Theory of enhanced optical transmission through a metallic nano-slit surrounded with asymmetric grooves under oblique incidence

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Abstract: A metallic nano-slit surrounded with asymmetric grooves is proposed as the plasmonic concentrator for oblique incident light. A theoretical model based on the surface plasmon polariton (SPP) coupled-mode method is derived for the extraordinary optical transmission (EOT) through such a structure under oblique incidence. The model is quantitatively validated with the finite element method. With the model, the physical insight of the EOT is then interpreted, i.e., the major contributions to the transmission include the vertical Fabry-Perot resonance of the slit, and the interference among slit modes excited by the incident light, by SPPs generated from groove arrays and their first-order reflections. This is quite different from the EOT through a nano-slit surrounded with symmetric grooves under normal incidence.

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1. Introduction

Since the first experimental report of the extraordinary optical transmission (EOT) phenomenon [1], surface plasmon polaritons (SPPs) have attracted world-wide attention in fundamental research as well as in optoelectronic applications. A metallic nano-slit surrounded with symmetric periodic corrugations on the illuminated surface, which acts as the plasmonic concentrator, is particularly attractive in applications such as the near-field scanning optical microscopy, the high-density optical storage, and the high-speed photodetector [2–4]. To maximize the optical transmission through such a structure, there has been a lot of research in the structure optimization and the underlying physics [5–11]. It has been widely accepted that the slit-groove distance plays a key role in the transmission, and different distances may lead to enhanced or suppressed transmission. Based on the phenomena, it was believed that the interference between the incident light and the SPPs generated by grooves was responsible for the EOT [8, 9]. However, the interference effect was soon challenged and claimed to be incorrect [10]. The debate continued until quite recently, the authors found that the horizontal Fabry-Perot (F-P) resonance effect of SPPs due to the reflection by surrounding grooves also plays a key role and finally clarified that the EOT originates from the interference between the slit fundamental modes excited by the incident light and by groove-generated SPPs, where SPPs are modulated by the horizontal F-P resonance effect [11].

In all those works, the incident plane wave is limited to normal incidence, and the grooves surrounding the slit are symmetric accordingly. However, in applications such as the photodetector array used in biological or chemical sensing, the light scattered by the sample may obliquely impinge upon detectors. In this case, the plasmonic concentrator in front of the detector should be capable to collect light of oblique incidence. In this work, we propose a nano-
slit surrounded with asymmetric grooves to realize such a plasmonic concentrator for obliquely incident light for the first time to our knowledge, as illustrated in Fig. 1. A theoretical model for the EOT through the structure will be derived and quantitatively validated with numerical calculations. With the model, the physical insights will be also interpreted.

2. Theoretical model

As SPPs are shown to be the primary vector in the visible or near infrared regime [12], we only consider SPP-assisted transmission and neglect the contributions of other electro-magnetic fields such as quasi-cylindrical waves (CWs) mentioned in [12]. To efficiently excite SPPs under oblique incidence of angle $\theta$, the period of a groove array should be properly chosen to compensate the missing momentum between SPPs and the incident TM-polarized free-space light [13],

$$k_0 n_{sp} = k_0 \sin \theta + m \frac{2\pi}{p},$$

where $n_{sp}$ is the effective refractive index of the SPP mode at a air-metal interface, and $m$ is an integer. If the periods of grooves on the left and the right sides are set as $p_1 = m\lambda / (\Re(n_{sp}) - \sin \theta)$ and $p_2 = m\lambda / (\Re(n_{sp}) + \sin \theta)$ with “Re” referring to the real part, respectively, the generated SPPs by grooves on both sides will propagate toward the central slit under oblique incidence, as shown in Fig. 2(a). As a result, grooves surrounding the nano-slit in the proposed structure are asymmetric. Such structures are widely used in the optical off-axis beaming [14–16]. However, the physical mechanism of off-axis beaming is different from that of the EOT under oblique incidence, which has not been studied yet.

