Loss compensation in long-range dielectric-loaded surface plasmon-polariton waveguides

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Abstract: Loss compensation in long-range dielectric-loaded surface plasmon-polariton waveguides is theoretically analyzed when rare-earth-doped double tungstate crystalline material is used as the gain medium in three different waveguide configurations. We study the effect of waveguide geometry on loss compensation at the telecom wavelength of 1.55 µm, and demonstrate that a material gain as small as 12.5 dB/cm is sufficient for lossless propagation of plasmonic modes with sub-micron lateral confinement when using waveguide ridges with gain.

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References and links


1. Introduction

Surface plasmon polaritons (SPPs), evanescent electromagnetic waves propagating along metal-dielectric interfaces, have been the subject of numerous studies due to their unique properties promising applications in a variety of fields, such as optical biosensing [1], data storage [2], photovoltaic cells [3], and highly integrated photonic circuits [4]. The great interest in plasmonic waveguides is largely due to their capability to confine the electromagnetic field below the diffraction limit, which can potentially lead to photonic circuits suitable for very large scale integration [4]. Another interesting feature of SPP waveguides is the high sensitivity to their immediate environment that makes them very attractive for realizing ultra-sensitive optical sensors [1]. Furthermore, the presence of metal in the midst of propagating mode fields enables a direct and very efficient electrical control of their propagation characteristics by making use of, for example, thermo-optic effects [5, 6].
Many different plasmonic waveguiding configurations have been proposed and demonstrated over the past few years [7-16]. In general, SPP waveguides are subject to a trade-off between mode-field confinement and propagation loss due to absorption in the metal, exhibiting either good optical confinement but short propagation distances, typically in the few tens of micrometers (e.g., dielectric-loaded SPP waveguides [13]), or long propagation distances (in the millimeter range) that necessitate large mode profiles (e.g., long-range SPP waveguides [14]). Recently, a novel type of plasmonic waveguide configuration was proposed, long-range dielectric-loaded surface plasmon-polariton (LR-DLSPP) waveguides that combine the millimeter-range propagation with a relatively strong mode confinement [15, 16]. Reduced propagation losses provided by this novel structure (albeit at the expense of higher tolerances and increased complexity of configuration) permit enlarging the range of gain materials that can be selected for loss compensation.

Many efforts have been directed towards compensating propagation losses in plasmonic waveguides by use of different gain materials [17-25]. Although providing very high gain, laser dyes exhibit a limited lifetime due to photo-bleaching, which forces continuous refreshment of a dye in the solution, making them unpractical for integrated devices. Semiconductor quantum wells, which are capable of providing exceptionally high material gain, also encounter difficulties for their integration into plasmonic structures. On the one hand, a thin insulating layer is needed between the metal and the semiconductor gain material, which limits the gain available for very confined plasmonic modes. On the other hand, in the case of larger plasmonic modes, the overlap between this larger mode and the nanometer-scale quantum well gain region limits the resulting modal gain. Nevertheless, compensation of plasmonic losses by semiconductor gain materials, leading to lasing, has recently been demonstrated [26-28].

Very large optical gain, ~950 dB/cm, has recently been achieved in a rare-earth (RE)-doped double tungstate crystalline waveguide [29]. RE-doped gain materials do not exhibit the limitations of laser dyes or semiconductor gain materials discussed above. Furthermore, the optical gain provided by RE ions possesses very interesting features. RE gain materials can amplify very-high-rate signals in the small-signal-gain regime without distortion [30]. They provide a large gain bandwidth up to a few tens of nanometers, which is interesting for broadband optical amplification and the generation of ultra-short laser pulses. Finally, they enable the production of very-narrow-linewidth lasers due to the lack of detrimental linewidth broadening effects characteristic of semiconductor lasers [31]. When RE ions are doped into a double tungstate crystal, very large gain can be obtained due to the large absorption and emission cross-sections of RE ions in these materials [32] and the large dopant concentrations possible without significant luminescence quenching because of the large inter-ionic separation provided by the crystalline structure of double tungstates [29].

In this paper, loss compensation in LR-DLSPP waveguides due to optical gain provided by a RE-doped double tungstate material incorporated into the LR-DLSPP configuration is theoretically studied. Several structures are discussed in detail. The effect of different waveguide parameters on the efficiency of the material gain to compensate propagation losses is evaluated. Lossless propagation is predicted for material gain as low as 12.5 dB/cm, while maintaining a mode size comparable to conventional dielectric-loaded surface plasmon-polariton waveguides [13].

