Gain assisted surface plasmon polariton in quantum wells structures

M. Z. Alam, J. Meier, J. S. Aitchison, and M. Mojahedi

Department of Electrical and Computer Engineering, University of Toronto, Toronto, Ontario, Canada M5S 3G4
malam@waves.utoronto.ca

Abstract: In this paper we propose a structure to compensate the propagation loss of surface plasmons by using multiple quantum wells as a gain medium. We analyze the required gain for lossless surface plasmon propagation for different thicknesses and widths of the metallic guiding layer. We study the effects of the gain layers and a finite height superstrate on the surface plasmon mode and its propagation loss. It is shown that the gain required for lossless plasmon propagation is achievable with present technology.

OCIS codes: (240.6680) Surface Plasmons; (260.3910) Metals, optics of; (250.5980) Semiconductor optical amplifiers

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1. Introduction

There has been a great deal of interest in the potential applications of surface plasmons (SPs) in recent years [1]. Plasmonic devices have many attractive features; they are compact, allow light to propagate below the diffraction limit and have been shown to guide light through sharp corners and bends [2], [3]. Such devices are compatible with existing fabrication technologies, offering the possibility of integration of electronics and photonics on the same chip. However, one obstacle to the integration of photonic and electronic components is the problem of size-mismatch; in other words, while electronic devices are becoming progressively more compact, conventional photonic devices are larger in size due to the diffraction limit. Plasmonics may offer a solution to this size-mismatch problem. However, SP propagation is highly lossy and this is one factor limiting the realization of plasmonic devices for practical applications.

The main loss mechanisms for SPs are: scattering from the rough metallic surfaces, the propagation loss due to the surrounding dielectrics, and the inherent loss resulting from the complex dielectric constant of the metal. For smooth metallic surfaces surrounded by extremely good dielectrics, the major contribution to the loss is the metallic conduction loss. In order to reduce the losses further, one possible solution is to decrease the overlap between the plasmonic mode and the metallic film by reducing the metal thickness, resulting in long range SP propagation [4]. This in effect takes advantage of the so called symmetric mode for which the wave is loosely confined to the metal and spreads widely inside the dielectric. This long range SP mode can be used to design novel devices as has been demonstrated recently [5], [6]. However, this approach does not offer the possibility of compact design which is potentially one of the most attractive features of plasmonics.

An alternative approach is to use a gain medium to compensate the loss suffered by the SPs. Apart from the promise of designing compact devices this approach can lead to many new applications such as surface plasmon lasers [7] at optical frequencies. A scheme for loss compensation using a gain medium has recently been demonstrated experimentally by means of an optically pumped dye solution [8]. However, the observed amplification is small and this method is not suitable for designing compact devices. Moreover, Nezhad et al., have presented a study of the effects of gain on SP by examining the condition for existence of SP and SP wave front behavior on semi-infinite metal-gain medium boundaries. They have also estimated the gain requirements for lossless SP propagation for a number of simple structures [7].

Since SPs suffer significant losses while propagating even over a short distance, the gain medium should provide large enough amplification to realize appreciable propagation. Quantum wells are a good candidate for this case, since they can provide very high gain [9], [10]. On the other hand, quantum wells are essentially a multilayer medium, where the "layering" aspect of the structure will affect the mode profile and gain requirements. In this paper we propose a structure which can be fabricated using existing technology and which will reduce the SP losses appreciably. An interesting aspect of the proposed structure is that a mode profile is chosen which makes the coupling through the end-firing scheme [4] possible, resulting in an easier integration of the proposed structure with other peripheral devices. In the followings, after describing the proposed structure, we present our results on how the variations of the metallic film thickness and width along with the thickness and refractive index of the superstrate affect the modal shape and gain requirement.

