Optimizing the design of planar heterostructures for plasmonic waveguiding

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Received October 28, 2011; revised January 27, 2012; accepted January 30, 2012; posted January 31, 2012 (Doc. ID 157323); published March 6, 2012

We theoretically investigate planar heterostructures for subwavelength guiding of surface plasmon modes and optimize their design to enhance the waveguiding efficiency. We show that by appropriately selecting the thicknesses of metallic and dielectric layers of a two-layer waveguide, one can compensate the intrinsic damping of the mode by having minimal optical gain in the dielectric region. We also reveal that mode confinement can be significantly improved by the use of an additional metal layer adjacent to the dielectric, to form a metal–dielectric–metal (MDM) structure. By varying the layer thicknesses in the MDM waveguide, we demonstrate that the propagation length of the plasmonic mode can be maximized. We further show that the losses may be suppressed by minimal gain in the dielectric region by the careful choice of geometrical parameters. We note that the associated gain levels are relatively small; for example, the losses in a 300 nm thick Ag–ZnO–Ag waveguide can be compensated by a gain of ~225 cm⁻¹. Our results may prove useful for the realization of efficient optical interconnects in high-density nanophotonic circuitry. © 2012 Optical Society of America

OCIS codes: 230.7390, 250.5403, 240.0680.

1. INTRODUCTION

Because of the rapid increase in demand for ultrasmall optical devices and the need for highly compact nanophotonic circuitry, the field of plasmonics has received considerable attention over the recent years [1]. Researchers have focused on the means of gaining ultimate control over light at nanoscale, which is beneficial for a number of promising applications, including high-speed optical computing, biosensing [2], surface enhanced Raman spectroscopy [3], scanning near-field optical microscopy [4,5], and for the realization of plasmonic-based nanophotonic circuit elements such as interconnects, switches, couplers, and modulators [6–9]. The operation of these devices primarily relies on subwavelength guiding of the optical modes, which can be achieved using plasmonic waveguides [10]. Structures of different geometries have been identified as candidates for plasmonic waveguiding, such as planar waveguides [11,12] cylinders of circular [13,14] and square [15] cross sections, triangular metal wedges [16], dielectric gaps [18], as well as coupled metal [19] and composite [20] nanoparticles.

One of the key performance indicators of a plasmonic waveguide is its losses, which determine the lifetime of the plasmon mode. Several factors may contribute toward the waveguide losses, such as scattering losses that arise from surface imperfections, absorption losses in dielectrics, and ohmic heating in metals. The scattering losses may be minimized by the sophisticated fabrication techniques that are available in advanced material engineering technology [21]. At visible and telecommunication wavelengths, the losses in metals are predominantly high when compared with the absorption losses in dielectrics [22]. In order to reduce the detrimental effect of metal losses at optical frequencies, a significant portion of the SPP mode should be kept away from the metal [23]. However, these losses cannot be entirely eliminated, as metals are essential to sustain and guide plasmonic modes. Yet, they can be compensated by optical gain in the adjacent dielectric medium [18,24,25]. Although it is always possible to counteract the losses by increasing the gain, achieving high levels of gain can sometimes be challenging due to various reasons, such as limitations introduced by the material properties of the medium and the temperature of operation. Thus it is essential that the waveguide is optimally designed in such a way that the amount of the required gain level is minimal.

In our previous work, we optimized the design of cylindrical composite nanowires to minimize the gain requirement [14,26]. In this paper, we optimize the design of planar composite plasmonic waveguides to ensure efficient waveguiding of surface plasmon polaritons (SPPs). In Section 2, we briefly introduce the theory of SPP propagation in planar heterostructures and the gain model we use. Metal–dielectric waveguides are discussed in Section 3, where we come up with key design guidelines that ensure the compensation of losses with minimal gain. We investigate metal–dielectric–metal (MDM) waveguides in Section 4, in order to show that the mode confinement is significantly improved and optimize the waveguide design to maximize the propagation length of SPPs and compensate for the losses with minimal gain. The summary of our findings is presented in Section 5, which concludes the paper.

