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Anomalous optical coupling between two silicon wires of a slot waveguide in epsilon-near-zero metamaterials

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ABSTRACT

Anomalous optical coupling properties between two silicon wires in a silicon slot waveguide embedded in epsilon-near-zero (ENZ) metamaterials are proposed and demonstrated. The dependences of optical field enhancement in the slot region and transverse optical force on the slot size and the permittivity of surrounding material are studied in details. It is demonstrated that the optical field in the slot region is significantly enhanced due to the giant index contrast at the slot interface between silicon wires and ENZ metamaterials, but the optical mode coupling between silicon wires is greatly reduced so that the transverse optical force is suppressed into almost zero. Moreover, metal-dielectric multilayer structures are designed to realize ENZ metamaterials in the slot region for achieving the electric field enhancement.

1. Introduction

The emergence of metamaterials with artificially engineered subwavelength structures offers a flexible method to control the permittivity and permeability of materials. With metamaterials, many exotic optical phenomena have been demonstrated, such as negative index of refraction [1], ultrahigh index of refraction [2], and epsilon-near-zero (ENZ) materials [3]. Due to the anomalous electromagnetic properties, metamaterials with near-zero permittivity have been widely investigated in both theory and engineering [4–7]. Maxwell's equations state that, for a high-index-contrast interface, the continuity of the normal component of electric displacement will result in a considerable electric field enhancement at the low-index region. Conventional silicon slot waveguides embedded in low-index materials have been widely studied to enhance the optical field and confine light in the slot region [8]. In order to further boost the electric field enhancement, either the index of the waveguide material can be increased, or the index of the slot material can be reduced. Due to the ultrahigh refractive index of hyperbolic metamaterials, metamaterial slot waveguides embedded in air have been proposed to achieve strong optical field enhancement [9]. Another concept is to use ENZ metamaterials as the low-index material in order to achieve the ultra-large index contrast, which has been used to realize anomalous field enhancement [10,11].

In this paper, we present a new type of silicon slot waveguides embedded in ENZ metamaterial surroundings, where the electric field in the slot region can be significantly enhanced, due to the giant index contrast at the slot interface. The dependences of the electric field enhancement in the slot region with the slot size and the permittivity of surrounding material are systematically studied. Furthermore, it is also demonstrated that the transverse optical force between two silicon wires of silicon slot waveguides with different slot sizes will keep almost zero, due to the weak mode coupling of silicon wires in the ENZ metamaterial surroundings. Such extraordinary properties of silicon slot waveguides embedded in ENZ metamaterial surroundings will be very useful for enhanced light-matter interactions, such as nonlinear optics [12], sensitive mechanical sensors [13], and optomechanical device actuation [14].

2. Electric field enhancement

Fig. 1(a) shows the schematic of the silicon slot waveguides, where two silicon wires with square cross sections are closely placed in the isotropic ENZ environment with a nanoscale slot size g along x direction. The permittivity of silicon is $\varepsilon_{si}=12.124$. By assuming that $a=350$ nm and $g=2$ nm, Fig. 1(c) and (d) show the calculated electric field distributions at $\lambda_0=1.55$ μm with the ENZ metamaterial ($\varepsilon_{surr}=10^{-4}$) and air ($\varepsilon_{surr}=1$) surroundings, respectively. Considerable electric field enhancement can be observed at the slot region in both cases. Since the gap is very small, mode coupling exists between the two silicon wires. The leaked electric field from the silicon wires will be greatly enhanced in the slot

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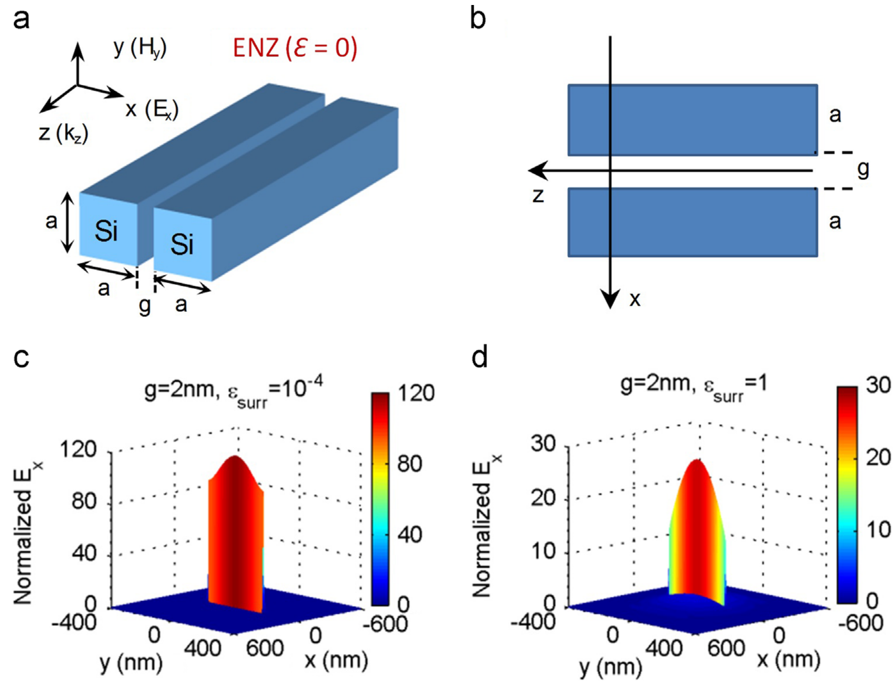

