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Ultra-sensitive long-range surface plasmon modes in asymmetric double-electrode waveguide

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ABSTRACT

We present a theoretical study on an index-asymmetric double-electrode waveguide structure and identify a long-range surface plasmon polariton (LRSP) super-mode for index-sensing. We propose to operate the LRSP by monitoring its cut-off wavelength which promises ultra-sensitivity. The sensitivity is calculated to be 6.5×10^4 nm per refractive index unit (RIU), which is one order magnitude higher than most plasmonic sensors based on spectral interrogation. Additionally, based on computations from the transfer matrix theory, we present the properties of this LRSP supermode.

Keywords: waveguide, surface plasmon, index measurement

1. INTRODUCTION

Surface plasmon polaritons (SPP) are transverse magnetic (TM) polarized surface waves that typically propagate on the interface of dielectric and metallic materials^{1,2}. However, bound SPP associated with a single metal/dielectric interface is usually characterized by high propagation loss. A practical way of reducing the attenuation is to use thin metal film bounded by identical dielectric half-spaces and to operate in the long-range plasmon mode³. Long-range SPP (LRSP) is usually characterized by low propagation attenuation and considerable lateral extension into the cladding dielectric.

Due to its low-propagation-loss, LRSP is increasingly involved as an alternative to single-interface SPP for sensing applications⁴. Structural asymmetry and mode isolation are two critical challenges associated with LRSP sensing schemes. The structural asymmetry addresses the problem where LRSP is not supported in multilayer waveguide structure with asymmetric index distribution⁵. On the other hand, mode isolation addresses the problem whereby the sensing signal is always complicated by short-range SPPs. Although sensing using both long and short-range SPP gives the benefit of self-referencing, the bulk sensitivity is usually on the order of 10^3 nm/RIU⁶.

In this work, we study an index-asymmetric double-electrode waveguide structure that supports a long-range super-mode of SPP which can be used to counter the above-mentioned problems. In order to understand and control the performance of the index-asymmetric double-electrode waveguide for sensing using the LRSP cut-off wavelengths, we present a theoretical study on the SPP super-modes supported by the structure. Many theoretical efforts have been dedicated to the waveguide structure where index asymmetry exists between the core (the middle insulator-layer) and the cladding (superstrate and substrate)⁷⁻¹⁰, i.e. the structure is still symmetric about the core. However, the index-asymmetry we considered has an index difference between the superstrate and all the other dielectric layers which suits practical sensing needs. Analysis reveals the nature and behaviour of one LRSP super-mode that can be potentially used for high-sensitivity index sensing.

2. ANALYTICAL MODEL

Transfer matrix theory (TMT) is used to obtain the modal solutions of a multilayer planar waveguide structure and we use Reflection Pole Method (RPM) as root-searching algorithm^{11,12}. Such implementation is widely used for planar waveguide calculations. The modes discussed in this work are labelled either long-range or short-range, depending on its associated propagation loss. A general structural model is depicted in Figure 1 (a). It is a multilayer structure stacked with finite number of layers of metal (M) and dielectric/insulator (I) materials; the layers have finite thickness and

infinite length as well as infinite lateral width. The covering and bottom medium are termed superstrate and substrate respectively; they are treated as semi-infinite.

Suppose TM incident light shines onto the boundary of the substrate and the immediate layer above, light will penetrate and reflect at each boundary of two layers, exciting optical waveguide modes along the way. The excited bound plasmon modes travel in the z direction and we are interested in the magnetic field H_y which is pointing outward from the xz plane. Each layer is associated with a transfer matrix. The overall effect as the light exits the structure is expressed in Equation (1).

$$\begin{pmatrix} A_N \\ B_N \end{pmatrix} = T_{N-1} T_{N-2} \dots T_1 \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} \quad (1)$$

Where T_N is the transfer matrix of the N-th layer and A_N and B_N are coefficients responsible for the magnetic field in the x and -x direction respectively. From Equation (1) we can derive an overall transfer matrix by multiplying each matrix together. If the incident light coefficient is 0 and no light is reflected back in the -x direction in the final layer, we have the overall transfer matrix as Equation (2).

$$\begin{pmatrix} A_N \\ 0 \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix} \begin{pmatrix} 0 \\ B_1 \end{pmatrix} \quad (2)$$

Equation (2) gives the reflection coefficient as shown Equation (3).

$$R = -\frac{t_{21}}{t_{22}} \quad (3)$$

As t_{22} tends to zero, the reflection coefficient tends to infinity, which signifies an optical waveguide mode. Hence solving the pole of R enables us to find the modal solutions.