2. Proposed structures

The generic LR-DLSPP structure includes a low-refractive-index substrate material, a buffer layer of a high-refractive-index material, a metal stripe and a dielectric ridge, the dimensions and refractive index of which should be chosen to balance the electric fields at both sizes of the gold stripe in order to ensure long-range propagation [15, 16]. The three waveguide geometries studied in this paper are shown in Fig. 1 and their corresponding material
properties are summarized in Table 1. The radiation wavelength utilized throughout this study is chosen in the telecom wavelength range and equal to 1.55 µm.

The materials considered in this study are selected for their availability in a standard microfabrication facility. They should be easy to deposit and pattern and the temperatures involved in the processes should be compatible with previous fabrication steps and integration onto a CMOS platform. In an attempt to stay as close as possible to the passive structures proposed in [15, 16], the substrate material chosen is SiO₂ (n ~ 1.46) and the metal selected is gold (n_{gold} = 0.55+j11.5 [33]). The dimensions of the gold stripe were fixed in all cases to a thickness of 15 nm [15, 16] and a width of 200 nm. In Structures 1 and 2, the gain material, RE-doped double tungstate with refractive index ~2.05, is added as the buffer layer by direct bonding. The ridge is made of the photo-patternable polymer benzocyclobutene (BCB) in Structure 1 (n_{BCB} ~ 1.535) and of polyimide (n ~ 1.9 [34]) in Structure 2. The effect of ridge material and dimensions on the efficiency of material gain to compensate the plasmonic losses was analyzed. Finally, in the third structure, the buffer layer is chosen as Si₃N₄ (n_{Si₃N₄} ~2.05) and the gain is added to the ridge instead of the buffer layer. A 100-nm-thin BCB adhesive layer is introduced between the buffer layer and the ridge as part of the integration of the gain material to the structure. Although this configuration leads to a more involved fabrication and integration process, it drastically reduces the necessary material gain for lossless propagation.

![Fig. 1. Layout of the LR-DLHPP structures with gain analyzed in this work. (a) Gain material, RE-doped double tungstate, as buffer layer and ridge in BCB. (b) Gain material in the buffer and polyimide ridge. (c) Gain material in the ridge, buffer layer in silicon nitride and 100-nm-thin BCB adhesive layer between buffer and ridge.](image)

Table 1. Parameters of the structures used for the simulations.

<table>
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<th></th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
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<tr>
<td>Buffer Material</td>
<td>RE double tungstate</td>
<td>RE double tungstate</td>
<td>Si₃N₄</td>
</tr>
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<td>h_{buffer} [µm]</td>
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<td>0.25-0.4</td>
<td>0.2-0.5</td>
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<tr>
<td>n_{buffer}</td>
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<td>2.05</td>
<td>2.05</td>
</tr>
<tr>
<td>Ridge Material</td>
<td>BCB</td>
<td>Polymide</td>
<td>RE double tungstate</td>
</tr>
<tr>
<td>h_{ridge} [µm]</td>
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<td>0.6-1.6</td>
<td>0.5-0.8</td>
</tr>
<tr>
<td>w_{ridge} [µm]</td>
<td>1-1.6</td>
<td>0.6-1.6</td>
<td>0.5-0.8</td>
</tr>
<tr>
<td>n_{ridge}</td>
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<td>1.9</td>
<td>2.05</td>
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<td>Metal Material</td>
<td>Gold</td>
<td></td>
<td></td>
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<tr>
<td>n_{gold}</td>
<td>0.55+j11.5</td>
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<tr>
<td>Substrate Material</td>
<td>SiO₂</td>
<td></td>
<td></td>
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<tr>
<td>n_{s}</td>
<td>1.45</td>
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3. Finite difference calculations

Finite difference (FD) calculations with perfect magnetic conductor (PMC) boundary conditions were carried out using the FieldDesigner module of PhoeniX B.V. [35]. A perfectly matched layer (PML), which absorbs both outgoing and reflected radiation, was also
applied around the calculation window. A sufficiently large calculation window, 20 µm by 20 µm, was used. Special attention was paid to the grid size due to the large difference in dimension between the different parts of the simulated structure (i.e., thickness of the gold layer, 15 nm, and buffer layer, 40-500 nm, versus height of the ridge in the micrometer range). FieldDesigner permits the utilization of a dynamic grid. In order to ensure that enough grid points were assigned to the thinner layers (i.e., buffer and gold layer) present in the y-direction, these thin structures were artificially divided in the required number of sublayers. In such configuration, the software assigns at least a grid point at the interface between two such sublayers. The number of layers was selected so that the addition of more layers only produced negligible variation in the results. Such construction permits using 129 × 129 grid points without loss of accuracy when compared with the results obtained with a mesh of 129 × 1025 grid points (i.e., denser grid in the y-direction), but drastically reducing the computation time. In the x-direction, the dimensions are relatively large and, therefore, such construction was not necessary. Fig. 2 shows an example of the mesh utilized in the simulations for Structure 1. In the metal, a grid size of 0.75 nm was utilized (i.e., the metal stripe of 15 nm thickness was represented by 20 sublayers). Such a fine mesh size sufficiently resolves the electromagnetic field inside the metal.

