Physica E 41 (2008) 106–109

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Characteristics of a dielectric–metal–dielectric plasmonic waveguide

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ARTICLE INFO

Article history:
Received 29 February 2008
Received in revised form
10 June 2008
Accepted 18 June 2008
Available online 24 June 2008

PACS:
42.82.Et
73.20.Mf
42.82.−m

Keywords:
Waveguides
Plasmons

ABSTRACT

We report the results concerning the theoretical optimization of a surface plasmon-polariton-based waveguide at the optical communication wavelength of 1.55 μm. In particular, the effect of metal thickness and grating depth on the excitation of long- and short-range surface plasmon-polaritons in a dielectric/metal/dielectric structure are considered. It is shown that the coupling between these modes increases as the metal thickness decreases with the tendency of modes to overlap when the grating depth and metal thickness are reduced to values of, respectively, 50 and 25 nm. Also, the attenuation and confinement in these waveguide structures are inspected theoretically as the thicknesses of the three most used metals (Ag, Au and Al) are varied. The results confirm the established requirement of a trade-off between high confinement and low loss.

1. Introduction

Communication using light has proved, so far, to be the only reasonable way to move the worldwide data traffic over long distances. Fiber-optic cables are, in fact, able to carry digital data with a capacity tremendously higher than that of conventional electronic interconnects. Over very short distances, however, and specifically at the chip level, interconnects remain exclusively electrical given that the optical components' dimensions are limited to the order of the light wavelength due to diffraction problems.

Moreover, it is desired and advantageous to have optical components such as light sources, detectors, modulators and waveguides monolithically integrated with electronic devices. But as the electronic components continue to shrink in dimensions towards the nano-scale regime, there is a need to bridge the gap between the dimensions of optical and electronic components. In the quest of achieving this goal, a new and promising research field known as 'plasmonics' is emerging [1]. In particular, a waveguiding scheme based on surface plasmons has been proposed recently and is being extensively investigated in both its theoretical and practical aspects [2–5].

Surface plasmon-polaritons (SPPs) are electromagnetic modes occurring due to coupling of incident radiation and collective electron oscillations at the interface of a medium with negative permittivity such as a metal and a dielectric. These modes are bound to the interface between the metal and the dielectric and propagate along this interface. SPPs can be excited by an optical input so that the light can be converted to plasmons of much shorter wavelengths, which can then be used to transmit data over a short distance and finally converted back to light (optical output). As such, SPPs are of prominent interest for light guiding purposes in integrated optics.

The advantages of SPP waveguides (SPPWG) compared to conventional dielectric waveguides include ease of fabrication, ability to carry both electrical and optical signals. Also, since SPPs are of TM type, light guided within the dielectric region will suffer attenuation only in its TM mode, while the TE mode remains essentially unaffected, which is of importance in coherent detection systems in engineering communication networks [6,7], where polarization sensitive and selective components are required.

One possible structure of an SPPWG would consist of a thin metal film surrounded by two dielectric claddings or a thin metal film completely embedded in one dielectric material. Such a structure supports both short-range surface plasmon-polaritons (SRSPPs) and long-range surface plasmon-polaritons (LRSPPs). The latter are preferred for waveguiding purposes. With respect to this dielectric–metal–dielectric structure, two figures of merit, namely the propagation length and confinement, have been the focus of recent publications (see, for example Refs. [8–13] for relatively recent reviews on plasmonic waveguides).

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1386-9477/$ - see front matter
doi:10.1016/j.physe.2008.06.012

The purpose of the present contribution is to look into the efficiency of an SPWG design that includes the excitation scheme. We consider, in particular, the efficiency of a double-grating structure that supports both SRSPP and LRSPP. It is shown that such a waveguide structure can be designed by optimizing a number of related parameters such as grating depth, grating period, symmetry of structure and properties of metal and dielectrics used at the optical communication wavelength of 1.55 μm.

2. Propagation distance and confinement

The basic geometry (Fig. 1) of interest here consists of a metal of complex dielectric function $\varepsilon_m = \varepsilon_m^r + j\varepsilon_m^i$ (with $\varepsilon_m^r < 0$) bounded by two dielectric media of dielectric constants ε_1 and ε_3.

The dispersion relation of the SPP can be obtained by applying Maxwell equations to the boundaries in this multilayer structure. For isotropic media the surface electromagnetic waves are of TM type and can be described by their magnetic field component (H_y), which propagates along the x-axis with z normal to the interface [14]:

$$H_y = Cf(z)\exp[j(\omega t - \beta x)],$$

where C is a normalization constant, $f(z)$ describes the depth-profile of the field and $\beta = \beta_r + j\beta_i$ is the complex propagation constant parallel to the interface.

The dispersion relation for such a dielectric–metal–dielectric system is given by [14]

$$\tanh(S_2 h) = \frac{-\varepsilon_m S_2(S_3\varepsilon_1 + \varepsilon_3 S_1)}{\varepsilon_1\varepsilon_3 S_2^2 + \varepsilon_m^2 S_1 S_3}, \tag{1}$$

with $S_1^2 = (\beta^2 - \varepsilon_1 k_0^2)$; $S_2^2 = (\beta^2 - \varepsilon_m k_0^2)$; $S_3^2 = (\beta^2 - \varepsilon_3 k_0^2)$; $k_0 = 2\pi/\lambda$.

