Gain assisted propagation of surface plasmon polaritons on planar metallic waveguides

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Abstract: The propagation of surface plasmon polaritons on metallic waveguides adjacent to a gain medium is considered. It is shown that the presence of the gain medium can compensate for the absorption losses in the metal. The conditions for existence of a surface plasmon polariton and its lossless propagation and wavefront behavior are derived analytically for a single infinite metal-gain boundary. In addition, the cases of thin slab and stripe geometries are also investigated using finite element simulations. The effect of a finite gain layer and its distance from the SPP waveguide is also investigated. The calculated gain requirements suggest that lossless gain-assisted surface plasmon polariton propagation can be achieved in practice for infrared wavelengths.

OCIS codes: (240.6680) Surface plasmons; (130.2790) Guided waves; (260.3910) Metals, optics of; (250.3140) Integrated optoelectronic circuits

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#4632 - $15.00 US
Received 18 June 2004; revised 13 August 2004; accepted 15 August 2004

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1. Introduction

The ability to guide optical fields through a prescribed route is critically important for realization of compact integrated optical devices and circuits. Traditionally, waveguides have been implemented through local modulation of the shape and/or refractive index profile of the optical dielectric medium, examples of such waveguides being step index, graded index, buried, ridge and rib architectures, which have been extensively investigated in the past three decades [1], [2].

A more exotic approach to guiding optical fields is based on excitation and manipulation of surface electromagnetic waves (SEWs), or equivalently, surface plasmon polaritons (SPPs). These waves propagate along the interface between two media possessing permittivities with opposing signs. They can potentially be used to channel and concentrate light in dimensions much lower than the conventional diffraction limit [3], leading to dense integration of optical circuits. However, in practice a medium with negative permittivity is realized using a metal near the plasma frequency where the negative real component of the complex permittivity, ε', is accompanied by an energy dissipating imaginary part ε'', causing lossy propagation of SPPs. Consequently, this energy dissipation limits the effective propagation length of SPPs to values in the micrometer to millimeter range, thereby creating an obvious obstacle in utilizing them in practical optical devices and circuits.

As a possible solution to this fundamental problem, we study the propagation of SPPs on metal waveguides in the presence of an optical gain medium. The influence of a gain medium on SPP propagation has previously received some attention. Plotz *et al.* [4] have considered gain-enhanced total internal reflection (TIR) [5] in the presence of a metal film, where the gain medium enhances the free space TIR wave through the mediation of excited SPPs on the metal surface. The paper shows that above a certain threshold, a reflection singularity exists for any metal thickness. The authors also estimate the amount of gain required in the case of a silver metal film, which was found to surpass what was available in dye based gain media at that time. Sudarkin and Demkovich [6] continue this work by studying the propagation of SEWs on the boundary of a metal and a gain medium for transversally bounded and unbounded excitation laser beams. They also mention the possibility of creating a surface plasmon based laser.

In this paper we will expand upon these concepts from a guided wave standpoint, by investigating gain-assisted propagation of SPPs on planar metal waveguides for different waveguide geometries. Instead of using Fresnel reflection coefficients for the analysis, as in [4] and [6], we will directly work with propagation constants and Poynting vectors, as these are better suited for treating wave propagation on the surface of planar slabs and stripes. Also, the Poynting vector approach will enable us to investigate the wavefront behavior when the gain is varied. The analysis is carried out rigorously for the case of an infinite metal-gain medium boundary, and later supported by finite element analysis (FEA) simulations of SPP propagation in thin slab and stripe waveguide configurations. Finally, we assess the practicality of implementation and experimental testing of our theoretical predictions.

#4632 - $15.00 US Received 18 June 2004; revised 13 August 2004; accepted 15 August 2004

2. SPP propagation on an infinite metal-gain medium boundary

We will assume SPP propagation in the positive x direction on a metal-dielectric boundary lying in the x-y plane, with the fields tailing off into the positive (dielectric) and negative (metal) z directions, described by the following TM waves (the indices 1 and 2 denote dielectric and metal regions, respectively):

$$\begin{cases} \mathbf{E}_j = (E_x, 0, E_{z_j}) \exp(i(k_x x + k_{z_j} z - \omega t)) \\ \mathbf{H}_j = (0, H_y, 0) \exp(i(k_x x + k_{z_j} z - \omega t)) \end{cases}, \quad j = 1,2 \tag{1}$$

