LIGHT ENHANCEMENT IN PHOTONIC NANOSTRUCTURES: SOME SPECIFIC EXAMPLES

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The aim of this paper is to overview some achievements on light enhancement in photonic nanostructures. Results from litterature and from own research are presented. In recent years, a number of photonic nanostructures have been proposed to enhance light in low-index materials based on external reflections provided by interference effects at a high-index contrast interface. Since interference is involved, these structures are strongly wavelength dependent. Plasmonic devices have attracted increasing attention in recent years due to their ability to confine light below the diffraction limit, thereby potentially enabling device miniaturization at the nanoscale. Several types of plasmonic waveguides have been proposed and investigated in the literature with the aim of achieving tighter light enhancement and longer propagation lengths.

1. Introduction

Enhancing light in low-index materials, such as air, is thought to be prohibited in conventional waveguides based on total internal reflection. Instead, external reflections from multiple dielectric layers or photonic crystals are usually employed. However, these structures are wavelength sensitive and have relatively large dimensions to provide high reflections. In recent years, a number of structures have been proposed to enhance light in low-index materials based on external reflections provided by interference effects. A slot waveguide eigenmode can be seen as being formed by the interaction between the fundamental eigenmodes of the individual slab waveguides.

Surface plasmons are free electron density oscillations on the surface of metals in contact with dielectric materials. Surface plasmons can propagate along the metal-dielectric boundaries and form surface plasmon waves. Since surface plasmon waveguides can provide tightly confined sub-wavelength modes, surface plasmon modes in various waveguide structures, such as thin metal films, finite width thin film metal stripes and metal wires, trenches in metal surfaces, metal dielectric layer structures, dielectric-loaded metal films, and metal wedges have been extensively investigated in the past. Plasmonic devices have attracted increasing attention in recent years due to their ability to confine light below the diffraction limit, thereby potentially enabling device miniaturization at the nanoscale. Several types of plasmonic waveguides have been proposed and investigated in the literature with the aim of achieving tighter light confinement and longer propagation lengths. Among them, the metal–insulator–metal (MIM) or plasmonic slot waveguide has emerged as a promising structure for surface plasmon guidance due to its true subwavelength mode confinement and its ability to route light through sharp bends with high efficiency. In the last years, silicon photonics has become one of the most active fields within optics. This can be explained by considering that the development of photonic integrated circuits using conventional complementary metal-oxide-semiconductor (CMOS) tools and processes would result in a significant reduction in costs because of the economies of mass manufacturing. Plasmonic structures have emerged as a promising route to improve light absorption in various optoelectronic devices due to their ability to confine light in spaces of significantly shorter than one fourth of the wavelength of the incident light, thereby providing strong light absorption or scattering. The paper is organized as follows: Section 2 contains an overview of some results from the litterature, Section 3 presents our own results, and Section 4 draws some conclusions.

2. Overview of Some Reported Results

Almeida et al. [1] represent a geometry for enhancing light in a nanometer-wide low-index material. They show that, through the use this structure, the field can be confined in a 50-nm-wide low-index region with a normalized intensity of 20 μm^{-2}. This intensity is approximately 20 times higher than that achieved in SiO_2 with conventional rectangular waveguides. The authors of [1] obtain the analytical solution for the transverse E-field profile E_x of the fundamental TM eigenmode of the slab-based slot waveguide as to be

$$E_x(x) = A\frac{1}{n_S^2}\cosh(\gamma_S x) \qquad \text{for} \qquad |x| < a, \tag{1a}$$

$$E_x(x) = A\{\frac{1}{n_H^2}\cosh(\gamma_S a)\cos[K_H(|x|-a)] + \frac{\gamma_S}{n_S^2 K_H}\sinh\left[K(|x-a)|\right]\} \quad \text{for} \quad a < |x| < b, \tag{1b}$$

$$E_x(x) = A\left[\cosh(\gamma_S a)\cos[K_H(b-a)]\right] + A\frac{n_H^2\gamma_S}{n_S^2 K_H}\sinh(\gamma_S a)\sin[K_H(b-a)]\exp[-\gamma_C(|x|-a)] \quad \text{for} \quad |x| > b, \tag{1c}$$

where K_H is the transverse wave number in the high-index slabs, γ_C is the field decay coefficient in the cladding, γ_S is the field decay coefficient in the slot, n_H the high refractive index, and constant A is given by

$$A = A_0\frac{\sqrt{k_0{}^2 n_H^2 - K_H{}^2}}{k_0}, \tag{2}$$

where A_0 is an arbitrary constant and $k_0 = 2\pi/\lambda_0$ is the vacuum wave number. The transverse parameters K_H, γ_S, and γ_C simultaneously obey the relations

$$k_0^2 n_H^2 - K_H^2 = k_0{}^2 n_C^2 + \gamma_C^2 = k_0^2 n_C^2 + \gamma_S^2 = \beta^2, \tag{3}$$

where β is the eigenmode propagation constant, which can be calculated by solving the transcendental characteristic equation

$$\tan[K_H(b-a)-\Phi]=\frac{\gamma_S^2 n_H^2}{K_H n_S^2}\tanh(\gamma_S a), \quad (4)$$

where

$$\Phi=\arctan[\gamma_C n_H^2/(K_H n_C^2)] \quad (5)$$

and *a* and *b* are the left and right coordinates of the right slot on the *Ox* axis. A conclusion is made that the slot waveguide can be used to greatly increase the sensitivity of compact optical sensing devices or to enhance the efficiency of near-field optical probes.

