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High-index waveguides for propagation of electromagnetic waves with high transversal angular momentum

N.G. Iukhtanov[1]✉, M.V. Rybin[1, 2]

[1] ITMO University, St. Petersburg, Russia;
[2] Ioffe Institute, St. Petersburg, Russia
✉ nikita.yuhtanov@metalab.ifmo.ru

Abstract. We study periodic waveguides of silicon cylinders for an optical isolator in the configuration of a Mach–Zehnder interferometer, as one of the possible applications in silicon photonics. Magneto-optical effect in silicon is considered under application of external magnetic field normal to the waveguide in the on-chip configuration that is Voight geometry. External magnetic field remains perpendicular to the direction of propagation of the electromagnetic wave for any direction of the waveguide on the surface, which allows us using a serpentine folding of waveguides. The nonzero integral electric field rotation in the plane of the waveguide is demonstrated. Our results uncover the possibility of using bare silicon as a magneto-optical material for optical isolators.

Keywords: electric field rotation, optical isolator, Voigt geometry

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Материалы конференции
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Высокоиндексные волноводы для распространения электромагнитных волн с большим поперечным угловым моментом

Н.Г. Юхтанов[1]✉, М.В. Рыбин[1, 2]

[1] Университет ИТМО, Санкт-Петербург, Россия;
[2] Физико-технический институт им. А. Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ nikita.yuhtanov@metalab.ifmo.ru

Аннотация. В настоящей работе мы предложили новую конфигурацию волновода для реализации кремниевого оптического изолятора (ОИ) на микрочипе с использованием магнитооптического эффекта в удобной для практической реализации геометрии Фойта. При разработке волновода мы основывались на структуре с нарушением зеркальной симметрии. Благодаря нарушению симметрии в продольной плоскости центрального сечения рассматриваемой волноводной структуры и магнитному полю, приложенному перпендикулярно волновому вектору, можно получить необходимую удельную фазу для конструирования ОИ на основе интерферометра Маха–Цендера. Главное отличие данной работы от известных подходов состоит в реализации ОИ только на кремнии и использование магнита, который не требует источников питания.

Ключевые слова: вращение электрического поля, оптический изолятор, геометрия Фойгта

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Introduction

In the recent years, researchers have been working on the problem of miniaturization of integrated optical devices, such as optical isolators, circulators, etc. [1]. An optical isolator is an analog of regular diodes designed for light, a device that allows for waves to pass but only in one direction. Obtaining an optimal and affordable device on a microchip leads to opportunities for developing promising integrated photonic circuits.

To date there are several approaches to the implementation of non-reciprocal on-chip devices, which are mainly based on electro-optical, nonlinear and magneto-optical effects. Electro-optical effects make it possible to break the time-reversal symmetry (T-symmetry) due to the modulation of the effective refractive index in time [2], which provides a different transmission coefficient for electromagnetic waves in the forward and backward directions. Besides, nonlinear effects, in particular, the nonlinear Kerr effect is exploited in possible devices for a non-reciprocal transfer of pulses [3]. In addition, magneto-optical effects are often used for structures with yttrium iron garnet (YIG) [4], the material with a high magnetic to optical response. Common materials among magneto-optical garnets, which are used to accumulate a non-reciprocal phase in the structure, are cerium substituted yttrium iron garnet (Ce:YIG). These materials show high Faraday rotation rates [5] and a low absorption coefficient in the infrared region of the spectrum [6]. The integration of silicon waveguides fabricated by silicon on insulator (SOI) technology, structures with YIG films is the outstanding technological problem in this approach. The discrepancy between the physical properties of garnets and A_3B_5 semiconductors provides difficulties in the epitaxial growth of such structures. Thus, magneto-optical garnet was not grown on semiconductors with sufficiently good crystallinity and the expected high effect indicators were not demonstrated yet [7, 8].