From Maxwell's equations and continuity at the boundary, the following relationships are derived [7]:

$$\begin{cases} \dfrac{\varepsilon_1}{k_{z_1}} = \dfrac{\varepsilon_2}{k_{z_2}} \\ k_x^2 + k_{z_i}^2 = \varepsilon_i k_0^2 \\ E_x = \dfrac{k_{z_i}}{\omega \varepsilon_i} H_y \quad , \; E_{z_i} = -\dfrac{k_x}{\omega \varepsilon_i} H_y \end{cases} \qquad i = 1,2 \tag{2}$$

where $k_0 = \omega / c$ is the free space wave vector of the incident excitation photon. From Eq. (2), the SPP dispersion relations can be derived [7]:

$$\begin{cases} k_x{}^2 = k_0{}^2 \dfrac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} & (a) \\ k_{z_i}{}^2 = k_0{}^2 \dfrac{\varepsilon_i{}^2}{\varepsilon_1 + \varepsilon_2} & (b) \end{cases} \tag{3}$$

The imaginary part of k_x is responsible for lossy propagation of the SPP along the interface. As mentioned, this results from the non-zero imaginary component of the metal permittivity. Apart from choosing a metal with a high plasmonic resonance (i.e., $(\varepsilon_2')^2/\varepsilon_2''>>1$), there seems to be no other method to reduce the metallic losses so as to increase the SPP propagation length in the metal-dielectric configuration.

However, replacing the passive dielectric medium in region 1 by a dielectric medium with gain will enable us to compensate for the losses in the metal, as evidenced by the calculations described below. We start by assigning to region 1 a gain medium with complex permittivity $\varepsilon_1=\varepsilon_1'+i\varepsilon_1''$ (with negative ε_1'' representing gain) and investigating the conditions for a bound wave to propagate at the interface. At this point our only assumption is that ε_2' is negative and its absolute value is much larger than the other three permittivity components. The equations governing the SPP propagation for this material configuration are:

$$\begin{cases} k_x^2 = k_0^2 \dfrac{(\varepsilon_1' + i\varepsilon_1'')(\varepsilon_2' + i\varepsilon_2'')}{(\varepsilon_1' + \varepsilon_2') + i(\varepsilon_1'' + \varepsilon_2'')} & (a) \\ k_{z_i}{}^2 = k_0{}^2 \dfrac{(\varepsilon_i' + i\varepsilon_i'')^2}{(\varepsilon_1' + \varepsilon_2') + i(\varepsilon_1'' + \varepsilon_2'')} & (b) \end{cases} \tag{4}$$

First, we find the limits on ε_1'' for a bound solution (i.e., $\mathrm{Im}(k_{z_1})>0$). From Eq. (4-b) we have:

$$k_{z_1} \simeq k_0 \sqrt{\frac{|\varepsilon_1' + \varepsilon_2'|}{(\varepsilon_1' + \varepsilon_2')^2 + (\varepsilon_1'' + \varepsilon_2'')^2}} (-\varepsilon_1'' + i\varepsilon_1')(1 - i\frac{(\varepsilon_1'' + \varepsilon_2'')}{2(\varepsilon_1' + \varepsilon_2')}) \tag{5}$$

#4632 - $15.00 US Received 18 June 2004; revised 13 August 2004; accepted 15 August 2004

From Eq. (5) and the condition $\mathrm{Im}(k_{z_1})>0$ we have:

$$(\varepsilon_1'')^2+\varepsilon_2''\varepsilon_1''+2\varepsilon_1'(\varepsilon_1'+\varepsilon_2')<0 \tag{6}$$

which is satisfied if:

$$\frac{-\varepsilon_2''-\sqrt{(\varepsilon_2'')^2-8\varepsilon_1'(\varepsilon_1'+\varepsilon_2')}}{2}<\varepsilon_1''<\frac{-\varepsilon_2''+\sqrt{(\varepsilon_2'')^2-8\varepsilon_1'(\varepsilon_1'+\varepsilon_2')}}{2} \tag{7}$$

