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Controlling the direction of propagation of surface plasmons via graded index effective dielectric media

V. Pacheco-Peña [1], **M. Beruete** [2-3]

[1] School of Engineering, Newcastle University, Merz Court, Newcastle Upon Tyne NE17RU, United Kingdom
[2] Antennas Group-TERALAB, Universidad Pública de Navarra, Campus de Arrosadía, 31006 Pamplona, Spain
[3] Institute of Smart Cities (ISC), Public University of Navarra, 31006 Pamplona, Spain
victor.pacheco-pena@newcastle.ac.uk, miguel.beruete@unavarra.es

Abstract – **In this work, we propose a mechanism to steer and tailor surface plasmon propagation by using graded index concepts. In this approach, a block of dielectric with fixed thickness is placed on top of a semi-infinite metal. The beam steerers are then designed by simply changing the height of the dielectric in the direction perpendicular to the propagation axis. The analytical design is presented and several structures are evaluated with the ability to steer the incoming surface plasmons at any desired output angle.**

I. INTRODUCTION

Surface plasmons (SPs) are surface waves which propagate along the interface between a dielectric and a conductor. They are evanescently confined in the direction perpendicular to the propagation axis [1], [2]. Their excitation is directly related to the dispersive permittivity of metals at nanometer scaled wavelengths (optical regime). SPs have been extensively studied because of the great opportunities they open in different fields such as sensors, waveguides and focusing devices [3]–[5], nanoantennas [6], [7], plasmonic nanoparticles for solar cells [8] and nanolithography [9], to name a few. Within this context, an interesting research field is to deflect and change the direction of propagation of SPs at will [10].

Inspired by the unlimited opportunities offered by SPs and the need to arbitrary controlling their direction of propagation, in this communication a mechanism to steer SPs by applying the graded index (GRIN) technique is studied [11], [12]. In the proposed method, a dielectric block (Si_3N_4) is placed on top of a semi-infinite gold (Au) substrate. The design of the GRIN-SP steerers is based on the effective refractive index (n_{eff}) produced in the region where the dielectric is present (air-Si_3N_4-Au). As it will be shown, the n_{eff} can be tuned by simply changing the height of the dielectric (along the direction perpendicular to the propagation axis). Several designs are presented for different output angles and their performance is compared with common prisms made by changing the profile of the dielectric along the propagation direction [13].

II. DESIGN: EFFECTIVE MEDIUM

To begin with, the schematic representation of the proposed GRIN-SP steerer is shown in Fig. 1a. It consists of a Si_3N_4 block with varying dimension l_y and fixed thickness l_z placed on top of a semi-infinite Au metal. As it is known, for the case region without the dielectric (air-Au) the effective propagation constant can be calculated $\beta_{a\_eff} = k_0[(n_0^2 n_{Au}^2)/(n_0^2+n_{Au}^2)]^{1/2}$ with k_0 as the wave number in free-space and n_0 and n_{Au} as the refractive index in vacuum and Au, respectively. For the region with the dielectric, β_{b_eff} can be calculated using the following transcendental equation [14]:

$$\tan(k_2 l_y) = -(\varepsilon_{Au}\varepsilon_2 k_2 k_1 + \varepsilon_1\varepsilon_2 k_{Au} k_2)(\varepsilon_{Au}\varepsilon_1 k_2^2 + \varepsilon_2^2 k_{Au} k_1)^{-1} \tag{1}$$

with ε_i and $k_i = (\beta_{b\_eff}^2 - \varepsilon_i k_0^2)^{1/2}$ are the permittivity in each medium and wavenumber, respectively. The subscript i = 1, 2 and Au represent the different media (air, dielectric and metal, respectively). Finally, the n_{eff} for each region (Air-Au and Air-Si_3N_4-Au) can be calculated by $n_{effa,b} = \beta_{a,b\_eff}/k_0$. The analytical results using (1) of the Re{$n_{eff,b}$} at the design wavelength of $\lambda_0 = 633$ nm as a function of the height of the dielectric (l_y) are shown in Fig. 1c. As observed Re{$n_{eff,b}$} can be changed by simply changing the dimension l_y, as expected in agreement with [4]. Now, the design of the GRIN-SP steerers can be easily done by using ray tracing [13], [15]. In this context, each position of the dielectric along the x axis should introduce a phase delay [defined as $\Delta\varphi(x) = \mathrm{mod}(\beta_0 l_z + \beta_{a\_eff} x \sin\theta, 2\pi)$ where mod is the modulo operator, β_0 and β_a are the propagation constant at the rightmost position and outside the dielectric (Air-Au region) and θ is the output angle. Finally, by combining this equation with (1) the dimension l_y at each location along the x axis can be obtained.

