Theory, figures of merit, and design recipe of the plasmonic structure composed of a nano-slit aperture surrounded by surface corrugations

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Abstract—We theoretically investigate a widely-used plasmonic structure composed of a nano-slit aperture surrounded by surface corrugations. A systematical semi-analytical theory in form of two nested coupled-mode models is developed to provide intuitive physical pictures. Based on the theory, figures of merit (FoMs) of the structures designed for normal and for oblique incidence/beamng are defined for the first time to incorporate the interlink among key structural parameters, making global optimization simple and efficient. Both the theory and the FoMs are quantitatively validated with exhaustive calculations and shown to be highly accurate on performance prediction and structural optimization. With the theory and the FoMs, an efficient, effective and standard recipe is introduced for optimal structure design. We believe this work will help to understand the mechanisms of and to facilitate the design of such a structure in various configurations used in various applications.

Index Terms—Aperture antennas, coupled mode analysis, design methodology, modeling, nanoscale devices, optical surface waves, performance evaluation, plasmons.

I. INTRODUCTION

PLASMONICS, as a new field of science and technology that exploits the unique optical properties of metallic nanostructures to manipulate light at nanometre length scales, has aroused increasing interest in fundamental science and device applications during the last decade [1]. One of its most successful applications is the extreme light concentration with various plasmonic antennas. Among these, a plasmonic structure composed of a subwavelength aperture flanked by surface corrugations, which is referred to as three-dimensional bull’s eye structure or two-dimensional slit-gratings structure [2], [3] as shown in Fig. 1, has received great attentions because the optical transmittance through it can be largely tailored with respect to that of an isolated aperture [4]. With such a structure, we witnessed many promising applications including plasmon-enhanced photodetectors [5]–[8], sensitive darkfield detection and imaging with bright background suppression (referred to as SWEDA microscopy) [9], [10], plasmonic photon sorters for spectral and polarimetric imaging [11], a plasmonic visible nanosource that could be applied in nanolithography or optical data storage [12], optical beaming [13]–[19], and laser beam collimation [20], [21].

To achieve high performance for specific applications with such a structure, great efforts, both theoretical and experimental, have been put on the physical mechanisms and the parameter optimization [2], [4], [15]–[17], [20]–[33]. In most of the previous works, the influence analysis of parameters on the performance was performed by varying only one or two parameters in sequence while keeping the others fixed [2], [4], [16], [17], [22], [23], [26]–[29]. Currently there is no generalized model to understand and design the structures for various applications such as optical concentration, optical beaming and collimation, with normal or oblique incidence/beamng. The design recipe varies according to different applications and different structures, making the device design very complex and empirical. For example, it has been suggested that the optimal groove width should be around half the period [2], [27], [29], and the optimal slit-groove distance should be just over half the surface plasmon polariton (SPP) wavelength $\lambda_{sp}$ [28] or be approximate to $m\lambda_{sp}/2$ with $m$ being an integer [4]. However, empirical recipes are not always applicable. A vivid example is that the optimized aperture-groove distance, which may lead to enhanced or suppressed transmission, has been under debate [28], [31] until recently. Moreover, it is accepted that the effects of many geometrical features are interlinked [28]–[30]. These properties greatly increase the complexity of structure design and aroused a global optimization by varying all the important structural parameters [30], which is very time-consuming and of excessive computational cost. To circumvent these problems, recently some authors developed semi-analytical models on optical transmission through the slit-gratings...
structures under normal [32] or oblique [33] incidence. In these models, closed-form expressions incorporating the dominant structural influences have been provided, and the horizontal Fabry-Perot (F-P) resonance effect due to the reflection of gratings has been unveiled for symmetrical structure under normal incidence. As a result, we largely resolved the debate on the optimal slit-groove distance, and also suggested a better choice of the groove duty cycle than the choice made in [28] for a special case. However, there are still many problems left to solve. Questions aroused such as why the duty cycle we picked is better than the one for the maximum SPP excitation efficiency, how to facilitate the usage of the models with tens of coefficients or parameters, and are there any figures of merit (FoMs) or standard design recipes to design various structures for various applications.

To answer these questions, we further developed theoretical models on the SPP reflectance [34] and excitation coefficients by periodic surface corrugations under normal incidence [35]. These coefficients were calculated by simulations with corrugations being treated as ‘black boxes’ and first optimized for maximum SPP excitation efficiency in our previous models on the slit-gratings structure [32], [33]. As the SPP reflectance and excitation coefficients of N corrugations are also accurately and efficiently predicted by quantitative models starting with those of a single one, it is possible to develop a systematical theory incorporating all these models elegantly, and to provide an efficient and standard recipe that could be followed by experimentalists without efforts.

In this paper, we present a systematical semi-analytical theory on the slit-gratings structure designed for any incidence/beaming angle, propose FoMs for such a structure for the first time to the best of our knowledge, and introduce a standard and simple recipe to design such a structure based on the theory and the FoMs. The slit-grooves structure is analyzed as the example, and ‘pure’ SPP coupled-mode models are set up for the performance prediction and the structure optimization with high accuracy at visible or near infrared regimes [35]. Both the theory and the FoMs will be quantitatively validated with exhaustive examples by comparing with simulation results using the fully vectorial aperiodic Fourier modal method (a-FMM) [36] and finite element method (FEM) [37]. With the FoMs, the above-mentioned problem on better choice of groove duty cycle will be solved elegantly. We will also show that it is easy to obtain better performance following the proposed recipe than a widely-adopted conventional recipe, where corrugations were first optimized for maximum SPP excitation efficiency. The remainder of the paper is organized as follows. We set up the systematical theory in forms of two nested semi-analytical models in Section II, deduce FoMs in Section III, and then validate them in Section IV. In Section V, the recipe will then be introduced and exemplified. Finally, some concluding remarks are summarized in Section VI.