Fig. 2. Mesh utilized in the simulations. (a) General view of Structure 1, i.e., BCB ridge and double tungstate buffer layer. (b) Zoom into the gold stripe region, marked as the red dashed rectangle in (a).

The different modes supported by the structures were calculated for a vacuum wavelength of 1.55 µm. The structures were verified to support a long-range SPP mode (TM polarized) and, in some cases, radiative TE modes with much shorter propagation distance than the main long-range SPP mode (i.e., typically less than a few tens of micrometers). From the imaginary part of the effective refractive index of the long-range SPP mode, the propagation losses (or gain when the sign is negative) of the different structures were calculated as:

\[
\alpha [\text{dB/cm}] = 2 \times k_0 \times \text{Im}(n_{\text{eff}}) \times 4.34
\] (1)

Here \(k_0\) is the vacuum wavevector, \(2\pi/\lambda\), where \(\lambda\) is the vacuum wavelength in cm, \(n_{\text{eff}}\) is the effective refractive index of the propagating SPP mode, and the factor 4.34 converts the loss value from 1/cm to dB/cm. The imaginary part of \(n_{\text{eff}}\) is positive for lossy materials, and becomes eventually negative for materials exhibiting sufficiently large optical gain. The absorption losses of RE-doped double tungstates responsible for the optical gain have been ignored in the simulations. In the case of passive structures, it has been assumed that the necessary optical pump power has been applied to the gain material in order to compensate for the absorption losses and obtain \(\text{gain} = \text{loss} = 0\) (i.e., zero imaginary part of the refractive index). It has also been assumed that the gain achieved in the material is uniform. The anisotropy of the double tungstate materials has not been considered, as it was assumed that the waveguides are aligned along one of the major axes of the optical indicatrix.
The optical power confinement in the gain region is an important parameter, as it determines how effective the material gain is in compensating the propagation losses. Another important parameter is the mode size, especially in the x-direction, as it indicates the mode confinement in the different configurations. Depending on the application, a mode size as small as possible in one or both directions can be an important design parameter. The mode size has been calculated as the width of a Gaussian fit to the major component of the H-field at the level of 1/e of its maximum value.

4. Effect of waveguide structure on loss compensation

A number of waveguide parameters must be taken into account for optimization of the waveguide structure. These parameters comprise the ridge material, ridge size (width and height), buffer layer material and thickness, metal stripe material, thickness, and width, and substrate material. In this work, the metal was fixed to gold with a width of 200 nm and a thickness of 15 nm. The effect of the remaining parameters on the net gain finally achieved in the LR-DLSPP waveguides will be discussed in this section.

4.1 LR-DLSPP waveguide with BCB ridge

Structure 1 was simulated as described in Section 3. Fig. 3 shows the transverse mode profile of the long-range SPP mode supported by the structure. A propagation loss of 3.6 dB/cm and mode width of 1.7 µm in the horizontal x-direction and 2.5 µm in the vertical y-direction were calculated for \( h_{\text{buffer}} = 60 \text{ nm} \) and \( h_{\text{ridge}} = w_{\text{ridge}} = 1.4 \mu \text{m} \). This structure exhibits two main drawbacks. Firstly, the thickness of the buffer layer is too thin to be easily realized in a double tungstate gain material. Secondly, as can be clearly seen in Fig. 3, the optical power confinement in the gain region (buffer layer) is very small (~2 %). The much lower refractive index of the ridge structure is more favorable for the plasmonic mode than the high refractive index of the buffer, pulling a large fraction of the optical power above the metal stripe. As a consequence, this structure is not very efficient to obtain lossless propagation or propagation with net gain. In order to permit penetration of the mode into the gain region, a structure with a better balanced refractive index profile is desirable. This goal can be achieved by selecting a high-refractive-index material for the ridge, such as polyimide.

