Ultrafast all-optical GaAs nanoswitch for photonic integrated circuitry

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Abstract. All-dielectric nanophotonics offers favourable opportunities for engineering of devices for various practical tasks. In this regard, a very promising field is integrated photonic circuitry, where the implementation of all-dielectric components can significantly increase the performance of nanodevices. In this paper, we numerically investigate a system formed by an ultrafast all-optical switch – a GaAs dimer nanoantenna – and a GaAs strip waveguide. The simulation of the light scattering in that system shows the relative change of the waveguide transmission coefficient $\Delta T/T$ up to 12.3 % for the fluence of the pumping pulse 0.19 mJ cm$^{-2}$. This proof-of-principle result paves the way for potential applications of the system as a logic element for nanophotonic chips.

1. Introduction

The effects that are considered to be within the scope of all-dielectric nanophotonics are characterized by the low level of ohmic losses at optical frequencies and by the coexistence of the electro-dipolar and magneto-dipolar modes of the comparable magnitude in scattering spectra of dielectric nanoresonators [1 – 3]. These factors provide more degrees of freedom and, hence, novel opportunities for the design of photonic devices, owing to the multitude of scattering effects enabled by the resonant nature of “meta-atoms” – the nanostructures’ building blocks [3].

The development of active, or reconfigurable, all-dielectric nanophotonic elements constitutes an important issue for the emerging field. All-optical switching is a promising solution to this task. This phenomenon can be characterized as the modulation of light’s properties by optical means and, actually, represents a group of effects. The recent works reveal all-optical switching as the change of the transmission coefficient for amorphous silicon nanoparticles [4] and the reflection coefficient for direct-gap semiconductor metasurfaces [5] induced by femtosecond-laser pumping. At the same time, the manipulation of the far-field scattering profile of a standalone dielectric nanoantenna can also be attributed to all-optical switching [6]. This concept was further developed for the case of a more complicated system – an asymmetric dimer comprised of two spherical silicon nanoresonators of different radii – and the corresponding numerical investigations of that system were performed in ref. [7].

The next step would be the experimental observation of the effect. To meet the requirements dictated by experimental methodology and processes of nanofabrication, a new choice of the nanostructure’s geometry and material was proposed: two cylindrical nanoresonators made of gallium arsenide (GaAs) [8]. The dimer itself has a direct application as an ultrafast all-optical switch for photonic integrated circuitry. Therefore, it is naturally to carry out the research of the system “dimer – waveguide” which represents a typical junction in nanophotonic chips.
2. Results and discussion

Two elements make up the simulated system: the dimer and the waveguide (Fig. 1. A.). The both objects are put into the passivating sapphire (Al₂O₃) layer. That feature is stipulated by the technological procedure aimed at producing samples of good quality, with minimal defects. The geometry of the dimer was taken from the previous studies [8]. Namely, the following parameters were used: \( r_j = 80 \) nm, \( r_s = 95 \) nm – for the radii of the smaller and the larger nanodisks respectively, \( h = 200 \) nm – for the cylinders height, and \( \Delta = 450 \) nm – for the distance between the nanoresonators’ centers of symmetry. To make light enter the waveguide, the incident radiation should fall under a nonzero angle on the surface. Using FDTD simulations, we revealed the optimal value of the angle of incidence, which equals 45°. Then, the influence of the carrier-induced effects [9] on the dimer’s far-field scattering profile was investigated (Fig. 1. B.). The results were obtained also by means of 3D finite-difference time-domain simulations [10].

The waveguide was designed to exhibit minimal losses in the spectral interval that is supposed to be used in experiment – the vicinity of 875 nm. The next aspect to be taken into consideration was to make a single-mode waveguide where the mode’s field is distributed inside the core, without leakage (Fig. 1. C, D). As a result, the waveguide’s width and was chosen to be \( w = 400 \) nm. It height was set to be \( h = 200 \) nm to properly complement the geometry of the dimer. This part of the calculations was performed by the finite difference eigenmode solver using Lumerical MODE solution [11].

![Figure 1](image-url)
The waveguide’s transmission modulation, which occurs in the system due to the pumping of the dimer, results from two major factors. Firstly, it is because of the deformation of the dimer scattering indicatrix, which becomes more symmetric after the pumping and, consequently, less suitable for the asymmetric orientation of the waveguide. The latter point means that the rotation of the scattering profile maxima, or the symmetrization of the indicatrix, prevents the scattered radiation from entering the waveguide. Secondly, the change of the material’s optical characteristics induced by the pumping brings the growth of the extinction coefficient leading to the decrease of the indicatrix maximal values. The magnitude of these effects, and, hence, of the transmission modulation, is defined by the concentration of the free-carriers that are generated in the dimer by the pumping. In turn, the value of this concentration depends upon the fluence of the pumping pulse. The relative transmission change for some values of the pulse fluence is presented in Fig. 2. The choice of the fluence interval is restricted by the system’s thermal resistance, from the upper boundary, because large amounts of the energy transferred by the pulse result into the complete destruction of the system.

![Figure 2](image)

**Figure 2.** The relative modulation of the transmission coefficient of the waveguide for the various values of the pumping pulse fluence.

3. **Conclusion**

We have proposed the design of an all-optical switch based on GaAs that can be used as a logic element in photonic integrated circuitry. The geometry of the switch and its material composition were taken to make it feasible in terms of nanofabrication processes and experimental characterization. The numerical simulations, inter alia, show that the system exhibits the relative transmission modulation 12.3 % for the relatively low rate of the pumping pulse fluence 0.19 mJ · cm$^{-2}$.

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