II. A Systematical Theory

In this section, we set up a systematical semi-analytical theory for the slit-grooves structure designed for any incidence/beaming angle $\theta$, where the surrounding grooves are assumed to be asymmetrical without loss of generality. Although the model on optical transmission of TM-polarized plane wave and the one on its reverse process, i.e., optical beaming as illustrated in Figs. 2(a) and (b), respectively, lead to similar results according to the Lorentz reciprocity theorem, here we address the former instead of the latter to make use of our previous works. The theory is expressed in form of two nested models: a global model that treats the grooves on both sides as ‘black boxes’, and embodies all the key parameters with emphasis on the slit parameters and the slit-groove distances since they may lead to enhanced or suppressed transmission [23], [28], [32], [33]; and a nested model on the SPP excitation and reflectance coefficients of the ‘black boxes’.

A. The Global Model on the Whole Structure

The global ‘pure’ SPP coupled-mode model on optical transmission is shown by Fig. 2(a), where $H_1$, $A_R$ and $A_1$, $B_R$ are complex amplitudes of magnetic field $H_y$ of the left- and right-going SPP modes at the air-metal interface, respectively, $F$ is that of the left-going SPP mode at the metal-substrate interface, and $D$ and $U$ are those of the slit fundamental modes propagating downward and upward, respectively. To obtain a closed-form expression for the transmission efficiency, which is defined as the total power transmitted into the far field normalized to the power incident on the slit aperture, we treat

\[\begin{align*}
A_1 & = B_1 + A_R, \\
B_1 & = D, \\
D & = -U.
\end{align*}\]
the gratings on both sides as ‘black boxes’ and start with the knowledge of the elementary-event scattering coefficients shown in Fig. 2(c)–(h): $\beta_R^\pm$ and $\beta_L^\pm$ are the excitation coefficients of the left- and right-going SPP modes by the slit, respectively; $\beta_R^+$ and $\beta_L^+$ are those by a groove array; $t_1$ and $t_2$ are the respective excitation coefficients of the slit fundamental mode under plane wave illumination from the air and the substrate, and vice versa according to the reciprocity theorem; $\rho_L$ is the SPP reflectance coefficient of a groove array; $\rho_s$ and $\tau$ are the SPP reflectance and transmittance coefficients of the slit; $\alpha_1$ (or $\alpha_2$) is the scattering coefficient from the SPP mode at the air-metal (or metal-substrate) interface to the slit fundamental mode and vice versa according to the reciprocity theorem; $F$ is the SPP reflectance and transmittance coefficients of the slit; $\omega_{\mu}$ (or $\omega_{\nu}$) is the SPP reflectance and transmittance coefficients of the slit fundamental mode at the top and the bottom openings, respectively. The coupled-mode equations lead to

\[
\begin{align*}
A_L &= w_l^{-1} \beta_{gL}^+ + \rho_{gL} u_l H_l, \\
B_L &= \beta_R^+ + \rho_s u_L A_l + \tau \omega_{\mu} R_A + \alpha_2 u V, \\
A_R &= \omega_{\mu} \beta_R^- + \rho_{gL} u R_h \beta_{gL}^-, \\
B_R &= \beta_R^- + \rho_s u_L A_l + \tau \omega_{\mu} R_A + \alpha_2 u U, \\
D &= t_1 + \alpha_1 \omega_{\mu} \beta_{gL}^+ + \alpha_2 u L \omega_{\mu} \beta_{gL}^-, \\
U &= r_{lB} v L
\end{align*}
\]

where $u_l = \exp(i k_0 n_{\mu} d_L)$ and $u_R = \exp(i k_0 n_{\nu} d_R)$ with $n_{\mu} = -n_{\sigma} r_{lB}^{1/2}/(2 n_{\sigma} + 1/2)$ being the complex effective refractive index of the SPP mode at the flat-air-metal interface, and $v = \exp(i k_0 n_{\nu} d_R)$ with $n_{\nu} = \exp(i k_0 d_R^\sigma)$ the phase shift introduced by the incident plane wave. This is because the zero phase of the incidence is assumed to be at the top opening’s center of the slit ($x = z = 0$); whereas at the top opening’s centers of the grooves nearest to the slit for the calculation of $\beta_{gL}^+$ ($x = -d_L, z = 0$) and $\beta_{gL}^-$ ($x = d_L, z = 0$). Note that the propagation losses of the SPP mode and of the slit fundamental mode have been embodied via complex $\omega_{\mu}$ and $n_{\sigma}$, respectively.

For a practical plasmonic structure with optimized grooves, $\beta_k^\pm$ can be omitted as $|\beta_k^\pm| \ll |\beta_{gL}^\pm|$ and $|\beta_L^\pm| \ll |\beta_{gL}^\pm|$. By neglecting some trivial terms related to multiple cross conversions between $A_{l,R}, B_{l,R}$ and $D, U$, we obtain a simplified form expression from (1):

\[
D \approx \frac{1}{1 - r_{lB} v L} \left[ t_1 + \alpha_1 \left( \psi_R w_{\mu} \beta_{gL}^+ + \psi_L u_R \omega_{\mu} \beta_{gL}^- \right) \right] (1 - \rho_s \sigma_L)(1 - \rho_s \sigma_R) - \tau^2 \sigma_L \sigma_R \approx 1. 
\]

Equation (2) is then further reduced into

\[
D \approx \frac{t_1 + \alpha_1 \left( \psi_R w_{\mu} \beta_{gL}^+ + \psi_L u_R \omega_{\mu} \beta_{gL}^- \right)}{1 - r_{lB} v L}.
\]

Specially, for the symmetrical structure designed for normal incidence, $\theta = 0$, $\rho_{gL} = \rho_{g} = \beta_{gL}^+ = \beta_{gL}^- = \beta_{g}$, $d_L = d_R = d$, and $u_L = u_R = u$. Equation (2) is then reduced into

\[
D \approx \frac{1}{1 - r_{lB} v L^2} \left[ t_1 + \frac{2 \alpha_1 u \beta_{gL}}{1 - (\tau + \rho_s) \rho_R n^2} \right].
\]

The optical transmission efficiency $\eta$ is then expressed as

\[
\eta = \int_0^\pi [D \sin \theta] \cos \theta^2 d\theta
\]

and $F$ is expressed as

\[
F = D \omega_2.
\]

Obviously, $\eta \propto |D|^2$, $F^2 \propto |D|^2$, thus $\eta \propto F^2$ when the slit width and material (and then $v$ and $f_2$) are usually given first according to the specific application requirement. As a result, we use $|F|^2$ or $\eta$ to assess the performance.

