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Zero average index design via perturbation of hexagonal photonic crystal lattice

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ABSTRACT

We study the effect of one-dimensional lattice compression on photonic band diagram and apply it to form a superlattice in order to obtain zero-$\bar{n}$ gap. Modulated hexagonal lattice has the ability to provide both positive and negative effective refractive indices. We analyze the dispersion characteristics in case the positions of holes in the lattice are varied in the orthogonal direction of applied light direction. We then compare modified structures with the conventional lattice and study the influence of the disorder on both photonic band structure and effective refractive index through numerical simulations. Proposed modulated photonic crystal introduces new ways of controlling light for on-chip applications. We show the benefit of this class of suggested devices in one particular structure, a zero-$\bar{n}$ gap superlattice, for the sake of comparison with the recently reported structures. However, other important implementations such as self-collimation, which may play a major role in photonic integrated circuits, can also benefit from these designs.

1. Introduction

Behavior of electromagnetic waves in the transmission medium directly depends on the relation between the temporal and spatial characteristics, which are associated with the frequency and wavelength of the traveling waves inside the medium [1]. Material with positive refractive index is the natural case and has limited design opportunities. On the other hand, materials with negative permittivity and/or permeability have various interesting applications. Even though proposal of such kind of structures has been around for a while, due to the need for artificial material design, the experimental verification of the theoretical expectations has not been performed for a long time. However, with the development of metamaterials, the desired permittivity and permeability properties are now available. To gain a deep understanding of the temporal and spatial characteristics relations, scientific community has achieved to demonstrate new optical properties such as negative permittivity or permeability [2,3], near-zero-epsilon [4–6] and near-zero-refractive index [7–17]. As the zero index is particularly interesting in some aspects, many studies have focused on obtaining zero refractive index over the past decade [18–22]. To obtain such new characteristics, changing either permittivity (ε) or permeability (μ) value to zero is enough to get zero refractive index ($n = \sqrt{\mu\varepsilon} = 0$). However, since the optical impedance also depends on the same parameters ($\eta = \sqrt{\mu/\varepsilon}$), near-zero-epsilon material leads to a highly-mismatched impedance with free space [23]. Thus, to avoid strong reflections on the interface due to this mismatch, permittivity and permeability are adjusted to zero value to obviate the mentioned issue. This type of metamaterials could be metallic or dielectric based on the required components on a variety of devices. Despite some extraordinary physical properties such as super-focusing beyond the diffraction limit [24–27], inverse Snell's law [28], Doppler effect [28], and their utilization capacity in new technological applications, due to high absorption losses, metals cannot be efficiently used for optical components. In other words, dielectric based components have a crucial competitive advantage over their metal-based counterparts [29]. With this motivation, all-dielectric metamaterials composed of rod structures have been shown to provide and experimentally demonstrated the desired zero-index value while its band structure possesses a Dirac cone at gamma (Γ) point [23,30].

Photonic crystals (PhCs) are all-dielectric periodic components with a period comparable to a light wavelength and as in the case of controlling electrons with solid state crystals, photonic crystals can

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control photons. They exhibit periodic refractive index variations and their optical behavior can be controlled by the band structure [31]. Also, it has been shown that photonic crystals can provide all four quadrants of permittivity-permeability response [32]. The negative refractive index is available in the third quadrant.

One of the main ways to obtain zero-index materials has been to utilize the alternating layers of positive index and negative index materials [7–14]. In such structures, negative and positive refractive index cancel each other and a band gap called zero-$\bar{n}$ gap is formed in the corresponding wavelength interval. The name of zero-$\bar{n}$ or zeroth order gap comes from the fact that when the condition of path-averaged zero index is satisfied, the Bragg condition is also satisfied for the zeroth order [8,9,12]. Since this band gap is due to averaged zero refractive index, within the corresponding frequency interval, photonic structures do not support any propagating modes, and the structural properties such as the period and the disorder in addition to the characteristics of the incident waves such as polarization and incident angle do not affect the band gap [33–35]. In other words, such band gaps might be omnidirectional and possess interesting optical properties such as complete photonic band gaps [25,36] and gap solitons [23,37]. Since bandgap transmission is zero and all the incident radiation is reflected, for the applications desiring light transmission, near-zero-refractive-index materials are more convenient and can be designed with the similar procedures [8]. These materials have been shown to provide self-collimation [8], modification of emission [16,19,29], super-coupling [1], phase matching approaches in nonlinear optics [38] and cloaking [39]. When the refractive index is near zero, phase velocity and wavelengths of waves become large [40] and this enables capturing evanescent beam incident from all angles, beam size in the order of sub-wavelength and near-field information transfer [41]. Apart from all these applications, application of near-zero-refraction-index materials as optical wire in all-optical circuits or integrated optical circuit is an important and promising development [42]. As a result, with optical interconnects providing paths for light without phase accumulation, frequency dispersion effects can be avoided [9].