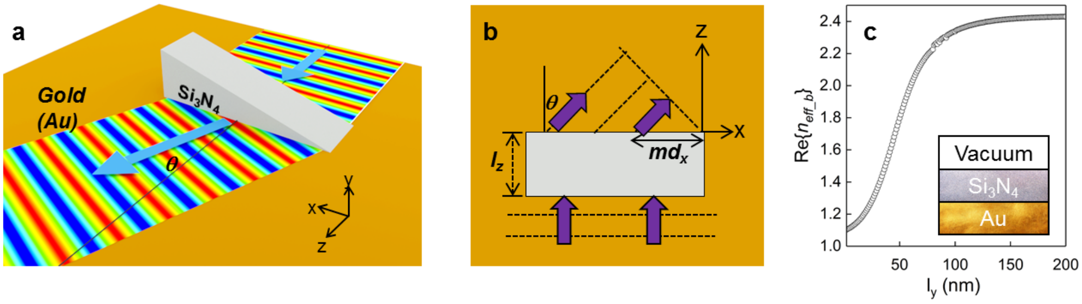

Fig. 1. Schematic representation of the proposed GRIN-SP steerers: (a) Perspective and (b) top view. (c) Analytical results of the effective refractive index for the region where the dielectric is present as a function of the dimension l_y.

III. RESULTS AND DISCUSSION

Let us now evaluate the response of the proposed GRIN-SP steerers. Here, the structures are desiged with an output angle of $\theta = 10°$ and $\theta = 30°$. By using (1) and $\Delta\varphi(x)$, the calculated dimensions l_y along the x axis for both output angles are shown as black symbols in Fig. 2a,d. The numerical results of the x component of the magnetic field (Hx) are shown in Fig. 2b,e. As observed, a clear steering of the incoming SP's is obtained. Other angles and designs at different wavelengths will also be presented during the conference.

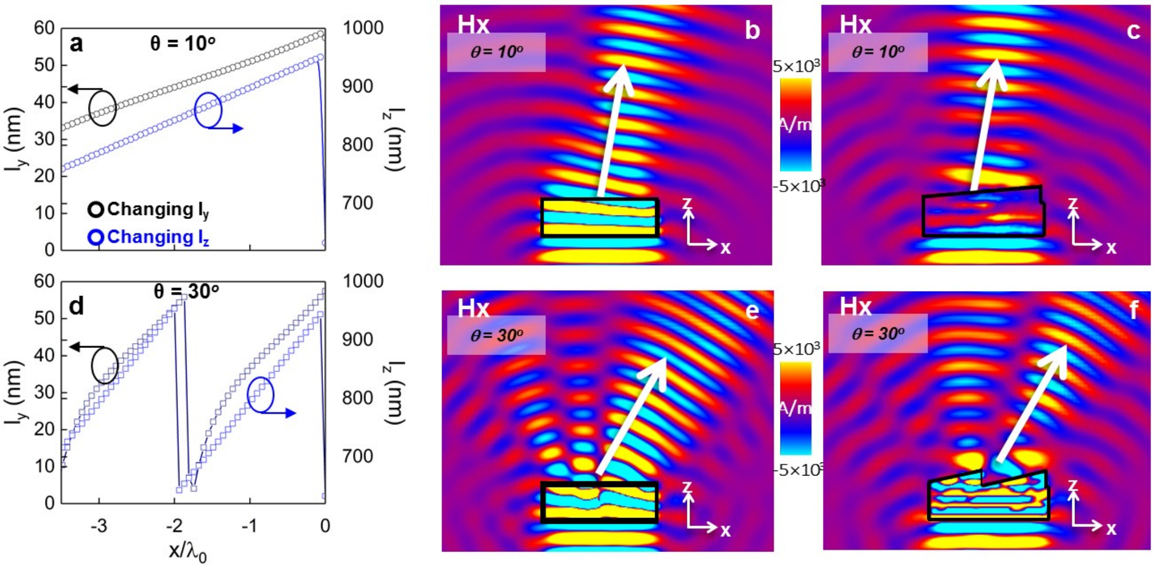

Fig. 2. Dimensions l_y (black symbols) and l_z (blue symbols) for the designs with (a) $\theta = 10°$ and (d) $\theta = 30°$. Numerical results of the magnetic field distribution on the xz plane for the designs with (b,c) $\theta = 10°$ and (e,f) $\theta = 30°$. The designs changing l_y and fixing l_z are shown in panels (b,e) and those with fixing l_y and changing l_z in panels (c,f).

These GRIN-SP steerers are designed by changing l_y while fixing l_z, however, it is also interesting to compare the results for designs where the l_y is fixed while l_z is varied, i.e., simple prisms. The dimensions l_z for both output angles are shown as blue symbols in Fig. 2a,d along with the numerical results of the H_x distribution on the xz plane in Fig. 2 c,f, respectively. As observed, SPs are deflected at the designed output angles. However, as it will be demonstrated during the conference, the performance is deteriorated for these designs when larger angles ($\theta > 60°$) are considered (details about power efficiency at each output angle will also be provided during the conference). This is because of the diffraction produced by the grating generated by the profile of the dielectric along the propagation z axis.

VI. CONCLUSION

In this communication, a mechanism to tailor the propagation direction of SPs has been proposed using GRIN concepts. The GRIN-SP steerers were designed by exploiting the effective refractive index produced when a piece of dielectric is sandwiched in between of two semi-infinite media. It has been shown how this effective index can be controlled by simply modifying the dimension of the dielectric in the direction perpendicular to the optical axis. Several designs have been presented considering different output angles demonstrating their ability to arbitrary control SP propagation direction at will. The technique here proposed may be implemented in applications where full control of the direction of SPs is needed opening new avenues on the control and manipulation of SP propagation.

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