

Long range surface plasmons on asymmetric suspended thin film structures for biosensing applications

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Abstract: We show that long-range surface plasmons (LRSPs) are supported in a physically asymmetric thin film structure, consisting of a low refractive index medium on a metal slab, supported by a high refractive index dielectric layer (membrane) over air, as a suspended waveguide. For design purposes, an analytic formulation is derived in 1D yielding a transcendental equation that ensures symmetry of the transverse fields of the LRSP within the metal slab by constraining its thicknesses and that of the membrane. Results from the formulation are in quantitative agreement with transfer matrix calculations for a candidate slab waveguide consisting of an H₂O-Au-SiO₂-air structure. Biosensor-relevant figures of merit are compared for the asymmetric and symmetric structures, and it is found that the asymmetric structure actually improves performance, despite higher losses. The finite difference method is also used to analyse metal stripes providing 2D confinement on the structure, and additional constraints for non-radiative LRSP guiding thereon are discussed. These results are promising for sensors that operate with an aqueous solution that would otherwise require a low refractive index-matched substrate for the LRSP.

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1. Introduction

While surface plasmons are of great interest for many applications [1], including biosensors [2–10], waveguides and photonic circuits [11–23], a major challenge remains overcoming propagation losses, for which long-range surface plasmons (LRSPs) have been investigated

extensively [24]. The long propagating lengths achievable with LRSPs potentially enable numerous applications, including biosensors having a high sensitivity and a low detection limit [8].

Past work on LRSPs was based mainly on symmetric insulator-metal-insulator (IMI) structures, which use a thin metal slab (infinite width) or stripe (finite width) to achieve low loss [24]. (The LRSP in the thin metal slab and stripe correspond to the s_b and ss_b^0 modes respectively [24].) Allowing the structure to become slightly asymmetric introduces cut-off conditions for the LRSP, constraining the dimensions of the metal slab or stripe, or the operating wavelength [25–30]. As the LRSP in an asymmetric structure approaches cut-off, its propagation length increases, but its confinement rapidly diminishes as does its coupling efficiency to finite-sized beams.

In practice, such symmetric (or slightly asymmetric) LRSP waveguides are not always convenient. Within the context of biosensors, for example, matching the refractive index of an aqueous sensing solution requires a cladding material having a refractive index of about 1.31 – 1.33 (depending on the operating wavelength). Few candidate materials exist satisfying this requirement; two are Teflon and Cytop. Teflon has an index that is slightly below that of de-ionised water and Cytop has an index that is slightly above. Both have been used to support metal slabs or stripes propagating LRSPs through aqueous solutions [31–34].

Enlarging the set of materials that could be used requires finding structures that are physically asymmetric but still support LRSPs. One approach involves combining thin layers of materials, as in Ref. [35], where a Teflon/Ta₂O₅ bi-layer system was used to match (effectively) the index of the aqueous environment on the other side of an Au slab. A second approach involves combining a finite 1D photonic crystal, which can support Bloch surface waves in the bandgap, with an Au slab (and the bounding medium on the other side) such that a symmetric LRSP field distribution is achieved throughout the structure [36]. A third approach is to minimally perturb the symmetry by using an ultrathin freestanding dielectric membrane to support the metal film and allowing the sensing environment to bound both sides of the structure [37,38].

Building on these ideas, we propose in this paper a novel asymmetric insulator-metal-insulator-insulator (IMII) structure that can support LRSP waves. The IMII waveguide works by effectively restoring the symmetry of the LRSP transverse fields within the metal film. The generic 1D IMII slab waveguide is investigated analytically first, and a TM (transverse-magnetic) transcendental equation that ensures LRSP propagation is derived. Cases implemented with specific materials are then verified quantitatively by the transfer matrix method (TMM), by which the surface sensitivity [8] and the figure of merit [39] of the proposed waveguide are also obtained. The corresponding 2D metal stripe structure is then investigated by the finite difference method (FDM), which shows parametric regimes where effective LRSP guiding can be accomplished. Results are given for a candidate structure relevant to biosensing, consisting of an H₂O – Au – SiO₂ – air suspended structure, which has a potential advantage over the membrane waveguide of Refs. [37] and [38] in that integration with microfluidic channels should be easier to achieve.