2. SPP MODES GUIDED BY PLANAR HETEROSTRUCTURES

Consider the multilayered planar plasmonic waveguide shown in Fig. 1, in which layers 1 and n extend to infinity. The electric field of the TM-polarized mode associated with the SPPs
propagating in the $z$ direction can be expressed in the form [27]

$$\mathbf{E}(x,z,t) = \frac{1}{2} [i \mathbf{E}_x(x) + \hat{y} \mathbf{E}_z(x)] \exp[i(\beta z - \omega t)] + \text{c.c.}$$

where $\beta = \beta' + i\beta''$ is the propagation constant, $\omega$ is the SPP frequency, and $\hat{y}$ is the unit vector of the axis $s$. The field amplitudes in the $j^{th}$ medium satisfying Maxwell’s equations are [28]

$$E_{\alpha j} = \frac{\beta}{c} [A_j \exp(\alpha_j x) + B_j \exp(-\alpha_j x)],$$

$$E_{\gamma j} = \frac{i\epsilon_j}{c} [A_j \exp(\alpha_j x) - B_j \exp(-\alpha_j x)],$$

$$H_{yj} = A_j \exp(\alpha_j x) + B_j \exp(-\alpha_j x),$$

where $k = \omega/c$, $\alpha_j = (\beta^2 - \epsilon_j k^2)^{1/2}$, $A_j$ and $B_j$ ($j = 1, \ldots, n$) are complex coefficients, and $H_{yj}$ is the component of the magnetic field along the $y$ direction. To ensure that the fields are finite for $x \to \pm\infty$, one should set $A_n = 0$ and $B_1 = 0$.

The value of $\beta$ can be calculated using the dispersion equation that is derived by ensuring the continuity of the tangential components of the fields $E_z$ and $H_y$ across the material interfaces (see Fig. 1). The quantities $\beta'$ and $\beta''$ determine the guiding wavelength and the attenuation coefficient of SPPs, respectively. If the materials are lossless (i.e., $\text{Im} \epsilon_j = 0$), the solution of the dispersion equation may lead to propagating modes with $\beta'' = 0$ and $\beta' \neq 0$, and evanescent modes with $\beta'' \neq 0$ and $\beta' = 0$. At the telecommunication wavelengths of interest, the absorption in dielectrics is relatively low and can be readily neglected, but the metallic losses are significant. In this case, the solution of the dispersion equation corresponds to complex modes with $\beta' = 0$ and $\beta'' \neq 0$. We consider only those complex modes that arise from the propagating modes.

The propagation length of the SPP mode is characterized by its propagation length $L_{\text{SPP}} = (2\beta'')^{-1}$, defined as the distance at which the intensities of the mode fields attenuate by a factor of $1/e$ [27]. When the mode is strongly localized to the interface, the damping of SPPs becomes more pronounced. In this case, $L_{\text{SPP}}$ can even be as low as a few wavelengths, and may limit the usability of the waveguide because of its high losses. However, it is known that these losses can be compensated by providing optical gain to the adjacent dielectric medium [29]. Practically, gain may be achieved by pumping the medium optically or electrically [30,31]. We assume that the difference in the pump and signal wavelengths is much larger than their bandwidths, and we neglect the interference between them. We model gain by assuming a negative imaginary part for the dielectric permittivity [14,29], i.e.,

$$\epsilon_j = \epsilon_j' - i\gamma_j = \epsilon_j' - i\gamma \sqrt{\epsilon_j'/\kappa},$$

where $\gamma$ is the gain coefficient. It should be noted that because $\epsilon_j'$ and $\epsilon_j''$ are linked to each other via the Kramers–Kronig relations, the inclusion of gain to the system would impose a change on $\epsilon_j''$ [32]. However, this change is extremely small and can be safely neglected [32–34]. With increasing $\gamma$, $L_{\text{SPP}}$ also increases as a result of the compensation for metallic losses [18]. When the gain reaches a certain limit (which we refer to as the critical gain, $\gamma_c$), the losses are entirely compensated and $L_{\text{SPP}}$ becomes infinite. Increasing gain beyond this limit would result in amplification of SPPs.