The zeros of the above dispersion relation allow simultaneous determination of effective index ($n_{\mathrm{eff}} = \beta_r/k_0$) and propagation (attenuation) distance ($L = 0.5\beta_i^{-1}$).

In the case of a symmetric structure ($\varepsilon_1 = \varepsilon_3$)—one of the most interesting in plasmonic waveguides—the two possibilities are $\pm S_1 = \pm S_3$ corresponding, respectively, to leaky-radiative modes ($-S_1$) in which the fields grow exponentially away from the metal–dielectric interface and bound modes ($+S_1$) in which the fields have their maximum at the metal–dielectric interface and decay exponentially into both dielectric and metal. Depending on the charge distributions of these modes, two coupling situations are possible: a symmetric mode in which the transverse electric field does not exhibit a zero inside the metal, leading to a highly attenuated mode and an asymmetric mode in which the transverse electric field has a zero inside the metal and the coupled surface wave will not be significantly attenuated. The latter mode, known as LRSPPs, is preferred for guiding purposes compared with the lossy SPP modes excited in the symmetric case.

The dispersion equation above was solved numerically using a Newton–Raphson method for three different metals with varying thickness. For some particular values of the metal thickness, exact analytical (symbolic) solutions using MATLAB were possible and these were used as a guideline for initial guesses for both symmetric and asymmetric solutions.

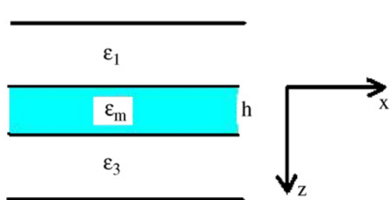

Fig. 1. The basic dielectric/metal/dielectric waveguide structure used to calculate SPPs propagation lengths.

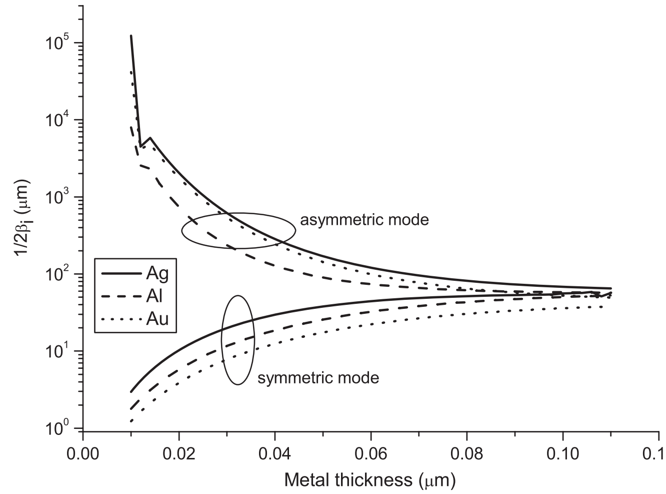

Fig. 2. Calculated propagation distances versus metal-film thickness in the case of three metals (Ag, Al and Au) for the two LRSP and SRSP modes corresponding to, respectively, asymmetric and symmetric charge distributions.

Two key figures of merit in SPP waveguide designs are the light propagation loss and the light confinement at the guiding interface. Usually, the losses arise due to Joule heating in the metal and are directly related to the imaginary part (β_i) of the propagation constant. The confinement is directly related to the penetration depth of the mode in medium i (either dielectric or metal) which is given by $D = 1/\mathrm{Re}(S_i)$.

The calculated propagation distances at an optical communication wavelength $\lambda = 1.55$ μm are shown in Fig. 2 as a function of the metal thickness in the case of the three most used metals for SPP excitations (Ag, Au and Al). The optical constants of Al, Ag and Au were taken from [15] and ε_1 and ε_3 were taken as $(1.5)^2$.

It is observed that the propagation distance in the case of the symmetric mode decreases with decreasing metal thickness while it increases significantly in the asymmetric case reaching the centimeter range for a metal thickness of the order of 10 nm.

It is shown (Fig. 3) that the calculated $S_1 = S_3$ and β_i have positive values for the given metal thickness-range and optical constants of the dielectric cladding. This is an indication that the SPP modes are in fact bound to the interface and decaying away from it. The penetration depth inside the metal side is very small, of the order of 20 nm, and does not depend significantly on the metal-layer thickness. In the dielectric side, however, the penetration depth extends over a few micrometers with the smallest values (most enhanced confinement) corresponding to a thicker metal layer (Fig. 4). This is a confirmation of the well-known trade-off that should be sought between the requirement of highly confined modes achievable for thicker metals and maximum propagation distance necessitating a thinner metal core.

3. Double-grating efficiency

The above flat-surface structure (Fig. 1) does not include the actual arrangement by which SPPs can be excited. To optically stimulate SPPs and efficiently couple light into a waveguide, three mechanisms are usually used [16]. The widely studied scheme is prism coupling in which incident photons are passed through a high refractive index prism followed by a lower refractive index