

Out of plane mode conversion and manipulation of Surface Plasmon Polariton Waves

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Abstract: We propose a rigorous design method of structured gratings for out of plane mode conversion, line focusing and manipulation of Surface Plasmon Polariton (SPP) waves. Employing a blazed grating to incorporate the directionality of SPP launch, and at the same time controlling grating depth and chirp to account for the radiation loss and diffraction angle, it was possible to achieve high efficiency and flexible SPP to freespace mode conversion. Devices with advanced functionalities, such as balanced SPP power splitter, and SPP wavelength demultiplexer are demonstrated with over 75% of power efficiencies at reasonable working distances of less than several wavelengths.

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References and links

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1. Introduction

Surface Plasmon Polariton (SPP), understood as electromagnetic waves formed by charge oscillations at the surface of a metal, have found serious interest among a wide cross section of scientists including physicists, chemists and biologists. From an engineering viewpoint, SPPs are considered as promising candidates to solve the current bottlenecks observed in

nanophotonic systems. Exploiting the fundamental SPP advantages such as confinement within subwavelength structures [1], it now becomes possible to construct nanoscale photonic structures which were impossible with traditional index guiding waveguides.

Coupling or converting of free-space or waveguide modes to SPP modes with high efficiency has thus been considered as one of the critical issues, as evidenced by a series of publications [2–4]. Serious efforts have been made for the focusing of SPP as well, in order to achieve enhanced field intensity at the focal point or to couple to other types of waveguides, utilizing metal-surface engineering or chirped dielectric grating at the exit of plasmonic waveguides [5,6] or through plasmonic nanoantennas [7]. Reports such as [8] which use SPPs in metallic nanoslits with variant widths, to focus light have also appeared. Still, noting that most of the demonstrations for SPP to waveguide mode conversion have been made with both the modes remaining in the same plane (direction of propagation), a highly efficient and compact device architecture enabling *off-plane* conversion between SPP and free-space or waveguide modes (or vice versa), enabling futuristic *multi-layered* plasmonic and/or hybrid nanophotonic circuit applications requires deeper attention. It may be noted that a multilayered nanophotonic circuit would have more or less, the same advantages as that a multilayered Printed Circuit Board would have over a single layered one, in addition to the footprint advantage.

In this paper, we propose a simple yet flexible and highly efficient structure for conversion and manipulation of SPP modes into *out of plane* modes of various forms. Out of plane focusing at focal lengths of few wavelengths, and power splitting & wavelength demultiplexing of SPP modes using the same fundamental principle is demonstrated. Design strategy will be detailed for various functional devices, with numerical confirmation through Finite Element Method (FEM) and Finite Difference Time Domain (FDTD) analysis.

2. Theory and design methodology

Excitation of SPP modes on a metal-dielectric interface, by illuminating a plane wave on a properly designed grating structure carved on the metal surface has been well addressed in the past [4]. The basic idea behind the coupling between these waves lies in the momentum conservation relation, as given below [Fig. 1(a)]

$$k_{SPP} = k_o \sin \theta + 2\pi m / \Lambda \quad m = \pm 1, 2, 3, \dots \quad (1)$$

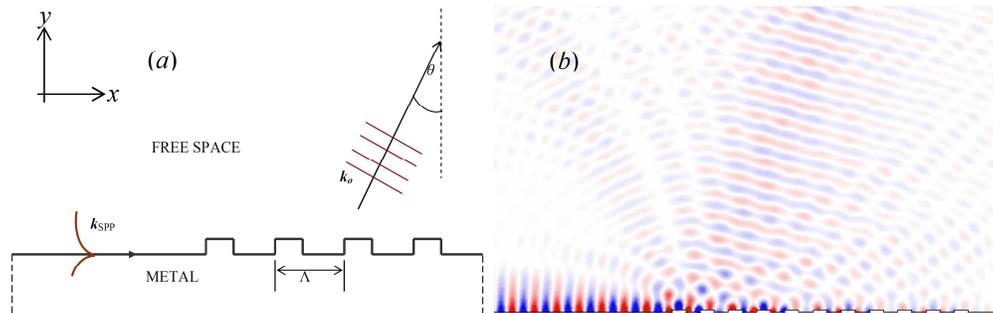


Fig. 1. (a) Schematic of SPP mode radiation into free space plane wave and (b) simulation results for magnetic field H_z in a grating to diffract at 12 degrees ($\Lambda = 1.24\lambda$); Material = gold, and operating wavelength $\lambda = 800\text{nm}$