As stated in [9, 11], there may be enhanced or suppressed transmission even when the surrounding grooves are designed to maximize the SPPs’ excitation efficiency. The key lies in the slit-groove distances. To analyze the EOT through the nano-slit surrounded with asymmetric grooves, we propose a theoretical model, in which the groove arrays are treated as “black boxes” that generate and reflect SPPs, as shown in Fig. 2. $A_1 (B_2)$ is the complex amplitude of the superposition of the left-going (right-going) SPP modes starting from the edge of the slit, $A_2 (B_1)$ is that of the left-going (right-going) SPP modes starting from the edge of the right (left) grooves, $D (U)$ is that of the fundamental slit mode propagating downward (upward). Here we use the $H_z$ component instead of $E_x$ or $E_y$ to model the EOT, because the incident, the scattered, and the transmitted fields have strong $H_z$ components [9].

The main elementary scattering processes involved in the proposed model are shown in Figs. 2(b) to 2(g). $r_{s1}$ and $r_{s2}$ are the respective reflectance coefficients of the slit fundamental modes at the top and the bottom openings. $\rho$ and $\tau$ are the reflectance coefficient and the transmittance coefficient of the SPP mode at the slit, respectively. The SPP mode at the air-metal interface and the slit fundamental mode can be converted to each other with a conversion coef-
center-to-center distances, we use the slit-groove edge-to-edge distances \( \beta \). The SPP scattering coefficients and reflectance coefficients of the left and the right groove arrays are \( \beta_1(\theta) \), \( r_{s1} \) and \( \beta_3(\theta) \), \( r_{s2} \), respectively. \( t_0(\theta) \), \( \beta_s(-\theta) \), and \( \beta_s(\theta) \) are the respective scattering coefficients of the slit fundamental mode, the left-going and the right-going SPP modes by a single slit under the illumination of a plane wave with amplitude \( I_0 \) and angle \( \theta \). Since the slits considered are very small (usually \( w_{sl} < \lambda / 2 \)), we only take into account the slit fundamental mode with the effective complex refractive index \( n_{sl} \). Finally, the coupled-mode equations lead to

\[
\begin{align*}
B_1 &= r_{s1}w_1A_1 + \beta_1(\theta)I_0, \\
A_1 &= \tau w_2A_2 + \beta_3(-\theta)I_0 + \alpha vU + \rho w_1B_1, \\
A_2 &= r_{s2}w_2B_2 + \beta_2(-\theta)I_0, \\
B_2 &= \tau w_1B_1 + \beta_s(\theta)I_0 + \alpha vU + \rho w_2A_2, \\
D &= r_{s1}vU + t_0(\theta)I_0 + \alpha w_1B_1 + \alpha w_2A_2, \\
U &= r_{s2}vD,
\end{align*}
\]

where \( w_1 = \exp(ik_0s_{dp}d_1) \), \( w_2 = \exp(ik_0s_{dp}d_2) \), and \( v = \exp(ik_0s_{st}) \). Instead of the slit-groove center-to-center distances, we use the slit-groove edge-to-edge distances \( d_1 \) and \( d_2 \), which are more convenient for the analysis as they are independent from the widths of the slit and grooves. Note that we set the phase of the incident magnetic field at the center of the slit’s upper opening \( (x = y = 0) \) to zero. As a result, \( \beta_1(\theta) \) includes a phase difference of the obliquely incident field \( \exp[-ik_0\sin \theta(d_1 + w_{sl}/2)] \), \( \beta_3(-\theta) \) includes \( \exp[ik_0\sin \theta(d_2 + w_{sl}/2)] \), and \( \beta_s(\pm \theta) \) includes \( \exp(\mp ik_0\sin \theta w_{sl}/2) \). One should notice that \( \beta_s(\pm \theta) \) can be omitted in practice due to