The aforementioned conditions on the size of ε_2' guarantee that these bounds are real and have opposite signs. This places a limit on the allowable amount of absorption or gain in the dielectric for bound waves to exist. The longitudinal propagation characteristics of the SPP are given by k_x in Eq. (4-a), which simplifies to:

$$k_x^2=\frac{k_0^2}{(\varepsilon_1'+\varepsilon_2')^2+(\varepsilon_1''+\varepsilon_2'')^2}[\varepsilon_1'((\varepsilon_2')^2+\frac{|\varepsilon_1|^2}{\varepsilon_1'}\varepsilon_2'+(\varepsilon_2'')^2)+i\varepsilon_2''((\varepsilon_1'')^2+\frac{|\varepsilon_2|^2}{\varepsilon_2''}\varepsilon_1''+(\varepsilon_1')^2)] \tag{8}$$

where $|\varepsilon|^2=(\varepsilon')^2+(\varepsilon'')^2$. Assuming ε_1', ε_2' and ε_2'' are fixed by the choice of the metal and gain medium, we solve for ε_1'' to find the roots of the imaginary part of Eq. (8), which has to be zero for lossless propagation of the SPP, yielding:

$$\varepsilon_1''=\frac{|\varepsilon_2|^2}{2\varepsilon_2''}\left(-1\pm\sqrt{1-\frac{4(\varepsilon_1'\varepsilon_2'')^2}{|\varepsilon_2|^4}}\right)\simeq\begin{cases}-\dfrac{|\varepsilon_2|^2}{\varepsilon_2''}+\dfrac{(\varepsilon_1')^2\varepsilon_2''}{|\varepsilon_2|^2} & (a)\\ -\dfrac{(\varepsilon_1')^2\varepsilon_2''}{|\varepsilon_2|^2} & (b)\end{cases} \tag{9}$$

where the approximation is valid assuming a metal with high plasmonic resonance. Note that the sign of ε_1'' is opposite to that of ε_2'', which implies gain in region 1. The magnitude of the solution in Eq. (9-a) is very large and outside the bounds given in Eq. (7), so we will only consider Eq. (9-b). Note that for this solution, the stronger the plasmonic resonance, the less gain is required for lossless propagation. Note also that this result is in approximate agreement with the result derived in [4], where the TIR reflection is enhanced for $|\varepsilon_1''/\varepsilon_2''|(\varepsilon_2'/\varepsilon_1')^2>1$. (The reason for the slight difference is that the approximations used in [4] assume $|\varepsilon_2|^2\simeq\varepsilon_2'^2$, which is correct for $|\varepsilon_2'|>>\varepsilon_2''$).
To relate the value of ε_1'' derived in Eq. (9-b) to the actual optical power gain, we use $\gamma=-k_0\varepsilon_1''/(\varepsilon_1')^{1/2}$ where γ is the power gain coefficient. This gives us the gain coefficient required for lossless SPP propagation:

$$\gamma_0=\frac{2\pi}{\lambda_0}\frac{\varepsilon_2''(\varepsilon_1')^{3/2}}{(\varepsilon_2')^2+(\varepsilon_2'')^2} \tag{10}$$

Evidently if the gain coefficient is less than γ_0 , the SPP propagation will still be lossy but the propagation length will increase accordingly. If the gain is increased past γ_0, the SPP amplitude (i.e., the amplitude of the fields in Eq. (1)) will increase as the SPP propagates along the interface. In practice, the gain medium will saturate at a specific amplitude level, which will inhibit further increase of the amplitude. An interesting point to note is that if the metal-gain medium interface is placed inside a longitudinal cavity and the gain is high enough to compensate for both cavity and SPP losses, sustained oscillations (i.e., lasing) will occur. The experimental realization of surface plasmon quantum cascade lasers in the middle to far infrared range [8], where surface plasmon losses are relatively small, give support to this prediction. However, the focus in this case has not been using SPPs for low-loss waveguides and devices, but rather taking advantage of the fabrication simplicity of a plasmonic waveguide (compared to a thicker dielectric waveguide) to create a laser cavity. In contrast we provide a rigorous quantitative analysis and a design methodology for the effect of a gain medium on SPP propagation, which, for high enough gain, can lead to the aforesaid lasing situation.

