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Numerical modeling of optical transmittance of 2×2 directional couplers based on GaP nanowires

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Abstract. In this paper, the optical properties of the GaP nanowires-based directional X-coupler are investigated for the design and further fabrication of a passive nanophotonic device. Results of numerical calculations demonstrate how the coupling length, nanowires diameter, and the gap between them influence the spectral composition of the output signals. By optimizing these geometric parameters, efficient subwavelength directional X-couplers based on GaP nanowires can be fabricated for light control in photonic circuits.

Keywords: photonics, passive optical device, directional coupler, nanowires

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Численное моделирование оптического пропускания направляющих 2×2-разветвителей на основе нитевидных нанокристаллов GaP

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Аннотация. В работе исследуются оптические свойства направляющих 2×2-разветвителей на основе нитевидных нанокристаллов (ННК) GaP с целью изготовления пассивного нанофотонного устройства. Результаты численного расчета показывают, как длина оптической связи, диаметр ННК и зазор между ними влияют на спектральный состав выходных сигналов. Оптимизируя эти геометрические параметры, можно изготовить эффективные субволновые направляющие 2×2-разветвители на основе ННК GaP для управления светом в фотонных интегральных цепях.

Ключевые слова: фотоника, пассивные оптические элементы, направляющие разветвители, нитевидные нанокристаллы

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Introduction

Optical 2×2 or X-couplers are fundamental components of integrated photonic systems. They can serve as passive optical elements for light manipulation, acting as spectral filters or power splitters. Silicon is the primary material for such devices [1]. Despite its well-studied nature and technological maturity, this material has significant drawbacks, including difficulties in obtaining emitters and visible range opacity, which hinder its miniaturization and application. Gallium phosphide (GaP) meets the requirement of transparency in the visible range. Additionally, it exhibits a high refractive index [2] and nonlinear properties in this spectral region [3]. GaP is also an indirect-bandgap semiconductor with a bandgap of 2.26 eV at room temperature [4]. Due to this property and the ability to grow crystals with low sidewall roughness [5], GaP-based nanostructures demonstrate low absorption and scattering losses for visible light propagation and can be used as efficient waveguides [6]. Furthermore, GaP structure growth methods show great potential for compatibility with silicon technologies [7]. Additionally, there is a possibility of implementing emitters within a single GaP-based structure through chemical composition modification [8]. All these factors demonstrate GaP's significant promise for fabricating miniature elements of integrated nanophotonics, particularly 2×2-directional couplers. GaP structures in the form of nanowires (NWs) possess favorable elastic mechanical properties, and owing to their high refractive index, NWs can be bent while preserving waveguide properties [9]. This work investigates the optical properties of a 2×2-directional coupler based on GaP NWs, aiming to develop a full-fledged nanophotonic device and enable further optimization of its characteristics.

Materials and methods

The analysis of a structure was performed using numerical simulations in Ansys Lumerical software. The simulations involved solving Maxwell's equations using the Finite-Difference Frequency-Domain (FDFD) method according to the Yee algorithm [10]. The model schematic is shown in Fig. 1, *a*. The directional coupler was set from two NWs placed parallel and converging at the center, forming the optical coupling region. The coupler sections had a length of 5 μm, except for the bends and the optical coupling regions. SiO_2 was chosen as the substrate material. The following parameters were used in the simulation: the GaP nanowire diameter $D = 200$ nm, the gap distance $g = 50$ nm between the NWs within the optical coupling region, and the parameter $L_S = 5$ and 10 μm – the length of the straight section in the optical coupling region. It is important to note that a symmetric structure was modeled, and the nanowire diameter remained constant along length. For comparison, 2D calculations of device cross-section in the optical coupling region were performed using the finite element method eigenmode solver implemented in COMSOL Multiphysics software.

Results and discussion

For the presented 2×2-directional coupler geometry, it is sufficient to consider the fundamental TE-like mode responsible for optical coupling. For a comprehensive analysis, we should also consider higher-order waveguide modes that have a lower effective refractive index than the fundamental mode. This leads to electric field spreads more widely outside the waveguide resulting in stronger interaction between adjacent nanowires. However, this low effective index also makes higher-order modes highly susceptible to attenuation. In devices with bends, a portion of their energy radiates away, leading to significant losses. Consequently, by the time they reach the optical coupling zone, their power is extremely low, making their contribution to energy redistribution negligible in most practical calculations.

The main results of the 3D-calculation are the transmission spectra evaluated at the output ports. Typical spectra are presented in Fig. 1, *b*. They are featured by the presence of transmission bands at the output ports, with transmittance maxima alternating between these ports as the wavelength changes. The negligibly small transmittance at shorter wavelengths is associated with material absorption in GaP. The absence of transmittance at longer wavelengths is associated with optical losses due to field leakage into the substrate.

