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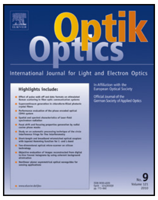

Analysis of low-loss hybrid silicon plasmon waveguide for telecommunications applications

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ABSTRACT

In this paper, a numerical method based upon finite-element method has been utilized to analyze of low-loss hybrid silicon plasmonics and metal plasmonics waveguides. Using silicon instead of noble metals (e.g. Au and Ag) is an advantage in designing of optical waveguides due to have low-loss in comparison to noble at telecom bandwidth. The presented results show that the new model has smaller structures and have better performance in the terms mode confinement and 90% lower propagation loss that guide the waves five times longer.

1. Introduction

The compact optical waveguide has attracted many research activities in recent years due to the capability to confine the sub-wavelength waves. They are key elements in integrated circuits and their interconnects. The optical confinement with conventional contrast index is very complex to attain, thus the use of surface plasmon polariton (SPP) which is not limited to diffraction, would be a good suggestion.

Surface plasmon polariton is defined as an electromagnetic excitation that propagates at the interface between a conductor and dielectric and evanescently confined in the perpendicular direction. These surface waves arise via the coupling of the electromagnetic fields to oscillations of the conductor's electron plasma [1].

In order to effective guidance with SSP phenomenon, some metal-dielectric schemes have been suggested such as gaps between metallic structures [2], trenches etched into metal films [3,4], slots in metal films on dielectric substrates [5,6], metal [7] stripes on dielectric substrates [7], dielectric stripes on metal substrates [8], heterostructures [9,10], quasi-coplanar schemes [11,12] and silicon on dielectric structures [13–17].

The mode confinement, propagation loss, and refractive index are three most important parameters in design of SPP waveguides. Also in some specific applications, using in telecom bandwidth (around 1550 nm) is another important parameter. Some of the literature waveguides have powerful mode confinement at 1550 nm, numerically or practically. However, confinement of wave in this narrow band needs the complex stages to fabricate accurately etching micrometer metal film trenches or patterning of features drilling which limit the slot photolithography [12]. By making use of SPPs for guiding the waves, the simplified approach is utilized.

This paper presents an optical waveguide based on SPP that has good confinement in the range of sub-λ_0^2 that means mode confinement is below λ_0^2, where λ_0 is the free space wavelength, especially around $\lambda_0 = 1550$ nm.

Fig. 1 shows the cross section of this waveguide. This waveguide is obtained through the conventional photolithography processes. In the previous waveguide each metal stripe with specific thickness is obtained by vertically etching metal layers in specific depth dielectric, which vary according to wavelength. However in this work, we use the 50 nm thickness stripes that have simple fabrication processes. It should be highlighted that generally, these waveguides are smaller than those based on trenching which work around 1550 nm.

In fact, the trapezoidal scheme of top and bottom stripes cannot support the wave confinement unless increasing the dimensions to micrometer. In contrast to slot based waveguides, this scheme uses third stripes. This configuration is similar to quasi coplanar waveguide in integrated microwave circuit, thus the configuration with three stripes called as quasi coplanar waveguide (QCPW) [12]. Also in contrast to slot based waveguides, at this scheme the distance between stripes can be extended to more than 100 nm.

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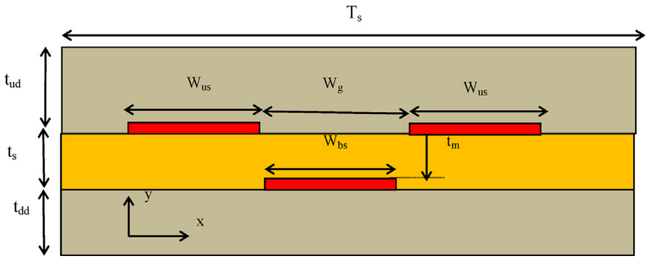

Fig. 1. 2-D cross section of QCPW geometry.

Table 1
Typical value for QCPW parameters shown in Fig. 1.

	t_{ud} (nm)	t_{dd} (nm)	t_s (nm)	W_g (nm)	W_{ts} (nm)	W_{bs} (nm)	n_{sup}	n_{spc}	n_{su}
Au	300	300	200	300	850	200	1.5	1.4	1
Si	300	300	70	300	850	100	1.5	1.4	1

Within this context, this paper focuses on the analysis of the QCPWs by making sue of full-wave finite-element package [18]. The use of finite-element method (FEM) for accurate numerical solution of problems needs huge amount of computation within the computers with high speed and storage. Combination of numerical method like FEM and high speed computers help the design and implementation of optical equipment. Thus, the FEM is used for widely applications.

The organization of the paper is as follows. Section 2 describes the finite-element implementation of QCPW. Section 3 presents the numerical results and related discussion. Finally, the conclusion remarks are presented in Section 4.