B. The Nested Model on the Gratings

Now let us consider the ‘black boxes’ that excite and reflect SPPs. In previous works [16], [17], [27], [28], the gratings were usually first optimized by simulation scan for optimal $\beta_{gL}^+$ and $\beta_{gL}^-$. However, for a large groove number $N$, the optimization suffers from a high computational cost. What is worse, one has to repeat the optimization if $N$ should be increased for better performance. To circumvent these problems, here we develop an efficient theoretical model for $\beta_{gL}^+$ and $\beta_{gL}^-$ for any $N$.

We take $\beta_{gL}^+$ and $\rho_{gL}$ of grooves on the left side as an example, where the zero phase of the incident plane wave is at the top opening’s center of the rightmost groove, as shown in Fig. 3. $\beta_{gL}^+$ and $\rho_{gL}$ are calculated similarly but with a different zero phase position, as mentioned previously. The model may be expressed in two equivalent forms: the linear-equations form and the recursive form. The equivalence of the two forms has been verified in [34], thus it will not be discussed here due to space limitations. The model in a linear-equations form for $\beta_{gL}^+$ and $\rho_{gL}$ is shown in Fig. 3(a) and expressed as

\[
\begin{align*}
B_j &= w_{gL}^\pm N \beta_{gL}^+ + \beta_{gL}^+ u_{gL} \omega_{\mu} \beta_{gL}^- + \beta_{gL}^- u_{gL} \omega_{\mu} \beta_{gL}^+ \\
A_j &= \rho_{gL} u_{gL} \omega_{\mu} \beta_{gL}^+ + \beta_{gL}^+ u_{gL} \omega_{\mu} \beta_{gL}^-
\end{align*}
\]

where $w_{gL} = \exp(i k_0 d_L \sin \theta)$ and $u_{gL} = \exp(i k_0 n_{\nu} d_L)$ with $d_L$ being the groove period, $j = 1, 2, \ldots, N$ with $N = 1$. $\beta_{gL}^+ = \beta_{gL}^-$ are the right-going and left-going SPP excitation coefficients, the SPP reflectance and transmittance coefficients of a single groove, respectively, as shown in Figs. 3(c) and (d). To calculate the SPP excitation coefficients, $\beta_{gL}^+ = A_N$, $\beta_{gL}^- = B_1$, one sets $A_0 = 0$; whereas to calculate $\rho_{gL}$ and $\rho_{gL}$, we use $\rho_{gL} = \frac{1}{1 - r_{lB} v L^2} \left[ t_1 + \frac{2 \alpha_1 u \beta_{gL}}{1 - (\tau + \rho_s) \rho_R n^2} \right]$. 

Equation (2) is then reduced into

\[
\begin{align*}
D &= \frac{t_1 + \alpha_1 \left( \psi_R w_{\mu} \beta_{gL}^+ + \psi_L u_R \omega_{\mu} \beta_{gL}^- \right)}{1 - r_{lB} v L^2}.
\end{align*}
\]
Fig. 3. (a) Schematics of the linear-equations form and (b) the recursive form of the coupled-mode model for the SPP excitation and reflectance coefficients by \( N \) periodic grooves on the left side of the central slit. \( u_{gL}, A_0, A_1, A_2, \ldots, A_N, B_0 \) are complex \( H_0 \) amplitudes of SPP modes at the air-metal interface. (c) and (d) show the SPP excitation coefficients \( \beta^+_{N,L} \), reflectance coefficient \( \rho_{R,L} \) and transmittance coefficient \( \tau_{T,L} \) by a single groove, respectively. The vertical blue-dashed lines in (a) and (b) indicate the incidence zero phase at the top opening’s center of the rightmost groove.

the SPP reflectance coefficient, \( \rho_{gL} = A_1/(u_{gL}A_0) \), one sets \( \beta^+_{1,L} = 0 \).

The model may also be expressed in a recursive form (see Appendix A for details), as shown in Fig. 3(b)

\[
\beta^-_{N,L} = \frac{w_{gL}^{1-N} \beta^-_{1,L}}{1 - \rho_{1,L} \beta^-_{N-1,L} u_{gL}^{1-N} \beta^+_{1,L}},
\]

\[
\beta^+_{N,L} = \beta^+_{N-1,L} + \tau_{N,L} u_{gL}^{-N} \beta^+_{1,L} + \rho_{1,L} u_{gL} \beta^-_{N-1,L} \frac{w_{gL}^{1-N} \beta^+_{1,L}}{1 - \rho_{1,L} \beta^-_{N-1,L} u_{gL}^{1-N} \beta^+_{1,L}}.
\]

After the recursion, one obtains \( \beta^+_{N,L} = \beta^+_{1,L} \) and \( \rho_{gL} = \rho_{N,L} \).