2. LRSP along an IMII slab structure (1D)

2.1 Geometry of the IMII slab waveguide

The 1D IMII structure is studied first in order to provide insight into the conditions under which the LRSP may be supported. Figure 1(a) shows an example implementation of a structure that is of interest for biosensing. All layers are infinite in the x and y directions. The LRSP is assumed to propagate along the $+x$ -direction at a vacuum wavelength of $\lambda_0 = 1310$ nm according to $e^{+j\beta x}$ ($e^{-j\omega t}$ time dependence assumed). The H₂O region is semi-infinite and its relative permittivity is $(1.3159 + j1.639 \times 10^{-5})^2$. The second layer is a Au slab, which has a relative permittivity of $-86.08 + j8.322$ and a thickness t . Beneath the Au slab is a

supporting dielectric membrane of thickness d , such as SiO₂ having a relative permittivity of 2.0932. The bottom semi-infinite layer is air, having a relative permittivity of 1. (The values of relative permittivity originate from Ref. [38]).

This structure is practical, provided that the SiO₂ layer is thick enough to be mechanically stable and deposited without too much compressive strain. It can be fabricated by etching through an underlying Si substrate (not shown) to release the SiO₂ layer, thereby creating a free-standing SiO₂ membrane supported around its perimeter [37]. The sensitivity of the LRSP in this structure to changes in an adlayer located at the Au/ H₂O interface is high, based on results obtained for similar structures [8], and based on computations given below.

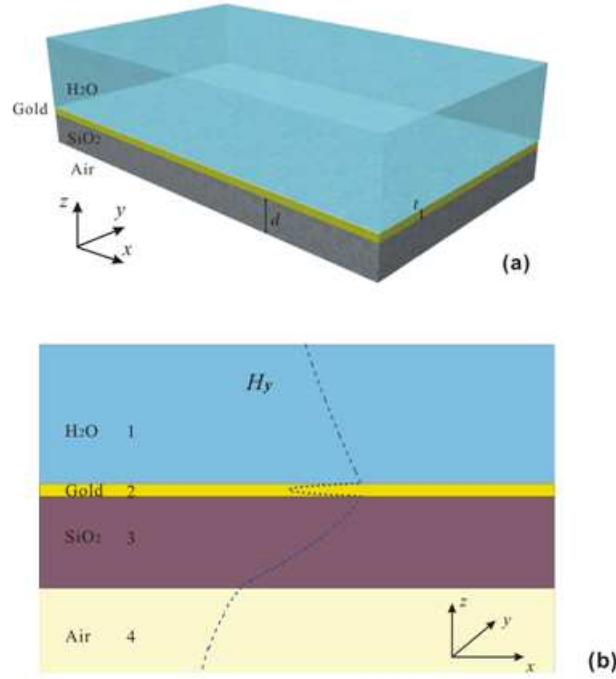


Fig. 1. (a) Schematic of a 1D IMII slab waveguide; the layers from top to bottom are H₂O, Au, SiO₂ and air, respectively. (b) Sketch of the transverse magnetic field of the symmetry constrained LRSP (dashed curves) having identical field values along the upper and lower boundaries of the Au layer.

2.2 Theoretical model of the IMII: restored LRSP symmetry in the metal

In the symmetric IMI structure, the transverse LRSP mode fields are symmetric about the centre plane bisecting the metal slab, so a transverse field is identical along its top and bottom boundaries. Building on this point, one approach to obtaining a low-loss IMII structure is to find the thickness of the dielectric layer d that restores the symmetry of the transverse LRSP mode fields within the metal slab. Practically, this is achieved by enforcing that the transverse magnetic field (and transverse electric field) be identical along its boundaries, as sketched in Fig. 1(b). Although field symmetry over the full cross-section is not achieved, symmetry within the metal slab is achieved, thus capturing an IMII configuration that supports a LRSP; this LRSP shall henceforth be referred to as the “*symmetry-constrained LRSP*”.

