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Effective refractive index analysis of optical Kerr nonlinearity in photonic bandgap structures

Jisoo Hwang [a], J.W. Wu [b,*]

[a] Division of Physical Metrology, Korea Research Institute of Standards and Science, Daejeon 305-340, Republic of Korea
[b] Department of Physics and Division of Nano-sciences, Ewha Womans University, Seoul 120-750, Republic of Korea

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Abstract

A numerical dispersion relation is employed to analyze the linear and nonlinear optical effective refractive indices of 1-D finite periodic photonic bandgap structures. A Bragg reflector (BR) and a photonic crystal microcavity (PCMC) are examined by assuming that the high indexed layer of the two constituent layers possesses a nonlinear optical response. For the BR, the singularity of refractive index, appearing at bandgap edges in a Bloch index description, is removed. In the case of the PCMC, the optical responses at a defect mode and bandgap edges are properly described, thanks to the use of the numerical dispersion relation. This also allows us to quantitatively compare the Kerr nonlinearity observed at the defect mode and the bandgap edges. The efficiencies of the BR bandgap edge and the PCMC defect mode in achieving a given transmission change are compared by calculating the required nonlinear optical refractive index change. The PCMC defect mode is found to be 1.5 times and twice more efficient than the BR bandgap edge in 20 and 10 dB transmission modulation, respectively.

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1. Introduction

Inside a photonic bandgap (PBG) structure, the wave propagation characteristics of an electromagnetic (EM) wave is governed by the energy-momentum dispersion relation, which is determined from a spatial distribution of refractive indices of constituent periodic layers. For example, the electric field-enhancement at PBG edges is understood in terms of a low group velocity and the anomaly in the dispersion relation. An analytic expression of dispersion relation is readily available in the form of a Bloch index for an infinite periodic PBG structure. On the other hand, in the case of a finite periodic PBG structure, a dispersion relation is numerically obtained from the measured transmission coefficient. When the PBG structure has to be designed in order to obtain highly efficient generation of harmonics, using nonlinear optical (NLO) processes, the numerical dispersion relation (NDR) can be very useful. In fact, using the NDR allows us properly tailor the PBG characteristics, in order to achieve the phase matching condition [1]. Galisteo-Lopez et al. compared the dispersion relation measured by a white light interferometry and the calculated NDR of a 3-D PBG structure, and found that the agreement was remarkable [2]. The NDR analysis was further extended to obtain an explicit relation between the real and the imaginary components of an EM wave emerging from a PBG structure by use of a Kramers–Kronig relation [3]. While all-optical switching at bandgap edges [4,5] and a defect mode [6,7], originating from optical Kerr related nonlinearity, has been demonstrated experimentally in a PBG structure, NLO analysis of the beam

* Corresponding author. Tel.: +82 23 277 2369; fax: +82 23 277 2372.
E-mail address: jwwu@ewha.ac.kr (J.W. Wu).

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propagating properties based on the NDR was not pursued, mainly due to the difficulty in obtaining an analytical dispersion relation.

In this paper, we utilize the NDR to investigate the Kerr NLO changes in two important 1-D finite periodic photonic bandgap structures, namely, a Bragg reflector (BR) and a photonic crystal microcavity (PCMC). A BR is a 1-D finite periodic photonic bandgap structure without a defect layer, and a PCMC is in a structure of two identical BRs sandwiched symmetrically with a defect layer-between, hence exhibiting an optical defect mode. We report three major findings. First, the singularity of a Bloch index, occurring at bandgap edges of a BR, is removed. Second, the optical properties of a PCMC, based on the dispersion relations of linear and nonlinear refractive indices, are properly described. In particular, optical Kerr nonlinearity is found to be more enhanced at a defect mode than at bandgap edges of a PCMC, which is understood by taking account of the density of modes (DOM) and the EM field localization. Third, the NLO transmission property associated with the optical Kerr nonlinearity is investigated and compared for the BR bandgap edge and the PCMC defect mode. The NLO refractive index changes required to achieve transmission changes from 100% to 10% and 100% to 1% are numerically simulated.

2. Effective refractive indices of a Bragg reflector

Originally, the NDR has been developed to overcome the singularity problem of Bloch index occurring at band edges in description of the linear optical properties of a 1-D PBG structure [8]. The Bloch index n_{B} refers to the refractive index of an infinite periodic structure, which is introduced through a Bloch phase β related with n_{B} as $n_{\mathrm{B}} = \beta c/(\omega \Lambda)$ with Λ the period, and can be obtained from the analytic dispersion relation in a straightforward way [3,9]. On the other hand, NDR is equivalent to introducing an effective refractive index (ERI) in the PBG structure. Once the transmission coefficient is determined for an inhomogeneous optical structure, the ERI is numerically obtained through the relation $n_{\mathrm{eff}}(\omega) = (c/\omega L)\,[\tan^{-1}(y/x) + m\pi - (i/2)\ln(x^2+y^2)]$, with x and y the real and the imaginary parts of transmission coefficients and L the sample length. In the experimental case, the transmission coefficient is determined through the measurement of both transmittance T and phase ϕ, since they satisfy the relation $x + iy = \sqrt{T}e^{i\phi}$. Or, simply, we can determine ERI from the measured T and L in cooperation with the Kramers–Kronig relation, due to the fact that the real and imaginary parts of ERI satisfy the Kramers–Kronig relation [1]. First of all, in order to clarify the difference between the Bloch index n_{B} and the ERI n_{eff} obtained through NDR in describing the linear optical and NLO properties of band edges, we study the transmission spectrum, linear optical and NLO refractive indices of a BR. All the calculation of transmission spectrum and ERI are performed using transfer matrix method [9].