Specially, for normal incidence, \( w_{gL} = 1 \), and

\[
\beta_{N,L} = \beta_{N-1,L} + \tau_{N,L} u_{gL} \frac{\beta^+_{1,L} + \rho_{1,L} \beta^-_{N-1,L}}{1 - \rho_{1,L} \rho_{N-1,L} u_{gL}^{2-N} \beta^+_{1,L}}.
\]

For fully periodic grooves (\( N = \infty \)) or large enough \( N \), one has \( \rho_{1,L} \rho_{N-1,L} u_{gL}^{2-N} \beta^+_{1,L} \ll 1 \), \( \beta^+_{N,L} \approx w_{gL}^{-N} \beta^+_{1,L} \) and \( \rho_{N,L} \approx \rho_{N-1,L} \). From (8), we obtain the generalized grating equation and Bragg equation expressed as

\[
\arg(\tau_{1,L}) + k_0 \text{Re}(n_{eff}) p \pm k_0 n_0 \sin \theta = 2 m_0 \pi \quad (10a)
\]

\[
\arg(\tau_{1,L}) + k_0 \text{Re}(n_{eff}) p = m_0 \pi \quad (10b)
\]

where ‘+’ and ‘−’ correspond to the excitations of the left- and right-going SPP modes, respectively. Compared with the conventional grating equation and Bragg equation, the ‘generalized’ ones with an additional term \( \arg(\tau_{1,L}) \) are versatile for a general grating composed of periodic defects, where the defect may be of various geometries and refractive index profiles, as their influences have been embodied via \( \arg(\tau_{1,L}) \). This additional term is quite important for dielectric [14], [16] or metal-dielectric composite [17] surface gratings since \( \arg(\tau_{1,L}) \) may be relatively large in these cases. However, for grooves usually used because of manufacturing convenience, \( \arg(\tau_{1,L}) \) is negligible. In other words, it is suitable to use the conventional grating equation and Bragg equation for periodic grooves for the sake of simplicity. In this paper, we restrict ourselves to periodic grooves.

By combining (3) for oblique incidence/beaming or (4) for normal incidence/beaming with (8), two theoretical models are nested elegantly, resulting in a systematical semi-analytical theory on the whole structure. Note that one may expect a whole set of linear equations based on the elementary-event scattering coefficients of a slit and a single groove, i.e., \( \beta^+_{gL}, \rho_{gL}, \beta^-_{gL}, \rho_{R,L} \) and \( \rho_{R,R} \) in (2) are replaced by linear equations similar to (7). In this case, however, the linear equations are so complex that it is difficult to obtain a closed-form expression for \( D^2 \) (and \( F^2, \eta \)) and to provide intuitive physical pictures. This is the reason why we express the systematical theory in form of two nested models.

III. FIGURES OF MERIT

The systematical theory incorporates the dominant structural parameters. Based on the model, in this section we propose FoMs that lead to global optimization and a standard recipe, which will be introduced in the next section.

Comparing (3) and (4), we notice they share the same denominator, i.e., \( 1 - r_{tp} r_{bt} v^2 \). Neglecting the propagation loss of the slit fundamental mode, \( |1 - r_{tp} r_{bt} v^2| \leq 1/(1 - |r_{tp} r_{bt} v^2|) \) with equality holds when

\[
2 k_0 \Re(n_{eff}) t_m + \arg(r_{tp}) + \arg(r_{bt}) = 2 m_1 \pi \quad (11)
\]

where ‘Re’ and ‘arg’ mean the real part and the argument of a complex number, respectively, and \( m_1 \) is an integer. Equation (11) attributes to the vertical F-P resonance effect in the cavity formed by the slit’s top and bottom openings. As this is well known and widely used to determine the optimized slit parameters [38], [39], we will spare space for groove parameters and the slit-groove distances. With (11), given the slit width \( w_o \) and material \( n_s \), one obtains the optimal thickness of the metal film \( t_m \) simply by calculating \( n_{eff}^* \), \( r_{tp} \), and \( r_{bt} \), which are determined by \( w_o \) and \( n_s \).
Let us focus on the numerators of $D$ in (3) and (4). For normal incidence/beaming
\[
|t_1 + \frac{2\alpha_1 u \beta_k}{1 - (r_\tau + \rho_\tau) \rho_k u^2}|^2 
\approx |t_1|^2 + \frac{4 \alpha_1 \beta_k \cos \Psi'}{1 - (r_\tau + \rho_\tau) \rho_k u^2} + \frac{4 \alpha_1 |\beta_k| \cos \Psi'}{1 - (r_\tau + \rho_\tau) \rho_k u^2} 
\leq |t_1|^2 + \frac{4 \alpha_1 \beta_k \rho_k}{1 - (r_\tau + \rho_\tau) \rho_k} 
\leq \left|\beta_k\right|^2 \left[1 - (r_\tau + \rho_\tau) \rho_k\right] 
\tag{12a}
\]
where $\Psi' = \arg(\alpha_1 \beta_k / t_1) + k_0 \text{Re}(n_{xy}) d$. The approximation in (12b) is performed by neglecting the propagation loss of SPP mode. Equality in (12c) holds if and only if the SPP propagation loss is neglected and there is horizontal F-P resonance effect due to the SPP modes’ multiple reflections by the surrounding gratings
\[
2k_0 \text{Re}(n_{xy}) d + \arg(\tau_\rho + \rho_\tau) + \arg(\rho_k) = 2m_2 \pi. 
\tag{13}
\]
Equality in (12d) holds when the slit fundamental modes excited by the incident light and by the groove-generated SPPs interfere constructively
\[
k_0 \text{Re}(n_{xy}) d + \arg(\alpha_1 / t_1) + \arg(\beta_k) = 2m_5 \pi. 
\tag{14}
\]
Because the interference effect dominates when $2|\alpha_1| / \beta_k$ is comparable to or smaller than $|t_1|$, it prevails in most of previous works [24]-[28] and only a few works addressed the horizontal F-P resonance effect [4], [32]. As a result, it was natural to consider only the interference effect and determine the optimal aperture-groove distance according to (14). However, as $N$ increases, $2|\alpha_1| / \beta_k$ becomes several times of $|t_1|$, and the contribution of the horizontal F-P resonance effect becomes preponderant. Bear these in mind, we make sure that (13) for the horizontal F-P resonance is always satisfied, and define a FoM from (12) by substituting (13) into $\Psi'$. The FoM is defined as
\[
\text{FoM}_{\text{norm}} = \frac{\beta_k \cos \Psi'}{1 - (r_\tau + \rho_\tau) \rho_k} 
\tag{15}
\]
where $\Psi' = \arg(\alpha_1 \beta_k / t_1) - 1/2 \arg[(\tau_\rho + \rho_\tau) \rho_k]$. We emphasize that (15) embodies the interlinks among the slit parameters (via $\alpha_1 / t_1$ and $\tau_\rho + \rho_\tau$), the groove parameters (via $\beta_k$ and $\rho_k$), and the slit-groove distance (determined by (13) according to the basic assumption). As a result, it is convenient to achieve global optimization via FoM$_{\text{norm}}$, with only a few parameters.