where, k_o is the free space momentum, Λ the period of an infinite grating, θ the angle defined by propagation direction of the radiated plane wave with respect to the normal to the grating surface, m the diffraction order, and k_{SPP} the momentum of the SPP mode. Based on Eq. (1), the simplistic approach one could take is to use the same metallic grating structure, reciprocally, both for conversion from SPP modes to free space plane waves and vice versa [9]. Improved result also can be expected by reciprocally employing the asymmetrical SPP

excitation structure built upon blazed gratings [3,4]. Though this reciprocity approach could be handy in the design and implementation of a simple device for conversion between SPP and plane wave, considering the associated properties of the medium, such as metallic and radiation loss in the grating, direction of k_{SPP} vector, and finally the SPP scattering at waveguide-grating interface, a different and more systematic approach is essential to realize advanced devices with higher functionalities.

Before embarking on devices with advanced functionalities, we start with a simple example where a detector (or waveguide) is placed at a distance of F , *out of plane* [vertically above], from the SPP waveguide. Direct application of Eq. (1), with the structure optimized for planewave-to-SPP conversion [9] (Fig. 1]) would obviously fail, due to; (1) impedance mismatch between SPP waveguide and grating structure, (2) metallic and radiation loss breaking the reciprocity, and (3) x -symmetric grating for the x -asymmetric launch of SPP wave.

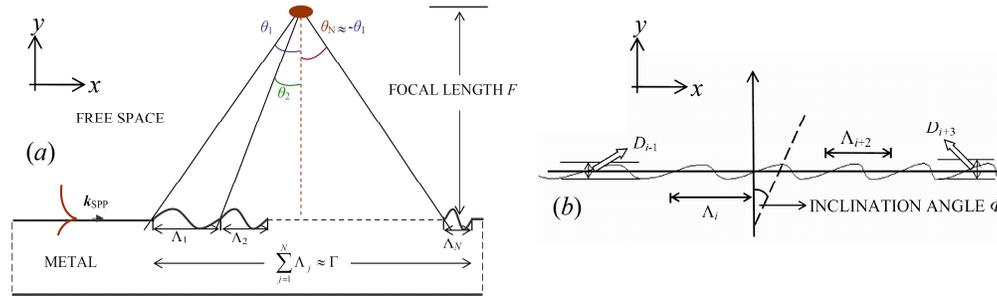


Fig. 2. Illustration of (a) SPP coupling to small size detector or waveguide, (b) a chirped, blazed and adiabatically depth increasing grating structure

As can be seen from Fig. 1(b), with the spurious harmonics introduced by the non-blazed, lamellar grating structure, and the lack of penetration of SPP field into the grating, there exists strong scattering of the SPP wave at the entrance of the grating leading to failure to fully couple to a plane wave. To enable a much higher coupling efficiency of SPP wave into a small size detector or a dielectric waveguide [Fig. 2(a)] without heavy back reflection, we first conduct a theoretical treatment of generalized, non-linearly chirped grating structures. Worth to note, in the following we employ a sinusoidal grating to suppress higher order diffraction ($m > 1$) coupling into unwanted spurious modes [3], and also use a blazed grating geometry (construction methods detailed in [3,4]) to break the symmetry in grating structure and thus possibly assist better asymmetrical coupling of SPP wave into free space modes.