Another distinctive feature is the pattern of electromagnetic wave propagation within the structure. To demonstrate this, stationary electric field distributions in the optical coupling region were calculated (Fig. 1, *c*, *d*, *e*). The field distributions reveal EM field energy exchange between the coupler arms, where the number of exchange cycles increases as operating wavelength increases, owing to the greater possibility of interference.

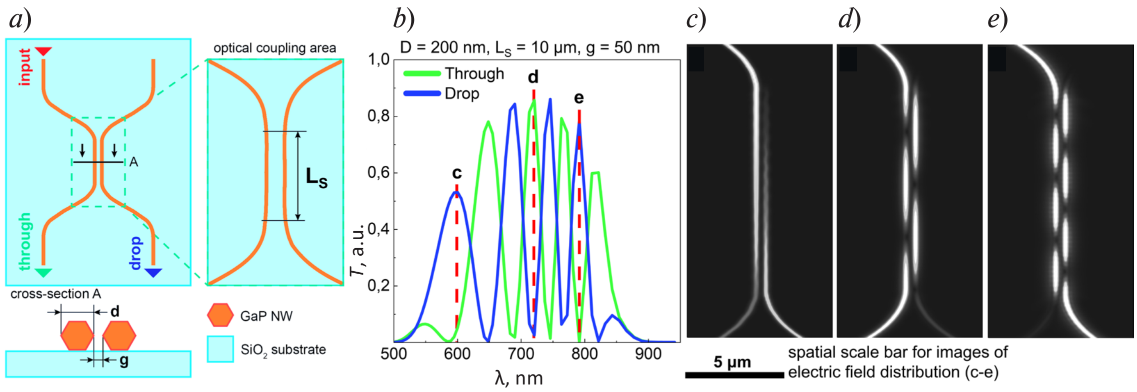

Fig. 1. GaP-based directional coupler 3D-simulations:
Device model to simulate in Ansys Lumerical (*a*), calculated transmittance spectra for geometrical parameters D = 200 nm, L_S = 10 µm, g = 50 nm (*b*); electric field intensity distributions in the optical coupling region for alternating transmittance maxima of both ports 550 nm (*c*), 600 nm (*d*), 648 nm (*e*), 690 nm (*f*), 720 nm (*g*), 746 nm (*h*), 768 nm (*i*), 791 nm (*j*)

The numerical calculation presented above provides the most comprehensive characterization of the structure's optical properties, as it accounts for the geometric parameters. However, such calculations are extremely resource-intensive, making them difficult to use for designing devices with optimized parameters. Computational costs can be significantly reduced by considering a 2D problem. Region of the optical phenomena of interest lies within the optical coupling region, so it is enough to simulate the cross-section of this region (Fig. 2, *a*). Since sufficiently small distances between the NWs are considered, waveguide modes overlap and interaction occurs, leading to the phenomenon of cross-talk. The cross-talk induces optical coupling and energy transfer from one nanowire to the other and leads to the formation of two supermodes: symmetric (even) and antisymmetric (odd). They are characterized by propagation constants β_+ and β_-, determined for each wavelength via the corresponding effective refractive indices: $\beta_{+,-} = 2\pi n_{+,-}/\lambda$, where λ is the light wavelength in vacuum. The field of the modes propagating in this system follows an exponential law $E \sim \exp[-\beta \cdot L]$. It is necessary to consider the distance L over which the modes effectively interact with each other, as the coupling length (L_C). Previously, to characterize the couplers, the length of the straight section within the optical coupling region (L_S) was introduced. This distance is merely a geometric parameter and cannot fully characterize the optical coupling region because field interaction occurs not only on the straight sections but also within the bend regions. The signal intensities distribution at the output ports depends on the linear combination of the fields propagating along the coupling length L_C, specific expressions are given in Fig. 2, *a*. Values of n_+ and n_- were obtained via COMSOL Multiphysics simulations.

As a result, spectral maps of the output signal intensity distributions depending on geometric parameters were obtained. The transmittance dependence on coupling length L_C for different ports is shown in Fig. 2, *b*. An increase in the coupling length L_C leads to an increase in the number of transmittance bands, a decrease in their width, and a transmittance maxima blue shift. The maps also demonstrate the alternation of signal intensities at the output ports, except in loss-prone regions. In particular, material losses dominate in the short-wavelength region; it is evident how these losses increase with the coupler length, leading to significant signal attenuation. Fig. 2, *d* presents a map of the through-port spectrum dependence on the gap width *g* between the NWs. As *g* increases, the number of transmission bands decreases, and their width increases due to the weakening of interference effects. Furthermore, increasing *g* causes a transmittance maxima red shift (shift towards longer wavelengths). A stronger influence on the maxima position is exerted by changing the nanowire diameter *D* (Fig. 2, *e*). However, varying *D* practically does not affect the number of transmission bands. Figures 2, *d*, *e* clearly show the waveguide mode cutoff spectral position. At wavelengths below this point, the structure functionalizes as a directional coupler.

