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Optical properties of nanowire metamaterials with gain

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ABSTRACT

The transmittance, reflectance and absorption of a nanowire metamaterial with optical gain are numerically simulated and investigated. It is assumed that the metamaterial is represented by aligned silver nanowires embedded into a semiconductor matrix, made of either silicon or gallium phosphide. The gain in the matrix is modeled by adding a negative imaginary part to the dielectric function of the semiconductor. It is found that the optical coefficients of the metamaterial depend on the gain magnitude in a non-trivial way: they can both increase and decrease with gain depending on the lattice constant of the metamaterial. This peculiar behavior is explained by the field redistribution between the lossy metal nanowires and the amplifying matrix material. These findings are significant for a proper design of nanowire metamaterials with low optical losses for diverse applications.

1. Introduction

Nanowire metamaterials (NWMMs) are artificial media that are composed of aligned metal nanowires (NWs) embedded into a dielectric matrix [1,2]. In such materials, both the NW diameter and the separation between adjacent NWs are well below the operating wavelength, which allows one to consider them as effectively homogeneous. A large aspect ratio (length/diameter) of the constitutive NWs dictates a strong optical anisotropy of NWMMs while their plasmonic character leads to strongly enhanced light-matter interactions. These peculiar features result in unusual optical properties such as hyperbolic dispersion [3], nonlocal optical response [4] and enhanced spontaneous emission [5] and are important for numerous applications in subwavelength imaging [6–10], biosensing [11] and active nanophotonics [12–14].

Despite their remarkable properties, NWMMs suffer from appreciable dissipative losses, inherent to all plasmonic structures. This disadvantage constitutes the main obstacle on the way to their successful applications in practice. One can, however, significantly reduce the losses by means of introducing optical gain in the NWMM matrix [15–17]. Such gain can be provided by atomic or molecular impurities, pumped by an external light source to create a population inversion in them [18]. On the other hand, a semiconductor material being used as a host medium for metal NWs [19] can act under optical pumping or carrier injection as an amplifying medium similar to that in conventional semiconductor lasers [18].

In this paper, we numerically investigate the optical properties of NWMMs with semiconductor host material as a gain medium. We calculate the transmittance, reflectance and absorption at normal incidence in the visible and near infrared ranges. We study how gain in the structure influences these quantities at different geometrical and physical metamaterial parameters.

2. Numerical simulations

Fig. 1 shows the unit cell of the nanowire metamaterial under consideration. The rectangular unit cell cross section represents a hexagonal closed-packed lattice of nanowires. The geometrical parameters were chosen to obtain a structure similar to the one presented by Tsai et al. [2]. In all simulations, the radius and length of the nanowires were fixed to be 25 nm and 1 μm, respectively. The simulated structure was composed of three layers. Two of them were air slabs on both top and bottom of the metamaterial of lengths 400 nm and 600 nm, respectively. The third layer was a Perfectly Matched Layer (PML) of length 400 nm.

In our simulations, we assumed that the nanowires are made of silver (Ag) while the host material was either silicon (Si) or gallium phosphide (GaP). For the dielectric function of silver we adopted the Drude model

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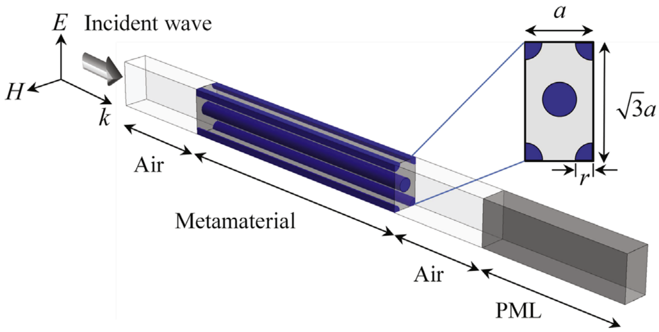

Fig. 1. Geometry of the nanowire metamaterial unit cell and its cross section.

$$\epsilon_m = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\omega\gamma}, \tag{1}$$

where ω_p is the plasma frequency, γ is the relaxation rate, ϵ_∞ denotes the high frequency limit of the dielectric function and $\omega = 2\pi c/\lambda$ with c and λ being the speed and wavelength of light in vacuum, respectively. The dielectric function of the semiconductor materials were taken from Refs. [20,21].

The material gain in the semiconductor can be modeled by adding a small negative imaginary part $\Delta\epsilon''$ to the dielectric function of the semiconductor [22,23]

$$\epsilon_d(\lambda) = \epsilon'(\lambda) + i[\epsilon''(\lambda) + \Delta\epsilon''], \tag{2}$$

where ϵ' and ϵ'' are the real and imaginary parts, respectively, of the dielectric function of the semiconductor in thermal equilibrium.