Fig. 2. (a) Schematic of the proposed model for the metallic nano-slit surrounded with asymmetric periodic grooves. The groove periods, slit-groove distances, and the duty cycles for the left and the right arrays are \( p_1, d_1, f_1 \) and \( p_2, d_2, f_2 \), respectively. The depths for grooves on both sides are \( h \). The electromagnetic quantities \( A_1, B_1, A_2, B_2, U, D \) are all defined in the text. (b)-(g) show the main elementary scattering processes involved in the EOT. (b) and (c) show the scattering coefficients under the fundamental slit mode illumination. (d) is the scattering of incident SPP mode by a nano-slit. (e) and (f) show the generation and reflectance of the SPP mode by a groove array, respectively. (g) shows the generation of the SPP modes and the slit fundamental mode by a nano-slit.
which agrees well with our previous results [11]. For the sake of clarity, we calculate \( \beta_{rg} \) there will be no closed-form solutions. A vivid example is on the SPP’s reflectance coefficient distribution of every groove. However, in this case, the resulted equation system is so complex that the grooves can also be further modeled using the coupled-mode equations in terms of the constants, [19]. The coefficients involved in the model are calculated as follows. The mode conversion Equation (3) is then reduced into

\[
D = \frac{I_0}{1 - r_{s1}r_{s2}v^2} \left\{ l_0(\theta) + \frac{\alpha[1 + (\tau - \rho)\delta_2]w_1\beta_1(\theta) + \alpha[1 + (\tau - \rho)\delta_1]w_2\beta_2(-\theta)}{(1 - \rho\delta_1)(1 - \rho\delta_2) - \tau^2\delta_1\delta_2} \right\},
\]

(3)

where \( \delta_1 = r_{s1}w_1^2 + r_{s1}w_2^2 \) and \( \delta_2 = r_{s2}w_2^2 \). Specially, for a slit surrounded with symmetric groove arrays under normal incidence, we have \( r_{s1} = r_{s2} = r_s \), \( w_1 = w_2 = w \), \( \beta_1 = \beta_2 = \beta \), and \( \delta_1 = \delta_2 = r_s w^2 \). Equation (3) is then reduced into

\[
D = \frac{I_0}{1 - r_{s1}r_{s2}v^2} \left[ l_0 + \frac{2\alpha w \beta}{1 - (\tau + \rho)r_s w^2} \right],
\]

(4)

which agrees well with our previous results [11]. For the sake of clarity, we calculate \( |D|^2 \) instead of the transmission efficiency \( \eta \), which is defined as the total energy transmitted into the far field normalized to the energy incident on the slit opening [9]. This is because \( \eta \) is proportional to \( |D|^2 \) for a nano-slit. The proportional coefficient denotes the conversion efficiency from the slit mode to the propagating light through the slit on the output side of the slit. Given the slit’s parameters, the coefficient is fixed, thus \( |D|^2 \) and \( \eta \) result in identical conclusions, as will be validated in the next section.

3. Results and discussions

3.1. Model validations

In this section, we first validate the theoretical model by quantitatively comparing \( |D|^2 \) predicted by the model with the transmission efficiency \( \eta \) calculated by the finite element method (FEM) [19]. The coefficients involved in the model are calculated as follows. The mode conversion coefficients, \( \alpha \) and \( l_0(\theta) \), are obtained analytically [20]. The reflectance coefficients \( r_{s1}, r_{s2}, \rho, r_{g1}, r_{g2} \) and the transmittance coefficient \( \tau \) are calculated by the a-FMM [17]. The SPP generation coefficients \( \beta_1(\theta) \) and \( \beta_2(\theta) \) can be calculated by either the method combining the a-FMM with the reciprocity theorem [21]. The wavelength of \( \lambda = 800 \text{nm} \), the substrate of silica with permittivity \( \varepsilon_s = 1.46 \), and gold with relative permittivity \( \varepsilon_m = -26.2 + 1.85i \) [22] are used to illustrate our discussions throughout the paper.
Fig. 3. (a) $|D|^2$ predicted by the proposed model as a function of slit-groove distances $d_1$ and $d_2$. The calculations are performed for $N = 10$, $w_{sl} = 100$ nm, $t = 174$ nm, $h = 70$ nm, and $\theta = 20^\circ$. The period and the duty cycle are $p_1 = 1180$ nm, $f_1 = 0.38$ for the grooves on the left side, and $p_2 = 588$ nm, $f_2 = 0.5$ for those on the right side. (b) and (c) show the comparisons between $|D|^2$ predicted by the model and the transmission efficiency $\eta$ calculated by FEM simulations. The calculations are performed along the vertical green line with $d_1 = 160$ nm and the horizontal white line with $d_2 = 100$ nm in (a), respectively. (d) and (e) show the scattered magnetic field $|H_z|^2$ calculated by the FEM. The slit-groove distances for (d) and (e) correspond to the point “Q” ($d_1 = 160$ nm, $d_2 = 80$ nm) and the point “P” ($d_1 = 160$ nm, $d_2 = 360$ nm) in (a), respectively.