Robin Buckley and Pierre Berini [2] discuss and apply three Figures of Merit (FoMs) used as quality measures for 2D surface plasmon waveguides, to help trade-off mode enhancement against attenuation for the symmetric mode propagating along metal stripes. The optical properties of metals have been studied and are known to exhibit a negative real part of permittivity at optical frequencies. This property allows the metal-dielectric interface to support a surface plasmon-polariton (SPP) mode which is bound to the interface through the coupling of electromagnetic waves to oscillations in conduction electrons in the metal. Different stripe geometries are considered, and Au, Ag and Al are compared as the stripe metal over a wavelength range of 200 to 2000 nm. A conclusion is made that, based on all of the FoMs, Al provides the best performance for $\lambda_0 \leq 400$ nm, with Au possibly being better for $\lambda_0 > 1630$ nm and Ag performing better throughout the rest of the spectrum. These conclusions, which depend on the measured optical parameters of the metals, should also hold for other 2D SPP waveguides.

Alexey V. Krasavin and Anatoly V. Zayats [3] propose and comprehensively investigate Si-based plasmonic waveguides as a means to enhance and manipulate photonic signals. The high refractive index of Si provides strong enhancement and a very high level of photonic integration with achievable waveguide separations on the order of 10 nm and waveguide bends with 500-nm radius at telecommunication wavelengths, while the use of Al and Cu plasmonic material platforms makes these waveguides fully compatible with existing CMOS fabrication processes. It is found that, as the width of the waveguide increases up to 200 nm and higher, the mode becomes more and more localized in the waveguide.

Husain A. Jamid [4] puts forward a multilayer antiresonance reflecting optical channel waveguide difference geometry (ARROW) for enhancing the evanescent field in low-index materials. The finite method is used in the analysis of the structure. The fraction of the fundamental TE-like-mode power in the low-index material (air) is used as a measure of the evanescent field enhancement. The calculated results suggest that the evanescent field of the fundamental TE-like mode can be significantly increased in air, while the low modal loss that characterizes the leaky nature of the structure is maintained.

R. F. Cregan et al. [5] demonstrate the enhancement of light within a hollow core (a large air hole) in a silica-air photonic crystal fiber. Only certain wavelength bands are guided down the fiber, each band corresponding to the presence of a full two-dimensional band gap in the photonic crystal cladding. Single-mode vacuum waveguides have a multitude of potential applications from ultrahigh-power transmission to the guiding of cold atoms.

Pablo Sanchis et al. [6] analyze two different silicon slot waveguide configurations in order to achieve the optimum nonlinear performance. In the slot region, a complementary metal–oxide–semiconductor-compatible material made by silicon nanocrystals embedded in silica SiO2 has been considered. This material has demonstrated very promising characteristics for nonlinear applications. The optimum parameters for each configuration are first designed to achieve maximum field enhancement in the slot region. The influence of the variation of the refractive index in the slot region and the variation of the sidewall angle on the field confinement is investigated. The influence of the sidewall angle on the field confinement depends on the configuration chosen.

Yingran He et al. [7] propose and demonstrate nanoscale slot waveguides of hyperbolic metamaterials for achieving large optical field enhancement. The dependence of the enhanced electric field within the air slot on waveguide mode coupling and permittivity tensors of hyperbolic metamaterials is analyzed both numerically and analytically. Optical intensity in the metamaterial slot waveguide can be more than 25 times stronger than that in a conventional silicon slot waveguide due to tight optical mode confinement enabled by the ultrahigh refractive indices supported in hyperbolic metamaterials. The electric field enhancement effects are also verified with the realistic metal-dielectric multilayer waveguide structure.

3. Results and Discussion

Some of the authors of this paper deal with this topic [8, 9], as revealed by numerical modeling with the aid of the MPB code. For a high-index contrast interface, Maxwell's equations state that to satisfy the continuity of electric flux density *D*, the corresponding electric field *E* must undergo a large discontinuity. Their chosen configuration consisted of two high-index slabs, one of them having dimensions of 150 x 50 x 30 nm, and the other one 70 x 50 x 30 nm; both slabs had the same refractive index $n_H = 3.4$ separated by a lower index material of $n_L = 1.4$. The distances between the slabs were considered equal to 30, 35, and 40 nm, respectively. In each case, electric field *E* was computed and displayed.

In figures 1a-1c, the time-averages of electric field, for different distances w_s between slots are plotted.