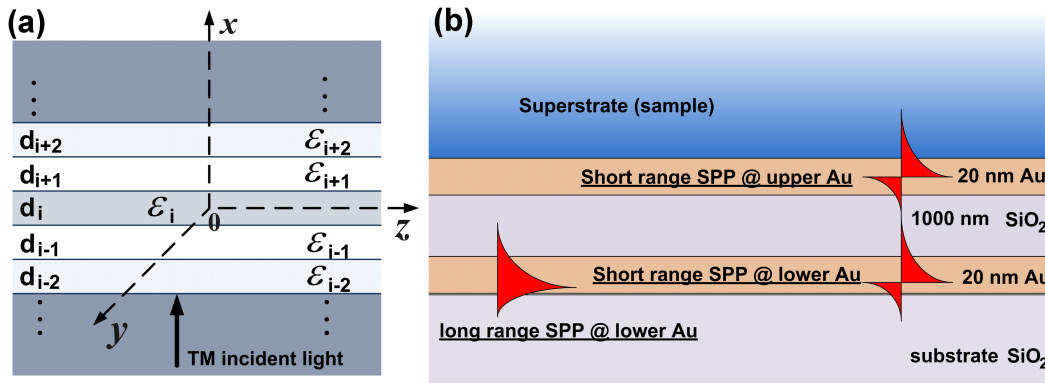


Figure 1. (a) A general computational structure of multilayer waveguide stacked with layers of metal and dielectric; (b) a double-electrode structure with isolated SPPs excited on both sub-systems. The upper IMI subsystem supports one short-range SPP when the index difference between superstrate and other I-layers is large.

The structure depicted in Figure 1 (b) is considered in this work. It is divided into two sub-systems of IMI, each with a metal-layer in the middle and an insulator substrate and superstrate. The superstrate index can be actively tuned to result in an index difference between the superstrate and all the other I-layers. Drude model and Sellmeier equations are used to represent the dielectric function of gold and the I-layers respectively. It is observed that the dispersion effect of silica for the range of wavelengths considered can be neglected. For most cases, the index of the silica is assumed to be 1.45. The resulting sub-systems both support one long-range and one short-range bound SPP (when substrate and superstrate have the same index). It is known that these isolated SPPs couple and result in four bound super-modes: two

short-ranging and two long-ranging^{7,13}. Past studies have verified that one of the long-range SPP, whose field distribution is hyperbolic sine (\sinh) in the middle I-layer, exhibits a cutoff thickness below which the mode does not exist^{7,13}. At a thickness of $1\mu\text{m}$ for the middle I-layer, one of the long-range mode cuts-off, so that single mode long-range SPP isolation is achieved.

3. RESULTS AND DISCUSSION

Dispersion relation (real part of the mode index n_{eff}) of the SPP supermodes are plotted in Figure 2 (e) for a water superstrate ($n=1.33$). The index difference between superstrate and all the other dielectric layers is considered large, therefore creates a spectral gap. All bound modes of a slab waveguide lie above the boundary of $n=1.45$, and the corresponding modal solutions are denoted the "proper" solutions; the "improper" solutions, which represent the radiation and leaky waves, lie below the boundary [1]. The spectral gap is observed at the transition from bound SPP to leaky SPP. Chen *et. al.* presented a theoretical study that revealed the existence of a spectral gap between bound SPPs and leaky SPPs¹⁰. The spectral gap happens because inherently, there are two eigenvalues for the long-range super-mode.

