Dynamic control of optical transmission through a nano-slit using surface plasmons

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Abstract: We demonstrate how the optical transmission by a directly illuminated, sub-wavelength slit in a metal film can be dynamically controlled by varying the incident beam's phase relative to that of a stream of surface plasmon polaritions which are generated at a nearby grating. The transmission can be smoothly altered from its maximum value to practically zero. The results from a simple model and from rigorous numerical simulations are in excellent agreement with our experimental results. Our method may be applied in all-optical switching.

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1. Introduction

Surface plasmon polaritons (SPPs) are collective excitations of electrons that travel along the interface between a metal and a dielectric [1]. Since SPPs can be laterally confined below the diffraction limit by subwavelength metal structures, they are prime candidates for use in future miniaturized all-optical circuits. The field of plasmonics explores the coupling of optical fields with SPPs in nanostructures [2]. In recent years, extensive research efforts have produced novel plasmonic devices such as waveguides [3], couplers [4], lasers [5], solar cells [6], switches [7, 8], holograms [9], and sensors [10]. Many of these devices use subwavelength apertures, like tiny holes or slits, in SPP-supporting metal films. It is now well-established that SPPs play a crucial role in the transmission of light through nano-apertures, see for instance [11–16]. It has indeed been observed that SPPs modulate the transmission process to some extent [17]. However, a complete, dynamic control of the transmission through a nano-slit by using SPPs has not yet been demonstrated.

Here we report a theoretical, numerical, and experimental analysis of a plasmonic configuration in which the light transmission through a metallic nano-slit can be fully controlled. Inside the slit, a TM_0 mode is generated both by a normally incident laser beam and by SPPs which are created at a nearby grating. Because the slit width is less than half a wavelength, other TMpolarized modes are evanescent and the total field is a linear combination of only these two spatially coherent contributions. We find that by varying the phase of the laser beam, the total transmission ranges from effectively zero to about four times that of the laser beam alone.

2. Theory and simulations

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A sketch of our configuration is shown in Fig. 1. A thin metal film contains a slit and a grating. Two TM-polarized, monochromatic, coherent beams are used to separately illuminate the grating and the slit. The slit width is less than half a wavelength, which means that only the TM₀ mode is non-evanescent. The normally incident beam A only illuminates the slit. Beam B, which is incident at an angle θ_i , illuminates only the grating. The angle θ_i is set to optimize the generation of SPPs [18] that travel from the grating to the slit where they also produce a TM₀ mode. A variable phase difference between the two beams is applied, and the total transmission of the nano-slit is measured with a CMOS detector. If A_A and A_B are the amplitudes of the TM₀ modes due to beams A and B, respectively, then the intensity *I* of the transmitted field *C* can be written as [19]

$$= |A_{\rm A}|^2 + |A_{\rm B}|^2 + 2|A_{\rm A}||A_{\rm B}|\cos\delta, \tag{1}$$

where δ denotes the phase difference between the two modes. If we arrange the two amplitudes to be equal, i.e., $|A_A|^2 = |A_B|^2 = |A|^2$, and then vary the phase difference between the two laser beams, the phase δ will also vary, and the total transmission ranges from 0 to $4|A|^2$ for destructive and constructive interference, respectively.

I



Fig. 1. Schematic diagram of plasmon-controlled light transmission through a metallic nano-slit. Beam A is normally incident onto the slit, whereas beam B illuminates the grating under an angle θ_i and produces SPPs that travel towards the slit. This creates a coherent superposition of two TM₀ modes within the slit. A tunable phase between the two beams leads to a varying phase difference δ between the two modes and modifies their interference, and thereby controls the intensity of the transmitted field C.

In order to gain more insight into the transmission process, we have utilized a Fourier modal method (FMM) [20] to simulate the field intensity and the time-averaged Poynting vector near the slit in our actual sample (details of which are given below). Figure 2 shows the intensity $|\mathbf{E}|^2$ of the transmitted field in a plane at an intermediate distance of 400 nm behind the slit. The radiated field is seen to be spreading rapidly in the *x* direction. When the modes due to the



Fig. 2. Simulation of the field intensity $|\mathbf{E}|^2$ in a plane at a distance 400 nm behind the exit of the slit. The lowest curve (blue) shows the zero field that occurs when beams A and B are out of phase ($\delta = \pi$) and their interference is destructive. The middle curve (black) is the field due to either beam A or beam B alone. The highest curve (red) represents the field when the interference is constructive ($\delta = 0$).

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#240791 © 2015 OSA two beams are out of phase, i.e., $\delta = \pi$, there is a complete cancellation and the transmission is completely blocked (blue curve). The field intensity when only beam A or only beam B is present is represented by the middle curve (black). When the two modes are in phase, i.e., $\delta = 0$, constructive interference leads to a peak intensity that is four times higher than that of beam A alone (red curve). At larger observation distances the shape of these curves remains essentially unchanged.