Figure 3(a) shows $|D|^2$ as a function of slit-groove distances $d_1$ and $d_2$. Obviously, the influences of $d_1$ and $d_2$ on the transmission under oblique incidence are not identical because of the asymmetric surrounding grooves, which have different reflectance coefficients for the SPP modes. This phenomenon will be further explained in the next section. From Fig. 3(a), the peak transmission position (point “Q”) and the dip one (point “P”) of $d_1$ and $d_2$ are determined. The corresponding strong transmission enhancement and suppression are shown in Figs. 3(d) and 3(e), respectively, validating the accuracy of the model predictions.

Figures 3(b) and 3(c) compare the model predictions ($|D|^2$) and the FEM simulations ($\eta$) on the proposed plasmonic concentrator for the incidence angle $\theta = 20^\circ$. In this case, the periods for the left grooves and the right ones should be 1180 nm and 588 nm according to Eq. (1),
respectively. As one can see, the general trends of the transmission efficiencies, especially the positions as well as the periods of transmission peaks, are well captured by the proposed model. Predictions on peak values may be inaccurate sometimes, as illustrated in Fig. 3(c). This is because our model is a “pure” SPP model which only takes into account the SPPs’ contributions, while the CWs’ are neglected. Due to the characteristic damping of CWs in the visible or near infrared regime [12], their influences on the EOT decrease quickly as the slit-groove distances increase. For the sake of simplicity, we only consider the “pure” SPP mode. The derived model has also been quantitatively validated by FEM simulations for various wavelengths, from the visible to the near infrared, and under different angles of incidence.

3.2. Physical interpretations

To have a better understanding of the EOT under oblique incidence, we further simplify Eq. (3) by neglecting ρ, which is usually very small (|ρ| < 0.1) compared with τ (|τ| > 0.85) for small slits (w_{sl} < λ/2) [23], leading to,

\[ D = \frac{l_0}{1 - r_{s1}r_{g2}v^2} \left[ t_0 + \frac{\alpha w_1 \beta_1 (1 + \tau \delta_2) + \alpha w_2 \beta_2 (1 + \tau \delta_1)}{1 - \tau^2 \delta_1 \delta_2} \right] \]  \tag{5}

Equation (5) is intuitively meaningful. The first term, i.e., \( l_0 / (1 - r_{s1}r_{g2}v^2) \), represents the vertical F-P resonance effect of the cavity formed by the top and the bottom openings of the slit, as mentioned in Ref. 24, and the maximum transmission is achieved when

\[ 2k_0 \text{Re}(n_{sl})t + \arg(r_{s1}) + \arg(r_{g2}) = 2q\pi, \] \tag{6}

where the function “arg” refers to the argument of a complex number, and q is an integer. Hereafter, we set \( w_{sl} = 100 \text{nm} \) to illustrate our discussions. Calculated by the a-FMM, the reflectance coefficients are \( r_{s1} = -0.2389 - 0.4411i \) and \( r_{g2} = 0.1081 - 0.4125i \), and the effective refractive index of the silt fundamental mode is \( n_{sl} = 1.2346 + 0.0082i \). According to Eq. (6), the resonant film thickness should be \( t = 174 \text{nm} \) (\( q = 0 \)).