First, we write the transverse magnetic field in the different layers, $H_{i,y}$, for a TM mode:

$$\left\{ \begin{array}{ll} H_{1y} = Ae^{-k_1(z-\frac{t}{2})} & \text{in H}_2\text{O} \\ H_{2y} = Be^{-k_2(z+\frac{t}{2})} + Ce^{k_2(z-\frac{t}{2})} & \text{in Au} \\ H_{3y} = De^{-k_3(z+\frac{t}{2}+d)} + Fe^{k_3(z+\frac{t}{2})} & \text{in SiO}_2 \\ H_{4y} = Ge^{k_4(z+\frac{t}{2}+d)} & \text{in Air} \end{array} \right. \quad (1)$$

The corresponding longitudinal electric field in each layer $E_{i,x}$ is obtained from:

$$E_{i,x} = -j \frac{1}{\omega \varepsilon_0 \varepsilon_i} \frac{\partial H_{i,y}}{\partial z} \quad (2)$$

A, B, C, D, F, G are the amplitude coefficients for $H_{i,y}$ and $E_{i,x}$ at the boundaries. Subscripts 1-4 indicate the H₂O, Au, SiO₂ and air layers, respectively, and $k_i = (\beta^2 - k_0^2 \varepsilon_i)^{1/2}$ where k_0 represents the vacuum wavenumber, ε_i is the complex relative permittivity of the i^{th} layer and β is the complex TM mode wavenumber. Then by applying the boundary conditions (tangential fields must match) to Eqs. (1) and (2), we obtain the β - d - t transcendental equation for TM modes on this structure:

$$e^{2k_3 d} = \frac{(r_3(Re^{k_2 t} + e^{-k_2 t}) - r_2(Re^{k_2 t} - e^{-k_2 t}))(r_3 - r_4)}{(r_3(Re^{k_2 t} + e^{-k_2 t}) + r_2(Re^{k_2 t} - e^{-k_2 t}))(r_3 + r_4)} \quad (3)$$

where $r_i = \frac{k_i}{\varepsilon_i}$ and $R = \frac{r_2 + r_1}{r_2 - r_1}$.

In the lossless case ($\text{Im}\{\varepsilon_i \beta\} = 0$) mode cut-off occurs when $\beta = k_0 \varepsilon_1^{1/2}$ (mode wavenumber equals the wavenumber of plane waves in H₂O). Substituting this condition into Eq. (3) yields the following equation which constrains d and t at the cut-off point of the TM modes:

$$e^{2k_3 d} = \frac{(r_3 \cosh(k_2 \cdot t) - r_2 \sinh(k_2 \cdot t))(r_3 - r_4)}{(r_3 \cosh(k_2 \cdot t) + r_2 \sinh(k_2 \cdot t))(r_3 + r_4)} \quad (4)$$

As mentioned above, the transverse magnetic field of the LRSP must be identical along the boundaries of the metal slab if the field is to be symmetric therein; this implies $B = C$. Adding this constraint to the boundary conditions (tangential fields must match), and applying them to Eqs. (1) and (2) yields:

$$e^{2k_3 d} = \frac{(r_3 \cosh(k_2 \frac{t}{2}) - r_2 \sinh(k_2 \frac{t}{2})) \cdot (r_3 - r_4)}{(r_3 \cosh(k_2 \frac{t}{2}) + r_2 \sinh(k_2 \frac{t}{2})) \cdot (r_3 + r_4)} \quad (5)$$

and:

$$\tanh(k_2 \frac{t}{2}) = -\frac{k_1 \varepsilon_2}{k_2 \varepsilon_1} \quad (6)$$

Thus, the introduction of the additional constraint $B = C$ yields two transcendental equations, instead of one (Eq. (3)) as is usually the case; the system is overspecified with this constraint, and to remain consistent, the Eq. (5) and (6) must be simultaneously satisfied to provide the symmetry-constrained LRSP solution. Eq. (6) is generated from the field solutions

in the H₂O and Au layers only (H_{1y} , H_{2y} , E_{1x} , E_{2x}), and is the same as for the LRSP of the symmetric IMI [26]. The symmetry-constrained LRSP satisfies Eqs. (5) and (6) simultaneously in the lossless case only ($\text{Im}\{\epsilon_i, \beta\} = 0$). A solution strategy then consists of first solving Eq. (6) using a root-finding algorithm to determine β for a value of t , and then inserting both values into Eq. (5) to determine d directly. Equations (5) and (6) are thus useful for generating t , d pairs for which the LRSP is symmetry-constrained. Equation (3) always holds (including losses) so the complex mode wavenumber (including attenuation) can then be readily determined for a particular design.