The numerical simulations were carried out by using the frequency finite element method [24,25] and commercial software COMSOL Multiphysics. In all calculations it was assumed that a plane electromagnetic wave is normally incident at the metamaterial surface and polarized as shown in Fig. 1. The transmittance, $T(\lambda)$, reflectance, $R(\lambda)$, and absorption $A(\lambda) = 1 - R(\lambda) - T(\lambda)$ coefficients were calculated for different values of the parameters a and $\Delta\epsilon''$ in the spectral range $\lambda = 400 - 800$ nm.

3. Numerical results

The optical properties of nanowire metamaterials with $a = 100$ nm in the absence of gain ($\Delta\epsilon'' = 0$) for gallium phosphide and silicon matrices are presented in Fig. 2a and b, respectively. In both cases the transmittance is negligible at the wavelengths longer than 550 nm. The domination of absorption over reflectance at shorter wavelengths ($\lambda < 580$ nm for GaP and $\lambda < 650$ nm for Si) is changed by their inverse ratio at longer wavelengths. The oscillations at short wavelengths can be attributed to the Fabry-Pérot modes of the metamaterial slab [2].

The introduction of the gain in the host materials leads to dramatic changes in the optical spectra at the wavelengths below 550 nm (see Fig. 3a and b). The transmittance is noticeably increased in this spectral range and the oscillations in both reflectance and absorption become more pronounced. On the other hand, the spectra at $\lambda > 550$ nm are only slightly modified, their maximums being shifted to longer wavelengths.

To investigate the influence of gain on the optical coefficients of the metamaterial more systematically, we have calculated their dependence on $\Delta\epsilon''$ for different lattice constants and for a fixed value of the wavelength (see Figs. 4 and 5). The chosen wavelengths correspond to maximum transmittance for the NWMMs without gain (see Fig. 2). They are important, therefore, for various applications and it is worthwhile to know how the gain influences the optical constants at these specific wavelengths. The full spectra of the optical coefficients for different gain and lattice constant values are given in the Supplementary material [26]. As one can see, the optical coefficients depend non-monotonically on the gain and the character of this behavior is dictated by the value of the lattice constant. The larger variations in the optical properties are observed for the NWMM with a GaP matrix which will be investigated in more detail in Section 4.

To shed more light on this feature, we have simulated the field intensity distribution along the metamaterial output surface. Fig. 6 illustrates how this distribution varies with the lattice constant, while Fig. 7 shows how it depends on the gain in the host matrix.

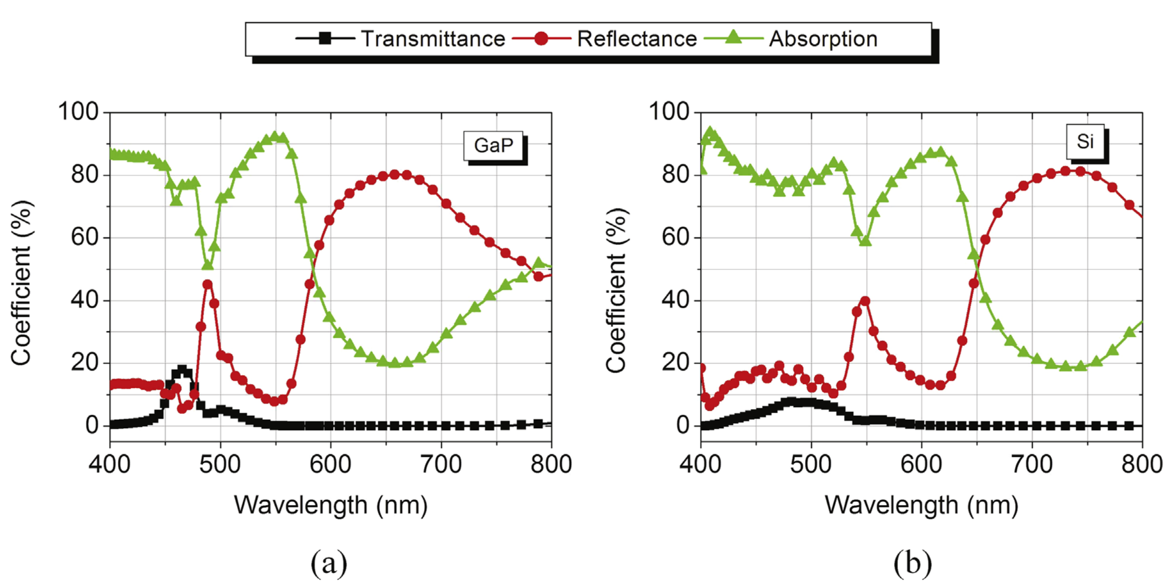

Fig. 2. Transmittance, reflectance and absorption spectra of the silver nanowire metamaterial without gain at normal incidence in the range 400–800 nm for $a = 100$ nm. (a) Gallium phosphide matrix, (b) silicon matrix.