Recently, approach to creating an optical isolator on-chip based on Faraday effect in silicon waveguide structures were proposed [9]. However, the experimental confirmation is challenging since the necessary conditions for optical isolation due to the residual anisotropy of the waveguide, which is difficult to compensate in appropriate degree.

Here we study a silicon-based periodic structure as a two-dimensional (2D) problem that can be used to design an optical isolator in a Mach–Zehnder interferometer (MZI) configuration [10], where the magnetic field is applied perpendicular to the plane of a transverse rotation element (TRE). The advantage of such Voigt geometry [11] lies in the possibility of changing the photonic structure in the plane of the wave vector (Fig. 1). In this way, it is possible to fold the waveguide structure into a compact on-chip geometry.

Design

In this paper, we consider an array of silicon cylinders in air background. Geometric dimensions are optimized for the telecom wavelength around $\lambda = 1.5$ μm. Note that due to the scalability of the Maxwell equations, the operating wavelength can be shifted by changing the geometric parameters to the near or even far infrared range. Our structure has the following geometric dimensions. The lattice constant is a = 590 nm. Cylinders with radii $R = 142$ nm and $r = 154$ nm, respectively, are shifted relative to their central axes by $l = 89$ nm and $d = 348$ nm in the y and z directions, respectively (Fig. 2). The refractive index for silicon cylinders is $n = 3.48$ based on [12] for the telecom wavelength $\lambda = 1.5$ μm.

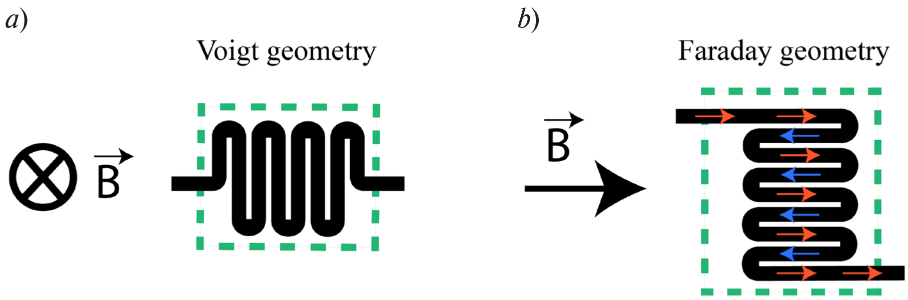

Fig. 1. Schematic comparison of Voigt (*a*) and Faraday (*b*) geometries: (*a*) there is no effect compensation in the Voigt geometry, (*b*) red arrows indicate the effect in one direction, and blue arrows in the opposite direction with the opposite effect, which leads to compensation of the Faraday effect along the entire length of the waveguide

We consider modes with TM polarization, where the electric field vector E lies in the *yz* plane, since we are interested in the integral rotation of electric field in this plane for the subsequent use of a configuration where an external magnetic field $B = 1$ T is applied perpendicular to the *yz* plane (Voigt geometry). This configuration makes it possible to consider silicon as a magneto-optical material with a permittivity tensor containing off-diagonal components ε_{yz} and ε_{zy}, respectively (1).

$$\hat{\varepsilon} = \hat{\varepsilon}_0 + \Delta\hat{\varepsilon} = \begin{pmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i\Delta\varepsilon \\ 0 & i\Delta\varepsilon & 0 \end{pmatrix}, \quad (1)$$

where coupling between $\Delta\varepsilon$ and Verdet constant in silicon V_{Si} is $\Delta\varepsilon = \nu_{\mathrm{Si}} n\lambda B/180°$.

It is important to note that we use the Voigt configuration but not the similarly named Voigt effect. The Voigt effect is quadratic on the applied magnetic field and cannot help for isolation. Nevertheless, if we assume that the quadratic term in the permittivity tensor will be comparable in magnitude with the linear terms of the tensor, then it will only lead to a slight change in transmission constant in both directions and will practically not affect the calculation results. The proposed periodic structure of silicon cylinders provides the non-zero integral rotation of electric field, as shown in Fig. 3.