For oblique incidence/beaming, the numerator in (3)
\[
|t_1 + \alpha_1 \left(1 + \rho_\text{gR} u \beta_k \right) / \beta_{\text{gL}} + \left(1 + \rho_\text{gR} \beta_{\text{gR}} \right) u \beta_{\text{gL}} + \left(1 + \rho_\text{gL} \beta_{\text{gR}} \right) u \beta_{\text{gL}}| 
\leq t_1 + |\alpha_1 (1 + \arg(\rho_\text{gR})/2)| \beta_{\text{gL}} + \left(1 + \rho_\text{gL} \right) \beta_{\text{gR}}. 
\tag{16a}
\]
This evokes multiple interference among the slit modes excited by the incidence, by groove-generated SPPs and by their first-order reflection by grooves on the other side. Because $|\rho_{\text{gL}}|$ and $|\rho_{\text{gR}}|$ are relatively small since $\beta_{\text{gL}}^+$ and $\beta_{\text{gR}}^-$ are usually optimized or quasi-optimized, the interference between the slit modes excited by the incidence and by groove-generated SPPs dominates. As a result, we make sure the constructive interference satisfies, i.e., $|t_1 + \alpha_1 (u_{\text{gR}} / u_{\text{gL}}) \beta_{\text{gL}} + u_{\text{gR}} \rho_{\text{gR}} \beta_{\text{gR}}| 
\leq |t_1| + |\alpha_1 (|\beta_{\text{gL}}^+| + |\beta_{\text{gR}}^-|)|$, where equality holds when
\[
k_0 |\text{Re}(n_{xy}) / \sin \theta| d_1 + \arg(\alpha_1 / t_1) + \arg(\beta_{\text{gL}}^+) = 2m_4 \pi 
\tag{17a}
k_0 |\text{Re}(n_{xy}) / \sin \theta| d_1 + \arg(\alpha_1 / t_1) + \arg(\beta_{\text{gR}}^-) = 2m_5 \pi. 
\tag{17b}
\]
As $N$ increases, $|\alpha_1 (|\beta_{\text{gL}}^+| + |\beta_{\text{gR}}^-|)|$ becomes larger than $|t_1|$, and the contribution of the first-order reflection of SPPs by grooves on the other side increases and should not be omitted. From equality in (16b), which is achievable when parameters are properly designed, we define a FoM for the structure designed for oblique incidence/beaming as
\[
\text{FoM}_{\text{obI}} = (1 + \rho_\text{gR}) |\beta_{\text{gL}}^+| + (1 + \rho_\text{gL}) |\beta_{\text{gR}}^-| 
\tag{18}
\]
It is clear that two gratings on both sides are interlinked, resulting in a complex optimization. Taking into account the fact that $\beta_{\text{gL}}^+$ and $|\beta_{\text{gR}}^-|$ are comparable, we redefine the FoM as
\[
\text{FoM}_{\text{obI}} = \text{FoM}_{\text{gL}} + \text{FoM}_{\text{gR}} 
\tag{19a}
= (1 + \rho_\text{gL}) |\beta_{\text{gL}}^+| + (1 + \rho_\text{gR}) |\beta_{\text{gR}}^-|. 
\tag{19b}
\]
In such a way, there are two independent FoMs for gratings on each side, $\text{FoM}_{\text{gL}}$ and $\text{FoM}_{\text{gR}}$, greatly facilitating the optimization procedure. After the gratings are optimized, the optimal or quasi-optimal slit-groove distances $d_1$ and $d_4$ are then determined by (17).

### IV. Computational Validations

In this section, we shortly validate the nested theoretical models (referred to as ‘model A+B’ for clarity) with $\rho_{\text{gL}}$ and $\rho_{\text{gR}}$ of the groove array calculated by the nested model (referred to as ‘model B’), by comparing with the sole global model using $\beta_{\text{gL}}^+$, $\beta_{\text{gR}}^-$ and $\rho_{\text{gL}, \text{gR}}$ calculated by simulations (referred to as ‘model A’), as done in our previous works [32], [33], and the fully vectorial a-FMM and FEM computations. The effectiveness of FoMs with $\beta_{\text{gL}}^+$, $\beta_{\text{gR}}^-$ and $\rho_{\text{gL}, \text{gR}}$ calculated by simulations (referred to as ‘model A’), as done in our previous works [32], [33], and the fully vectorial a-FMM and FEM computations. The effectiveness of FoMs with $\beta_{\text{gL}}^+$, $\beta_{\text{gR}}^-$ and $\rho_{\text{gL}, \text{gR}}$ calculated by simulations (referred to as ‘model A’), as done in our previous works [32], [33], and the fully vectorial a-FMM and FEM computations. The effectiveness of FoMs with $\beta_{\text{gL}}^+$, $\beta_{\text{gR}}^-$ and $\rho_{\text{gL}, \text{gR}}$ calculated by simulations (referred to as ‘model A’), as done in our previous works [32], [33], and the fully vectorial a-FMM and FEM computations.
of an out-going plane wave by the same structures with the SPP mode incidence (Figs. 2(b) and (e)).

Throughout the paper, we assume that the incident/beaming plane wave is normalized such that its power flow over the slit aperture is unitary, and the SPP mode is normalized such that its power flow along the x direction is also unitary. The analysis will be performed with gold at 528 nm (43), and 470 nm and 495 nm according to (11).