4.2 LR-DLSPP waveguide with polyimide ridge

Using polyimide (\( n \approx 1.9 \) at 1.55 \( \mu \text{m} \) wavelength [34]) as the ridge material, the effective refractive indices on both sides of the metal stripe are better balanced than in the previous case (Structure 1), permitting the LR-SPP mode field to penetrate much stronger into the gain buffer layer. Fig. 4 shows the evolution of net loss versus buffer layer thickness for a fixed
ridge height (0.6 µm) and several ridge widths (0.8 to 1.6 µm) for several material gain values of the buffer layer [(a)-(d)]. Fig. 5 shows the same evolution, however for a fixed ridge width (1.6 µm) and several ridge heights (0.6 to 1.6 µm). Note that the occurrence of net modal gain corresponds to the net loss of LR-SPP mode being negative.

Fig. 4. Effect of ridge width in Structure 2. Net optical loss versus thickness of buffer layer for a fixed ridge height (0.6 µm) and several ridge widths (0.8-1.6 µm). Several buffer layer material gain values have been studied. (a) 0 dB/cm. (b) 35 dB/cm. (c) 106 dB/cm. (d) 246 dB/cm. (e) Power confinement to the gain region (buffer layer). (f) Lateral mode width in the x-direction.

For a passive structure (i.e., a material gain of 0 dB/cm), as the ridge width increases for a given ridge height [Fig. 4 (a)], the losses decrease and the location of the minimum loss shifts towards larger buffer thicknesses that balance increasing ridge widths. As the ridge width increases, the field intensity close to the metal layer decreases, because the mode is pulled both into the ridge and buffer layers, increasing the ratio between the mode power concentrated in dielectric regions and that in the (absorptive) metal region. The propagation losses are, therefore, reduced. For each ridge dimension, the waveguide structure providing minimum losses corresponds to the configuration for which the mode is balanced on the top and bottom of the metal stripe [15]. For a given ridge height, as the ridge width increases, this
condition is met for thicker buffer layers, as can be appreciated in Fig. 4 (a). As the ridge width increases, both the mode confinement to the active layer [Fig. 4 (e)] and the mode width in the x-direction [Fig. 4 (f)] increases. Comparison of Fig. 4 (a) to (d) indicates that with increasing material gain of the buffer layer the parameter space for which net gain is obtained increases. For a buffer layer material gain of 246 dB/cm [Fig. 4(d)] practically all investigated geometrical configurations exhibit net gain. A similar physical behavior governs the influence of ridge height on net loss (Fig. 5).

Fig. 5. Net optical loss versus thickness of buffer layer in Structure 2 for a fixed ridge width of the ridge (1.6 µm) and several ridge heights (0.6-1.6 µm). Several buffer layer material gain values have been studied. (a) 0 dB/cm; (b) 35 dB/cm. (c) 106 dB/cm. (d) 246 dB/cm. (e) Confinement to active buffer layer. (f) Lateral mode width in the horizontal x-direction.

Two distinct zones can be observed. In the first zone (i.e., small buffer thickness), losses increase as the ridge height increases. In the second zone (i.e., large buffer thickness), the opposite behavior is observed. The behavior in both zones can again be qualitatively explained by the fact that the losses decrease, as the effective refractive indices above and below the metal stripe approach the point of balance. For small buffer layer thickness and
fixed ridge width, as the height of the ridge increases, the structure moves farther away from this low-loss condition. For large buffer thickness, the opposite occurs: as the ridge height increases, the structure moves closer to the balanced condition. In all cases, the minimum propagation loss as a function of buffer thickness shifts to larger buffer thicknesses, as the height of the ridge increases. An increase of ridge height forces both the mode confinement to the active layer [Fig. 5 (e)] and the lateral mode width in the $x$-direction [Fig. 5 (f)] to decrease. Again, with increasing material gain of the buffer layer the parameter space for which net gain is obtained increases, and, for the highest investigated buffer layer material gain of 246 dB/cm [Fig. 5 (d)] practically all investigated geometrical configurations provide net gain.