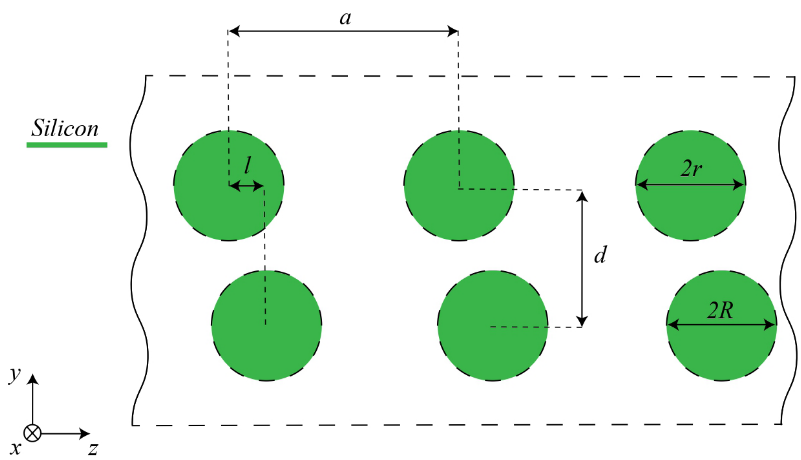

Fig. 2. Schematic view of silicon cylinders array. Infinite rods (along the *x* axis) with radii $R = 142$ nm and $r = 154$ nm. The displacement values between the central axes of the cylinders are $l = 89$ nm and $d = 348$ nm in the *y* and *z* directions, respectively. The refractive index of silicon is $n = 3.48$ and lattice constant is $a = 590$ nm. TM polarization is considered

Calculation of the specific phase

For the isolator, we consider a structure with finite length L. In this structure of silicon cylinders, the specific additional phase accumulates due to magneto-optical effect over the length of the waveguide structure L is expressed in terms of the phase φ (rotation of the vector **E**), Verdet constant in silicon V_{Si}, and the magnitude of the magnetic field B:

$$\Delta\varphi = \Delta\beta L, \tag{2}$$

where the Verdet constant for silicon is 15° cm^{-1}·T^{-1} [13].

To calculate the specific phase in Eq. (2), we use the time-independent perturbation theory [14], since the external magnetic field B is assumed to be constant in time. Below is the wave-equation for the electric field **E**:

$$\nabla \times \nabla \times \mathbf{E} - \mu\hat{\varepsilon}\frac{\omega^2}{c^2}\mathbf{E} = 0. \tag{3}$$

where μ = 1, ω is the eigenfrequency and c is the speed of light in vacuum.

We use the known solution of the generalized eigenvalue problem [14] with periodic boundary conditions in our case. Thus, the final expression for the correction to the eigenfrequency Δω due to applied magnetic field is expressed as follows

$$\Delta\omega_j = \frac{\omega_j}{2}\frac{\iint_S \mathbf{E}_j^* \cdot \Delta\hat{\varepsilon} \cdot \mathbf{E}_j dydz}{\iint_S \mathbf{E}_j^* \cdot \hat{\varepsilon}_0 \cdot \mathbf{E}_j dydz}, \tag{4}$$

where are $\mathbf{E}_j$ the electric field of the jth mode and S is the area of the periodic unit cell.

So the group velocity of the eigenmode is the power over the linear energy density (energy per unit length) which can be calculated as follows:

$$V_{g,j} = \frac{\iint_S \mathbf{z}(\mathbf{E}_j \times \mathbf{H}_j^*) dydz}{\iint_S \mathbf{E}_j^* \cdot \hat{\varepsilon}_0 \cdot \mathbf{E}_j dydz}, \tag{5}$$

where z is the unit vector along z direction and $\mathbf{H}_j$ is the magnetic field of the jth mode.