A. Normal Incidence/Beaming

For normal incidence/beaming ($\theta = 0^\circ$), we first compare $|F|^2$ calculated by ‘model A’, by ‘model A+B’ and by the a-FMM approach combined with the reciprocity theorem, and $\eta$ calculated by FEM. As shown in Fig. 4, theoretical predictions on $|F|^2$ and especially on the optimal $d$ by ‘model A’ and by ‘model A+B’ agree well with a-FMM and FEM calculations, and $\eta \propto |F|^2$. Compared with Fig. 2(a) in [32], where most parameters are the same except $n_{\text{tot}} = 1.46$, $n_s = 1.0$, $w_s = 50$ nm and $t_{\text{m}} \approx 178$ nm according to (11).

Fig. 5 compares the a-FMM computational data and ‘model B’ predictions (b), (d) on $|F|^2$ (a), (c) and FoM$_{\text{norm}}$ (c), (d) as functions of the groove duty cycle and depth. The blue circles stand for the optimized groove sizes: $(w_{g}/p, h) = (0.56, 66)$ nm (a), (0.57, 64) nm (b), (0.61, 70) nm (c), (0.63, 72) nm (d). The calculations are performed with $p = 786$ nm, $N = 11$.

B. Oblique Incidence/Beaming

The model validation on $|\beta|^2$ and $\eta$ of the groove array is exemplified with $\theta = 20^\circ$, $N = 10$, and $\beta^{2+}_{g}$ and FoM$_{\text{norm}}$ of the groove array is determined according to the conventional grating equation. Comparisons of the ‘model B’ predictions and the a-FMM computational data, as illustrated in Fig. 7, reveal that the model quantitatively captures all the salient features of $|\beta|^2$ and FoM$_{\text{norm}}$, especially the optimized groove sizes.

We notice that there is also a pronounced shift on the optimized groove duty cycle for the optimal $|\beta|^2$ and for the optimal FoM$_{\text{norm}}$. This shift is introduced by the first-order reflection of grooves-generated SPPs by grooves on the other side, and is better illustrated by Fig. 8, where the optimal FoM$_{\text{norm}}$ is achieved when $|\beta|^2$ is not optimized while $|\mu|$ is relatively
Fig. 7. Comparisons of the a-FMM computational data (a), (c) and ‘model B’ predictions (b), (d) on $|S_{m}^{+}|$ (a), (b) and $\tilde{F}_{m}$ (c), (d) as functions of the groove duty cycle and depth. The blue circles indicate the optimized parameters: $u_{x}^{\text{opt}}/p = 0.38$ (a), 0.42 (b), 0.39 (c), 0.43 (d), and $h = 70$ nm for (a)–(d). The calculations are performed with $\theta = 20^\circ$, $N = 10$, and $p_{x} = 1185$ nm.

Fig. 8. Comparisons of $F_{m}$, $|S_{m}^{+}|$, and $|S_{m}^{-}|$ (circles) and $|F_{m}|$ (lines) calculated by a-FMM using the reciprocal method (red dots), where $\beta_{\text{gl}}$ and $\beta_{\text{gr}}$ are calculated by a-FMM. The calculations are performed with $w_{x} = 588$ nm, $u_{x}^{\text{opt}}/p_{x} = 0.52$, $h_{x} = 70$ nm, and other parameters same as in Fig. 7.

Fig. 9. Comparisons of model predictions and the a-FMM computational data (a) and theoretical predictions by ‘model A’ (b) and ‘model A+B’ (c) on $|F|^{2}$ as functions of the slit-groove distances. The thick-blue circles indicate the optimized slit-groove distances, $d_{\text{opt}} = 0.79$ m, 0.98 m) (b), (0.81 m, 0.98 m) (c). The thin-white circles indicate determined by (17), where $\beta_{\text{gl}}$ and $\beta_{\text{gr}}$ are calculated by simulations ($d_{\text{opt}} = 0.94$ m if $m_{d} - m_{d}' = 2$). The calculations are performed with $p_{1} = 1180$ nm, $u_{x}^{\text{opt}}/p_{x} = 0.42$, and other parameters same as in Fig. 8.

V. STANDARD DESIGN RECIPE

With the systematical theory and the FoMs, we now introduce an efficient, standard and simple design recipe for preparing a slit-grooves structure with optimal performance for optical concentration, beaming or collimation at a given wavelength ranging from the visible to the near infrared regime. It takes four steps:

1) The slit width $w_{x}$, the material filling the slit $n_{s}$, the metal $n_{m}$, the substrate $n_{sub}$, the incidence/beaming angle $\theta$ and the operating wavelength $\lambda$ should be set first according to the specific application requirements.

2) The slit depth (or the metal film thickness) $t_{m}$ is optimized using (11) to satisfy vertical F-P resonance in the slit. This step has been widely accepted and adopted.

3) Given the groove number $N$, the groove widths and depth are then optimized using $F_{m}$ for oblique incidence/beaming or using $F_{m}$ for normal incidence/beaming, where the groove periods are determined by the conventional grating equation, $\beta_{\text{gl}}$, $\beta_{\text{gr}}$ and $\rho_{\text{gl}}$, $\rho_{\text{gr}}$ (or $\beta_{\text{gl}}$ and $\rho_{\text{gr}}$ for $\theta = 0$) are calculated theoretically using ‘model B’.

4) For oblique incidence/beaming, the optimal $d_{L}$ and $d_{R}$ are determined by (17), whereas for normal incidence/beaming, the optimal $d$ is determined by (13), where $\beta_{\text{gl}}$, $\beta_{\text{gr}}$, or $\rho_{\text{gl}}$ are calculated by simulations with the optimized groove parameters.