Figure 2(a) shows the collection of thicknesses t and d satisfying Eq. (5) for the LRSP in the IMI considered (H₂O - Au - SiO₂ - air at 1310 nm) in the lossless case, and so corresponds to designs for which the LRSP is symmetry-constrained. Note that the thinner the Au slab, the thicker the SiO₂ layer must be to compensate for the index discrepancy between H₂O and air. For example, for a 50 nm thick Au slab, a 342 nm thick SiO₂ layer is needed, but for a 20 nm thick Au slab, a 382 nm thick SiO₂ layer is needed. The other curve in Fig. 2(a) corresponds to cut-off configurations obtained using Eq. (4), below which there is no purely bound LRSP. The symmetry-constrained designs are above cut-off but as the metal slab thickness decreases, cut-off is approached.

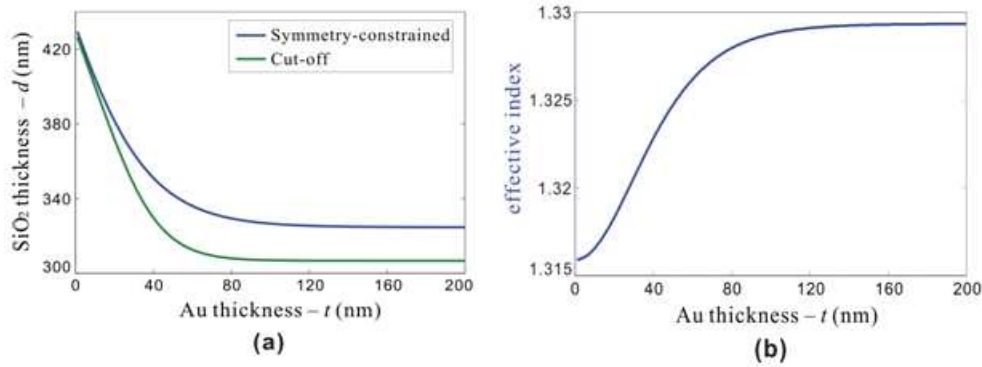


Fig. 2. (a) Symmetry-constrained (blue curve) and cut-off (green curve) thicknesses for the LRSP in the IMI of interest (H₂O - Au - SiO₂ - air at 1310 nm). (b) Effective index (blue curve) and attenuation (red curve) of the symmetry-constrained LRSP in the IMI of interest (H₂O - Au - SiO₂ - air at 1310 nm) as a function of the Au slab thickness.

Figure 2(b) shows the effective index (n_{eff}) of the symmetry-constrained LRSP computed using Eq. (5), which increases with Au thickness as expected, approaching limiting values when the Au thickness is larger than ~100 nm. When the Au layer is thinner, the effective index is close to the refractive index of H₂O.

2.3 Computations using the transfer matrix method

The transfer matrix method (TMM) is broadly used for solving the modes of multilayer slab waveguides. The formulation reported in Ref. [40] was applied to verify the theory presented in Subsection 2.2.

Figure 3(a) shows the effective index and attenuation of the LRSP in the IMI of interest as a function of the membrane thickness for 20 and 50 nm thick Au slabs computed via the TMM. There is excellent quantitative agreement in the effective index between the TMM results (curves) and the theory for the symmetry-constrained LRSP (Eq. (5) - stars). When the Au slab is 50 nm thick, the symmetry-constrained LRSP occurs at $d = 341.7$ nm and its effective index and attenuation (TMM) are 1.324633 and 31.39 dB/mm, respectively. When the Au slab is 20 nm thick, the symmetry-constrained LRSP occurs at $d = 381.5$ nm and its effective index and attenuation (TMM) are 1.3182884 and 3.26 dB/mm, respectively.

The lowest attenuation does not occur for the symmetry-constrained LRSP, but rather for a slightly asymmetric LRSP at a nearby membrane thickness. Further away from the symmetry-constrained design, the LRSP becomes increasingly localised to the Au/H₂O interface for increasing d , and to the Au/SiO₂ interface for decreasing d . The LRSP tends towards cut-off with decreasing d , explaining the decreasing effective index.