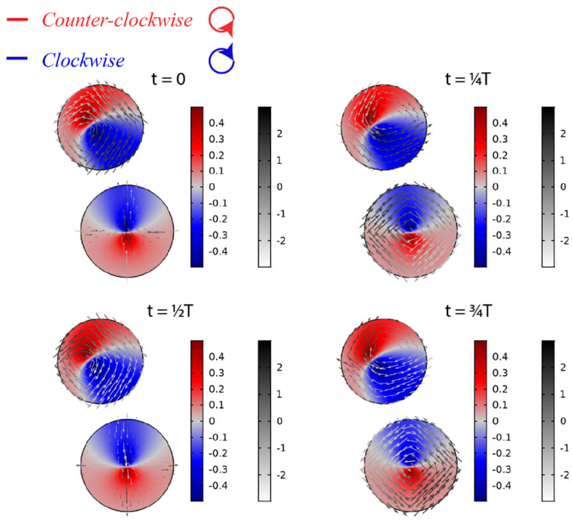

Fig. 3. Snapshots of electric field distribution at four consecutive time intervals. The red marks are the areas where the rotation is counterclockwise, and the blue is ones with clockwise, where the values of rotation are defined as the upper integral of rotation in Eq. (4) normalized by $|\mathbf{E}|^2$. T is the period of electromagnetic oscillations. The black-and-white gradient scale shows the normalization of electric field on $|\mathbf{E}|^2$

Then the specific phase $\Delta\beta_j$ will be expressed in terms of $\Delta\omega$ (Eq. (4)) and $V_{g,j}$ (Eq. (5)) as follows:

$$\Delta\beta_j = \frac{\Delta\omega_j}{V_{g,j}} = \frac{1}{2}\omega_j \frac{\iint_S \mathbf{E}_\mathrm{j}^* \cdot \Delta\hat{\varepsilon} \cdot \mathbf{E}_\mathrm{j} dydz}{\iint_S \mathbf{z}(\mathbf{E}_\mathrm{j} \times \mathbf{H}_\mathrm{j}^*) dydz}. \quad (6)$$

The eigenmode was optimized and calculated in COMSOL Multiphysics for the considered structure at the wavenumber $k = 0.42\ \pi/a$ and frequency of 200 THz ($\lambda = 1.5$ μm) $\Delta\beta \approx 0.11$ cm^{-1} (Fig. 4). It is important to note that the calculated value $\Delta\beta = 0.11$ cm−1 is achieved due to the low group velocity V_g, which is $0.004c$ for the considered mode in the dispersion branch.

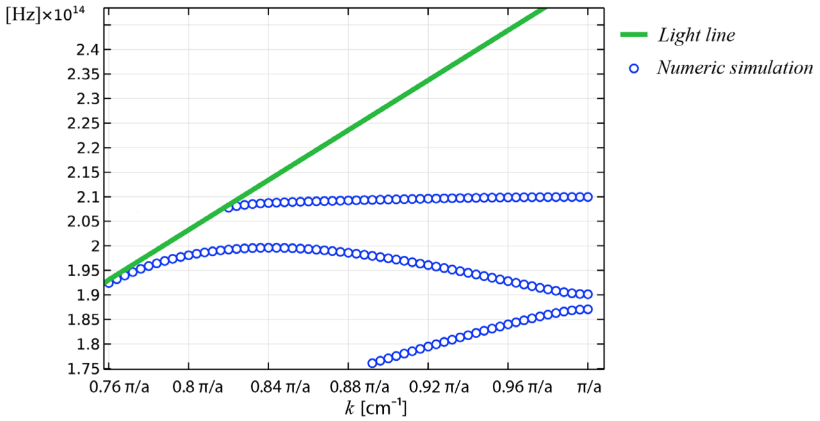

Fig. 4. Dispersion relation for silicon cylinder array (Fig. 2). The operating wavenumber is $k = 0.42\ \pi/a$ and frequency is 200 THz ($\lambda = 1.5$ μm). Calculated indicator $\Delta\beta \approx 0.11$ cm^{-1}

