FDTD Simulation of 3-D Surface Plasmon Polariton Band Gap Waveguide Structures

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1 Introduction

Fundamental to progress in integrated optical systems are techniques for controlling light propagation on small spatial scales. The development of photonic band gap (PBG) waveguides [1] represents a major step towards achieving such control, as it permits the nearly lossless redirection of light flows through sharp waveguide bends, a feat unachievable using conventional optical waveguide structures. Recently, a new kind of optical waveguide was introduced that exploits the existence of surface plasmon polaritons (SPP) on metals in the optical regime to construct surface-based PBG structures [2, 3]. These SPPBG waveguide structures introduce interesting mechanisms for controlling light flow beyond the possibilities offered by conventional PBG waveguides. Notable experimental progress in the construction and characterization of SPPBG waveguides notwithstanding, to date, few efforts have been directed at their theoretical/computational analysis. Here, we report on the implementation of a three-dimensional (3D) finite difference time domain (FDTD) scheme for simulating wave propagation in SPPBG waveguides. In addition, two specific SPPBG bended waveguide geometries are analyzed.

2 SPPBG optical waveguides

Consider a planar interface between dielectric and plasma half spaces with relative permittivities ε_d and $\varepsilon_r(\omega)$, respectively (Fig. 1). For frequencies ω at which $\mathrm{Re}(\varepsilon_r(\omega)) < -\varepsilon_d$, this interface may support so-called SPPs, viz, TM polarized electromagnetic surface waves that propagate with wavenumber k_ρ along the interface given by

$$k_\rho = k_d \sqrt{\varepsilon(\omega)/(\varepsilon(\omega)+\varepsilon_d)} \tag{1}$$

and propagation constants normal to the interface given by $k_z = \sqrt{k_d^2 - k_\rho^2}$ and $k_z = \sqrt{k_p^2 - k_\rho^2}$ in the dielectric and plasma, respectively; here $k_d = \omega\sqrt{\varepsilon_d \varepsilon_0 \mu_0}$ and $k_p = \omega\sqrt{\varepsilon_r(\omega)\varepsilon_0\mu_0}$. As k_z has a large imaginary part, the SPP is tightly bound to the interface. The SPP can effectively propagate on the dielectric-plasma interface over distances of order $O(\mathrm{Im}(k_\rho))^{-1}$ [4]. An SPPBG structure results upon introducing a doubly periodic perturbation in the planar dielectric-plasma interface (Fig. 1, only one axis is shown). When properly designed, these perturbations prohibit SPPs to propagate on the interface, much like classical PBGs restrict the propagation of volume fields in optical crystals. SPPBG waveguides result upon introducing defects in the SPPBG array, thereby creating a channel for SPPs to propagate on the dielectric-air interface, unhindered by the periodic perturbation.

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Although it was shown that regular PBG waveguides can deflect electromagnetic waves around sharp corners [5], the efficiency of SPP propagation through SPPBG waveguide bends has not been studied thoroughly. Here, a numerical scheme is proposed to simulate various aspects of wave propagation in SPPBG waveguides, including bend reflections and losses. Specifically, a three-dimensional FDTD code is developed that, by and large, adheres to the standard Yee recipe [6]. However, because the plasma properties are frequency dependent, the FDTD updates there are carried out using a piecewise linear recursive scheme [6] that accelerates the evaluation of the temporal convolution of the electric field with the plasma permittivity. To simplify the FDTD analysis, it is assumed that the SPPBG array is of finite extent while the plasma substrate extends to infinity. In the direction normal to the (planar part of) the dielectric-plasma interface, the plasma half space is truncated by a perfect electrically conducting plate (Fig. 1); this does not affect the phenomenon being studied as the SPPs decay very fast in plasma anyway. On all other FDTD boundaries, perfectly matched layer (PML) boundary condition are used to absorb outgoing waves. A regular PML is used to truncate the dielectric half space in the direction normal to the dielectric-plasma interface [6] (Fig. 1, PML region I), while a PML specifically designed to truncate plasma media is used on all remaining boundaries [7] (Fig. 1, PML region II).

3 Simulation results and discussion

The above described FDTD implementation was applied to the analysis of wave propagation in two bent SPPBG optical waveguide structures. In both cases, $\varepsilon_d = 1$ and $\varepsilon_r(\omega)$ is approximated by a Drude's model [2] as

$$\varepsilon_r(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\nu_c)} \tag{2}$$

where $i = \sqrt{-1}$, $\omega_p = 1.0746 \times 10^{16}$ rad/s is the angular plasma frequency, $\nu_c = 6.7566 \times 10^{12}$ rad/s is the collision frequency, and $\varepsilon_\infty = 1.0$ is the relative permittivity of the plasma at $\omega \to \infty$. Side and top views of the two SPPBG waveguide structures studied are shown in Figs. 2 and 3, respectively. In both structures, a z-directed electric Hertzian dipole (denoted by "S" in Fig. 3) excites the SPPBG waveguide. The dipole resides in the waveguide center, 0.025 μm above the plasma substrate. The time signature of the excitation is

$$\mathbf{J}_z(t) = \hat{\mathbf{z}} e^{(t-t_0)^2/(2\sigma^2)} \cos(\omega_m t), \tag{3}$$