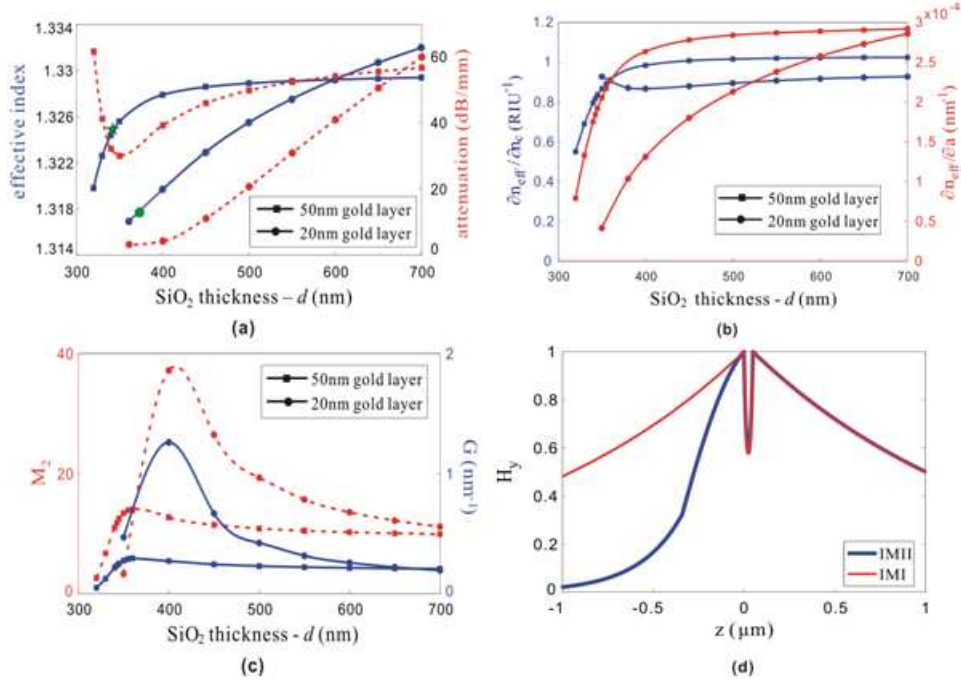


Fig. 3. (a) Effective index (blue solid) and attenuation (red dashed) of the LRSP on the IMII of interest (H₂O - Au - SiO₂ - air at 1310 nm) for two thicknesses of the Au slab (20 and 50 nm) computed by the TMM. The values marked by the stars and the pentagons (green and magenta) were computed for the symmetry-constrained LRSP via Eq. (5). (b) Bulk ($\partial n_{eff}/\partial n_c$ - blue solid) and surface ($\partial n_{eff}/\partial a$ - red dashed) sensitivities, and (c) surface sensing parameter G (blue solid) and M_2 figure of merit (red dashed), of the LRSP on the 1D IMII of interest. (d) Distribution of the H_y field component of the LRSP on the IMII of interest for $t = 50$ nm and $d = 341.7$ nm (Blue thick), and on the corresponding IMI (H₂O-Au-H₂O with $t = 50$ nm, red thin); the bottom boundary of the Au slab is located at $z = 0$.

For biosensor applications, we consider typical figures of merit for this type of system. Figure 3(b) plots the bulk ($\partial n_{eff}/\partial n_c$) and surface ($\partial n_{eff}/\partial a$) sensitivities of the LRSP computed using the TMM. n_c denotes the refractive index of the carrier fluid, in this case H₂O, and a denotes the thickness of a thin biochemical adlayer of refractive index 1.5 placed on the metal slab at the Au/H₂O interface [8]. The trends in the sensitivities with d follow the trends of the mode fields described in the preceding paragraph. In the case of the $t = 20$ nm thick Au slab, the bulk sensitivity increases as d decreases below the symmetry-constrained design because the mode nears cut-off, and as it does its fields extend deeply into the higher index medium which is H₂O. The sensitivities are larger for the $t = 50$ nm slab because of the stronger mode confinement.

Figure 3(c) shows the surface sensing parameter G and the M_2 figure of merit [8,39] for different SiO₂ membrane thicknesses, calculated using the TMM. G is the ratio of the surface sensitivity to the normalised attenuation (k_{eff}), and is particularly relevant for surface sensing [8]. M_2 measures the confinement-to-loss ratio, where confinement is defined as the mode's distance from the light-line [39]. Both G and M_2 are maximised at the same membrane thickness, which is fairly close to the symmetry-constrained design. For example, when the

Au slab thickness is $t = 50$ nm, G and M_2 peak at $d = 350$ nm (the symmetry-constrained membrane thickness in this case is $d = 341.7$ nm). Thus the symmetry-constrained structure generates good designs for sensing applications.