In this paper, we study a novel method to obtain a photonic superlattice with zero-$\bar{n}$ gap that is based on negatively refracting photonic crystals. Proposed design is in the agreement with the general implementation rules for various photonic integrated circuit fabrication steps. We demonstrate the effect of lattice expansion/compression on photonic band diagram and construct a superlattice consisting of regions with different optical properties. In other words, by altering the dielectric distribution in the lattice of the specific regions, without altering any design parameters such as radii or thickness, we obtain positive refractive index that compensates the negative refractive index created in other regions. This increases compatibility between two cascaded regions in the superlattice and provides path averaged zero refractive index with low loss.

2. Theory

The main focus here is on superlattices manipulating the light such that there is no additional phase accumulation for increasing device lengths and photonic crystals can provide a complete or partial control over phase, amplitude and direction of light propagation. As described above, one of the main implementations in the literature to obtain zero phase accumulation is to get vanishing average refractive index with a structure that consists of a superlattice cascaded of negative-index PhC and positive index silicon slab [9]. In this design, the positive-refractive-index region is simply a slab waveguide and its schematic representation is given in Fig. 1a.

In order to find the effective refractive index of the slab waveguide, we need to find the propagation coefficient (β) supported by the waveguide. Since the structure does not contain any perturbation, one can assume that waveguide is 1D, simply solve the boundary conditions and reach Eq. (1), which is the asymmetric Eigenvalue equation for the TM mode [43,44].

$$\tan\left(h\kappa_f\right) = \frac{\kappa_f\left[\frac{n_f^2}{n_s^2}\gamma_s + \frac{n_f^2}{n_c^2}\gamma_c\right]}{\kappa_f^2 - \frac{n_f^4}{n_c^2 n_s^2}\gamma_c\gamma_s} \tag{1}$$

In Eq. (1) $\boldsymbol{h}, \boldsymbol{n_f}, \boldsymbol{n_s}, \boldsymbol{n_c}, \boldsymbol{\gamma_s}, \boldsymbol{\gamma_c}$ and $\boldsymbol{\kappa_f}$ represent the thickness of the slab, refractive index of the slab waveguide, substrate index, cover layer (air) index, attenuation term of a wave in the substrate, attenuation term of a wave equation in the cover layer and the transverse wavevector, respectively. The attenuation terms and the transverse wavevector all depend on the propagation coefficient, and the wavelength of the wave (λ). Therefore, one can solve Eq. (1) graphically by choosing a wavelength and writing all the others in terms of one parameter. Once, both sides of Eq. (1) are plotted; the solution will be the intersection of the two graphs. For λ = 1550 nm, h = 320 nm and by expressing other parameters in terms of κ_f, the results are illustrated in Fig. 1b.

After obtaining the solution, all the parameters for the supported modes can be calculated. Eq. (2) and Eq. (3) are describing the propagation constant and the effective index, respectively. If the same procedure is repeated for multiple wavelengths, the variation in the effective index can be found. All the corresponding data covering the spectrum interested is given in Table 1.

$$\beta = \sqrt{k_0^2 n_{Si}^2 - \kappa_f^2}, \text{ where } k_o = \frac{2\pi}{\lambda} \tag{2}$$

$$n_{eff} = \frac{\beta}{k_o} \tag{3}$$

After obtaining the positive refractive index, a design for negative index with the same polarization is necessary in order to obtain a superlattice with zero average index. In order to have an efficient design [9,12], the thickness and the material system should be same with the positive slab. Therefore, an air hole based PhC etched into a silicon slab with 320 nm is designed via MIT Photonics-Bands (MPB) program [45].

The band diagram of Fig. 2a–b shows the supported modes of the photonic crystal slab composed of air holes with a radius of 0.320a and a thickness of 0.640a for TM-like polarization. Note that, PhC period, a, needs to be 0.5 μm to be able to match silicon slab discussed above. The light cone shows the limits for coupling into the high index medium, the silicon waveguide. Therefore, during the calculations associated with photonic bands, corresponding region is neglected [43,45]. The normalized frequency range of 0.294–0.302 is the photonic band gap (PBG) for this structure. The refractive index of the PhC is determined by using the band diagram and the slope of the band with (Eq. (4)) [46]. Effective refractive indices for the frequencies related to the first two bands that show both positive and negative refraction are shown in Fig. 2c.

$$n_{eff} = \omega\frac{d}{d\omega}\left(\left|\frac{c\left|\vec{k}\right|}{\omega}\right|\right) + \left|\frac{c\left|\vec{k}\right|}{\omega}\right| \tag{4}$$

Transmission spectrum of the designed structure is also calculated with MEEP, a 3D finite-difference time-domain (FDTD) simulation package [47], and the solutions verifying the band diagram are summarized in Fig. 2d.