Figure 2 shows the schematics of our suggested grating profile, for out of plane manipulation and focusing of the SPP launched from the left. With the focal line fixed at a distance of F from the grating surface, let the angle defined by the plane wave radiated into free space by the first grating element be θ_1 . Now with these two parameters fixed, the physical length Γ of the grating structure could be estimated as $\Gamma = 2F \tan \theta_1$. Next, using Eq. (1), and as diffraction order $m = 1$ is most dominant, we first determine the length Λ_1 of the *first* grating element,

$$\Lambda_1 = 2\pi(k_{SPP} - k_o \sin \theta_1)^{-1} \quad (2)$$

Having identified the length of the first grating element, the angle θ_2 can be readily identified [Fig. 2(a)] and hence the length Λ_2 of the second grating element in the grating structure. Continuing this approach, a set of iterative equations as given below could be easily derived to obtain the preliminary design of a vertically focusing grating structure

$$\theta_i = \tan^{-1}(((\Gamma/2) - \sum_{j=1}^{i-1} \Lambda_j) / F) \quad (3.a)$$

$$\Lambda_i = 2\pi(k_{SPP} - k_o \sin \theta_i)^{-1} \quad (3.b)$$

The iterations are for $i > 1$ and stop at $i = N$ such that θ_N is approximately equal to $-\theta_1$, whereby $\sum \Lambda_j \approx \Gamma$. It can be visualized that the resulting grating structure will be that of a desired one, focusing the radiated SPP at F . For achieving even higher focusing efficiency, the grating structure obtained through Eq. (3) above needs further optimization.

Firstly, an inclination angle to the grating could be introduced [3] to account for the directionality of the launched SPP wave [4]. Secondly, the depth of the individual grating elements need to be adiabatically adjusted for the following critical reasons: 1) to provide better matching of the impedance for waveguide-grating transition point and thus to ensure minimal back reflections of the field, and 2) to provide equal distribution of radiated power density from the grating elements for ideal free-space focusing.

To identify the optimal profile for the grating depth control, we note that most of the SPP power depletion from the grating will be due to the free-space coupled radiation loss from individual grating elements. Further, as the radiated power *density* within the angle $(\theta_i - \theta_{i-1})$ from these *chirped*, individual grating elements will be non-linear [Eq. (3.b), now, in order to achieve uniform power density entering into the focal point, we use in good approximation [10], an exponentially increasing depth for the grating, $D_i = A \exp(\rho(i-1)/(N-1))$ where $i = 1, 2, \dots, N$ identify the individual elements in the grating. Here, A stands for the depth (amplitude) of the first grating element while ρ being the exponential rate of increase in the grating depth.

Thus, our final grating structure can be expressed as a series of N sinusoidal functions on a blazed geometry, *each* of which can be expressed as $G_i(x)$ in Eq. (4) below.

$$G_i(x) = D_i \sin \left(\frac{2\pi}{\Lambda_i} \left(x - \sum_{j=1}^{i-1} \Lambda_j \right) \right), \quad \sum_{j=1}^i \Lambda_j > x > \sum_{j=1}^{i-1} \Lambda_j \quad (4)$$

$i = 1, 2, \dots, N$ with $D_i < D_{i+1}$, $\Lambda_i > \Lambda_{i+1}$, and the inclination angle Φ taken into account through the coordinate transform $x' = x + G_i(x) \tan(\Phi)$. The new profile is now given by $G_i(x')$. Figure 2(b) shows an example of a designed grating structure.

3. Results

Finite element method using COMSOL (FEMLAB) has been used to analyze and optimize the suggested grating structure. Figure 3(a) shows the H_z field distribution for $F = 7\lambda$ at an operating wavelength of 800nm. The TM-polarized SPP was launched from a mode source located at the left end (not seen) of the simulation space. The structure was assumed to be made of gold and the permittivity was calculated from the Drude model for near-infrared [11]. The initial angle θ_1 [Fig. 2(a)] was chosen as 45° . The optimum inclination angle for the blazing, and the grating depth parameters were found to be about 35° [Φ , Fig. 3(c)], and $(A, \rho) = (0.08\lambda, 0.5)$. To note, too large (small) A or ρ will result in increased (decreased) scattering at the front section of grating element; inhibiting the equal distribution in radiated power density and thus reducing the focusing efficiency, symmetry and line spot shapes in the vertical coupling.

The high-efficiency focusing from the optimized grating structure is evident from Fig. 3(a) (H_z) and Fig. 3(b) (magnitude of y Poynting vector). Defining the focusing efficiency as the ratio between the power at the focal line (detector size $\sim 3\lambda$) and the launched SPP power *entering* the grating structure (for a straight, infinite metal-air SPP waveguide), a highly efficient focusing up to $\sim 80\%$ is obtained. Figure 3(d) shows a plot of focusing efficiency optimized (in A , ρ , and Φ) for each focal line, F ranging from 4 to 13λ . As can be seen from this figure, focusing efficiencies well over 75% could be obtained for a range of values of F above $\sim 6\lambda$.