2. Full wave finite element method implementation

Fig. 1 shows the geometry of a QCPW. The geometry has three dielectric, up dielectric, spacer dielectric, and down dielectric that respectively, have thickness t_{ud}, t_s and t_{dd}. The scheme also contains three stripes with thickness of t_m that are separated by a spacer dielectric. The two-top stripes have width of W_{us} while the base one has width of W_{bs}. Table 1 lists the value of these parameters as well as the refractive index for each medium.

As mentioned earlier, we use a full-wave finite element package, COMSOL Multiphysics [18]. For the analysis, we have used the RF module of COMSOL Multiphysics software [19] that allows the calculation of electromagnetic fields and waves in 2-D and 3-D spaces. All modeling formulations are based on Maxwell's equations together with material laws for propagation in various media. The RF module allows the modeling of electromagnetic fields and waves in frequency domain, time domain, or eigen-frequency and mode analysis. In particular, we use the electromagnetic wave (EMW) interface of the RF-module, which is based on the finite-element solution of the frequency-domain wave equation [19]. In our modeling, the boundary mode solution domain is selected.

In mode analysis and boundary mode analysis, COMSOL multiphysics solves for the propagation constant, which is possible for the perpendicular waves and boundary-mode analysis problem types. The time-harmonic representation with a known propagation in the out-of-plane direction is almost used for representation of mode analysis. The governing time-harmonic electromagnetic equations for the considered case are [19],

$$E(r,t) = \mathrm{Re}(\tilde{E}(r_T)e^{-j\beta z + j\omega t}) = \mathrm{Re}(\tilde{E}(r)e^{\alpha z + j\omega t}) \qquad (1)$$

In (1), the spatial parameter $\alpha = \delta z + j\beta = -\lambda$ has real and imaginary parts. The propagation constant is equal to imaginary part β, while the real part δz represents the attenuation constant along the propagation direction. The parameters that are influenced by mode analysis are summarized in Table 2.

Table 2
Parameters influenced by mode analysis [19].

Name	Description	Expression	Complex
β	Propagation constant	Imag($-\lambda$)	No
δz	Attenuation constant	Real($-\lambda$)	No
δz – dB	Attenuation per meter in dB	$20 \times \log10(\exp(1)) \times \delta z$	No
n_{eff}	Effective mode index	$j \times \lambda / k0$	Yes

In COMSOL, each medium is meshed by elements whose size is selected on the basis of skin depth δ and wavelength λ. The maximum length of each mesh element is selected to be smaller than $\lambda/10$.

3. Numerical results

In order to simulate the QCPW, at the first stage the Au stripes are studied, which have thickness of 50 nm. Then the Au stripes are replaced by Si with the same thickness. The related parameters are summarized in Table 1.

Figs. 2 and 3 show the profile of electric field intensity (|E|) for the fundamental mode of QCPW at wavelength of λ_0 = 1550 nm, respectively, for Au and Si stripes. These two figures completely show the coupled electric field between base and two-top stripes. The results in these figures illustrate that the electric fields are polarized in vertical (y) direction. However, the magnetic fields are polarized in horizontal (x) direction (arrow line). Thus, it can be concluded that these QCPWs in fundamental mode guide the wave in TEM mode.

In fact, the wave confinement is influenced by two different mechanisms. First, the near electric field coupling between base

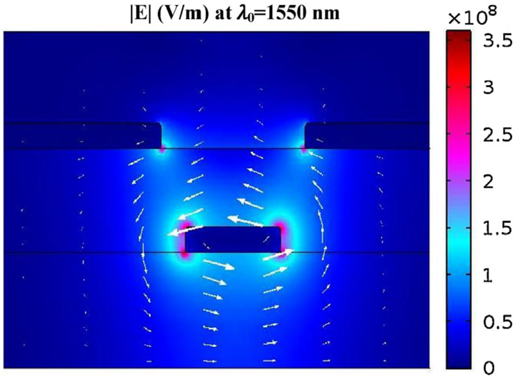

Fig. 2. The electric field |E| for the fundamental QCPW mode and Au stripes at λ_0 = 1550 nm. The arrows show the magnetic field |B|.

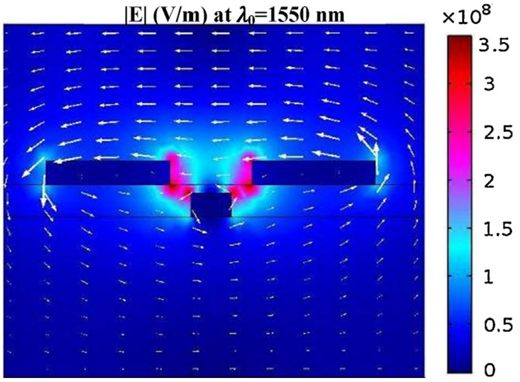

Fig. 3. The electric field |E| for the fundamental QCPW mode and Si stripes at λ_0 = 1550 nm. The arrows show the magnetic field |B|.