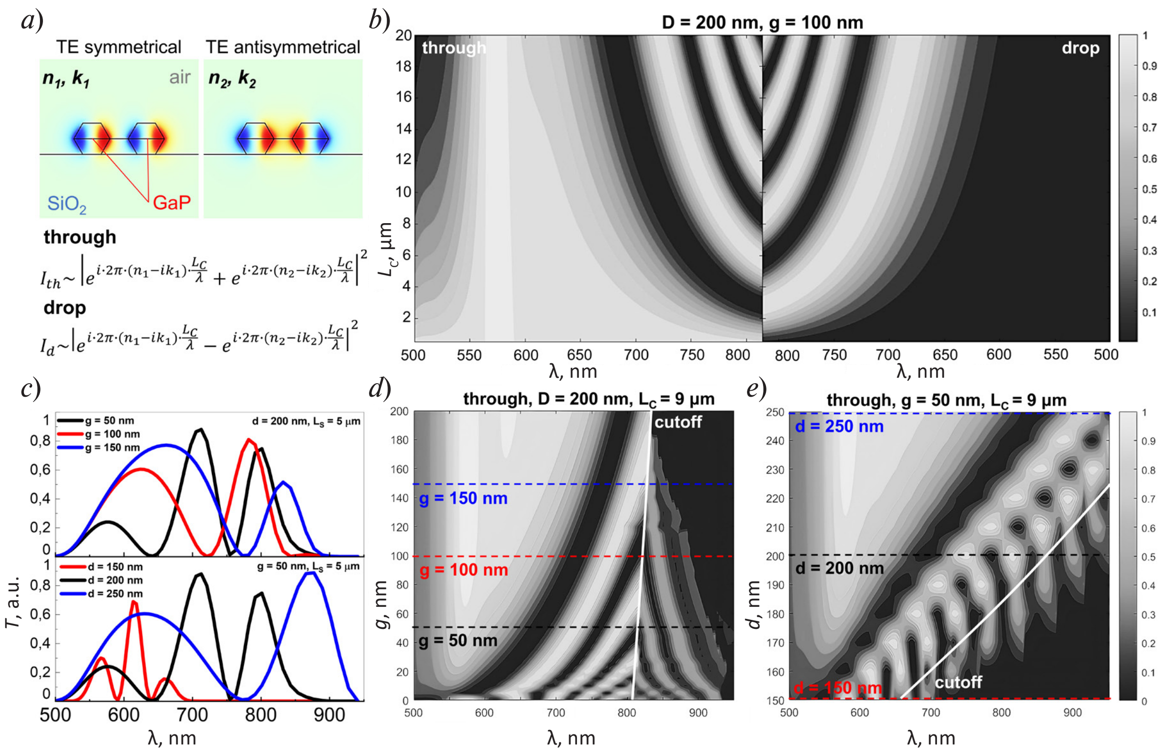

Fig. 2. GaP-based directional coupler 2D-calculations: even and odd modes and analytical formulas used to calculate the intensity at the optical coupling zone outputs (*a*), spectral maps of signal intensity distribution at through and drop ports depending on optical coupling length for fixed $D = 200$ nm and $g = 100$ nm (*b*), transmittance spectra obtained in the 3D-simulations for several sets of parameters (*c*), given for comparison with the spectral maps of signal intensity distribution at through port depending on gap between NWs for fixed D = 200 nm and L_C = 9 μm (*d*), spectral maps of signal intensity distribution at through port depending on NWs diameter for fixed g = 50 nm and L_C = 9 μm obtained in 2D-calculations (*e*)

Although the 2D calculation requires significantly fewer computational resources, it does not account for all geometric features of GaP-nanowire-based directional couplers. However, the coupling length L_C serves as an effective parameter and with the correct choice of L_C, the 2D model can adequately characterize the 3D system. To demonstrate this, a part of the 3D through-port simulation results for the structure with L_S = 5 μm (Fig. 2, *c*) were sorted to compare with 2D calculation results. For the maps in Figures 2, *d*, *e*, the L_C value was chosen as 9 μm, and the parameters *D* or *g* were fixed at values corresponding to the 3D calculation. Examining intensity maps cross-sections along the remaining varied parameter, it is evident that the transmittance spectra obtained from the 2D model fully match the spectra calculated in 3D.

Conclusion

In summary, this work demonstrates that GaP NWs-based 2×2 directional couplers can effectively control visible light at nanoscale. By determining the effective parameter of L_C, significant optimization of the design process can be achieved by replacing resource-intensive 3D modeling with 2D calculation. Optimizing the structure's geometric parameters leads to precise tuning of the device's spectral characteristics. This tunability enables multiple operational modes, from optical switching to power splitting, making these GaP NW couplers versatile components for integrated photonic systems.

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