Figures 3(a) and 3(b) show the Poynting vector when only the normally incident beam A or only the SPP-generating beam B is present. In Fig. 3(a) the power flow is symmetric about the line x = 0. Notice the presence of two vortices of the Poynting vector on the illuminated side of the sample (z < 0) near $x = \pm 0.35 \ \mu$ m. In Fig. 3(b) with only the SPPs generated at the grating present, the power flow near the slit entrance (z = 0) is mostly upward in the figure. However, at the exit of the slit ($z = 0.4 \ \mu$ m) the Poynting vectors have become symmetric about the line x = 0. This demonstrates that only the symmetric TM₀ mode is non-evanescent in our configuration, i.e., even a non-symmetric field at the entrance of the slit produces a symmetric output field. It is in fact essential that the slit sustains only a single mode. If the slit were wider, the SPPs would excite an additional asymmetric TM₁ mode. Symmetry dictates that the normally incident beam A cannot generate such a mode. This means that the two beams could then no longer completely cancel each other's contribution, leading to a less than perfect



Fig. 3. Poynting vector near a subwavelength slit. (a) Only the normally incident beam A is present. (b) Only the plasmon-generating beam B is present. (c) Constructive interference $(\delta = 0)$ leads to enhanced optical transmission. (d) Destructive interference $(\delta = \pi)$ leads to a near-zero transmission. In these figures the Poynting vector is shown as arrows whose color indicates their magnitude. The black lines define the metallic film and the TiO₂ layer with the slit, deposited on top of a silica substrate. For clarity, the Poynting vectors within the metal plate are not shown.

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modulation of the transmitted radiation.

In Figs. 3(c) and 3(d) the case of the two interfering mode fields (of the same intensity) is shown. Depending on the phase difference between the two beams, this can either be constructive [Fig. 3(c)] or destructive [Fig. 3(d)]. Notice that in Fig. 3(d) the transmission is nearly fully blocked, in agreement with our interference model. There is practically no field formed inside the slit, in contrast to the case of constructive interference (or individual beams). It is seen from this figure that the case of (effectively) zero transmission coincides with the formation of a vortex of the Poynting vector near (x, z) = (0, 0). The correlation between the presence of such vortices and enhanced or frustrated transmission has been discussed in [21].

3. Experiments

The experimental setup is depicted in Fig. 4. We employ a linearly polarized He-Ne laser operating at 632.8 nm, and spatially filter it to obtain a uniform, clean beam. This step allows smaller spot sizes when the two beams are eventually focused. The beam is then collimated and directed to a non-polarizing 50:50 beam splitter, from which the two beams A and B emerge. The intensity of beam A is controlled by an adjustable neutral density filter. The phase between the two beams (and hence the phase difference δ) is modulated by a glass plate (with thickness ~ 3020 μ m) on a rotation mount. The beams are passed through two polarizers to ensure they are both TM polarized. They are then focused by a pair of plano-convex aspheric lenses L_A and L_B with focal lengths $f_A = 20$ mm and $f_B = 11$ mm, respectively. While beam A is perpendicular to the sample, beam B is tilted so that the angle of incidence $\theta_i = 20^\circ$. This angle was determined through simulations to optimize surface plasmon generation at the grating. Because of the relatively low coherence length of the laser (~ 10 cm), the difference between the path lengths of the two beams from the beam splitter to the sample is minimized. This ensures that their contributions are mutually fully coherent.

The sample consists of a 400 nm thick aluminum layer deposited on a silica (SiO₂) substrate.



Fig. 4. Schematic diagram of the setup and the parameters of the slit-grating system. A grating with period d = 951 nm and a slit with width a = 170 nm are etched on an aluminum layer on top of a silica substrate. A protective 10 nm TiO₂ layer is deposited on the aluminum. The layer depth z = 400 nm, the binary grating height h = 130 nm, and the slit-to-grating distance $r = 25 \ \mu$ m. The path lengths of beams A and B are set approximately equal.

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The aluminum film has a 170 nm wide nanoslit (4 mm long) etched down to the substrate, together with a binary grating structure (period d = 951 nm, depth h = 130 nm, and width 1 mm) at a distance $r = 25 \ \mu$ m. The structures were produced using plasma etching (PlasmaLab 100, Oxford Instruments). The Al film is coated with a 10 nm thick titanium dioxide (TiO₂) layer to prevent damage from oxidation. A CMOS detector is positioned close to the transmission side of the sample.

In order to verify that the contribution of beam B to the field at the slit is solely due to SPPs, beam A was switched off, and we observed the total intensity I (obtained by adding all pixel values of the detector) when beam B is first focused onto the slit and then is slowly moved towards the grating. The results of recording the intensity every 5 μ m are shown in Fig. 5(a). The intensity gradually decreases from I = 1 at 0 μ m up until $\sim 25 \ \mu$ m, the location of the grating, where a sudden threefold rise in the intensity occurs: I = 0.0115, compared to neighboring values I = 0.0042 and I = 0.0019 at 20 μ m and 30 μ m, respectively. This is clearly consistent with the generation of SPPs. To exclude the possibility of beam deformations or too large a spot size, we conducted a similar measurement by turning the sample around and illuminating its non-grating side as we moved away from the slit [i.e., obtaining the situation shown in the inset of Fig. 5(b)] while keeping beam B and its angle of incidence θ_i the same. This means that the grating is now not illuminated. As Fig. 5(b) shows, in this case the intensity drops gradually from the maximum value and we do not see a similar rise in intensity as when the grating is present. That the intensity at $r_b = 20 \,\mu$ m is larger in Fig. 5(a) than in Fig. 5(b), namely 0.0042 compared to 0.0031, is due to partial illumination of the grating at that position. Similarly, at $r_b = 30 \,\mu$ m the intensity is larger in the situation of Fig. 5(a) than of Fig. 5(b), which is also expected, due to the generation of SPPs in the former case.

