Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Optical Nanowaveguides Based on Zinc Oxide Plasmonic Materials

To cite this article: A M Lerer *et al* 2016 *J. Phys.: Conf. Ser.* **741** 012159

Optical Nanowaveguides Based on Zinc Oxide Plasmonic Materials

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Abstract. The numerical study of nanowaveguides containing ZO, AZO, GZO and other materials are studied in infrared range. The dispersion relation for the waveguides contained an arbitrary number of layers are solved numerically. The integral-differential equations in vector form of the electromagnetic waves propagation in nanowaveguides containing a finite width plasmon films are calculated by the Galerkin' method and the effective dielectric constants method. The opportunity of surface plasmon-polariton propagation with a large deceleration ratio are shown.

Introduction

The surface TM-wave (surface plasmon-polariton [1], SPP) with a large deceleration ratio [2] can propagate at the interface of plasma-insulator or metal-dielectric in optical range. The phenomenon allows to create plasmonic waveguides conducting the light signals in the volumes smaller than the diffraction limit. It can significantly reduce the size and increase the efficiency of optical integrated circuits. The main disadvantage of plasmon waveguides are strong losses due to the large absorption in metals. The metal waveguides provide a large deceleration at wavelengths less than micrometer. The main aims of the nanophotonic circuits developers [3] are to extend the operating band of plasmon waveguides and to achieve an optimal balance of SPP localization and waveguide losses.

Recently, the new materials based on zinc oxide (ZO) such as AZO, GZO and other were created [4, 5]. So the goal of this paper is a numerical study properties of nanowaveguides containing such materials in the infrared range. Subject matter of the study is the following nanowaveguides: 1) semi-infinite dielectric structures, the new material, dielectric, 2) planar nanowaveguides formed by plane-parallel dielectric layers, the new material, and 3) planar nanowaveguides formed by the finite thickness films of the new material lying on the multilayered dielectric substrate.

The well-known analytical expressions [6] are used to calculate the wavelength and the decay constant of SPP and to study the first type waveguides. The optimal wavelength ranges for spread of SSP are found. The ranges are used to investigate the second type nanowaveguides.

The dispersion relation for the second type waveguide contained an arbitrary number of layers are obtained and solved numerically. The waveguide is a prototype of the third type nanowaveguide that can be practically implemented.

The way to find the complex propagation constant in waveguide structures with small losses are proposed in this article. The properties of SPP propagating in offered structures are investigated and applied to study the third type nanowaveguides. The solution of the integral-differential equations in vector form of the electromagnetic waves propagation in nanowaveguides containing a finite width plasmon films is given by the Galerkin' method [7]. The possibility of SPP propagation with a large deceleration ratio is also shown.

1. The wave propagated on "dielectric – plasmonic material" boundary

The expression [6] are used to calculate the dispersion in case of "dielectric – plasmonic material" boundary:

$$n = n' - in'' = \frac{\beta}{k} = \left(\frac{\varepsilon \varepsilon_{pl}}{\varepsilon + \varepsilon_{pl}} \right)^{1/2} \tag{1}$$

where β is the complex propagation constant, k is the wave number in vacuum, ε and ε_{pl} are the dielectric constants of dielectric and plasmonic material, respectively. The length L of wave propagation can be expressed as the distance at which one is attenuated *e* times.

The numerical results of SPP propagated on "dielectric – plasmonic material" boundary are presented in figure 1: solid curves are dielectric with $n = 1.77$, dashed curves are ZnO dielectric, curves 1 are HfN material, 2 – TiN and 3 – ZrN. The refractive index is normalized $n'_{\text{norm}} = n' / (\text{Re}\,\varepsilon)^{1/2}$, where ε is the permittivity of dielectric semi-infinite layer.

The figure shows that the losses of SPP propagation at this boundary are high and the wave propagation length is also comparable to the wavelength. Moreover, the lower wavelength is, the higher losses are and so shorter the propagation distance is. Compared with the silver and argentum metalic layers, the high deceleration ration can be obtained at $\lambda \geq 800\text{nm}$.