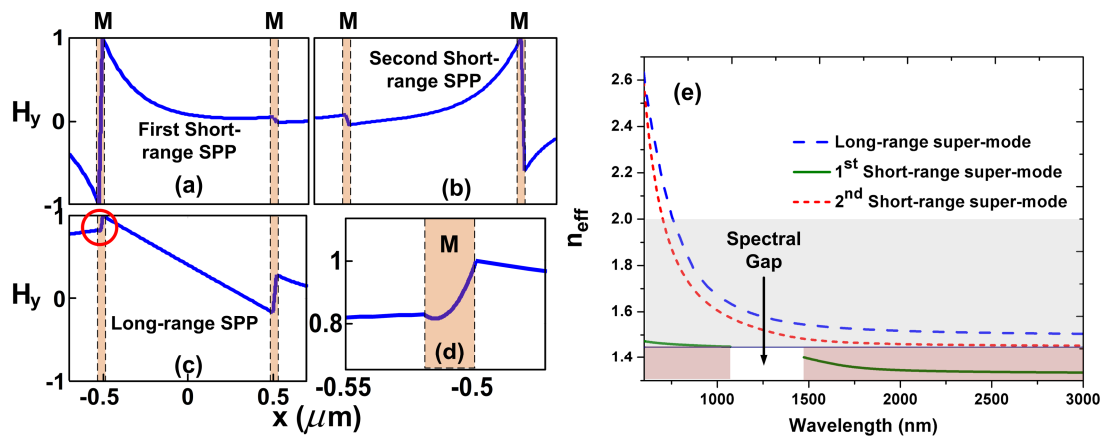


Figure 2. Characteristic field profiles at a wavelength of 1000 nm for the structure depicted in Figure 1 where the superstrate is water ($n_{\text{superstrate}}=1.33$). Field profiles for (a) the 1st short-range super-mode SPP; (b) the 2nd short-range super-mode SPP; (c) the long-range super-mode SPP; (d) zoom-in view of (c) at lower M-layer; (e) Effective mode indices of the SPP super-modes for a spectral range. Straight line at $n=1.45$ represents the boundary between bound SPPs (above) and leaky SPPs (below).

When the index symmetry is broken, field distributions are unbalanced. Figure 2 (a)-(d) show the magnetic field profiles of the three super-modes. Field intensity in the upper IMI silica-Au-water sub-system ($x>0$) is decreased while the second short-range super-mode in the lower IMI silica-Au-silica sub-system ($x<0$) is decreased. For the long-range super-mode, which is shown in Figure 2 (c), the field distribution becomes mostly \sinh -dependent in the middle I-layer ($-0.5<x<0.5$). It is observed that the magnetic field has a zero-crossing in the upper M-layer ($0.5<x<0.52$), suggesting a short-range SPP field distribution. Around the lower M-layer ($-0.52<x<-0.5$), a loss dip is observed which is characteristic of the LRSPP field distribution (Figure 2 (d)). The field distribution of the long-range super-mode indicates that this super-mode has both long-range and short-range characteristics.

Propagation losses of the three SPP super-modes are shown in Fig. 4 (a). The propagation loss is characterized by propagation length, which is defined as the distance where field intensity decreases a factor of $1/e$. The loss curves also confirm the existence of a spectral gap which agrees with that shown in Figure 2 (e).