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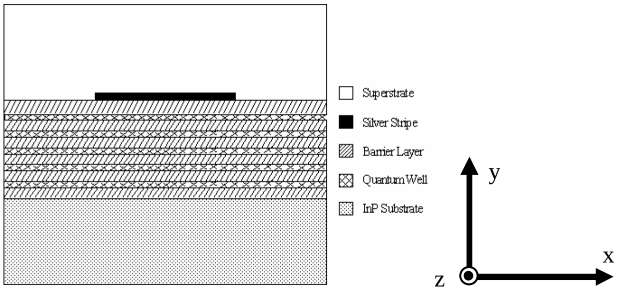

Fig. 1. Proposed multilayer structure for compensating the SP propagation loss

2. Proposed structure

Figure 1 shows the proposed structure consisting of a metal film placed on a quantum well gain medium. Though the analysis is done for a particular material system, the results are qualitatively valid for other similar structures as well. The gain medium consists of 5 quantum well layers, each 8 nm thick and separated from each other by 16 nm thick barrier layers. To reduce the loss due to free carriers, the top quantum well layer is separated from the metal film by a 50 nm barrier layer. The entire structure is supported by a semi-infinite InP substrate. A superstrate of finite height is assumed to cover the metal film. Here, we note that the presence of the finite height superstrate will have significant effects on the modes as will be described in Section 3.2. The compositions of quantum wells and barriers are $Al_{0.12}Ga_{0.12}In_{0.76}As$ and $Al_{0.3}Ga_{0.18}In_{0.52}As$ respectively and corresponding permittivities are 12.2 and 11.2. The superstrate dielectric constant is matched to that of the barrier layers. Variations from this symmetrical condition will be investigated in Section 3.3. The dielectric constant of silver at 1.55 µm wavelength is taken as -116.38+ i 11.1 [11]. The losses in substrate and barrier layers are assumed to be negligible while the effect of superstrate loss is investigated in Section 3.3.

3. Analysis of the structure

The commercial finite element code FEMLAB (version 3.1) was used to analyze the structure. FEMLAB has been reported to be very reliable for simulation of plasmonic devices and has shown very good agreement with results obtained from other numerical methods [12]. For the case under consideration, FEMLAB solves the following equation for finding the transverse magnetic field $\vec{H}_t$.

$$\nabla_t \times (\varepsilon_r^{-1} \nabla_t \times \vec{H}_t) - \nabla_t (\mu_r^{-1} \nabla_t . \mu_r \vec{H}_t) - (k_0^2 \mu_r - \beta^2) \vec{H}_t = 0 \qquad (1)$$

Here $\nabla_t = \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y}$ and ε_r, μ_r are the relative permittivity and permeability of the medium, β is the propagation constant. Details of the solution process are discussed in [13]. Assuming for the moment that dielectric constants of the superstrate and barrier layers are matched, we note that the SPs for the proposed structure are also strongly influenced by the superstrate height and the higher dielectric constant of the wells located close to the metallic film. In other words, the structure is highly asymmetric. Previously, Berini has conducted a detailed analysis of the SP modes in a simple asymmetric structure [14]. However, unlike the structure investigated in [14] our proposed device has a layered dielectric substrate with gain and finite height superstrate. Therefore, a detailed study is needed to examine the effects of different parameters on the operation of the proposed device. Moreover, since the structure is designed to be used in an end-fire excitation scheme, an SP mode which has low loss and is suitable for the end fire excitation has been examined closely.

3.1 Effects of changing film width and thickness

Figure 2(a) shows the dispersion characteristics of the long range SP mode as a function of metal film width for various film thicknesses. For this analysis, the superstrate height was taken as 400 nm. This superstrate height results in low attenuation of the SP mode, and good overlap with quantum wells, as will be discussed in Section 3.2. Figure 2(b) shows that as the film thickness is reduced attenuation falls. This is expected since the overlap of the SP mode and metal decreases with decreasing film thickness.

