in the transmission peaks at \( \lambda_0 = 435, 554, \) and \( 682 \) nm in Fig. 1(b). From field distributions at the peak positions in Figs. 5(b)–5(d), 2, 1, and 0 near-zero-field nodes are observed in the slits, corresponding to the 3rd-, 2nd-, and 1st-order resonances in the slit cavities, respectively.

From all the analyses above, it can be seen that, once the quasi surface wave mode is established by modification of the metallic nanostructures with an HID coating layer, the processes and mechanisms of transmission for TE-polarized light are similar to those of SP-assisted transmission for TM-polarized light.\(^{3,12,18}\) Here, three coupled processes play critical roles in transmission under assistance of the quasi surface waves, i.e., funneled coupling of incident light into the slits, Bloch-mode resonances of the quasi surface waves at the top MDA surface, and cavity resonances in the slits. Besides, the effects of the quasi surface waves’ cut-off in slits define the low transmission in the long-wavelength regime.

In summary, a method is proposed to enable the transmission of TE-polarized light through metallic nanoslit arrays. The concept of quasi surface waves in an MDA metasurface also provides opportunities for the manipulation of TE-polarized light in metallic subwavelength structures or nanostructures, which can be used to devise novel micro/nanophotonics elements.

**Acknowledgments**  The authors acknowledge the financial support from NSFC (No. 61275063), the Natural Science Foundation of Fujian Province of China (No. 2011J06002), and the Fundamental Research Funds for the Central Universities (No. 2012121009).

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\( \lambda_0 = 512 \) nm, \( \lambda_0 = 435 \) nm, \( \lambda_0 = 554 \) nm, \( \lambda_0 = 682 \) nm

**Fig. 5.** Steady-state distributions of the field \( |E_x| \) within a period of the slit array at resonance positions in the transmission spectrum of Fig. 1(b). The light is normally incident from the top (air) side in the images.

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