It is instructive to compare the symmetry-constrained LRSP in the IMII of interest with the LRSP supported by the corresponding IMI. Figure 3(d) plots the distribution of the associated H_y fields, showing that they are identical for $z > 0$, *i.e.*, within the metal slab and in the H_2O region. The field below the metal slab in the case of the IMII is more confined due to the SiO_2 and Air layers. Table 1 summarises the modal quantities for $t = 20$ and 50 nm. The effective indices are similar, though not identical, but the attenuation of the LRSP in the IMII is significantly larger. Although the field distribution in the metal is nearly identical to that of the corresponding IMI (Fig. 3(d)), the mode overlap with the metal is stronger because of the increased confinement in the SiO_2 and air regions, leading to the larger attenuation. The overlap with the biochemical adlayer is also larger for the LRSP on the IMII (due to the same reason) leading to a larger surface sensitivity. Despite the higher losses of the IMII structure, the figure of merit G is actually improved for the IMII structures as compared to the IMI structures, which favours their use for biosensor applications. (Only one adlayer was assumed for the IMI in the sensitivity calculations, which is more practical for microfluidic implementation.)

To investigate the influence of an H_2O layer of finite thickness and an additional air top-layer, we also calculated the effective index (n_{eff}) with different H_2O layer thicknesses for the 50 nm gold layer symmetry-constrained configuration. For a distance of one free-space wavelength (1310 nm), the real part of the effective index of the mode shows only 0.4% change as compared to the semi-infinite H_2O layer (shown in Table 1). The percentage change then drops by an order of magnitude for each additional wavelength in thickness.

Table 1. Comparison of modal quantities for the LRSP supported by the IMII of interest (H_2O - Au - SiO_2 - air at 1310 nm), and by the corresponding IMI (H_2O -Au- H_2O), for the two metal slab thicknesses.

Structure	n_{eff}	Att (dB/mm)	$\partial n_{eff} / \partial a$ (nm^{-1})	G (nm^{-1})
IMI ($t = 50$ nm)	1.324683	20.07	0.00011	0.22
IMII ($t = 50$ nm, $d = 341.7$ nm)	1.324633	31.39	0.00018	0.23
IMI ($t = 20$ nm)	1.318295	2.23	0.00006	1.07
IMII ($t = 20$ nm, $d = 381.5$ nm)	1.318288	3.26	0.00011	1.29

2.4 Comparison with TE and TM dielectric waveguide modes

The existence of TE and TM modes in the corresponding dielectric slab waveguide (*i.e.*, the IMII without the Au slab) can lead to leakage in the case of the 2D metal stripe waveguide (Section 3). This occurs when the effective index of the LRSP on the IMII becomes less than that of the dielectric slab modes on either side of the Au stripe [38].

Figure 4(a) shows the effective index of the symmetry-constrained LRSP in the IMII of interest (H_2O - Au - SiO_2 - air at 1310 nm), and of the TE_0 and TM_0 modes in the corresponding dielectric slab waveguide. When the thickness of the membrane (d) is less than 390 nm, the LRSP has a larger effective index than the TE_0 and TM_0 modes. From Fig. 2(a), this range of thickness ($d < 390$ nm) corresponds to an Au slab thickness (t) that is greater than 18 nm. It is therefore expected that the corresponding metal stripe waveguide will support a purely bound (non-radiative) symmetry-constrained LRSP for $d < 390$ nm and $t > 18$ nm (approximately). Note that this additional constraint leads to a lower bound on the Au thickness, and thus a lower bound on the achievable attenuation.

The effective indices for the case of Si_3N_4 as the membrane are also computed, as shown in Fig. 4(b). In this case, the effective index of the TE_0 mode is larger than that of the

symmetry-constrained LRSP over the entire range of membrane thickness, suggesting that Si_3N_4 is not a good choice for the corresponding metal stripe waveguide.