### 3. METAL–DIELECTRIC WAVEGUIDES

Consider first a metal–dielectric waveguide consisting of adjoined metal and dielectric slabs, as shown in Fig. 2(a), and assume that $\epsilon_n = \epsilon_1$. Compared to the simpler structure of a metal-slab waveguide (which corresponds to $d = 0$), the extension of SPP fields to the surrounding medium is significantly reduced in the metal–dielectric waveguide, as some of the mode energy may reside within its dielectric region. Furthermore, if doped with rare earth ions, one may optically pump the dielectric layer of the metal–dielectric waveguide to

![Fig. 1. (Color online) Planar heterostructure consisting of $n$ layers made of dielectrics and metals; $\epsilon_j$ is the permittivity of the $j^{th}$ layer. The heterostructure is assumed to extend infinitely in the $y$ direction.](Image 328x98 to 534x209)

![Fig. 2. (Color online) (a) Schematic of the metal–dielectric waveguide and the notations employed. (b) Density plot of electric field amplitude for a Ag–ZnO waveguide surrounded by air. It is assumed that $d = 250 \text{ nm}$ and $h = 50 \text{ nm}$.](Image 328x98 to 534x209)
compensate for the metallic losses. Although the SPP damping in a metal-slab waveguide can also be suppressed by pumping the host medium, this method is less efficient because it would increase the functional size of the waveguide in nanophotonic circuitry.

The dispersion relation governing the propagation of SPPs in the metal–dielectric waveguide is of the form

\[-\tanh(\alpha_x h) = \frac{\alpha_x^2 \epsilon_2^2}{\alpha_x^2 \epsilon_2^2 + \alpha_x^2 \epsilon_3^2 + \alpha_x^2 \epsilon_1^2} + \alpha_x \epsilon_1 \tanh(\alpha_x d)(\alpha_x^2 \epsilon_2^2 + \alpha_x^2 \epsilon_3^2)\].

It should be noted that by setting \(d = h\) and \(\epsilon_3 = \epsilon_2\) in this equation, one may obtain the dispersion relation of a three-layer planar heterostructure [35].

We solve the dispersion equation numerically, at the wavelength of 1.55 \(\mu\)m. Figure 3(a) shows the variation of \(\gamma_c\), with the parameter \(p\), which denotes the dielectric thickness as a fraction of the total waveguide width, i.e.,

\[p = d/w,\]

where \(w = d + h\). It is important to note that for relatively thick waveguides (\(w = 100, 150,\) and \(200\) nm), \(\gamma_c\) becomes minimal (\(\gamma_c = \gamma_0\)) at a certain \(p\) value (\(p = p_0\)) between 0 and 100%. Thus, one can compensate for the losses in the waveguide with minimal pump power at the optimal dielectric slab thickness \(p_0\). As shown by the blue curve in Fig. 3(b), the gain requirement decreases when the thickness of the waveguide is increased. This can be explained by the variation of \(p_0\) with the waveguide width [see the red curve in Fig. 3(b)].

When the waveguide thickness is increased, the optimum thickness of the dielectric increases. This means that the thickness of the gain medium (\(h\)) is higher in relatively thick waveguides, and hence the losses may be compensated with lesser pump power. We note that the gain requirement can be significantly reduced by choosing a thicker waveguide. For example, the gain needed for a waveguide with \(w = 300\) nm is about 184 \(\text{cm}^{-1}\), which is approximately 7% of that needed for an 80 nm thick waveguide. The value of \(p_0\) for waveguides thinner than ~80 nm is unity [see the red curve in the shaded region in Fig. 3(b)]. In this region, SPPs do not exist because the waveguide is purely dielectric.

Even though in a metal–dielectric waveguide the SPP field confinement is always better than that of a metal-slab waveguide, the extension of fields to the surrounding medium may still be appreciable. This can be clearly seen from Fig. 2(b), which shows the density plot of the electric field for a 300 nm thick Ag–ZnO waveguide. We note that the extension of fields to the outer medium is even more pronounced for thinner waveguides. This may limit the applicability of the waveguide in high-density nanophotonic circuitry, as the SPPs can tend to couple with nearby circuit elements. A possible way to enhance the field confinement is to cap the waveguide with another metal slab to form an MDM structure, which will be discussed in the following section.