In the main experiment the transmitted intensities I_A and I_B due to the two individual beams



Fig. 5. Normalized total intensities, set to I = 1 at $r_b = 0 \ \mu$ m, of the field transmitted through the slit when the tilted beam B is focused at different distances r_b from the slit. (a) The grating is present, and there is a sudden rise of the intensity at the position of the grating. (b) No grating is present, and the intensity keeps dropping as the center of beam-to-grating distance r_b is increased.

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are approximately set equal with the help of an adjustable neutral density filter in the path of beam A, as shown in Fig. 4. For the case $I_A \approx 1.12 I_B$, we expect [from setting $|A_A|^2 = 1.12|A_B|^2$ in Eq. (1)] a maximum transmitted intensity 4.46 I_B , rather than $4I_B$. This is in excellent agreement with the observed average peak value I_{avg} , shown as the dashed green line in Fig. 6(a). The total transmitted intensity is plotted as a solid black curve. The two angle-averaged beam intensities I_A and I_B (dashed red and blue lines) are also plotted. If the glass plate is rotated over an interval of three degrees, six maxima and six minima are observed. It is seen that the transmission can also be blocked significantly: the first minimum is 2.0% of the first maximum, whereas the second minimum is 0.3% of the second maximum.

In the first experiment the initial angle of the glass plate was about 2°. In a second experiment the initial angle was ~ 1°, and measurements were taken at smaller intervals. The results are shown in Fig. 6(b). As in Fig. 6(a), the modulation is quite apparent, with an approximate fourfold maximum transmission when $\theta = 0.20^{\circ}$ or 1.17° , and a near total blockage of the transmission occuring near $\theta = 0.68^{\circ}$ and 1.70° .

While ideally I_A would remain constant during the experiment, this is not the case. The intensity of beam A changes with the angle θ , because the glass plate rotation causes a small shift of the focus. As a result, I_A and I_B will be slightly different, resulting in less than perfect blocking of the transmission at the minima in Fig. 6. It is worth noting that in the experiment we took measurements of a single detector column in the CMOS array in order to minimize the problems arising from spatially matching the individual outputs. In practice, this means that the individual intensities were matched on a single detector column only. Measurements with a larger detector area yielded effectively the same results in the sense that the same modulation is still visible even if the contrast between interference extremes is lowered due to intensity differences between beam A and the SPP signal along the slit.

It is of interest to compare our work to that reported in [22]. There, a similar interference effect between a directly illuminating beam and a stream of SPPs was employed to modulate the transmission through a narrow slit. The SPPs were made to pass through a layer of quantum



Fig. 6. Experimental demonstration of SPP-controlled transmission. The intensity transmitted through the slit (solid black line) varies as a function of the glass-plate rotation angle θ . The angle-averaged intensities of the two individual beams, I_A and I_B , are shown as blue and red dashed lines, respectively. The average peak value, I_{avg} , is plotted as a green dashed line. When the mode fields produced by the two beams are in phase, the total transmission rises approximately fourfold, when they are out of phase the intensity is nearly zero. (a) Experiment with rotation range $0^{\circ}-3^{\circ}$ with starting angle $\sim 2^{\circ}$, and (b) a second experiment with range $0^{\circ}-1.7^{\circ}$ with starting angle $\sim 1^{\circ}$. The standard deviations of the individual beam intensities are about 6% in case (a) and 4% in case (b).

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dots. Using a separate laser with a variable power, the absorption coefficient of the quantumdot layer could be altered. The resulting change in the amplitude of the SPP field produces an all-optical modulation of the transmitted field. The modulation, however, was not 100% as in our case, but rather of the order of 70%.

We note further that because the generation of SPPs and their reconversion into a propagating light field is somewhat inefficient, the intensity of beam B must be larger than that of beam A. In our setup a 50:50 beam splitter is used. Therefore a neutral density filter is needed to attenuate beam A. If desired, a more power-efficient operation can be achieved by coupling most of the laser output directly into beam B.

4. Conclusions

In summary, we have analyzed how in a slit–grating configuration the transmission through the slit due to a normally incident laser beam can either be canceled or increased fourfold by surface plasmons that are generated by a separate, coherent beam that illuminates the grating. By varying the phase difference between the two beams the total transmission can be controlled dynamically. Our approach may find use in the design of plasmonic switches.

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