The net modal loss (or gain) is determined by two contributions, the LR-SPP mode propagation loss and the optical gain of the mode fraction confined within the gain material, and can be evaluated as follows:

$$\alpha_{\text{net}} = \alpha_{\text{loss}} - \Gamma g_{\text{mat}}$$  \hspace{1cm} (2)$$

where $\alpha_{\text{net}}$ is the net modal loss in dB/cm, $\alpha_{\text{loss}}$ is the propagation loss of the passive structure in dB/cm [Eq. (1)], $\Gamma$ is the fraction of optical power overlapping with the gain region (in this case the buffer layer), and $g_{\text{mat}}$ is the material gain provided by the material utilized in the gain region. One can qualitatively explain the dependencies shown in Fig. 5 (a)-(d) by combining the loss dependencies in the absence of material gain [Fig. 5 (a)] with the corresponding dependencies of the mode confinement within the gain material [Fig. 5 (e)] in accordance with Eq. (2). Indeed, for a given ridge dimension, the mode fraction confined within the active area increases as the thickness of the buffer layer increases [Fig. 5 (e)]. Therefore, the compensation of propagation losses is more efficient for larger buffer layer thicknesses, a circumstance that results in shifting the location of minimum losses [Fig. 5 (b)-(d)]. It is, therefore, apparent that not only the waveguide dimensions but also the expected material gain should be considered in the design of the optimized structures. For example, although the combination $h_{\text{ridge}} = 1.6 \mu m$ and $w_{\text{ridge}} = 1.6 \mu m$ provides the lowest net loss [Fig. 5 (a)], this ridge structure is the one providing the lowest net gain for the material gain of 106 dB/cm due to lower confinement of the optical power to the gain region [Fig. 5 (e)]. If lossless propagation should be achieved, a material gain of ~37 dB/cm in a 375-nm-thick buffer layer would be sufficient for a ridge with $h_{\text{ridge}} = w_{\text{ridge}} = 1.6 \mu m$, resulting in the LR-DLSP mode being 1.4-μm wide. Fig. 6 shows the 2-dimensional mode profiles and vertical mode profile across the center of the metal stripe for Structure 2 for a 1.6-μm-wide ridge and two different ridge heights, 0.6 μm [Fig. 6 (a)] and 1.6 μm [Fig. 6 (b)].
Fig. 6. Two-dimensional mode profile and vertical mode profile across the center of the metal stripe for Structure 2 at zero gain. (a) Ridge height 0.6 µm, ridge width 1.6 µm, buffer thickness 0.25 µm. (b) Ridge height 1.6 µm, ridge width 1.6 µm, buffer thickness 0.375 µm.

4.3 LR-DPSPP with Si₃N₄ buffer layer and gain ridge

As was discussed in the previous sections, substantial mode confinement in the gain material is necessary in order to enhance the net modal gain. In all the cases described above, the optical power confinement to the ridge region was larger than that to the buffer layer. It is, therefore, desirable to fabricate the ridge in the gain material whenever the application permits (Structure 3 in Fig. 1 (c)).

The net loss of such a structure was simulated as a function of thickness of the buffer layer for several ridge dimensions. The power confinement to the active region (in this case the ridge) and lateral mode dimension in the horizontal $x$-direction were also calculated. In Fig. 7 (a), (c), and (e), the effect of ridge width is shown for a given ridge height. As the ridge width increases, the propagation loss minimum shifts towards thicker buffer layers, consistent with the balancing of the effective refractive indices above and below the metal stripe. Furthermore, increasing the ridge width leads to a decrease of the minimum of the propagation losses, slight increase in mode waist in the horizontal $x$-direction, and increase of mode confinement to the active area (ridge). The latter effect improves the exploitation of available material gain, which is shown in Fig. 8 for two values of material gain. The influence of the ridge height is shown in Fig. 7 (b), (d), and (f). As the ridge height increases, the propagation loss minimum shifts towards thicker buffer layers, again as a result of balancing the refractive indices at both sides of the metal. The mode size in the $x$-direction increases, as the ridge height decreases. This phenomenon can be intuitively explained by the squeezing out of the optical mode, as the ridge height decreases, forcing the mode to widen in the $x$-direction. The mode confinement to the ridge also decreases, because the mode is pushed towards the metal by a reduction of the ridge height.
Finally, for obtaining a manufacturable design it is important that the waveguide behavior does not change drastically if the ridge height or width or thicknesses of the buffer and adhesive layer vary within typical fabrication tolerances. In Fig. 8, the minima for the ridge dimensions 0.8 μm × 0.8 μm are flatter than those for the ridge dimensions 0.8 μm × 0.5 μm. Therefore, the larger ridge will be more tolerant to small variations of the buffer thickness (in this case determined by control of the Si₃N₄ deposition process). Furthermore, at the target buffer thickness, h_buffer = 0.35 μm, the curves corresponding to ridge widths of 0.8 μm and 0.7 μm are very close to each other. Thus, a small variation of the ridge width, controlled by the lithography and etching processes, should have very little influence on the characteristics of the final devices. The same applies for the ridge height [Fig. 7 (b)]. The influence of thickness of the adhesive layer has been analyzed for a passive structure with 0.8 μm × 0.8 μm ridge size. As the thickness of the adhesive increases, the mode becomes
more confined in the ridge, losing its plasmonic character. A tolerance of ~50 nm around the 100-nm target can, however, be tolerated.