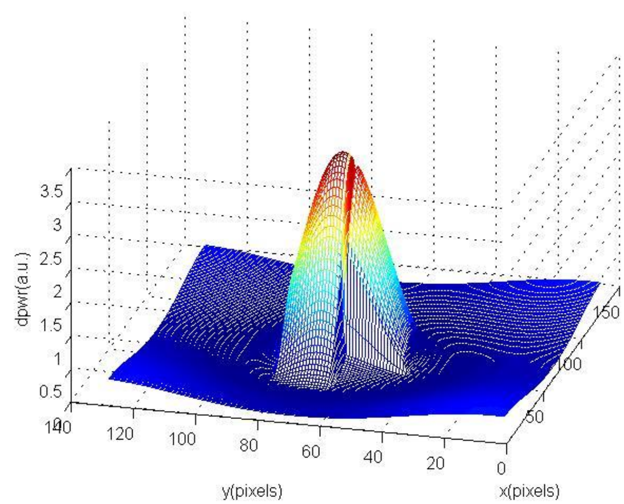

Fig. 1a. Time-averaged electric-field for w_s =30 nm.

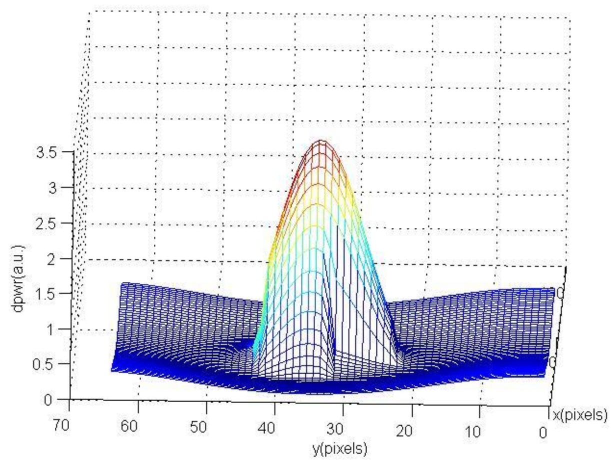

Fig. 1b. Time-averaged electric-field for w_s =35 nm (arbitrary units).

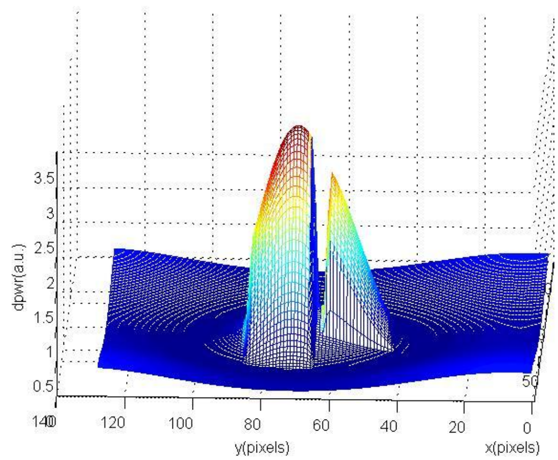

Fig. 1c. Time-averaged electric-field for w_s = 40 nm (arbitrary units).

As a result of the *E*-field enhancement in the slot, the optical intensity is also much higher than that in the high-index regions, as can be seen from the above figures. Figures 1a and 1b show an enhancement by a factor of about 1.5, whereas the enhancement in Fig. 1c is smaller. Light propagation in the slot waveguide shows a much higher intensity than that achievable with conventional waveguides. The vertical enhancement of the *E*- field in the slot region is dictated by that in the high-index regions.

Note that we have obtained enhancement only for asymmetric slabs. When we changed the slab configuration and dimensions to 100 x 20 x 15 nm, no enhancement was present, at least for w_S =15, 20, and 25 nm, as can be seen from Fig. 2 bellow.

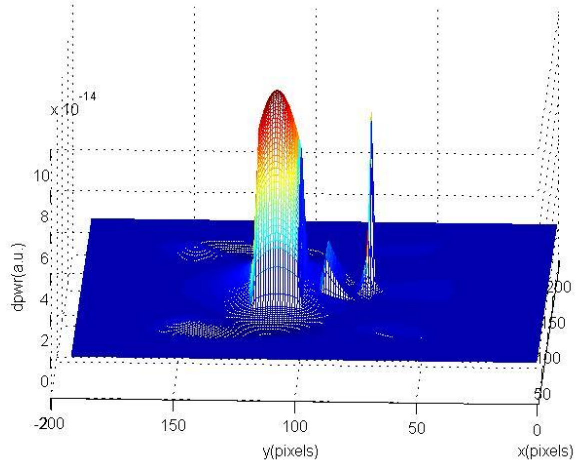

Fig. 2. Time-averaged electric-field energy density for w_s =15 nm (arbitrary units)

4. Conclusions

In this paper, we have tried to get some insight into the very interesting and modern research area belonging to photonics. The field has a lot of technological applications, which will be addressed in another paper. For the moment, we have underlined some aspects of photonic nanostructures which accomplish an enhancement of light. Some results from the literature and our own results have been presented, but the presentation is certainly far from being exhaustive.

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