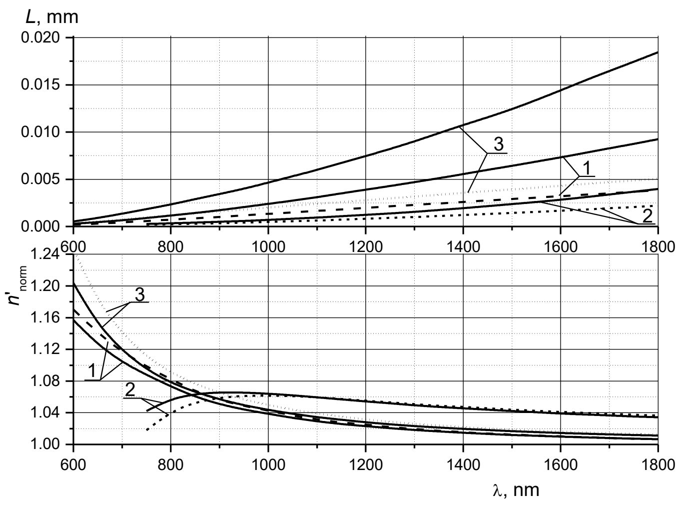

Figure 1. Dispersion curves of the SPP propagated on "dielectric – plasmonic material" boundary. Solid curves are dielectric with refractive index $n = 1.77$, dashed curves are ZnO dielectric, curves 1 are HfN plasmonic material, 2 – TiN and 3 – ZrN.

2. Planar waveguides

The dispersion relation in case of arbitrary number of dielectric layers having complex permittivity is obtained in recurrent form. The approximate method for numerical searching the complex roots of a complex function used during the finding of dispersion solutions is described in the article [6].

The calculated layered structure consists of the substrate with refractive index n = 1.77, the ZnO layer having thickness h_2 and the ZrN layer with thickness h_1. As shown in figure 2, the deceleration ratio n' at wavelengths far from the critical wavelength weakly depends on the layer ZnO and ZrN thickness. It confirms the existence of SPP near the interface of layers. When the wavelength is close to critical wavelength n' and the thickness of ZnO layer decreased, the losses are reduced.

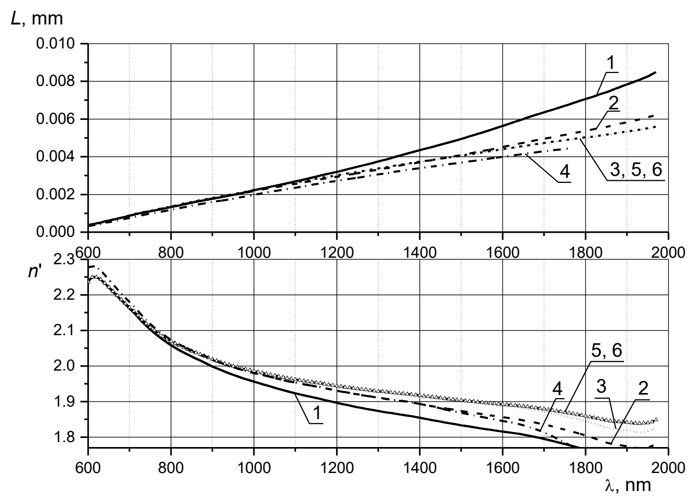

Figure 2. Dispersion curves of the planar waveguide: 1 – h_1 = 100nm, h_2 = 200nm; 2 – h_1 = 100nm, h_2 = 400nm; 3 – h_1 = 100nm, h_2 = 1000nm; 4 – h_1 = 50nm, h_2 = 1000nm; 5 – h_1 = 200nm, h_2 = 1000nm; 6 – h_1 = 400nm, h_2 = 1000nm.

3. Rectangular waveguides

The investigated structure consists of the substrate with refractive index n = 1.77, the ZnO layer having thickness 400nm and the rectangular waveguide filled with plasmonic material placed on ZnO layer with thickness 100nm and width w.

The two different methods are used to calculate the structure. The first one is the volume integral method [6]. The second method is the effective dielectric constants method (EDCM). The EDCM has simple numerical implementation [7]. It comprises two stages.

At first step, the waveguide having complex geometric shape divides by the vertical lines of multilayer waveguide structures (uniform waveguides). In general, the investigated model has an arbitrary number of horizontal layers. Each of these layered waveguides is planar in the horizontal direction. In case of the model in the vertical direction is uniform, the deceleration rate of the waveguide is equal to the refractive index. If the structure can't propagate some Eigen modes (e.g., structure formed by two semi-infinite vertical dielectric layers having same signs of permittivity), the deceleration ration is equal to the refractive index of the waveguide layer adjacent to the studied waveguide. So the deceleration ratio can be calculated, if the Eigen waves exists.

A planar waveguide formed by multiple parallel vertical layers are considered at the second step. Because the refractive index of each layer and the deceleration ratio has already calculated previously, the deceleration ratio of waves propagated in studied waveguide can be found considering it as an original waveguide deceleration rates with complex cross-sectional shape.