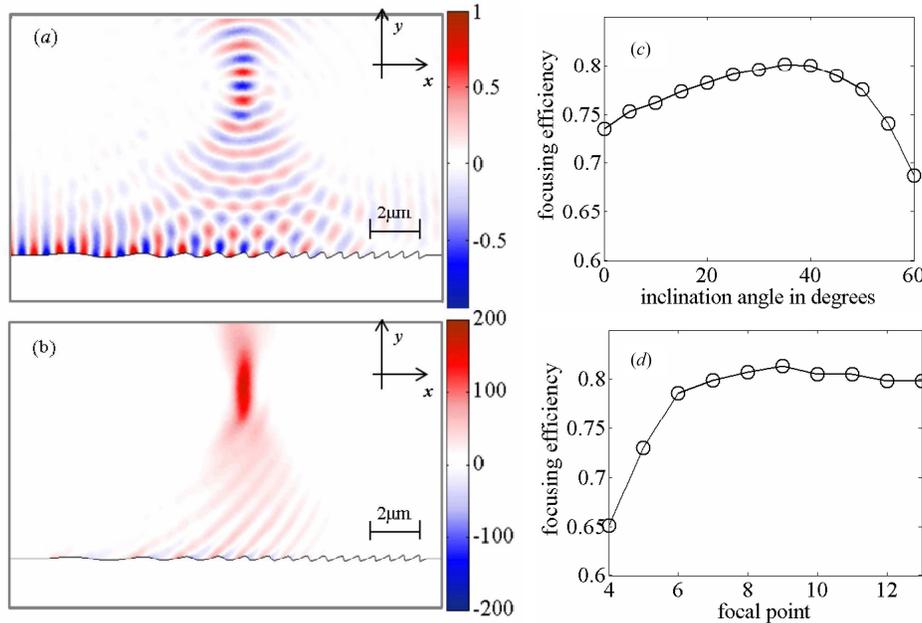


Fig. 3. Simulation results for out-of plane focusing grating. H_z shown in (a), y directed Poynting vector magnitude in (b), efficiency as function of inclination blazng angle in (c), and focusing efficiency as function of focal length $F(\lambda)$ in (d); Material = gold, $F = 7\lambda$ (for (a), (b) and (c)) and operating wavelength = 800nm

Utilizing this design methodology, advanced manipulation of SPP waves also becomes possible. Figure 4(a) shows a simple example of balanced SPP power splitter. At an operating wavelength of 800nm, F is chosen as 7λ with the initial angle θ_1 and inclination angle Φ set as 30° and 40° respectively. By cascading two (but not equal) grating structures in series (each designed using Eq. (3) with independent depth control. $(A, \rho) = (0.038\lambda, 0.55)$ and $(0.06\lambda, 0.6)$ respectively for the front and rear part gratings), a balanced SPP splitter with two focal points separated by 9λ and equal in power (38%, and 35%) was successfully achieved.

Another exciting application of the proposed grating structure is a compact SPP wavelength division demultiplexer. Though currently not very well conceived, the possibility of future nanophotonic circuits using wavelength division multiplexing in the form of SPP cannot be ruled out. In cases SPP modes co-propagate with more than one wavelength, the grating structure proposed here could as well act as a compact wavelength division demultiplexer. Figure 4(c) shows the FDTD analysis results of SPP modes, multiplexed with 850nm and 650nm interacting with a single grating structure optimized for nearly equal power demultiplexing at the focal line at $F \sim 12\lambda$ ($(A, \rho) = (0.08\lambda, 0.4)$, θ_1 and Φ set as 30° and 45°) separated by about 2λ . To note, here we use the FDTD instead of frequency domain FEM to demonstrate the *simultaneous* co-propagation and demultiplexing of two different SPP waves. As can be clearly seen, focusing of freespace radiated out-of plane SPP waves at two distinct, spatially separated points in free space is clearly achieved for SPP modes at different wavelengths. The focusing efficiency for the two wavelengths was found to be 82% (650nm) and 76% (850nm).