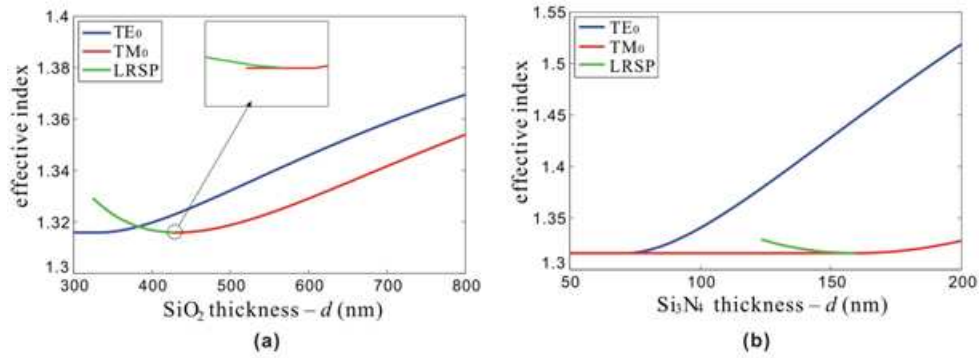


Fig. 4. (a) Effective indices for TE_0 (blue curve), TM_0 (red curve) and symmetry-constrained LRSP (green curve) modes as a function of SiO_2 thickness in the IMII of interest (H_2O - Au - SiO_2 - air at 1310 nm). (b) Same as Part (a), except using Si_3N_4 as the membrane (the refractive index of Si_3N_4 is ~ 2).

3. LRSP along an IMII stripe structure (2D)

3.1 Geometry of the IMII stripe waveguide

For waveguide and integrated optics applications, a stripe geometry providing confinement in the plane transverse to the direction of propagation is typically preferred to a slab. Figure 5 shows the stripe structure that corresponds to the slab of Fig. 1. The metal stripe of width w provides additional confinement in the y dimension, and propagation occurs along the stripe in the x dimension. The same material parameters and operating wavelength (as in Subsection 2.1) are retained and the width of the Au stripe is selected as being $w = 5 \mu\text{m}$. Due to the geometrical complexity of the structure, theoretical and TMM approaches are not suitable for analysis, so the finite-difference method (FDM) implemented in commercial software [41] was used to compute the LRSP mode characteristics.

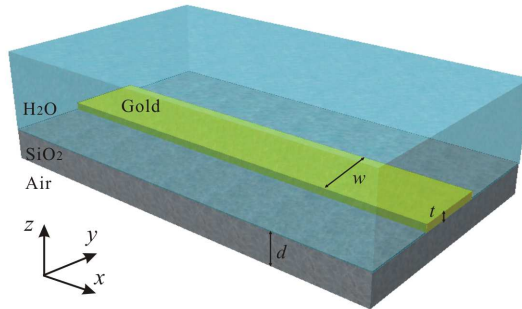


Fig. 5. Sketch of a 2D IMII stripe waveguide of width w ; the layers are the same as in Fig. 1.

3.2 Finite difference results

Figure 6 shows the effective index and attenuation of the LRSP in the IMII as a function of the membrane thickness for 20 and 50 nm thick Au stripes computed via the FDM. Similar trends are noted as in the corresponding slab waveguide (Fig. 4), however, the effective index is lower and the attenuation is higher in the case of the stripe for the same membrane and metal slab thicknesses (d, t) (also observed in [38]). Features are evident in the MPA curves

due to variations in the mode fields (perturbations) as the membrane thickness (d) varies (also observed in [38]).

The symmetry-constrained LRSP occurs at $d \sim 330$ and 380 nm in the case of the 50 and 20 nm thick Au stripes, respectively (as shown in Fig. 7), similarly to the slab waveguide (Fig. 4). One reason for the similarity is the large width selected for the stripe ($w = 5 \mu\text{m}$) which reduces the interaction of the LRSP fields with the stripe corners. Another reason is the relatively small contrast between the selected membrane material (SiO_2) and H_2O . Indeed assuming Cytop [34] for the membrane (which has an index close to H_2O) renders the slab and stripe results essentially indistinguishable. Also, the lower the index of the membrane the larger the design space for the stripe waveguide because radiation into the TE_0 and TM_0 modes of the dielectric slab (on either side of the stripe) occurs over a smaller range of membrane thickness.

The similarity of the results to the 1D case is interesting because it allows use of the 1D theory (Subsection 2.2) to find good initial symmetry-constrained designs for the stripe waveguide.

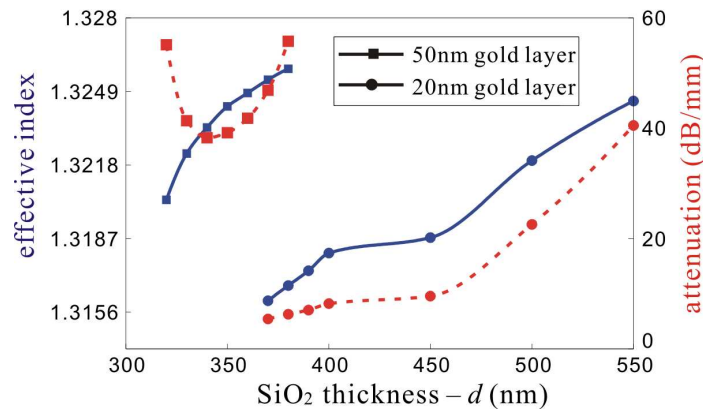


Fig. 6. Effective index (blue - solid) and attenuation (red - dashed) of the LRSP on the stripe IMII of interest ($w = 5 \mu\text{m}$, H_2O - Au - SiO_2 - air at 1310 nm) for two thicknesses of the Au stripe (20 and 50 nm) computed by the FDM.