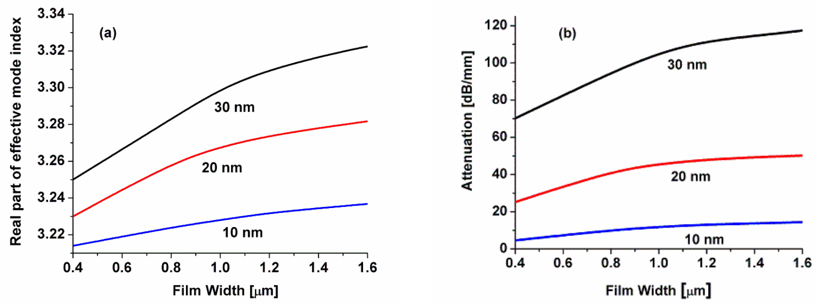

Fig. 2. Dispersion characteristics for a long range SP mode on a silver film as a function of the film width and thickness (10 nm, 20 nm and 30 nm). (a) Real part of the effective mode index (b) Attenuation

Figure 2 suggest that the SP losses can be made very small by reducing the film width and thickness simultaneously. However, the ability of the film to guide SP modes decreases in such cases and this is illustrated in Fig. 3. For a 100 nm wide and 40 nm thick silver film the mode is well guided as shown in Fig. 3(a), but there is very little overlap with the quantum wells. When the film width is kept at 100 nm and the thickness is reduced to 10 nm, the metal film significantly looses its guiding ability as evident from Fig. 3(b). Based on these results, the optimum film width and thickness are chosen to be 1 μm and 10 nm, respectively. For these dimensions, the film supports a well guided SP mode with relatively low loss and good overlap with the quantum wells. Furthermore, the mode size is suitable for the end fire excitation from a single mode optical fiber.

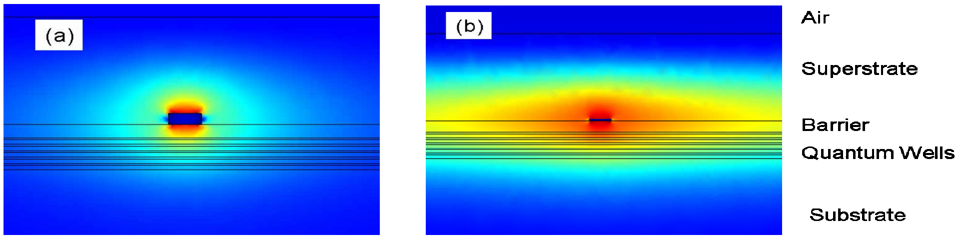

Fig. 3. Spatial distributions of Ey for a 100 nm wide silver film for two different film thicknesses. (a) 40 nm thick film (b) 10 nm thick film

3.2 Effects of finite height superstrate

Aside from the use of quantum wells as a gain medium and the layered nature of the substrate, another major difference between the structure proposed here and that in previous works is the optimization of the superstrate height. When a thin metal film is surrounded by asymmetric dielectrics, it can not guide SP below a certain film thickness [14]. This scenario can be remedied to a great extent by using a finite height superstrate. Since the electric field tends to concentrate in the higher dielectric material, the finite height of the superstrate forces

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the field to be confined and even a very thin metallic film can guide the SP mode in presence of large asymmetry. This is illustrated in Fig. 4; where a 1 µm wide and 10 nm thick film is covered with a semi infinite superstrate, no SP mode is present as shown in Fig. 4(a). On the other hand, when the superstrate height is reduced to 400 nm, a guided SP mode is formed [Fig. 4(b)].

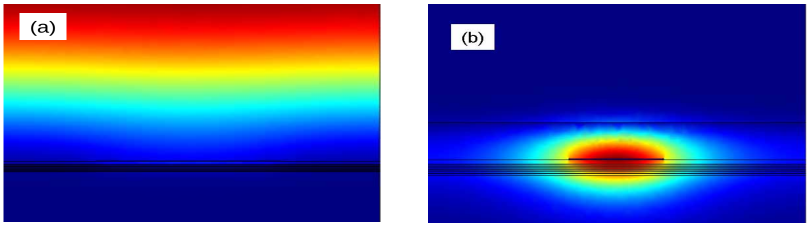

Fig. 4. Spatial distributions of E_y for a 1µm wide and 10 nm thick silver film for two different superstrate heights. (a) Semi-infinite superstrate (b) 400 nm thick superstrate

A finite superstrate height also significantly alters the mode characteristics. This is evident from Fig. 5. The E_z field looks different than that of a conventional SP mode. However, the two field components responsible for power flow in the *z*-direction, i.e., H_x and E_y remain similar to SP mode and therefore power is still well guided by the film. Hence we can conclude that this mode is still a SP mode.