Concept of an optical isolator

In this paragraph, we propose to use a periodic structure of silicon cylinders as TRE with the accumulated phase $\varphi = \pi/4$ in the upper arm and $\varphi = -\pi/4$ in the lower arm and $\varphi = -\pi/4$ and $\varphi = \pi/4$ in the backward direction correspondingly (Fig. 5). The length of the structure of silicon cylinders to achieve the value of the specific phase $\Delta\beta = 0.11$ cm^{-1} is $L \approx 7.14$ cm according to (2). Y-splitters divide the input and output signals into two identical propagating waves in one direction. An additional phase $\varphi_a = -\pi/2$ is required for the implementation of a non-reciprocal device, that is, the transmission of the input signal and the forbidden transmission of the backward signal due to the constructive interference of waves propagating along two Mach–Zehnder interferometer arms in forward direction and destructive interference in the opposite direction. Note that the waveguide in the lower arm is flipped to get an opposite phase of the waveguide in the upper arm (Fig. 5).

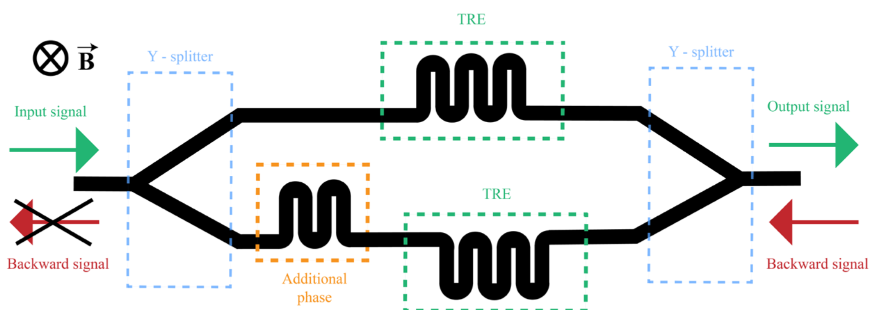

Fig. 5. Optical isolator based on Mach–Zehnder interferometer. Transverse Rotation Elements (TRE) accumulate phase $\varphi = \pi/4$ and $\varphi = -\pi/4$, respectively. Additional phase is $\varphi_a = -\pi/2$. The signal is transmitted in one direction and not transmitted in the opposite direction

Since in our work we consider the silicon waveguide with length of the order of several centimeters, then in such a line the losses due to light propagation will increase. Based on reported data [15], the loss is approximately 17.85 dB at 7.14 cm. This value of losses allows us to count on the registration of the effect under study. Thus, the tendency to reduce the propagation loss in SOI waveguides due to improved manufacturing technology allows us to expect for the use of our proposed concept of an optical isolator in the novel devices. It should be noted that the main objective of our work is that we are studying the very effect of polarization rotation in the Voigt geometry. In addition, the concept of an optical isolator acts as a possible example.

Conclusion

We have studied the 2D periodic structure of silicon cylinders, which can be used as a TRE in MZI configuration. According to our calculations, the effective length of waveguide in TRE is $L = 7.14$ cm at the value of the specific phase $\Delta\beta = 0.11$ cm^{-1}. The optimization of the geometric parameters of the silicon cylinders structure in the COMSOL Multiphysics program was carried out to shift the mode to wavelength $\lambda = 1.5$ µm, which satisfies the telecom wavelength. We have achieved a non-zero integral rotation of the electric field of the longitudinal plane (*yz* plane) of the considered structure.

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THE AUTHORS

IUKHTANOV Nikita G.
nikita.yuhtanov@metalab.ifmo.ru
ORCID: 0000-0003-4071-9047

RYBIN Mikhail V.
m.rybin@metalab.ifmo.ru
ORCID: 0000-0001-5097-4290

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