Though not explicitly demonstrated here, it can be visualized that the power splitting and demultiplexing arrangement in Fig. 4 can be further modified to guide them away to two opposite directions ($+x$ and $-x$), for example, with two separate metallic gratings accounting for directionality (blazed in opposite directions) in x plane placed up above the focal lines. It should also be quite obvious that the vertically focused beams, render themselves to be easily coupled into a conventional index guiding dielectric, or even a photonic crystal waveguide (possibly with slight adjustments depending on the intrinsic mode features of the waveguides).

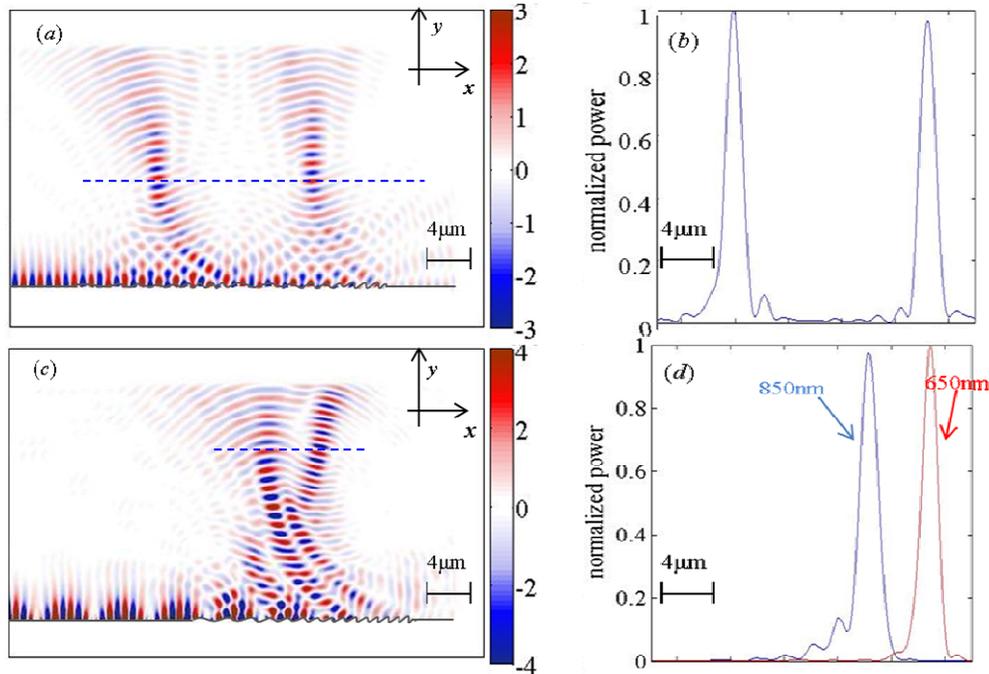


Fig. 4. Simulation results for SPP power splitter and wavelength demultiplexer: (a) H_z distribution for SPP power splitter, (b) normalized power distribution along the dotted line in (a), (c) H_z distribution for SPP wavelength demultiplexer, and (d) normalized power distribution along the dotted line in (c): The x axis in (b) and (d) are identical to the x axis values under the dotted blue lines in (a) and (c)

Before we conclude, it is worth pointing out that there has been reports which make it possible to realize 1 D blazed gratings through a more fabrication friendly 2 D technique identified as the blazed area coded effective medium structures (BLACES) [4,12,13]. This addresses any doubts on the fabrication of the proposed structures in this paper.

4. Conclusion

At the cost of adding a little complexity to the traditional SPP grating structure/design and no additional optics, we have proposed a novel method using chirped, blazed sinusoidal gratings to realize compact devices to optimally and efficiently manipulate SPP modes and vertically convert them to various forms of free space or waveguide modes at a distance of a few wavelengths. A simple set of equations to assist the preliminary design of such chirped grating structures are also derived. Other than vertical focusing, a few other interesting applications of the proposed grating structure, such as the balanced SPP power splitter and wavelength demultiplexer, are provided. We believe that our method provides useful and practical solutions to important questions related to manipulation and conversion of SPP fields into other forms of radiation while remaining within the nanophotonic regime.

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