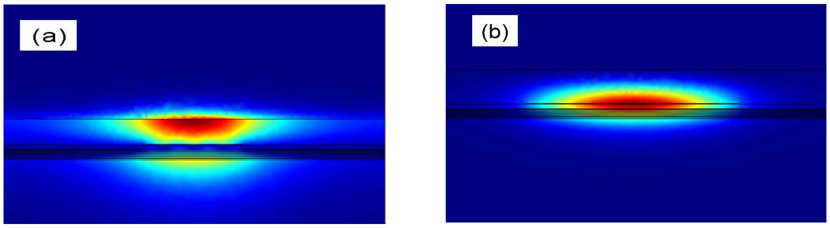

Fig. 5. Spatial distributions of (a) E_z and (b) power profile for a 1µm wide and 10 nm thick silver film covered by a 400 nm thick superstrate.

Figure 6(a) shows the variation of SP attenuation with superstrate height for the same film as in Fig. 5. As the figure indicates the SP attenuation increases sharply as the superstrate height is reduced, while increasing the superstrate thickness results in a reduction of the attenuation. However, this is only one consideration. Another important consideration is the overlap between the SP and the quantum wells (gain regions). To utilize the quantum wells effectively, it is important that there is sufficient overlap between the plasmonic field and the amplifying regions. To assess the fraction of the field confined inside the quantum well layers the confinement factor η is defined as

$$\eta = \frac{\iint_{QW} \left|E_y\right|^2 dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left|E_y\right|^2 dxdy} \tag{2}$$

i.e. the ratio of the power confined in the quantum wells to the total power. Figure 6(b) shows the variation of the confinement factor with superstrate height. The confinement is a maximum for a superstrate thickness of 330 nm. Considering the trade off between the attenuation and confinement factor, a superstrate thickness of 400 nm is chosen for our device to have simultaneously low loss and good confinement.

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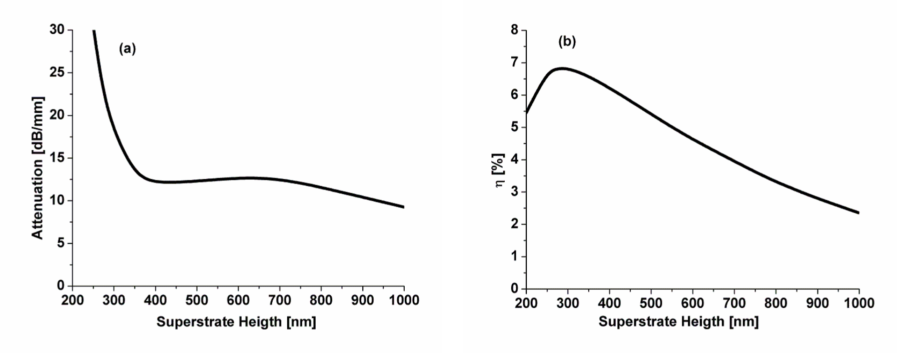

Fig. 6. Variation of SP characteristics with superstrate height for a 1µm wide and 10 nm thick silver film. (a) Attenuation (b) Confinement

3.3 Effects of superstrate dielectric constant and loss

Figure 7(a) shows the attenuation of the SPs as a function of the superstrate dielectric constant. The device parameters are given in the figure caption. We note that attenuation is minimized when the dielectric constant of the superstrate is matched to that of the barrier layer and dramatically increases as the mismatch is increased. The dielectric constant of the superstrate also plays an important role in the power confinement as indicated in Fig. 7(b). We observe that matching the dielectric constant of the superstrate and the barrier region can lead to a relatively good confinement factor.