To illustrate the recipe, here we present an example for $\theta = 0$ by comparing with a conventional recipe adopted in [28]: step 3 is replaced by optimizing the groove width and depth for maximum $\beta_{m}$; in step 4, the optimal $d$ is determined by the constructive interference condition, i.e., (14). Table I summarizes the optimized parameters and transmission performance for different $\lambda$. First of all, we set $w_{x} = 50$ nm, $n_{s} = n_{\text{air}} = 1.0$ (air). We then obtain the optimal metal film thickness $t_{m} \approx 200$ nm according to (11), where $n_{\text{eff}} = 1.4313 + 0.0143i$, $\tau_{L} - \tau_{H} = -0.4317 - 0.4739i$. To optimize the groove width and depth using $F_{\text{norm}}$, we first calculate $\beta_{L}$, $\rho_{L}$ and $\tau_{L}$ of a single groove as functions of $w_{x}$ and $h$. The groove period is determined by the conventional grating equation, $p = 785$ nm. Given the groove number $N$, $\beta_{\text{gl}}$, $\rho_{\text{gl}}$ and $F_{\text{norm}}$ as functions of $w_{x}$ and $h$ are obtained by ‘model B’ with high efficiency and accuracy, followed by the optimized $w_{x}$ and $h$. Finally, the optimal slit-groove distance $d$ is determined by (13) using $\rho_{g}$ calculated by a-FMM. Note that $\tau_{H} + \rho_{H} \approx 0.8779 - 0.0782i$ with $\arg(\tau_{H} + \rho_{H}) \approx 0$. In other words, the optimal slit-groove distance is determined by the horizontal F-P resonance in the large.
TABLE I
Performance of the Proposed Standard Recipe, Where \( w_{\text{gl}} / \mu \), \( h \), \( \text{FoM}_{\text{norm}} \), and \( \eta \) Are Obtained Theoretically, \( \rho_c \) Is Calculated by A-FMM, and \( \eta^* \) Calculated by FEM. \( \eta^* \) Is Taken From Fig. 3 in [28]

<table>
<thead>
<tr>
<th>( N )</th>
<th>( w_{\text{gl}} / \mu (\mu \text{m}) )</th>
<th>( \text{FoM}_{\text{norm}} )</th>
<th>( \rho_c )</th>
<th>( d(\mu \text{m}) )</th>
<th>( \eta )</th>
<th>( \eta^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.62</td>
<td>100</td>
<td>5.959</td>
<td>0.422-0.092i</td>
<td>0.411</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>0.64</td>
<td>88</td>
<td>7.760</td>
<td>0.496-0.122i</td>
<td>0.413</td>
<td>45</td>
</tr>
<tr>
<td>8</td>
<td>0.64</td>
<td>82</td>
<td>9.142</td>
<td>0.513-0.141i</td>
<td>0.415</td>
<td>59</td>
</tr>
<tr>
<td>10</td>
<td>0.64</td>
<td>76</td>
<td>10.246</td>
<td>0.528-0.170i</td>
<td>0.417</td>
<td>72</td>
</tr>
<tr>
<td>12</td>
<td>0.63</td>
<td>70</td>
<td>11.200</td>
<td>0.515-0.189i</td>
<td>0.420</td>
<td>85</td>
</tr>
<tr>
<td>14</td>
<td>0.63</td>
<td>66</td>
<td>12.062</td>
<td>0.525-0.213i</td>
<td>0.422</td>
<td>96</td>
</tr>
<tr>
<td>16</td>
<td>0.62</td>
<td>62</td>
<td>12.852</td>
<td>0.504-0.218i</td>
<td>0.423</td>
<td>106</td>
</tr>
</tbody>
</table>

Fig. 10. The optimized \( \text{FoM}_{\text{norm}} \) calculated by ‘model B’ (blue line with circles) and the optimized \( \eta \) calculated by FEM (red dots) scale with the number of grooves on each side \( N^{1/2} \) (a), while the optimized groove depth scales with \( N^{-1/2} \) (consistent with [28]). As a result, \( \text{FoM}_{\text{norm}} \) may also be used to evaluate the performances of different groove numbers.

The proposed recipe is very efficient and flexible. One only needs to scan \( \beta_{\text{gl}}^\pm(\theta) \), \( \rho_c \), and \( \tau_1 \) of a single groove instead of \( \beta_{\text{gl}}^\pm, \rho_{\text{gl}}, \beta_{\text{ER}}^\pm \) and \( \rho_{\text{ER}} \) of \( N \) periodic grooves as functions of \( w_{\text{gl}} \) and \( h \). With the information of \( \beta_{\text{gl}}^\pm(\theta), \rho_c \), and \( \tau_1 \) as functions of \( w_{\text{gl}} \) and \( h \), \( \beta_{\text{gl}}^\pm, \rho_{\text{gl}}, \beta_{\text{ER}}^\pm \), and \( \rho_{\text{ER}} \) for various groove numbers or periods are obtained with negligible computational cost using ‘model B’. In other words, the computational cost of simulation scan is greatly reduced. This cost reduction is especially remarkable when one needs to increase \( N \) to improve the performance, or when metallic, dielectric or metal-dielectric surface gratings are used, in that case the grating periods should also be scanned around the value determined by the conventional grating equation.

We emphasize that the proposed recipe provides clear physical picture and has great generality. It is capable to treat various structure configurations with surface gratings made of various shapes of grooves or dielectric ridges, with normal or oblique incidence/beamng. Furthermore, it provides a routine design procedure without relying on empirical experiences, making it a normalized recipe and easy to follow. We suggest it as a standard recipe for the design and optimization of the subwavelength aperture surrounded by surface corrugations.

VI. CONCLUDING REMARKS
Although we focused on 2D slit-grooves structure, the systematical coupled-mode theory, the FoMs, and the standard recipe are also applicable to 3D bull’s-eye structure by making some modifications. This is because there is no transmission mode in the subwavelength hole aperture. In this case, the EM field inside the hole should be expanded with a set of waveguide modes, and the related coefficients such as \( t_1, t_2, \rho_\text{ss}, \tau_\text{ss}, \alpha_1, \alpha_2, \tau_\text{sp} \), and \( \tau_\text{pl} \) should be replaced by a set of corresponding coefficients accordingly [4], [44]. As the optimal aperture-groove distance under normal incidence is determined by the grooves’ reflectance coefficient as if there is no slit or hole, it holds for 2D slit-grooves, 3D hole-grooves, and 3D bull’s eye patterns, as noted in [19], [24], [25], [28].