4. METAL–DIELECTRIC–METAL WAVEGUIDES

We investigate the MDM waveguide shown in Fig. 4(a), in which we assume that the thicknesses of the two metal layers are equal. This structure supports the propagation of SPPs along both the outer (\(\epsilon_3 - \epsilon_2\)) and inner (\(\epsilon_3 - \epsilon_1\)) metal–dielectric interfaces. The propagation length of SPPs corresponding

\[\text{Fig. 3. (Color online) (a) Critical gain as a function of relative thickness } p \text{ of the dielectric layer and (b) minimum critical gain } \gamma_0 \text{ (blue curve, left scale) and optimum thickness } p_0 \text{ (red curve, right scale) corresponding to } \gamma_0. \text{ The simulations were performed for a Ag–ZnO waveguide shown in Fig. 2(a); the material parameters are } \epsilon_1 = 1, \epsilon_2 = -120 + 3.3i \{22\}, \epsilon_3 = 3.73 \{30\}.\]

\[\text{Fig. 4. (Color online) (a) Schematic of MDM waveguide and the notations employed. (b) Density plot of electric field amplitude for a Ag–ZnO–Ag waveguide surrounded by air. The simulation parameters are } d = 120 \text{ nm and } h = 90 \text{ nm.}\]
to the outer interfaces is comparatively high, but the mode confinement is significantly poor. Thus, we only consider the propagation of SPPs associated with the inner interfaces, which ensures strong mode confinement. Even though the propagation losses of SPPs for the inner interfaces are high, we note that these losses may be compensated by providing the dielectric layer with gain. The dispersion relation of SPPs propagating along the MDM waveguide is given by

$$\tanh\left(\frac{\alpha_1 d}{2}\right) = \frac{\alpha_1 \epsilon_1}{\alpha_2 \epsilon_2} \tanh(\alpha_2 h) + \alpha_1 \epsilon_1 \frac{\alpha_2 \epsilon_2}{\alpha_1 \epsilon_1} \tanh(\alpha_1 h) + \alpha_2 \epsilon_2 \frac{\alpha_1 \epsilon_1}{\alpha_2 \epsilon_2}$$

It is readily seen that in the limits $\alpha_1 d \to 0$, $\alpha_2 h \to 0$, or $\alpha_2 h \to \infty$, the dispersion equation for a three-layer planar heterostructure [35] is again recovered.

When the dielectric layer is relatively thin, as is assumed in this paper, the SPPs in the two metal–dielectric interfaces are coupled. If the metal layers are thicker than the skin depth (for example, $h \gtrsim 20 \text{ nm}$ for Ag), almost the entire mode energy can be retained within the waveguide, thereby minimizing the extension of fields to the surrounding medium. Thus, the MDM waveguide features excellent field confinement [see Fig. 4(b)] as opposed to the metal–dielectric waveguide [see Fig. 2(b)].

A. Passive MDM Waveguides

Despite the fact that strong field confinement of SPPs can always be realized by having sufficiently thick metal layers, if the metal thickness is too large, it would increase the propagation losses of the mode. To investigate the dependency of the metal thickness on mode losses, we calculate the propagation length of SPPs for different material thicknesses of the waveguide. For this purpose, it is useful to define the parameter

$$q = 1 - d/w,$$

where $w = d + 2h$, which denotes the total metal thickness as a fraction of the total waveguide width.

In the limit $q \to 0$, the metal thickness vanishes and the hence the SPPs are no longer sustained. Similarly, the propagation of SPPs is ceased in the limit $q \to 1$, owing to the absence of the dielectric region. Thus, one may reasonably expect an optimum propagation condition for the SPPs amidst these two extreme cases. To examine this, in Fig. 5(a), we plot the propagation length of SPPs as a function of $q$. As expected, $L_{\text{SPP}}$ becomes maximum at an optimum $q$ value ($q_{opt}$). The blue curve in Fig. 5(b) shows the maximum propagation length of SPPs that can be achieved by adjusting the metal/dielectric layer thickness to the optimum value. It is important to note that despite the strong field confinement and subwavelength scale waveguide widths, the MDM waveguide is capable of carrying optical signals over reasonably large distances if fabricated with the optimal metal/dielectric layer thickness (e.g., for a 300 nm thick waveguide, $L_{\text{SPP}} = 40 \mu m$). The optimum $q$ values that enable the longest propagation length of SPPs are shown by the red curve in Fig. 5(b).