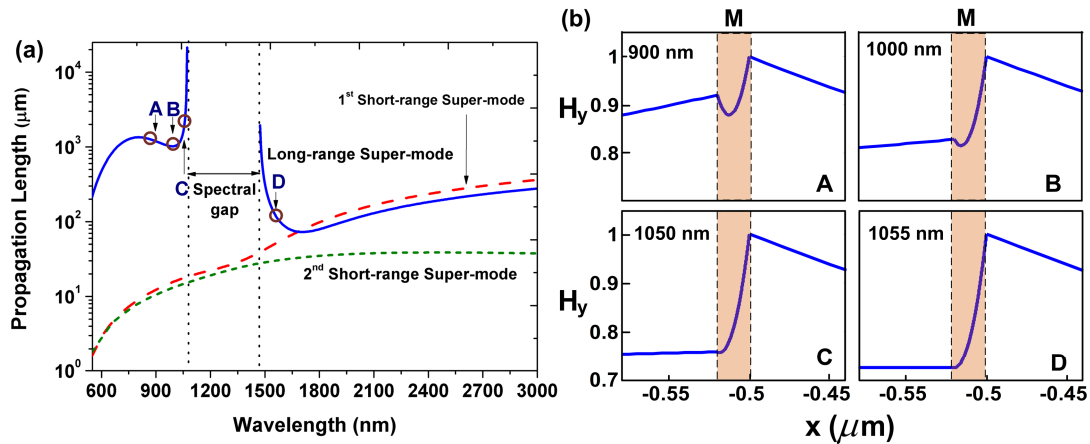


Figure 3. (a) Propagation loss of the three SPP super-modes supported by a structure depicted in Fig.1 (b) with a water superstrate. Corresponding field profiles at different wavelengths: A 900nm; B 1000nm; C 1050nm just before cut-off; D 1550nm after cut-off.

Field profiles for the long-range super-mode are plotted for four different wavelengths in Fig 4 (b) A-D. It shows the process of the long-range supermode tends to no-loss and extreme lateral expansion. Before cut-off (Fig. 3 A, B, C), the loss dip at the lower M-layer grows shallower as the wavelength increases. Field decays at a slower rate inside the substrate ($x < -0.52$). As the long-range super-mode approaches its cut-off wavelength, the mode spreads out into the dielectric layers and propagation loss is minimized. The field profile of the leaky SPP at 1550 nm of wavelength is exponentially growing inside the substrate ($x < -0.52$), which is characteristic of a leaky wave. The leaky waves are leaking through the high-index medium (silica substrate). In addition, the loss dip inside the lower M-layer is completely gone. Though no zero-crossing exists, the field profile resembles that of a short-range SPP.

Both the cut-off wavelength and width of spectral gap depend on the index difference between superstrate and the other dielectric layers. As shown in Figure 4, the larger the index difference, the earlier the cut-off happens, and the wider the gap opens. Accordingly, as shown in Figure 4 (b), the propagation loss follows the rule that the smaller the index difference, the longer the propagation length (consider only the regions where no mode cut-off happens). Hence sensitivity of the long-range super-mode in correspondence with the superstrate index can be tuned by varying structural indices.

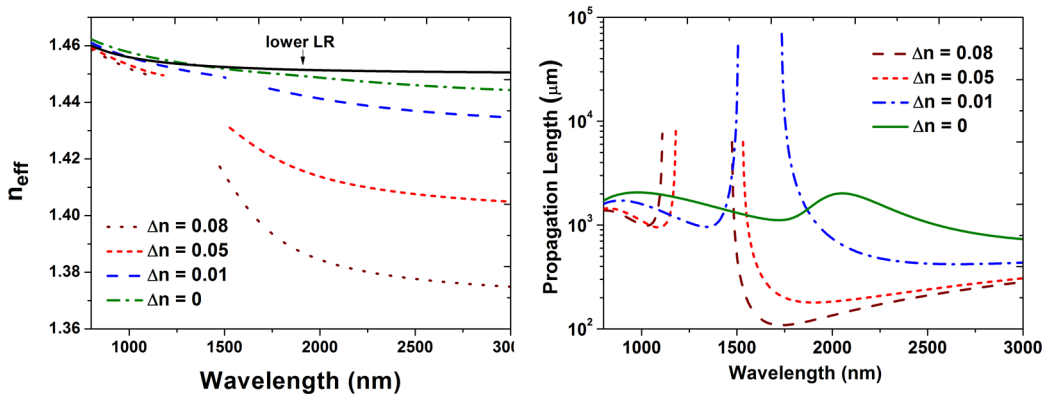


Figure 4. (a) n_{eff} (b) Propagation loss, as a function of wavelength for the long-range supermodes supported by a double-electrode structure of four different superstrate indices. Δn is the refractive index difference between the superstrate and all the other dielectric layers. For (a), the long-range mode of the lower subsystem is shown as a reference.