Figure 7 shows the transverse magnetic field distribution (H_y) of the LRSP over the cross-section of a stripe IMII with symmetry-constrained thicknesses as computed by the FDM. For a Au stripe thickness of $t = 50$ nm, the symmetry-constrained LRSP occurs for a membrane thickness of $d = 330$ nm, and for $t = 20$ nm, then $d = 380$ nm. The H_y field along the top boundary of the Au stripe is identical to that along its bottom boundary as observed.

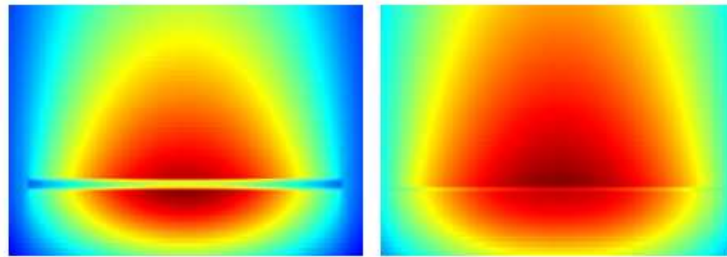


Fig. 7. Distribution of the transverse magnetic field (H_y) of the symmetry-constrained LRSP over the cross-section of the stripe IMII of interest ($w = 5 \mu\text{m}$, H_2O - Au - SiO_2 - air at 1310 nm); (a) $t = 50$ nm, $d = 330$ nm; (b) $t = 20$ nm, $d = 380$ nm.

5. Summary and concluding remarks

We demonstrated that LRSPs are supported in a physically asymmetric IMII thin slab structure, consisting of a low index medium on a metal slab on a dielectric layer (membrane) over air, as a suspended waveguide. An analytic formulation was derived in 1D yielding a transcendental equation that ensures symmetry of the transverse fields of the LRSP within the metal slab by constraining the thicknesses of the metal slab and the membrane. Mode characteristics obtained via the formulation for this “symmetry-constrained” LRSP are in quantitative agreement with TMM calculations for a candidate slab waveguide consisting of an H_2O -Au- SiO_2 -air suspended structure. We found that the symmetry-constrained LRSP exhibits fairly low attenuation at a particular metal slab thickness. Furthermore, its attenuation and confinement decreased with decreasing metal thickness, following the conventional IMI. We also found that the thinner the metal slab, the thicker the dielectric layer needs to be to satisfy the symmetry constraint because the LRSP extends further into the dielectric for a thinner metal slab. As expected, the LRSP in this IMII waveguide has a high surface sensitivity as well as high figures of merit (G for surface sensing and M_2 for waveguiding) supporting its potential for sensing applications.

The FDM was used to analyze metal stripes (instead of metal slabs) on the same suspended structure. A symmetry-constrained LRSP confined in the plane transverse to the direction of propagation was found thereon, but the metal stripe design space is more limited than that of the corresponding metal slab because of an additional constraint to non-radiative LRSP guiding: the effective index of the LRSP must remain above those of the TE_0 and TM_0 modes supported by the dielectric slabs on either side of the stripe to ensure no lateral radiation into these modes. This constraint places upper bounds on the thickness and the refractive index of the membrane, and on how thin the stripe may be, thereby also placing a lower bound on the LRSP attenuation. Despite these constraints, practical stripe designs have been found for the candidate structure ($w = 5\ \mu\text{m}$, $t = 20\ \text{nm}$, $d = 380\ \text{nm}$, yielding a symmetry-constrained LRSP attenuation of $\sim 3.27\ \text{dB/mm}$ at $\lambda_0 = 1310\ \text{nm}$).

The structures are promising for sensors that operate with an aqueous solution and would otherwise require a low refractive index matched substrate to achieve LRSP guiding.

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