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Optimal design of plasmonic waveguide with fabrication tolerance

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ABSTRACT

An optimization approach for a plasmonic waveguide is proposed taking fabrication tolerances into consideration. The genetic algorithm is used to optimize the geometry of the nano-scaled plasmonic waveguide so that it becomes insensitive to fabrication errors with high mode confinement and long propagation length. The design variable and objective functions are defined as waveguide geometry parameters and the averaged figure of merit over local neighborhood in parameter space, respectively.

1. Introduction

Plasmonic waveguides have attracted much attention due to compactness beyond diffraction limit compared to conventional dielectric optical waveguide and are reported to play an important role in building subwavelength photonic devices [1,2]. They are based on a variety of geometries such as thin-film planar metal [3]. and stripe [4–7], slots in metal films [8–10], various grooves in planar metal films [11,12], and dielectric-loaded surface plasmon polariton [13,14]. In practical applications, however, plasmonic waveguides have inherent high Ohmic loss during propagation along metal surface arising from high confinement of optical power. In order to overcome this limitation, recently hybrid plasmonic waveguides using buffer layer were proposed [15–18]. and demonstrated experimentally [19–21].

The waveguide geometries, which are assumed to be fabricated exactly in the above proposed designs, have some deviations from designed values in size. Fabrication inaccuracy can lead to significant performance degradation at critical dimensions and the fabrication tolerances, therefore, should be taken into consideration in waveguide design.

In this paper, we propose a systematic design approach to optimize plasmonic waveguides based on the genetic algorithm (GA) with different fabrication tolerances which is unavoidable for practical implementation. The propagation characteristics of optical modes supported by plasmonic waveguide such as the propagation distance and effective mode area are investigated and the objective function defined as an averaged figure of merit (FOM) is calculated using the finite element method (FEM) at the telecom wavelength of 1550 nm.

2. Numerical analysis of modal characteristics

We study the optical properties of the guided mode supported by the Si-loaded nanoridge plasmonic waveguide (SNPW) proposed in [18]. A schematic diagram for SNPW structure is shown in Fig. 1. The modal characteristics are investigated using a full-vectorial FEM mode solver (COMSOL^{TM}). The eigenvalue problems were solved under open boundary condition for investigating the propagation characteristics which is a most widely used. In our analysis, at the telecommunication wavelength 1550 nm the permittivities of air, SiO_2, Si, and Ag are $\varepsilon_a=1$, $\varepsilon_{SiO2}=2.33$, $\varepsilon_{Si}=12.09$, and $\varepsilon_{Ag}=-129+3.28i$, respectively [18]. The propagation distance L corresponding to the distance that the mode power is attenuated to the amount $1/e$ of its initial value is calculated as $L=\lambda/[4]$ $[\mathrm{Im}((\beta/k_0)]$ where λ is the wavelength in vacuum, β the complex propagation constant and k_0 the propagation constant in vacuum, respectively. The normalized mode area is defined as A_e/A_0 where A_0 is the diffraction-limited area of light in vacuum defined as $\lambda^2/4$. The effective mode area A_e is calculated as following equation

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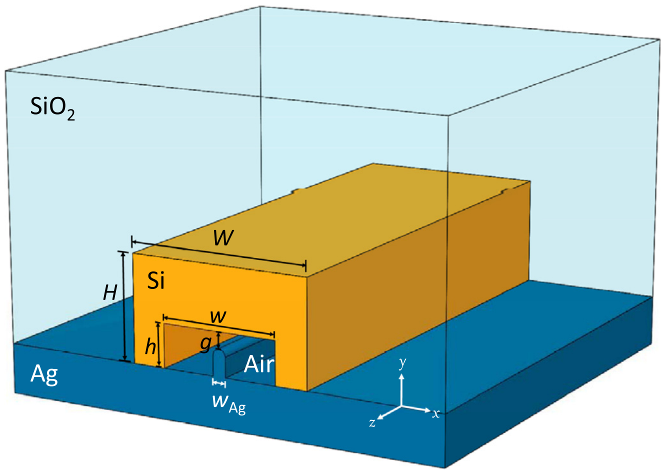

Fig. 1. Schematic of the SNPW.

$$A_e = \frac{1}{\max\{W(\mathrm{r})\}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(\mathrm{r})d^2\mathrm{r}$$

where

$$W(\mathrm{r}) = \frac{1}{2}\left(\frac{d(\varepsilon(\mathrm{r})\omega)}{d\omega}|E(\mathrm{r})|^2 + \mu_0|H(\mathrm{r})|^2\right).$$

The guided mode propagates along the z-axis and an exp($-i\beta z$) variation is assumed during mode propagation for all field components. We are specifically interested in the regime where the condition $w < W$ is required for practical fabrication. Thus, the dimensions of our reference structure are set as W=150 nm, H=150 nm, w=100 nm, h=100 nm, w_{Ag}=20 nm and g=2 nm and are not changed unless otherwise mentioned.