Since the long-range super-mode cuts off at different wavelength for different superstrate index, this wavelength can be used as an indicator for variant superstrate. Berini and colleagues have demonstrated an experimental detection of the

LRSP cut-off so as to confirm that such cut-off process is able to be experimentally detected¹⁵. A refractive index sensor based on an index-asymmetric double-electrode waveguide structure may utilize the cut-off wavelength from transmission spectrum in sensing applications. The short-range super-modes can be effectively filtered since they decay much faster than long-range SPPs.

Since the LRSP cut-off is an inherently abrupt process, the transmission spectrum is expected to be especially sensitive to the cut-off wavelength. Sensitivity of the sensor is calculated as the ratio of spectral variation and index change. Figure 5 shows the different cut-off wavelengths of the long-range super-mode for different middle-I layer thicknesses. It is observed that the sensitivity does not change linearly with the superstrate index. The closer the refractive index of the superstrate to the substrate, the faster the cut-off wavelength increases, and the higher the sensitivity. As the superstrate index is further increased, it reaches a value where the long-range super-mode no longer cuts off. Beyond this point, the transition from bound to leaky SPP is continuous and it would be hard to differentiate the two. For a middle insulator thickness of 1100 nm, the sensitivity takes a maximum value of 41290 nm/RIU at $n=1.433$, while for a thickness of 500 nm, the sensitivity takes a maximum value of 65120 nm/RIU at $n=1.431$. Overall, the cut-off wavelength of the long-range super-mode varies with the superstrate index at a sensitivity that is one order of magnitude higher than the common spectral-based surface plasmon resonance sensor¹⁵.

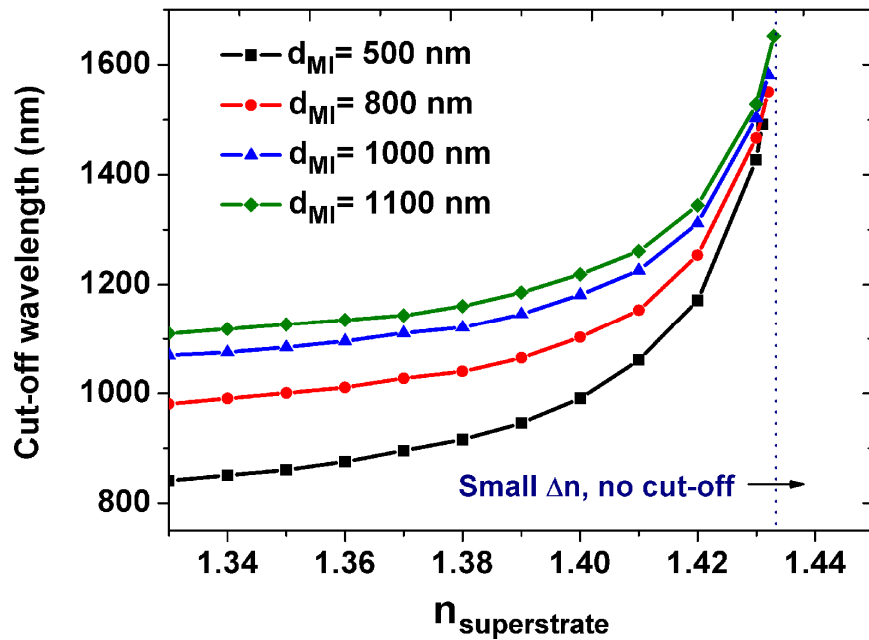


Figure 5. (a) Cut-off wavelengths of the long-range super-mode as a function of superstrate index for different middle I-layer thickness d_{MI} .

4. CONCLUSIONS

We have theoretically demonstrated the surface plasmon super-modes in a planar index-asymmetric double-electrode structure. We find that a long-range super-mode consists of a bound and a leaky mode component. When the refractive index difference between the superstrate and substrate is large, a spectral band-gap occurs. Mode cut-off is observed, and is found to be especially sensitive to the index difference between superstrate and all the other dielectric layers. The refractive index difference controls the width and position of the spectral gap, making it possible to be applied in index-sensing applications. The proposed waveguide is expected to have a spectral sensitivity as high as 65120 nm/RIU.

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