![Fig. 4. Interference interpretation of the term \( \alpha w_1 \beta_1 (1 + \tau \delta_2) \) in Eq. (5).](image)

Now let us consider the term \( \alpha w_1 \beta_1 (1 + \tau \delta_2) \), and rewrite it as \( \alpha w_1 \beta_1 + \alpha w_1 \beta_1 \tau r_{g2} w_{sl}^2 \). This term means the interference between slit fundamental modes, which are generated by the part of SPPs propagating from the left grooves directly coupled into the slit, and the part crossing over the slit, reflected back by the right groove array, and then coupled into the slit from the right side, respectively, as illustrated in Fig. 4. The term \( \alpha w_2 \beta_2 (1 + \tau \delta_1) \) can be understood similarly. The corresponding constructive interference conditions for \( \alpha w_1 \beta_1 (1 + \tau r_{g2} w_{sl}^2) \) and \( \alpha w_2 \beta_2 (1 + \tau r_{g1} w_{sl}^2) \) are given by

\[ 2k_0 \text{Re}(n_{sp})d_2 + \arg(r_{g2}) + \arg(\tau) = 2m_2\pi, \] \tag{7a}

\[ 2k_0 \text{Re}(n_{sp})d_1 + \arg(r_{g1}) + \arg(\tau) = 2m_1\pi, \] \tag{7b}
where \(m_1\) and \(m_2\) are integers. Obviously, the periods of these terms as functions of slit-groove distances are \(\lambda_{sp}/2\), where \(\lambda_{sp} = \lambda/\text{Re}(n_{sp})\) is the wavelength of the SPP mode.

The term \(1/(1 - \tau \delta_1 \delta_2)\), i.e., \(1/(1 - \tau r_{g1} r_{g2} w_1^2 w_2^2)\), results from the multiple reflection of SPPs in the cavity formed by the left and the right grooves. This effect was referred to as the horizontal F-P resonance in our previous work on normal incidence [11]. For the normal incidence, it was demonstrated that the horizontal F-P resonance is very important, sometimes it even dominates the transmission [11]. However, for oblique incidence and the asymmetric structure, this effect is very limited since \(r_{g1} r_{g2}\) is usually very small for grooves which are designed for high SPP excitation efficiency [25]. For example, in all the examples presented in this paper, \(|r_{g1} r_{g2}| < 0.1\). As a result, we further assume \(1 - r_{g1} r_{g2} \tau^2 w_1^2 w_2^2 \approx 1\), and reduce Eq. (5) into

\[
D = \frac{I_0}{1 - r_{g1} r_{g2} \tau^2} [t_0 + \alpha w_1 \beta_1 (1 + \tau \delta_2) + \alpha w_2 \beta_2 (1 + \tau \delta_1)].
\]  

From Eq. (8), it is easy to infer that the major contributions to the EOT through the proposed structure under oblique incidence are the vertical F-P resonance of the slit, the interference among slit modes excited by the incident light, by SPPs generated from groove arrays and their first-order reflections. This is quite different from the EOT through the nano-slit surrounded with symmetric grooves under normal incidence, which is due to the vertical F-P resonance of the slit, the interference between the slit modes excited by the incident light and by the groove-generated SPPs which are modulated by the horizontal F-P resonance effect [11], as indicated by Eq. (4).

