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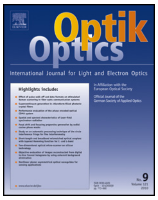

Design and analysis of a gallium lanthanum sulfide based nanoplasmonic coupler yielding 67% efficiency

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ABSTRACT

In this paper, we propose a novel ultra-compact nanoplasmonic coupler using gallium lanthanum sulfide (GLS) which yields an efficiency of 67% at the optical communication wavelength. The analysis has been done numerically using the finite-difference time-domain method. Our proposed coupler can operate at a broad frequency range and easier to fabricate than couplers with multi-section tappers since it is a simple rectangular-shaped coupler with no variation along the whole length.

1. Introduction

The field of plasmonics has attracted a lot of research interest in the last few years. The incredible ability of surface-plasmon-polariton (SPP) to overcome the diffraction limit of conventional optical modes [1] and propagate at the deep sub-wavelength scale [2] has been the key reason behind the boom of this field. Plasmonic waveguides, in particular the metal-dielectric-metal (MDM) configuration can tightly confine the optical mode within the dielectric core. This leads to the potential application in biosensing [3], Bragg reflectors [4], subwavelength imaging [5] and metamaterials [6]. However, the MDM configuration has a major drawback. The propagation loss of SPP is very high in this configuration of plasmonic waveguide which limits the length of propagation. Even the fabrication related disorders have far less impact on the propagation loss than the losses that occur in metallic layers of the MDM waveguide. This problem can be addressed by using both dielectric and plasmonic waveguide on the same chip. The dielectric waveguide will carry the fundamental optical mode while the plasmonic waveguide will address the sub-wavelength scale issue. This calls for the need of efficient coupling of optical modes from the dielectric waveguide to the plasmonic waveguide. Therefore, designing efficient nanoplasmonic couplers with different materials and structures can be a pioneering step in miniaturization of the integrated photonic devices.

Due to the amazing expected features of MDM waveguide, researchers have started to explore this configuration experimentally. Dionne et al. [7] have experimentally shown that quasi-two-dimensional MDM waveguides can guide sub-wavelength modes with significant propagation length.

In the recent time, chalcogenide glasses (ChG) have attracted a lot of research interest due to their photosensitivity to visible light and transparent behavior in the mid-infrared region. They provide strong confinement of optical modes and enhanced propagation length. Gallium lanthanum sulfide is one of the chalcogenide glasses with high refractive index [8] and a transparency band ranging from 500 nm to 10 μm [9]. With this as a background, we have chosen gallium lanthanum sulfide (GLS) as the material for the nanoplasmonic coupler.

In the past years, several plasmonic couplers have been proposed by different researchers. Veronis et al. [10] proposed a coupler with multi-section tapers. Ginzburg et al. [11] reported a $\lambda/4$ coupler to couple optical modes from a 0.5 μm to 50 nm wide plasmonic waveguide. Pile et al. [12] presented an adiabatic and a non-adiabatic tapered plasmonic coupler. Wahsheh et al. [13] reported an analysis on nanoplasmonic air-slot coupler and its fabrication steps.

In this paper, we present a novel design and analysis of a nanoplasmonic coupler using GLS based on the finite-difference time-domain method [14]. To the best of our knowledge, this is for the first time one proposes and analyzes a nanoplasmonic coupler using GLS. We have achieved a coupling efficiency of 67% at the telecommunication wavelength. The advantage of this design is that it can operate at a wide range of frequencies and is easier to

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fabricate since it is a simple flat terminal waveguide without any tapering placed at the entry of the MIM plasmonic waveguide.

2. Formulation of the materials and the structure

2.1. Material models

The frequency dependent permittivity function of single pole Lorentz model is given by [15],

$$\varepsilon_r(\omega)=\varepsilon_\infty+\frac{\omega_o{}^2(\varepsilon_s-\varepsilon_\infty)}{\omega_o{}^2+\boldsymbol{j}2\delta\omega-\omega^2} \tag{1}$$

where ε_∞ is the infinite frequency relative permittivity, ε_s is the zero frequency relative permittivity, $\boldsymbol{j}$ is the imaginary unit, δ is the damping co-efficient and ω_o is the frequency of the pole pair.

The frequency dependent permittivity function of Lorentz-Drude 6 (six) pole model is given by [15],

$$\varepsilon_r(\omega)=1-\frac{f_o\omega_p^2}{\omega^2-\boldsymbol{j}\Gamma_o\omega}+\sum_{i=1}^{5}\frac{f_i\omega_p^2}{\omega_{oi}^2+\boldsymbol{j}\Gamma_i\omega-\omega^2} \tag{2}$$

where ω_p is the plasma frequency, Γ_i is the damping frequency, f_i is the oscillator strength, $\boldsymbol{j}$ is the imaginary unit and ω_{oi} is the resonant frequency.