The EDCM provides sufficient accuracy and high speed to calculate the nanoplasmonic waveguides parameters in wavelength range in which the surface waves can propagate. The rigorous volume integral equations method is used to verify the EDCM.

The numerical results of rectangular nanowaveguides are presented in figure 3 and 4. If the width of the waveguide reduces, the operating wavelength range becomes narrower and the deceleration ratio reduces too, but at same time the losses reduces significantly. The dispersion characteristics of the ZnN rectangular waveguide shown in figure 3. The figure 4 contains the comparison of waveguides parameters formed by different plasmon materials. It's seen that the losses are rather high and comparable with optical waveguides formed by thin metal films. The losses could be reduced by using of active substrates or layers.

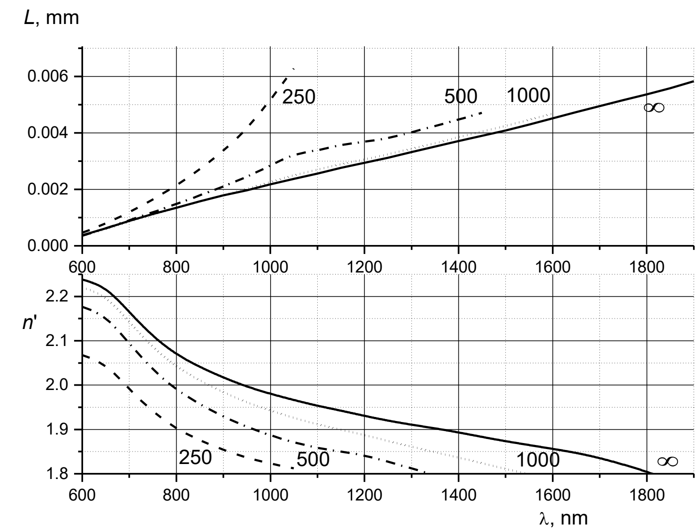

Figure 3. The dispersion curves of ZrN rectangular waveguide with various width *w*.

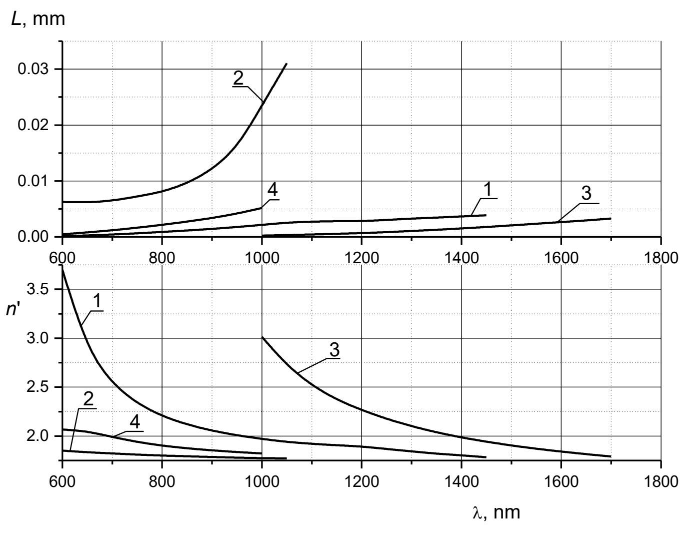

Figure 4. Dispersion curves of the rectangular waveguide with $w = 250$nm: 1 – HfN, 2 – ITO, 3 – TiN, 4 –ZrN.

Summaries

The Galerkin' method and the effective dielectric constants method are used to find the solution of a vector integral-differential equation to describe electromagnetic wave diffraction on three-dimensional bodies with complex dielectric permeability. Three types of nanowaveguide were calculated: 1) semi-infinite dielectric structures, the new material, dielectric, 2) planar nanowaveguides formed by plane-parallel dielectric layers, the new material, and 3) planar nanowaveguides formed by the finite thickness films of the new material lying on the multilayered dielectric substrate.

Acknowledgement

The authors acknowledge the support of the Russian Ministry of Education and Science, provided by grant 16.219.2014/K "The synthesis methods development, the theoretical and experimental investigation of the nanostructures based on ZnO performs to create photodetectors, optical nanoantennas, piezo- and chemosensors", and the part of the Internal Grant project of Southern Federal University in 2014 – 2016y., provided by grant 213.01.-07.2014/08PCHVG, for carrying out this research study.

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