Fig. 1. Schematic of the silicon slot waveguides and the electric field enhancement in the slot region. (a) Three-dimensional (3D) silicon slot waveguide structure, and (b) the approximated two-dimensional (2D) slot waveguide structure for theoretical analysis. 3D surface plots of the E_x field distributions [normalized to E_x ($y=0$, $|x|=|a+g/2|^+$)] for slot waveguides with (c) ENZ metamaterial surroundings and (d) air surroundings, respectively.

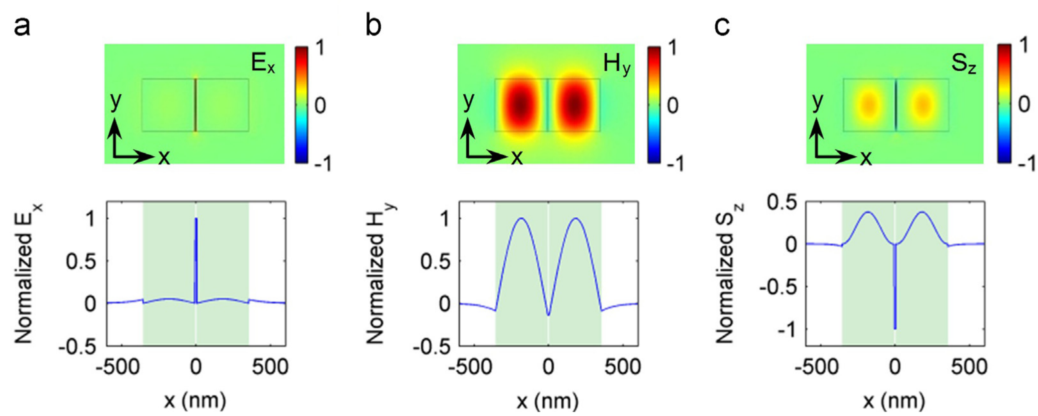

Fig. 2. The optical mode profiles of (a) E_x, (b) H_y and (c) S_z for the silicon slot waveguides with $g=10$ nm with ENZ metamaterial surroundings ($\varepsilon_{surr}=10^{-4}$). The crossing line plots at $y=0$ are also shown.

region due to its lower permittivity. However, it can be clearly seen that ENZ metamaterial surroundings can lead to a much stronger electric field enhancement. This is due to the giant permittivity contrast between the silicon wire and the slot region, so that even weak optical field leakage from the silicon wires can result in strong electric field enhancement. The symmetric mode profiles of the silicon slot waveguides with slot size $g=10$ nm in the ENZ metamaterial surroundings ($\varepsilon_{surr}=10^{-4}$) are shown in Fig. 2. It is shown that strong electric field E_x is localized inside the slot region, since the leaked electric field from the silicon wires can be greatly enhanced by the low permittivity in the gap. While the magnetic field H_y is tightly confined in the silicon wires, as shown in Fig. 2(b). Accordingly, there is strong optical energy flow guided in the slot region, as shown in Fig. 2(c).

The electric field enhancement factor η is defined as the ratio of the electric field E_x at the two boundaries of one silicon wire $\eta=E_x[|x|=(g/2)^-]/E_x[|x|=(g/2+h)^+]$, which represents the electric field enhancement in the slot region. The simulated effective refractive index along the propagation direction $n_{eff,z}$ and the electric field enhancement factor η as a function of slot size g for two different surrounding materials are shown in Fig. 3(a) and (b). It is shown in Fig. 3(a) that the effective refractive index of the slot waveguides with air surroundings gradually increases as gap size gets smaller. On the other hand, the effective refractive index of the slot waveguides with ENZ metamaterial surroundings is almost unchanged, indicating that the two silicon wires are optically insulated to each other by the ENZ material and the mode coupling between the silicon wires is quite weak. However, as shown in Fig. 3(b), the electric field in the ENZ slot can be greatly enhanced at the small gap size, which is much stronger than the case of air slot. Fig. 3(c) and (d) present the simulated effective refractive index $n_{eff,z}$ and the electric field enhancement factor η as a function of the permittivity of surrounding material ε_{surr} for $g=2$ nm and $g=5$ nm. As the permittivity of surrounding material gets smaller, the effective refractive index will get lower and reach almost a constant when ε_{surr} is less than 10^{-2}. At the