where $\sigma = 4.775 \times 10^{-15}$ s, $t_0 = 1.909 \times 10^{-14}$ s, and $\omega_m = 3.456 \times 10^{14}$ rad/s. The above parameters are chosen to ensure that $\mathrm{Re}(\varepsilon_r(\omega))$ is less than but close to -1 around the modulation frequency ω_m. The FDTD simulations of the waveguides shown in Figs. 3(a-b) are accomplished using grid comprising $600 \times 500 \times 50$ and $750 \times 450 \times 50$ cells, respectively. The cell size (along all Cartesian directions) is 0.025 μm. The time step is 4.582×10^{-17} s and the simulations last 7000 time steps. In the simulations of the two structures, the E_z fields are recorded at a series of observation points (denoted "1", "2", etc. in Fig. 3). These observation points all reside 0.025 μm above the plasma interface. The resulting waveforms are plotted in Figs. 4 (a-b), respectively. From this data, it is observed that the straight SPPBG waveguide section allows signals to propagate with relatively small losses. The bend, in contrast, causes signals to reflect into the SPPBG waveguide / be scattered into the dielectric half-space. A quantitative analysis of the various loss-mechanisms will be presented at the meeting.

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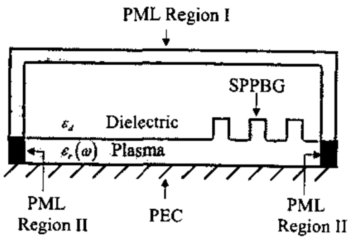


Figure1: SPP and SPPBG

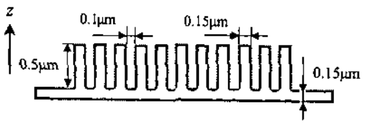
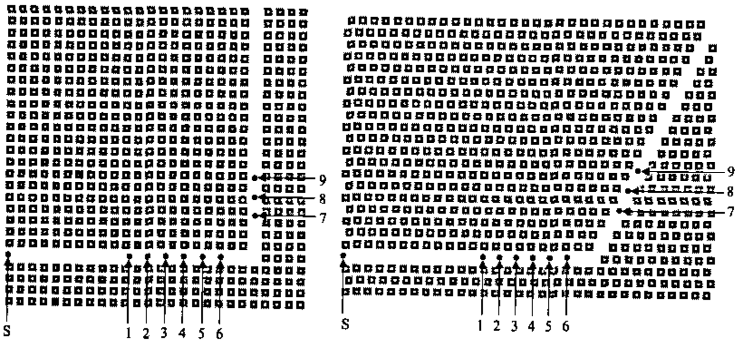


Figure 2: Side view of the SPPBG optical waveguides



(a) Rectangular lattice structure

(b) Triangular lattice structure

Figure 3: Top view of the SPPBG optical waveguides

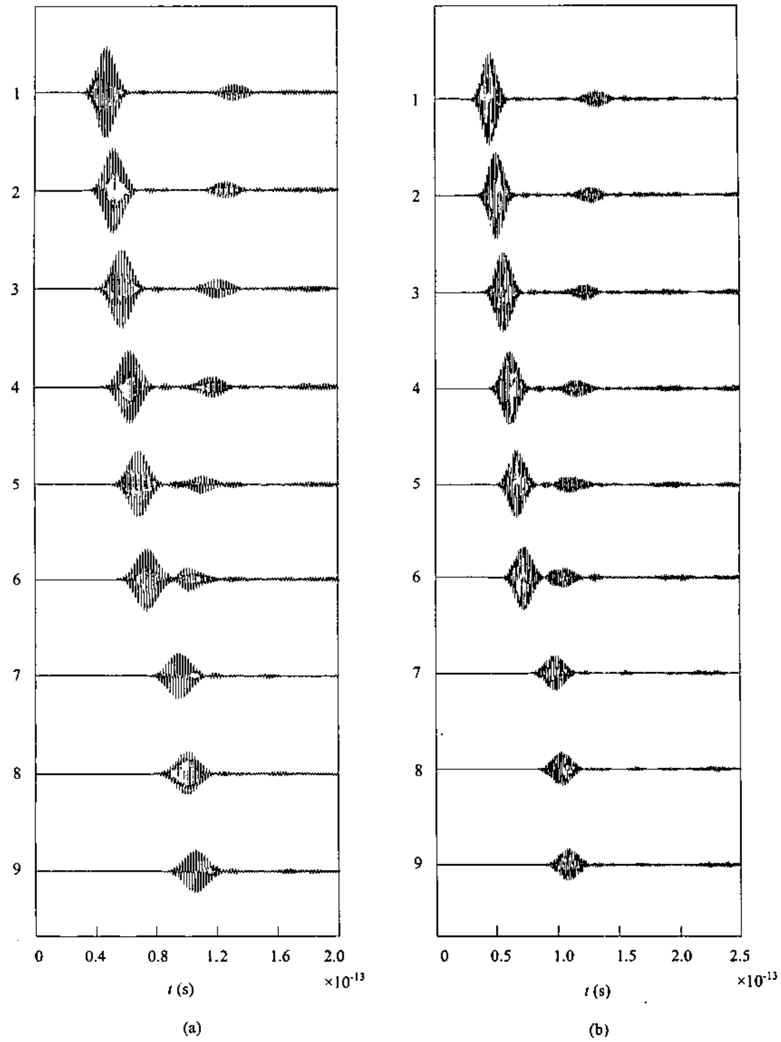


Figure 4: E_z fields observed in the SPPBG waveguides