With these interpretations, let us reconsider the different behaviors of \(d_1\) and \(d_2\) in Figs. 3(a) to 3(c), where the peak separations are quite different. For grooves used in Fig. 3, \(r_{g1} = -0.3036 + 0.0377i\), and \(r_{g2} = -0.0362 - 0.1077i\). Then \(r_{g2} \tau w_2^2\) can be further neglected because of small \(r_{g2}\), indicating that the first-order reflection of SPPs propagating from grooves on the left side makes little contribution. As a result, we rewrite Eq. (8) as

\[
D = \frac{I_0}{1 - r_{g1} r_{g2} \tau^2} [t_0 + \alpha w_1 \beta_1 + \alpha w_2 \beta_2 (1 + \tau \delta_1)].
\]  

From Eq. (9), it is not difficult to understand the differences between Figs. 3(b) and 3(c): given \(d_1\) (or \(w_1\)), the separation between peaks of \(|D|^2\) as a function of \(d_2\) is approximate to \(\lambda_{sp}\); however, given \(d_2\) (or \(w_2\)), this peak separation, as a function of \(d_1\), is approximate to \(\lambda_{sp}/2\) because of the term \(1 + \tau \delta_1\).

From the above discussions, the slit-grating distances \(d_i (i = 1, 2)\) play key roles in the interference between SPPs generated from groove arrays on the left and the right sides, and their first-order reflections. As a result, one can use different \(d_i\) to compensate the different phases of the SPPs launched from the left and the right to maximize the transmission.

4. Concluding remarks

The field-of-view (FOV) of the plasmonic concentrator is very important in applications such as photodetectors and the optical storage. The structure with symmetric surrounding grooves, which is designed for the normal incident light, is very sensitive to the incidence angle \(\theta\), as illustrated in Fig. 5. Its transmission efficiency reaches the maximum at the designed angle, i.e. \(\theta = 0^\circ\), but decreases rapidly when \(\theta\) deviates from \(0^\circ\), resulting a narrow FOV. The angular performance is similar for the proposed structure with asymmetric surrounding grooves, which is designed for the oblique incident light. It is clear that the angular pattern of the transmission efficiency for different structures are almost the same, except that transmission peaks are shifted to the designed angles.
Fig. 5. Angular transmission efficiencies for the plasmonic concentrators designed for θ = 0° (black), θ = 10° (red), θ = 20° (green) and θ = 30° (blue). The calculations are performed for $p_1=p_2=785$ nm, $f_1=f_2=0.52$, $d_1=d_2=240$ nm; $p_1=946$ nm, $p_2=670$ nm, $f_1=0.46$, $f_2=0.5$, $d_1=200$ nm, $d_2=130$ nm; $p_1=1180$ nm, $p_2=588$ nm, $f_1=0.38$, $f_2=0.5$, $d_1=160$ nm, $d_2=80$ nm; and $p_1=1540$ nm, $p_2=526$ nm, $f_1=0.5$, $f_2=0.56$, $d_1=400$ nm, $d_2=120$ nm, respectively. Other parameters are the same as those used in Fig. 3. The parameters $p_1$ and $p_2$ are chosen according to Eq. (1), $d_1$ and $d_2$ are predicted by the proposed model.

As shown in Fig. 5, the peak values of transmission efficiency for plasmonic concentrators designed for different angles are very close to one another. If an array of such structures, each of which is designed for a specific angle of incidence, are integrated in a chip, a wide FOV with almost flat transmission efficiency would be realized.

In conclusion, we have proposed a plasmonic concentrator composed of a nano-slit surrounded with asymmetric grooves under oblique incidence. A SPP coupled-mode model was derived to describe the EOT through such a structure. Comparisons of the model predictions with FEM computational data quantitatively showed that the general trend of the transmission efficiency is well captured by the model. The physical insight of the EOT was interpreted, i.e. the major contributions to the transmission enhancement are the vertical F-P resonance of the slit, the interference among slit modes excited by the incident light, by SPPs generated from groove arrays and their first-order reflections. With the proposed plasmonic concentrator for obliquely incident light, we believe the wide FOV optical receiver will be realized with a photodetector array integrated with an array of plasmonic concentrators, each of which is responsible for a specific angle of incidence.

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