Moreover, we should emphasize that the generalized grating equation and Bragg equation are also applicable for normal waveguide modes (simply by replacing \( n_{\text{sp}} \) with \( n_{\text{eff}} \)). A typical application is in the free-space excitation or the reflection [45] of a dielectric waveguide mode by high-index-contrast gratings, the additional term \( \text{arg}(\tau_1) \) should not be omitted.

In conclusion, we have developed a systematical theory in form of two nested ‘pure’ SPP coupled-mode models for the widely-used plasmonic structure composed of a subwavelength aperture surrounded by surface corrugations. Based on the theory incorporating interlinks among key parameters with clear physical pictures, FoMs of the structures designed for normal and for oblique incidence/beamng have been proposed for the first time, making global optimization simple and efficient. Exhaustive calculations have shown that the theory and the FoMs are highly accurate on performance prediction and structural optimization. A standard recipe making full use of the theory and the FoMs has been introduced to facilitate the structure design and optimization with great flexibility and computational cost reduction.

APPENDIX A
SPP SCATTERING COEFFICIENTS IN RECURSIVE FORM

The model on SPP scattering coefficients \( \beta_{\text{N,L}}^\pm \) and \( \rho_{\text{N,L}} \) expressed in a recursive form is illustrated by Fig. 3(b). The coupled-mode equations lead to

\[
\begin{align*}
H_1 &= w_{\text{gl}}^{1-N} \beta_{1,L}^- + \tau_{1,L} u_{\text{gl}} B_2 + \rho_{1,L} u_{\text{gl}} A_0 \\
A_1 &= w_{\text{gl}}^{1-N} \beta_{1,L}^+ + \rho_{1,L} u_{\text{gl}} B_2 + \tau_{1,L} u_{\text{gl}} A_0 \\
B_2 &= \beta_{N-1,L}^- + \rho_{N-1,L} u_{\text{gl}} A_1 \\
A_N &= \beta_{N-1,L}^+ + \tau_{N-1,L} u_{\text{gl}} A_1.
\end{align*}
\]

To calculate the SPP excitation coefficients, \( \beta_{N,L}^- = A_N \), \( \beta_{N,L}^+ = B_1 \), one sets \( A_0 = 0 \); whereas to calculate the SPP reflectance and transmittance coefficients, \( \rho_{N,L} = A_1 / (u_{\text{gl}} A_0) \) and \( \tau_{N,L} = B_2 / (u_{\text{gl}} A_0) \), one sets \( \beta_{1,L}^- = 0 \). Note that when calculating \( \beta_{N-1,L}^- \) and \( \beta_{N-1,L}^+ \), the zero phases of the incident plane wave are all set to be at the center of the rightmost groove’s top opening.

Then the SPP excitation, reflectance and transmittance coefficients are expressed recursively as

\[
\begin{align*}
\beta_{N,L}^- &= w_{\text{gl}}^{1-N} \beta_{1,L}^- \\
&+ \tau_{1,L} u_{\text{gl}} \frac{\beta_{N-1,L}^- + \rho_{N-1,L} u_{\text{gl}} w_{\text{gl}}^{1-N} \beta_{1,L}^+}{1 - \rho_{1,L} \rho_{N-1,L} u_{\text{gl}} w_{\text{gl}}^{1-N}}.
\end{align*}
\]
\[ \beta_{N,L}^+ = \beta_{N-1,L}^+ + \tau_{N-1,L} u_{gL}^{1-N} \beta_{N-1,L}^+ + \rho_{N-1,L} u_{gL} \beta_{N-1,L}^+ \]
\[ \beta_{N,L}^- = \beta_{N-1,L}^- + \tau_{N-1,L} u_{gL}^{1-N} \beta_{N-1,L}^- + \rho_{N-1,L} u_{gL} \beta_{N-1,L}^- \]
\[ \rho_{N,L} = \rho_{1,L} + \rho_{N-1,L} \]
\[ \tau_{N,L} = \tau_{1,L} u_{gL}^{N-1} \rho_{N-1,L} \]

Equations (21a) and (21c) are then reduced into

\[ \beta_{N,L} = \beta_{N-1,L} + \tau_{N-1,L} u_{gL}^{1-N} \beta_{N-1,L} + \rho_{N-1,L} u_{gL} \beta_{N-1,L} \]

(22)

which agrees with our previous results [35].

For fully periodic grooves (\( N = \infty \)) or \( N \) is large enough, one has \( |\rho_{1,L} u_{gL}^{1-N} \beta_{N-1,L}| \ll 1, \beta_{N,L} \approx u_{gL}^{1-N} \beta_{N-1,L} \) and \( \rho_{N,L} \approx \rho_{N-1,L} \). Equations (21a) and (21c) are then reduced into

\[ \beta_{N,L} = \beta_{N-1,L} + \tau_{N-1,L} u_{gL}^{1-N} \beta_{N-1,L} + \rho_{N-1,L} u_{gL} \beta_{N-1,L} \]

(23a)

\[ \rho_{N,L} \approx \rho_{1,L} \]

(23b)

respectively. From (23a), it is easy to obtain the condition for the constructive interference of left-going SPP modes excited by the groove array:

\[ \arg(\tau_{1,L}) + k_0 \text{Re}(n_p) p + k_0 n_0 p \sin \theta = 2m_0 \pi \]  

(24)

Similarly, the condition for the constructive interference of right-going SPP modes are also obtained. We refer to these conditions as the generalized grating equation:

\[ \arg(\tau_{1,L}) + k_0 \text{Re}(n_p) p \pm k_0 n_0 p \sin \theta = 2m_0 \pi \]

(25)

where ‘+’ and ‘-’ correspond to the excitations of the left- and right-going SPP modes, respectively.

From (23b), the generalized Bragg equation

\[ \arg(\tau_{1,L}) + k_0 \text{Re}(n_p) p - m_0 \pi \]

(26)

has been introduced and validated in [34].

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REFERENCES


Author biographies not included at author request due to space constraints.