Under zero gain conditions, the wavefront is tilted towards the interface as a result of the absorptive character of the metal. For our material system the wavefront tilt will be affected by the presence of gain, which we demonstrate next by calculating the Poynting vector in region 1 using Eqs. (1) and (2):

$$\mathbf{P} = \frac{1}{2}\mathrm{Re}(\mathbf{E_1}\times\mathbf{H}^*) = \frac{|H_y|^2}{2\omega}[\mathrm{Re}(\frac{k_x}{\varepsilon_1})\hat{\mathbf{x}} + \mathrm{Re}(\frac{k_{z_1}}{\varepsilon_1})\hat{\mathbf{z}}] \qquad (11)$$

Obviously, the tilt direction depends on the sign of $\mathrm{Re}(k_{z_1}/\varepsilon_1)$. From Eq.(3-b) we have:

$$\mathrm{Re}(\frac{k_{z_1}}{\varepsilon_1}) = \mathrm{Re}(\frac{k_0}{\sqrt{\varepsilon_1' + \varepsilon_2' + i(\varepsilon_1'' + \varepsilon_2'')}}) \simeq \frac{k_0(\varepsilon_1'' + \varepsilon_2'')}{2(|\varepsilon_1' + \varepsilon_2'|)^{\frac{3}{2}}} \qquad (12)$$

We observe that the tilt direction changes at the point $\varepsilon_1''=-\varepsilon_2''$, i.e., as the gain grows larger than this amount, the wavefront tilt increases away from the interface, until at the limit derived in Eq. (7) the wave is no longer bound to the interface. It should be noted that this amount of gain can not be achieved in practice for the visible/infrared range, such that the wavefront will always be tilted towards the metal surface. Figure 1 shows the different operating regions of the SPP versus ε_1''.

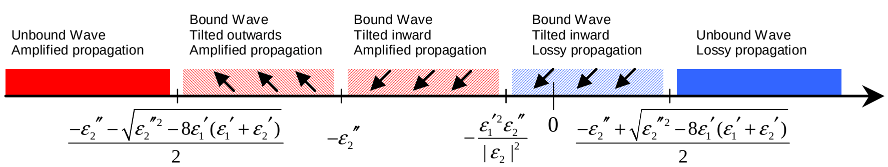


Fig. 1. Schematic illustration of various SPP propagation regimes as a function of ε_1''.

To justify the practical validity of a planar integration scheme based on gain-assisted SPPs we next use realistic material properties to verify that the gain limit indicated in Eq. (10) is attainable in practice. For our simulations and calculations we will consider the propagation of an SPP excited by a 1550nm light source propagating on a silver surface (ε_2=-116.38+i11.1 @ 1550nm) [9]. For the gain medium, we assume ε_1' to be 11.38, which approximates a InGaAsP-based gain medium. From Eqs. (9-b) and (10) we find ε_1''=-0.106 and γ_0=1275 cm^{-1} which is within the limits of currently available semiconductor based optical gain media ([10], [11]). Note that this estimated gain value is an approximate upper limit for lossless SPP propagation on a silver surface at 1550nm in the assumed configuration, since Eq. (10) shows that γ_0 decreases with decreasing ε_1'. Hence, we anticipate that using lower refractive index gain media will require lower gain compared to InGaAsP and similar high refractive index media. Examples of such gain media are quantum dots embedded in a glass matrix or polymer [12]. Also, other materials may also offer enough gain to satisfy the requirements of lossless propagation at other wavelengths [13].

Figure 2 shows the effect of varying gain on selected parameters of the SPP for the abovementioned material system, namely $\mathrm{Im}(k_x)$, the propagation length, $\mathrm{Re}(k_{z_1}/\varepsilon_1)$, and $\mathrm{Im}(k_{z_1})$. From these, the gain values for lossless propagation, zero wavefront tilt and bound propagation limit are found to be equal to 1264.3cm^{-1}, 13341cm^{-1} and 67045cm^{-1} respectively.

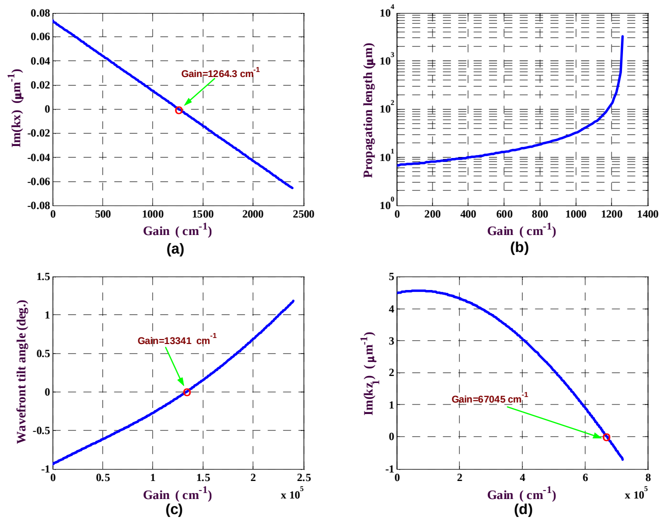


Fig. 2. Plots of: (a) Im(k_x), (b) propagation length, (c) wavefront tilt angle and (d) Im(k_{z1}) versus gain. The points corresponding to lossless propagation, zero wavefront tilt and bound surface wave limit, respectively, are also shown.