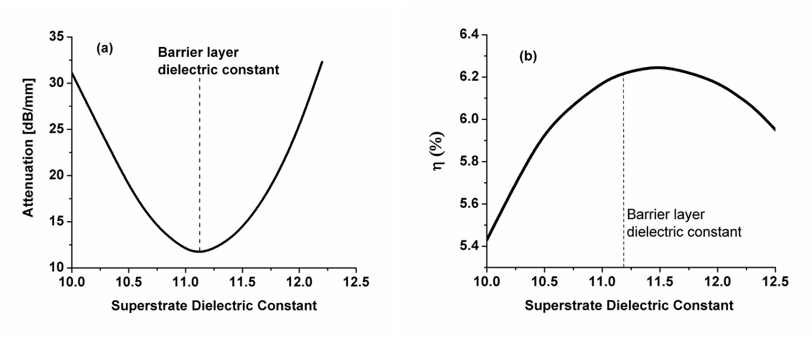

Fig. 7. Variation of attenuation and confinement with superstrate dielectric constant for a 1µm wide and 10 nm thick silver film. Superstrate height is 400 nm. (a) Attenuation (b) Confinement

The analysis so far has assumed a lossless superstrate, barrier layers, and substrate. From a fabrication point of view, it is relatively easy to fabricate a crystalline substrate with small losses. The metallic film, however, acts as a discontinuity making it extremely difficult to grow a crystalline superstrate on top of the metallic film. Therefore, the superstrate most likely will be either polycrystalline or amorphous. The losses in such superstrate will depend heavily on the fabrication process. For example at a wavelength of 1.55 µm, while crystalline silicon has a loss of only 1 dB/cm, polycrystalline silicon may suffer a loss of 15 dB/cm or as high as 350 dB/cm [15]. The same trend is true for other materials [16]. Figure 8 shows the required gain as a function of the superstrate loss, in order to obtain a lossless SP propagation. Here the gain is defined as $g = -k_0\varepsilon'' / \sqrt{\varepsilon'}$ where ε' and ε'' are the real and imaginary parts of the dielectric constant of the gain medium and k_0 is the free space wave number. The gain requirement rapidly increases with the increase of superstrate loss. Therefore, it is crucial to have a low loss dielectric as the superstrate in order to keep the gain requirement within the

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limit of available technology. Here, we must add that our analysis has neglected the attenuation due to the metallic film surface roughness. The surface roughness will result in scattering of the SPs and hence an increase in attenuation. Since the long range mode has most of its power inside the dielectric surroundings, effects of the surface roughness should not be very significant; this assumption is also supported by the results from [17]. Therefore, the gain values depicted in Fig. 8 are a reasonable estimate of the gain required for lossless SP propagation in a real structure. The gain required in the case of lossless superstrate is 402/cm. This is achievable with the present day quantum wells. For example, a material gain of around 1800/cm from AlGaInAs quantum wells at 1.55 μm wavelength has been reported [9]. Lossless SP propagation, therefore, is within the limit of current technology.

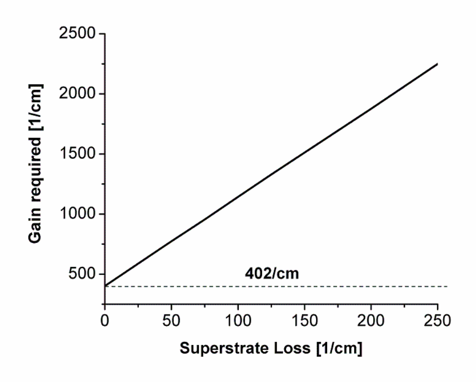

Fig. 8. Effect of superstrate loss on required gain for lossless SP propagation

4. Conclusion

A structure has been proposed which is realizable using current technology and which can provide lossless propagation of SPs with gain available from the quantum wells. The superstrate finite height makes it possible to guide a low loss plasmon mode by a very thin metal film even in the presence of large asymmetry. This results in a significant reduction of the gain required for lossless SP propagation. It is found that the presence of loss in the superstrate can significantly increase the gain requirement, and therefore it is important to control the quality of the superstrate optical properties. Suitable combination of the metallic film dimensions, superstrate height, and dielectric properties of the superstrate and barrier layers can be used to optimize the design in order to reduce the loss and to utilize the gain efficiently. Apart from providing a way to realize lossless SP propagation, the results from this investigation can also facilitate the design of other plasmonic devices.