We have used single pole-pair Lorentz model to account for the dispersive property of gallium lanthanum sulfide (GLS) and six-pole Lorentz-Drude model to integrate the dispersion property of silver (Ag) in the simulation model. An excellent agreement has been achieved with the experimental values [16] by fitting GLS to the single pole-pair Lorentz model with $\varepsilon_\infty=2.7$, $\varepsilon_s=2.257^2$, $\delta=8\times10^{11}$ rad/s and $\omega_o=0.70\times10^{16}$ rad/s. The modeling parameters for Ag that we have used, have been determined by Rakic et al. [17].

2.2. Structure formulation

We have developed the 2D simulator based on the finite-difference time-domain method proposed by Yee [14]. A general ADE-FDTD algorithm is used to integrate the frequency dependent dispersion properties of the materials. [18,19]. This algorithm is useful where materials with different dispersion properties are present. The perfectly matched layer (PML) has been used to avoid reflection of incident wave from the boundaries [20].

Considering the material dispersion, the frequency-dependent electric flux density can be given as

$$D(\omega)=\varepsilon_0\varepsilon_\infty E(\omega)+P(\omega) \tag{3}$$

The general Lorentz model is given by

$$P(\omega)=\frac{a}{b+\boldsymbol{j}c\omega-d\omega^2}E(\omega) \tag{4}$$

which can be written in time-domain through inverse Fourier transform as

$$bP(t)+cP'(t)+dP''(t)=aE(t) \tag{5}$$

The FDTD solution for the first order polarization of Eq. (5) can be expressed as

$$P^{n+1}=C_1P^n+C_2P^{n-1}+C_3E^n \tag{6}$$

where,

$$C_1=\frac{4d-2b\Delta t^2}{2d+c\Delta t},\quad C_2=\frac{-2d-c\Delta t}{2d+c\Delta t},\quad C_3=\frac{2a\Delta t^2}{2d+c\Delta t}$$

The values of C_1, C_2 and C_3 depend on the material under consideration.

Finally the electric field intensity becomes,

$$E^{n+1}=\frac{D^{n+1}-\sum_i^N P^{n+1}}{\varepsilon_o\varepsilon_\infty} \tag{7}$$

where D^{n+1} is the update value of the electric flux density calculated using the FDTD algorithm.

3. Structure specifications and simulation method

The proposed nanoplasmonic coupler structure that has been used for simulation is given in Fig. 1. Here the width of the GLS layer has been taken as 300 nm and the width of the air layer in the MDM waveguide has been taken as 60 nm.

A monochromatic point source has been used to excite the optical modes. Since the coupler can operate at a broad frequency range, we have used input signals of wavelengths ranging from 900 nm to 2000 nm. The reason we have limited our simulation within this wavelength range is that the modeling parameters for the materials we have used is applicable within this wavelength boundary only.

In order to get accurate results and maintain the courant stability criteria [21] we have taken $\Delta x=5$ nm, $\Delta y=5$ nm and the time step as $\Delta t=(0.95/c\sqrt{(1/\Delta x^2)+(1/\Delta y^2)})$.

In order to validate our developed simulation model, we have run a simulation using the given parameters ($\varepsilon_\infty=2.25$, $\varepsilon_s=5.25$, $\delta=2\times10^9$ rad/s and $\omega_o=4\times10^{14}$ rad/s) for a dispersive medium in Chapter 9 of the Taflove's book [21]. The results we obtained are presented in Fig. 2 and have been compared with the results given in the book (Fig. 9.3(a)) and we achieved a perfect match.

We have defined the coupling efficiency as the ratio of the transmitted power into the MIM waveguide to the incident power in the input dielectric waveguide. The incident power of the fundamental mode has been measured right before the interface between dielectric and MDM waveguide and the transmitted power has been measured right after the interface.

The reflection coefficient, return loss and voltage standing wave ratio (VSWR) has also been determined in order to analyze the performance of the coupler. The method we have used for calculating reflection coefficient is as follows. First an optical mode has

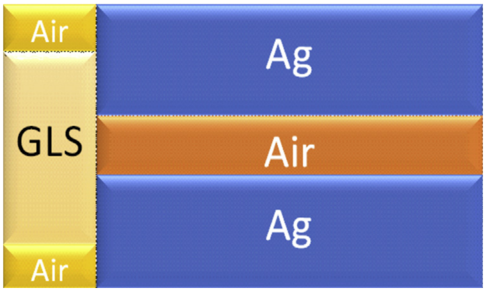

Fig. 1. Schematic diagaram of the coupling structure used for the numerical analysis.

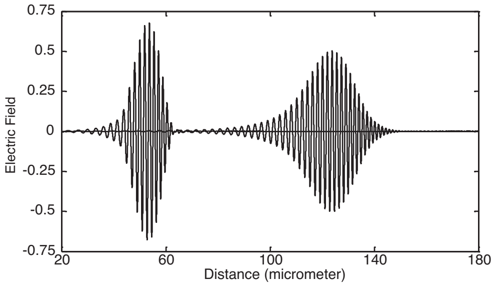

Fig. 2. Results obtained using the parameters given in Taflove's book.