The slight discrepancies between these numbers and values predicted from Eqs. (7) and (10) are due to the first order Taylor approximations used throughout the derivations. Note that the propagation length becomes very sensitive to gain values near γ_0, which may be of interest for switching and modulation applications.

3. Gain-assisted propagation of SPPs in slab and stripe geometries

The gain requirement can be further decreased by appropriate choice of the waveguide geometry. If instead of an infinitely thick metal, a metal slab with finite thickness is chosen for propagating the SPP, each side of the slab will support a SPP mode. If the thickness of the metal slab is reduced so that the two SPPs overlap, the structure will support symmetric and anti-symmetric bound modes, known as s_b and a_b, respectively [14]. Since the metal penetration depth of the s_b mode decreases with decreasing slab thickness, thereby reducing absorption losses, we can expect that the gain requirement will also be reduced. Figures 3(a) and 3(b) show FEA mode calculation results (calculated using FEMLAB from COMSOL Inc.) for a 40nm thick silver slab embedded in the same dielectric/gain medium of the previous example. The propagation constant for the passive (no gain) case is found to be $14.06+i0.0197\ \mu m^{-1}$ (Fig. 3(a)), the complex part corresponding to a loss of 0.17 dBμm^{-1}. Once the gain is set to 360.4 cm^{-1}, the propagation constant becomes a real number and equal to 14.06μm^{-1} (Fig. 3(b)), corresponding to lossless SPP propagation.

Applying the same approach to a stripe geometry, the gain requirement will be even less than that of the slab, since for the symmetric stripe mode, the interaction area of the SPP with the metal is further reduced. Figure 3(c) shows the mode distribution for a 400nm×40nm silver stripe embedded in InGaAsP. In this case the propagation constant and propagation loss are $13.76+i0.0094\ \mu m^{-1}$ and 0.081 dBμm^{-1}, respectively. For this case, the loss is completely compensated by a gain equal to 180.24 cm^{-1}, as shown in Fig. 3(d).

Compared to the value of γ_0 originally predicted by Eq. (10), the stripe configuration shows a substantial (almost an order of magnitude) reduction in the gain requirement for the same material system and further supports the viability of experimental and practical implementation of such a waveguiding scheme. Note that the mode profiles of the uncompensated and compensated cases in Fig. 3 are nearly identical, as predicted by Eq. (5).

#4632 - $15.00 US Received 18 June 2004; revised 13 August 2004; accepted 15 August 2004

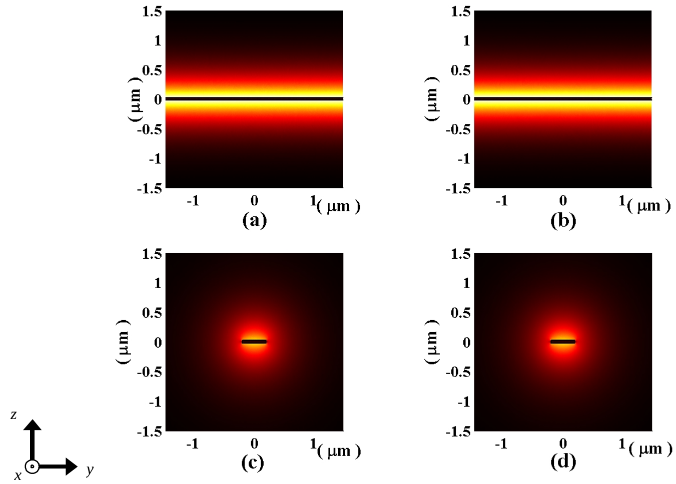
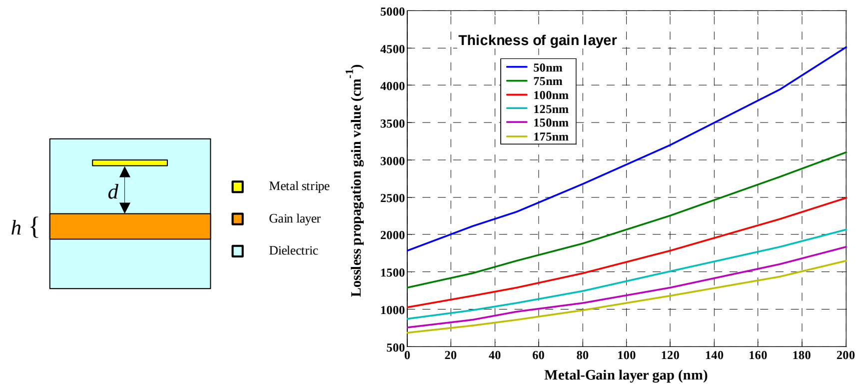