Fig. 8. Net optical loss in Structure 3 for $h_{ridge} = 0.8 \mu m$ and various $w_{ridge}$ when assuming a material gain of (a) 35 dB/cm and (b) 106 dB/cm.

Table 2. Waveguide dimensions and mode profiles for a large ridge structure (Waveguide 1) and for a smaller ridge structure (Waveguide 2).

<table>
<thead>
<tr>
<th>Waveguide 1</th>
<th>Waveguide 2</th>
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<td>Ridge height [µm]: 0.8</td>
<td>Ridge height [µm]: 0.8</td>
</tr>
<tr>
<td>Ridge width [µm]: 0.8</td>
<td>Ridge width [µm]: 0.5</td>
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<tr>
<td>Buffer height [µm]: 0.35</td>
<td>Buffer height [µm]: 0.25</td>
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<tr>
<td>Mode width $X$ [µm]: 0.92</td>
<td>Mode width $X$ [µm]: 0.78</td>
</tr>
<tr>
<td>Mode width $Y$ [µm]: 1.1</td>
<td>Mode width $Y$ [µm]: 1.08</td>
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<tr>
<td>Gain for lossless propagation [dB/cm]: 12.5</td>
<td>Gain for lossless propagation [dB/cm]: 26</td>
</tr>
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</table>

Fig. 9. (a) and (b) Vertical and 2-D mode profile (Re[$E_y$]) of Waveguide 1 described in Table 2. (c) and (d) Vertical and 2-D mode profile (Re[$E_y$]) of Waveguide 2 described in Table 2.
6. Conclusions

Loss compensation in plasmonic waveguides will pave the road toward utilization of these structures in a wide range of novel devices by permitting full exploitation of their potential. In this paper, a detailed investigation of the compensation of propagation loss in LR-DLSPP waveguides using RE-doped double tungstates as the gain material has been presented for three different configurations that were selected keeping in mind manufacturability using fabrication and assembly equipment commonly available in standard microfabrication cleanrooms. In the first two structures, the gain material is integrated as a buffer layer. We found that only a small fraction of the mode power is confined within the material gain region, making this approach not very favorable for loss compensation. Nevertheless, using a high-refractive-index ridge made of polyimide ($n \approx 1.9$) resulted in an increased mode confinement to the gain material. It was also found that, in the design of optimized structures, one should consider simultaneously the LR-SPP waveguide dimensions and the available material gain. For example, it was demonstrated that a material gain of $37 \text{ dB/cm}$ is sufficient to achieve lossless propagation in a LR-DLSPP waveguide structure with a $1.6 \times 1.6 \mu m^2$ ridge and a $375$-nm-thick buffer layer. In general, configurations with larger mode fractions within the gain (buffer) layer resulted in larger lateral mode widths, which are detrimental with respect to the bend loss (that increases with the mode width) and maximum achievable density of waveguide components [15, 16].

In the third structure, the gain material was integrated as the ridge material. A 100-nm-thin BCB layer was introduced between the gold stripe and the waveguide ridge in order to ease manufacturability. This structure ensures a considerably higher confinement of the mode optical power in the active material region, making the LR-DLSPP waveguide configuration much more amenable with respect to loss compensation. A material gain as low as $12.5 \text{ dB/cm}$ is sufficient to allow for lossless propagation in a waveguide structure with a $0.8 \times 0.8 \mu m^2$ ridge and 350-nm-thick buffer layer. Simultaneously, the hybrid LR-DLSPP mode supported by this structure has a lateral width of only $0.92 \mu m$.

The structures considered in this paper show a great potential to reach the goal of loss compensation in plasmonic waveguides and are promising for plasmon amplification and lasing. The low material gain required to compensate propagation losses broadens the range of gain materials that can be utilized. RE-doped double tungstate gain materials were selected in this study due to their very good match of refractive index with the materials utilized in the structure and the elevated gain they can provide. Experimental demonstration of LR-DLSPP waveguides corresponding to the considered structures will constitute the next milestone on the way towards lossless plasmonic waveguides.

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