Total reflection of near infrared range wave from subwavelength silicon 1D photonic crystal with small packing density

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Abstract. One-dimensional (1D) photonic crystals have been widely used in silicon photonics due to their simple structure and multiple working regimes. In this paper we present the computation of reflection and transmission spectra and spatial electric field patterns for 1D photonic crystal with packing density less than 10 percent with use of matrix Riccati equation technique in the theory of multiple electromagnetic wave scattering in inhomogeneous media. Narrow ($\Delta \lambda \lesssim 30$ nm with maximum at $\lambda = 1550$ nm) reflectivity peaks reaching 100 percent maximum were observed for photonic crystals represented as periodically located silicon threads with rectangular or round cross section. The shape and dimensions of the threads were altered to investigate their influence on the peaks width.

1. Introduction
Progress in nanoelectronics through the scaling of the traditional planar technology faces certain problems [1], the Moore’s law in its traditional form seems to come to an end, and at this moment other and new approaches are coming to the research forefront. One of the prominent examples is silicon photonics. It has been of large interest in past decades, which resulted in an extensive research in design, fabrication and integration of various photonic devices for different applications such as communication networks, optical computing, medical diagnostics and sensing [2, 3]. Among the most notable appliances, for instance, in computing is the analog-to-digital converter allowing for high-precision signal processing [4].

Component base of silicon photonics includes a number of basic units starting from conventional strip-like waveguides and fibers and ending with more complex ring structures or periodical ones like diffraction gratings and different types of photonic crystals. The subject of our research is one dimensional photonic crystal (PhC) represented as an array of periodically located silicon threads with round or rectangular cross section (Fig. 1). The exact and fast approach [5] to the theory of electromagnetic wave multiple scattering in inhomogeneous dielectric media, which uses the Riccati type equation for the matrix wave reflection coefficient and associated differential equation for the matrix wave transmission coefficient, is applied to calculate the reflection and transmission spectra and corresponding spatial electric field distributions. This method allows taking into account the effects of strong energy transformations between homogeneous and evanescent waves in the near wave zone of the PhC, appearing due to the subwavelength or comparable to the wavelength dimensions of the considered structures.
2. Matrix Riccati equation approach

Let us assume that a plane TE polarized wave of wavelength $\lambda$ is incident on the periodic structure with period $\Lambda$, height $h$ and dielectric permittivity $\varepsilon(r, \omega)$ at an angle $\phi$ (see Fig. 1). The method that we use allows representing the electric field of reflected and transmitted radiation as a superposition of plane waves with certain coefficients and wave vectors:

$$E_y(r) = \begin{cases} \exp(i k_0 (r - h n_z)) + \sum_{\mu=\infty}^{\infty} R_{\mu 0}(h) \exp(i k_0^* (r - h n_z)), & z > h \\ \sum_{\mu=\infty}^{\infty} T_{\mu 0}(h) \exp(i k_0^* r), & z < 0 \end{cases}$$

(1)

$$k_\mu^* = \begin{pmatrix} \beta_\mu \\ 0 \\ \pm \sigma_\mu \end{pmatrix} = \begin{pmatrix} k_0 \sin \phi + 2\pi \mu / \Lambda \\ 0 \\ \pm \sqrt{k_0^2 - \beta_\mu^2} \end{pmatrix}.$$  

(2)

Reflection and transmission coefficients are derived from the solution of the following matrix differential equations:

$$R_\mu' = RA(z)R + (A(z) + C)R + R(A(z) + C) + A(z),$$

(3)

$$T_\mu' = T(A(z) + C + A(z)R(z)),$$

(4)

$$R, T|_{z=0} = R_0, T_0, \quad \mu = 1, 2, \ldots, 2n + 1.$$  

(5)

where $R, T, A, C$ are $(2n+1) \times (2n+1)$-dimensional matrices with complex values and $n$ is selected in a special way. Components of the matrices $A$ and $C$ are defined as follows:

$$A_{\mu \nu}(z) = i \frac{2\pi}{\lambda^2} f_{\mu \nu}(z),$$

(6)

$$C_{\mu \nu} = i \sigma_\mu \delta_{\mu \nu},$$  

(7)

and $f_\mu(z) = \frac{\pi}{\Lambda} \int_0^\Lambda e(x, z) \exp \left( -i \frac{2\pi x \alpha}{\Lambda} x \right) dx$ is a transformation function, it describes the interaction between propagating and evanescent waves at multiple scattering in periodical inhomogeneous media.
3. Results and discussion

In this report reflection and transmission spectra of 1D PhC and electric field patterns are obtained (Fig. 2) for near infrared range waves at different parameters (structure period, shape and dimensions of threads cross section). Typical values for the wavelength, period and thread sizes are 1550 nm, 1500 nm and 100 nm respectively (see Fig. 1). Thus PhC duty cycle (or filling factor) defined as a ratio of thread’s width to the period is usually less than 10 percent. Similarly the packing density \((PD)\) is introduced as a ratio of thread’s volume to the one-period cell volume. For threads with rectangular cross section duty cycle and packing density coincide, for round threads packing density is less than duty cycle.

![Figure 2(a, b).](image)

Distinct peaks in reflectance up to 100 percent occur not far from the moments of the so called modes opening. They are also known as Wood–Rayleigh diffraction grating anomalies and defined by the relation between the wavelength and the period of the structure. At normal incidence when these two parameters become equal, modes of order \(\mu = \pm 1\) turn from evanescent to homogeneous if we move from longer wavelengths or shorter periods. These moments are clearly visible on graphs of the Fig. 2 – the points where dependencies have no derivative and change their type of convexity. The period \(\Lambda\) is selected for each structure in such a way that maximum is achieved at a wavelength of 1.55 \(\mu m\).

Electric field distributions are calculated at points of maxima (Fig. 3). They look very similar for different cross sections as well as reflection spectra, but field pattern for PhC comprised of round threads with diameter of 112 nm is more like that of PhC with square threads of 100 nm in size. Considering the full widths of the peaks at half maximum (FWHM) round threads show better results than rectangular ones at the same size parameters \((D = w = h = 100 \text{ nm})\) with \(\Delta \lambda = 32.5 \text{ nm}\) versus 66.0 nm (green line and wide dashed line on Fig. 2(a)), and, furthermore, they have smaller packing density. However varying separately width and height of rectangular threads gives more degrees of freedom, which helps to soften precision requirements for these and other geometrical parameters.
Fig. 3. Spatial electric field distributions for photonic crystals consisting of round threads with diameter $D$ (first row) and rectangular ones with width $w$ and height $h = 100$ nm (second row) at 1.55 $\mu$m. The more intense color means the greater absolute value of electric field. $PD$ – packing density.

It is possible to further decrease FWHM in order to reach more sharp resonances by reducing the sizes of threads. Examples of such cases are demonstrated on Fig. 4. The quality factor can reach $10^3$–$10^4$ for the peaks with $\Delta \lambda \approx 0.1$–0.4 nm. However, such structures require extremely high precision on geometrical parameters, especially on the period of the photonic crystal, which deviation could not be greater than the peak width itself. The use of rectangular threads slightly softens this requirement, but it is still not enough to allow for simple manufacturing process.

Fig. 4(a, b). Reflection spectra for round (a) and rectangular (b) threads with sharp resonances at a wavelength of 1550 nm.
It is worth mentioning that considering their small packing density such structures can be regarded as mirrors from almost nothing. Varying different parameters of the photonic crystal it is possible to achieve certain pattern of electric field, for example in application of sensing, or to obtain resonant dependence in reflection or transmission spectrum at a given wavelength to construct different devices like optical filters and resonators.

References
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