The modal properties of SNPW are shown in Fig. 2(a)–(c) where the dependence of air height h on the real part of the modal effective index (n_{eff}=Re($\beta/k0$)), the normalized mode area A_e/A_0, and the propagation distance L are illustrated for different ridge widths with other parameters fixed at those of the reference waveguide. In Fig. 2(a) we see that the n_{eff} decreases monotonically when h increases. It can be also seen from Fig. 2(b) and (c) that the mode confinement (inversely proportional to the mode area) and propagation distance tend to exhibit reverse trend in plasmonic waveguides; higher mode confinement shorter propagation distance, which is consistent with the result in [18]. To characterize the trade-off, the FOM defined as $\sqrt{\frac{\pi}{A_e}}\frac{1}{\mathrm{Im}(\beta)}$ the ratio of these parameters [22] are plotted in Fig. 2(d).

The modal characteristics versus the ridge width w_{Ag} for different Si heights H are shown in Fig. 3. In Fig. 3(a) we can see that the n_{eff} monotonically decreases as w_{Ag} increases and H decreases. In contrary, A_e/A_0 and L increase as w_{Ag} increases and H decreases. The larger H corresponding to smaller h relatively leads to smaller A_e/A_0 and L which is consistent with the results in Fig. 2(b) and (c). The peak FOM is found to be 1988.9 at the geometry of w_{Ag} =12 nm and H=120 nm.

To further examine the dependence of the geometry, the FOMs versus the air height h and air width w for different ridge widths (w_{Ag}=5, 10, 20, 30 nm) are plotted in Fig. 4(a)–(d). It can be seen

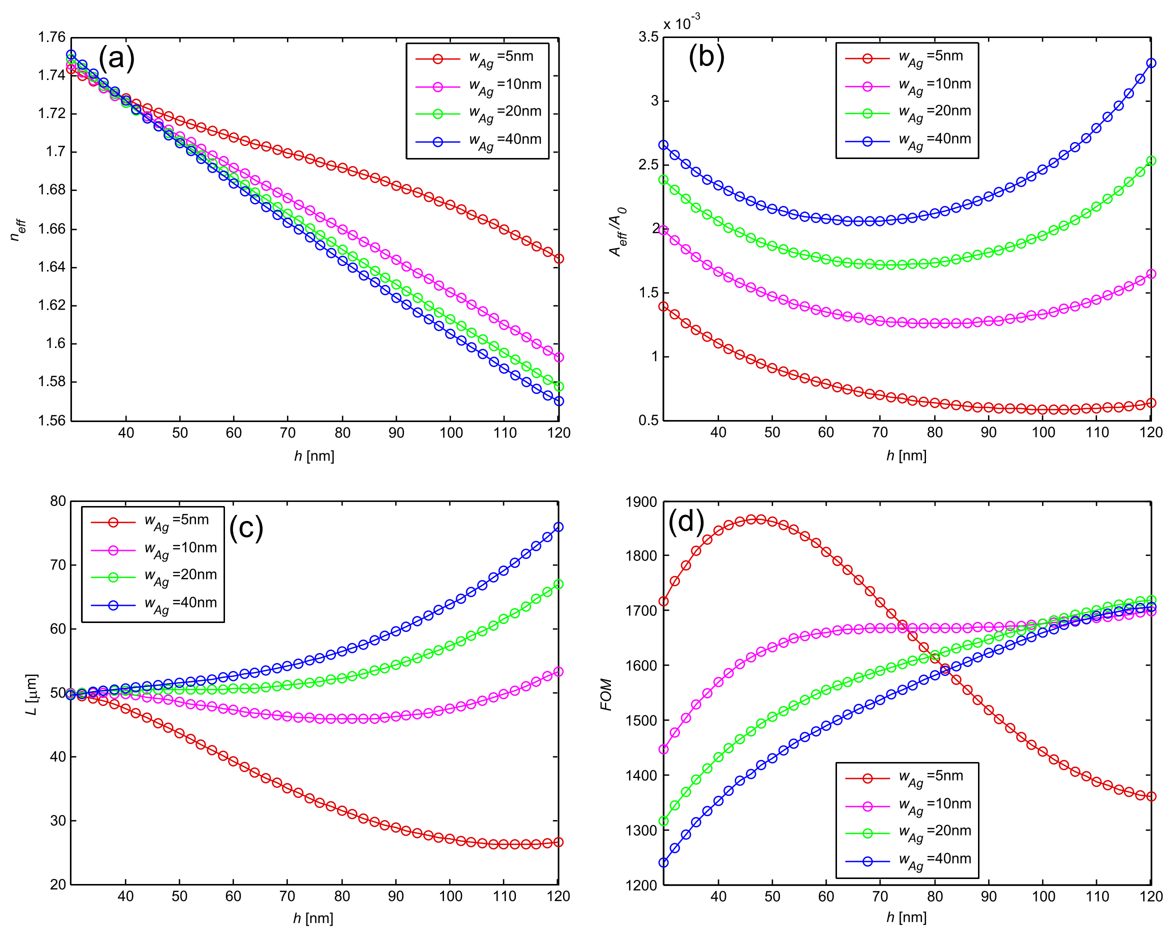

Fig. 2. Modal properties of SNPW: (a) real part of the modal effective index n_{eff}, (b) normalized mode area A_e/A_0, (c) propagation distance L, and (d) FOM as a function of air height h for different ridge widths w_{Ag}.

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