Numerical Investigation of SPP Propagation at the Nano-scale
MDM Waveguides with a Combiner

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Abstract—We present the propagation characteristics of Surface Plasmon Polariton (SPP) in the nanoscale Metal-Dielectric-Metal waveguides which consist of a combiner. The propagation loss due to absorption by metal and reflection at the point of recombination is analyzed numerically. We have investigated the structure with different dielectric materials (air, aluminum gallium arsenide, gallium lanthanum sulfide) and for different wavelengths of the input signal. The wavelength dependent reflection coefficient, return loss and voltage standing wave ratio have also been reported in order to analyze the performance of the combiner.

Much interest has been focused on the research of Surface Plasmon Polariton (SPP) in the recent years [1] because of its extraordinary capability to travel through sub-wavelength sized holes. Besides, SPP can overcome the diffraction limit [2] which indicates the potential application in various fields such as biosensing [3], metamaterials [4], Bragg reflector [5], and efficient light coupling in solar cells [6]. However, efficient guiding of SPP is required in order to achieve compact integrated photonic devices. Several plasmonic waveguides have been proposed by the researchers in the past few years [7-9]. Among them, the Metal-Dielectric-Metal (MDM) structure has received much interest due to its ability to squeeze the SPP modes in the dielectric region. It can support sub-wavelength propagation mode from dc to visible [10] wavelength range.

Bends, splitters and recombination are inevitable parts of the optoelectronic devices. To our knowledge, several works on the analysis of SPP propagation in these shapes have been reported. G. Veronis et al. [11] showed that bends and splitters can be designed over a wide frequency range without much loss by keeping the centre layer thickness small compared to the wavelength. H. Gao et al. [12] investigated the propagation and combination of SPP in Y-shaped channels. B. Wang et al. [13] analysed two structures which consist of splitting and recombination.

In this paper, we investigate the SPP propagation characteristics in a 2D MDM waveguide with a combiner constructed with different dielectric materials [air, gallium lanthanum sulphide (GLS), aluminium gallium arsenide (AlGaAs)]. The characteristics that we have analyzed for the combiner are reflection coefficient, return loss and voltage standing wave ratio (VSWR). The propagation loss along the length of the waveguide is also reported. We expect that this study will provide a better understanding about the SPP propagation characteristics in an MDM waveguide with a combiner.

The simulation presented here is based on the Finite-Difference Time-Domain (FDTD) [14] method proposed by Yee. A general ADE-FDTD algorithm [15] is used to integrate the frequency dependent permittivity terms in the simulator. We modelled the frequency dependent permittivity function of dielectric materials by a single pole Lorentz model which is given by,

\[
\varepsilon_\omega(\omega) = \varepsilon_\infty + \frac{\omega_p^2}{\omega_0^2 + j\delta \omega} + \sum_{i=1}^{n} \frac{f_0 \omega_i^2}{\omega_i^2 + j \Gamma_i \omega_i - \Gamma_i^2},
\]

where \(\varepsilon_\omega\) is the infinite frequency relative permittivity, \(\varepsilon_\infty\) is the zero frequency relative permittivity, \(j\) is the imaginary unit, \(\delta\) is the damping co-efficient and \(\omega_0\) is the frequency of the pole pair.

For modeling silver we used the six-pole Lorentz-Drude model which is as follows,

\[
\varepsilon_\omega(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - j\Gamma \omega} + \sum_{i=1}^{6} \frac{f_0 \omega_i^2}{\omega_i^2 + j \Gamma_i \omega_i - \Gamma_i^2},
\]

where \(\omega_p\) is the plasma frequency, \(\Gamma_i\) is the damping frequency, \(f_0\) is the oscillator strength, and \(\omega_{0i}\) is the resonant frequency.

The required parameters for simulation for different materials have been determined by many researchers. For silver we have used the parameter values obtained by Rakic et al. [16], for AlGaAs we have taken the values determined by M. Alsunaidi et al. [17] and for gallium lanthanum sulfide we have used the values determined by R.H. Sagor [18]. We take the step size as \(\Delta x=\Delta y=5\text{nm}\), and the time step as \(\Delta t = 0.95 \cdot c^{-1} \left[\frac{1}{\Delta x^2 + \frac{1}{\Delta y^2}}\right]^2\), where \(c\) is the speed of light and taken as \(c=3 \cdot 10^8 \text{ms}^{-1}\).

We set the mesh parameters FDTD algorithm accordingly in order to ensure the stability with minimum numerical dispersion.

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The schematic diagram of the structure used for simulation is given in Fig. 1. The thickness of the dielectric layer before recombination is taken as 25nm for each section and after recombination as 70nm. The recombination occurs at a distance of 2.3µm.

At the beginning, we simulated the MDM waveguide with a recombination structure with the input pulse given in Fig. 2 in order to generate the SPP modes. Then we pumped the mode given in Fig. 3 into the structure modulated by a gaussian pulse having a characteristic pulse width of 3 femtoseconds and different wavelengths.

From the numerically determined reflection coefficient, we have obtained the return loss and VSWR using analytical equations the plot of which is given in Figs. 4(ii)-4(iii). At the optical communication wavelength the return loss for air is 21.5dB whereas for GLS it is 6.74dB and for AlGaAs it is 1.21dB.

The reflection coefficient as a function of the wavelength has been determined numerically and presented in Fig. 4(i). From the figure it can be observed that the reflection coefficient is the highest at 600nm for air, 900nm for GLS and 1200nm for AlGaAs. At a telecom wavelength the reflection coefficient for air is the lowest having a value of 0.084 whereas for AlGaAs it is 0.863.
The dispersion induced broadening of the input pulse is negligible for a propagation distance of 25µm in the materials that we have used. In order to observe this phenomenon we need to take propagation distances of, at least, 100µm for AlGaAs and more for the other two materials. However, due to the limitation of the resources we could not simulate the MDM waveguide with a combiner up to that propagation length.

We report the numerical analysis of SPP propagation in an MDM waveguide with a combiner. From our simulation we find that a sudden fall occurs in a normalized power curve at the point of recombination due to the back reflection of SPP. We also report the wavelength dependent nature of propagation length, reflection coefficient, return loss and VSWR. This analysis will be useful in the fabrication process of integrated photonic devices with combiners.

References


Fig. 6. Normalized Power Curve for (i) Air (ii) GLS (iii) AlGaAs.