In Fig. 1 are plotted the transmission spectra and the n_{eff} of a 10 bilayer BR and n_{B} of an infinite periodic BR, which are composed of quarter-wave-thick layers with the refractive indices of $n_1 = 1.42$ and $n_2 = 2.08$ for low- and high-index layers, respectively. The thickness of each layers was chosen to satisfy the Bragg reflection at 780 nm. A PBG structure is seen in the transmission spectrum of Fig. 1a. The solid curve corresponds to the PBG structure of a 10 bilayer BR, while the dashed curve corresponds to that of an infinite periodic BR. In Fig. 1b and c, the real and imaginary parts of the linear n_{B} are plotted in the dashed curves, while the solid curves correspond to the linear n_{eff} of a finite periodic BR. In both n_{B} and n_{eff}, we observe that a PBG structure behaves as an optical layer possessing the anomalously dispersive real part and the absorptive imaginary part, which in fact arises from a multiple reflection of EM wave in a transparent periodic optical structure. We note that n_{eff} smooths out at the band edges and exhibits an oscillation outside the bandgap.

Now let us turn to the NLO refractive indices. The optical Kerr nonlinearity of a BR can be described in terms of the NLO coefficients $n_1^{(2)}$ and $n_2^{(2)}$ of the low- and high-index layers composing the BR. For the optical Kerr nonlinearities of $\Delta n_1 = n_1^{(2)} I = 0$ and $\Delta n_2 = n_2^{(2)} I = 0.05$, both irradiance-dependent Bragg index change, Δn_{B}, and ERI change, Δn_{eff}, are calculated. Δn_{B} and Δn_{eff} satisfy the relations, $n_{\mathrm{B}}(I) = n_{\mathrm{B}}^{(0)} + \Delta n_{\mathrm{B}}(I)$ and $n_{\mathrm{eff}}(I) = n_{\mathrm{eff}}^{(0)} + \Delta n_{\mathrm{eff}}(I)$, and I is the incident irradiance. The value of $n_2^{(2)} I = 0.05$ is assumed for NLO material with $n_2 = 10^{-11}\ \mathrm{cm^2/W}$ and

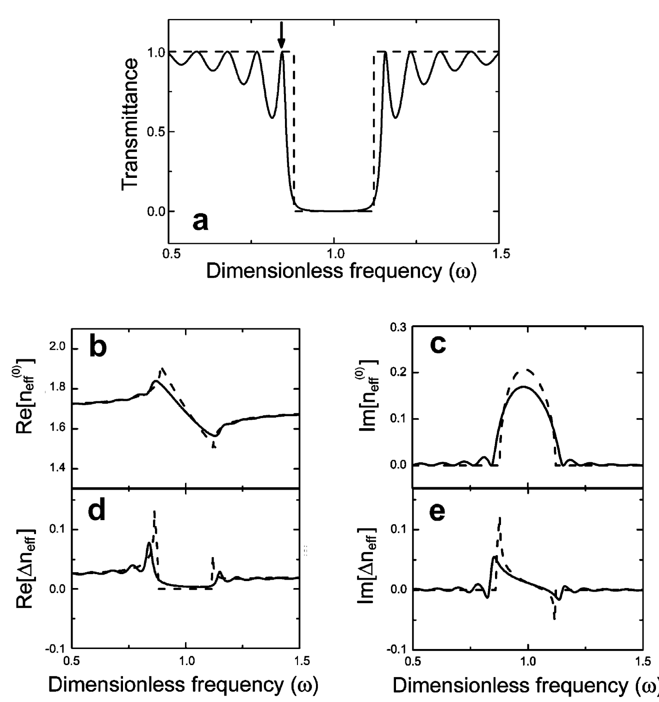

Fig. 1. Numerically calculated (a) transmission spectra, (b) real part of $n_{\mathrm{eff}}^{(0)}$, (c) imaginary part of $n_{\mathrm{eff}}^{(0)}$, (d) real part of Δn_{eff}, and (e) imaginary part of Δn_{eff} of BRs. The solid (dashed) curves correspond to a 10 bilayer (infinite) BR. The arrow in (a) indicates the low-frequency edge of 10 bilayer BR, $\omega = 0.844$.