B. Active MDM Waveguides

For relatively thin MDM waveguides, $L_{\text{SPP}}$ is considerably low (for example, $<4 \mu m$ when $w < 60 \text{ nm}$). Thus, for efficient operation of the waveguide, it is essential to enhance the propagation length of the SPPs by providing optical gain to the dielectric. To achieve gain, one may optically pump the doped dielectric layer in the $x$ direction, in cases where the metal is sufficiently thin [26]. In Ref. [18], Maier investigated the gain-assisted propagation of SPPs along a dielectric gap between two metallic half-spaces. The MDM waveguide holds a close resemblance to the above geometry, except for its metallic regions being of finite width. In fact, it may be considered as the structure which is closer to the real-life scenario.

Similar to the case of metal–dielectric waveguide, we examine the variation of critical gain by varying the metal/dielectric thickness. Importantly, the critical gain becomes minimal at a certain $q$ value [see Fig. 6(a)]. The solid blue curve in Fig. 6(b) shows the $\gamma_0$ values as a function of the waveguide width. For comparison, the gain required by the metal–dielectric waveguide is also shown by the dashed blue curve. It is observed that for waveguides thinner than $\sim 200 \text{ nm}$, the gain required by the MDM waveguide is lesser than that needed by the metal–dielectric waveguide. The reduction in gain is more pronounced for waveguides with $50 \text{ nm} \lesssim w \lesssim 100 \text{ nm}$. The red curve in Fig. 6(b) shows the thickness of the dielectric for which the required gain becomes minimum. It is worth noting that the variation of $d$ with $w$ is approximately linear in the range $150 \text{ nm} < w < 300 \text{ nm}$. Thus, it is possible to readily estimate the optimum material thickness that allows the compensation of losses by minimal pump power. For example, in an Ag–ZnO–Ag waveguide, the value of optimal thickness of the dielectric layer, which enables the compensation for losses by a minimal amount of gain, can be approximately related to the width of the waveguide as $d = 0.81w - 46$.

As a concluding remark, we would like to emphasize that the gains we report for optimally designed waveguides are of
the same order of magnitude of that have been previously achieved [37,38]. However, optical gain in ZnO has been demonstrated at wavelengths in the vicinity of its bandgap (∼3.3 eV [29]) and, hence, realizing gain at the wavelength of 1.55 μm (∼0.8 eV) would be challenging. One may possibly overcome this difficulty by doping ZnO with Er ions—the method used to achieve optical emission in the 1.55 μm band [40,41].

5. CONCLUSIONS

In this work, we analyzed plasmonic waveguiding in planar heterostructures and found important design guidelines that are vital for efficient propagation of SPPs. For a metal–dielectric waveguide, we showed that the metal/dielectric layer thickness can be set to an optimum value, in order to ensure the compensation of the metallic losses with minimal gain in the dielectric region. We further showed that the mode confinement of a metal–dielectric waveguide can be significantly improved by capping the dielectric region by another metal layer to form an MDM structure. We observed that in the MDM waveguide, the mode energy can be almost entirely concentrated into the dielectric layer, and thereby the effect of metallic losses can be reduced. By selecting the metal/dielectric layer thickness appropriately, the propagation length of SPPs can be maximized. Furthermore, the gain required for compensating for the propagation losses can be minimized by the careful choice of geometrical parameters of the waveguide. We found that the losses in relatively thin MDM waveguides can be compensated by a lesser amount of gain, when compared with the metal–dielectric waveguides. Our results will be particularly useful for the optimal design of planar plasmonic waveguides as optical interconnects in nanophotonic circuitry.

ACKNOWLEDGMENTS

The work of I. D. Rukhlenko and M. Premaratne is sponsored by the Australian Research Council (ARC) through its Discovery Grant scheme under grant DP110100713.

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