Fig. 3. FEA simulations of total electric field for SPPs propagating on a silver interface embedded in an InGaAsP-based gain medium: (a) Symmetric mode in slab configuration without gain, k_x=14.06+i0.0197 μm^{-1}. (b) Symmetric mode in slab configuration with gain, k_x=14.06 μm^{-1}. (c) Symmetric mode in stripe configuration without gain, k_x=13.76+i0.0094 μm^{-1}. (d) Symmetric mode in stripe configuration with gain, k_x=13.76 μm^{-1}.

However, the promising results obtained above are somewhat unrealistic from a fabrication standpoint. The assumption of a uniform gain medium surrounding the metal in close proximity may only be achievable with quantum dots embedded in polymer or glass, which do not currently offer as much gain as other amplifying media. On the other hand, the fabrication of multiple quantum wells (MQWs) and self-assembled quantum dot layers (which possess much higher material gain [15-18]) in close proximity to a metal layer is possible only on one side of the metal surface in most practical arrangements.

To incorporate the effects of these fabrication limitations, we now investigate the structure shown in Fig. 4(a). In this case the same stripe geometry of Figs. 3(c) and 3(d) is considered, however the gain medium is limited to a thin layer on only one side of the stripe. This could represent the active region in a semiconductor optical amplifier (SOA), a MQW stack or layers of self assembled quantum dots. The curves in Fig. 4(b) are derived using FEA simulations and show the gain required for lossless SPP propagation as the gap between the metal stripe and the gain layer is increased, with each curve corresponding to a different gain layer thickness.

As expected, the gain requirement increases as the layer thickness is reduced and the gap is widened. However, for the distances and thicknesses considered in the simulations, the gain values are in the range of a few thousand cm^{-1}, which are still within the values reported in the literature. For example, gain values of 1200cm^{-1}, 2600cm^{-1} and 6.8×10^4cm^{-1} are reported for a SOA with a 110nm thick active layer [10], a double quantum well structure [17] and a layer of self assembled quantum dots [18], respectively. These values suggest that currently available semiconductor-based gain media are expected to provide enough gain for lossless or nearly lossless SPP propagation, provided that the gap between the gain medium and the metal surface can be made sufficiently small.



(a) (b)

Fig. 4. (a) Metallic stripe waveguide of Fig. 3 in proximity to a gain layer with finite thickness. (b) FEA generated results showing variation of gain required for lossless propagation as the gap *d* increases. Each curve corresponds to a different value of gain layer thickness *h*.

It should be noted that these estimates do not include scattering losses due to surface roughness and metal grain boundaries, the inclusion of which would increase the gain requirements. The exact quantitative influence of this type of loss would be affected by factors such as surface quality and deposition technique and may have very large variations from one sample to another [19]. This should be taken into careful consideration in any practical implementation or experiment.

4. Conclusion

In conclusion, we have studied the propagation of SPPs across different metal-dielectric configurations in the presence of gain in the dielectric medium. The analytic analysis and numeric simulation results show that the gain medium assists the SPP propagation by compensating for the metal losses, making it possible to propagate SPPs with little or no loss on metal boundaries and guides. The simulations also show that constraints dictated by fabrication limitations on the size and relative location of the gain layer serve to increase the gain requirement for lossless propagation, however they also indicate that a judicious choice of these parameters and the metal waveguide geometry will cause the gain to be within the limits of available technology. This suggests a novel approach to planar optical integration based on gain-assisted propagation of SPPs along metallic guides and devices, which warrants further research into the subject. We are currently in the process of experimental verification of these results and predictions, which shall be reported in future communications. Finally, we would like to thank Dr. Uriel Levy for his helpful comments and suggestions.

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