International Conference on Photonics of Nano- and Bio-Structures, PNBS-2015, 19-20 June 2015, Vladivostok, Russia and the International Conference on Photonics of Nano- and Micro-Structures, PNMS-2015, 7-11 September 2015, Tomsk, Russia

Local density of states in one-dimensional photonic crystals and sinusoidal superlattices

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Abstract

We have calculated the local density of states (LDOS) for four Brillouin zones of a superlattice for a plane source depending on its location relative to the change in the profile of dielectricpermeability $\varepsilon(z)$ of the superlattice. It is shown that the LDOS for the cases of sinusoidal and rectangular profiles of $\varepsilon(z)$ are close to each other in the first and second Brillouin zones, and sharp differences between them appear beginning with the third zone. Radical changes in the LDOS occur in a rectangular superlattice with different thicknesses of adjacent layers. In this case, the function LDOS has a sharp jump at the edges of the allowed bands in the transition from one layer to another. The effects studied theoretically in this paper, can be detected and studied experimentally by the intensively developing currently methods of nanooptics.

1. Introduction

Sources of light in photonic crystal structures were intensively studied in recent decades. LEDs that are based on electroluminescence, are the most promising light sources for practical applications (Novotny and Hecht (2012), Mottier (2009), David et al. (2012)). Doped nanoparticles in a substance emitting by laser excitation, are used for studies of the effect of photonic crystal structures on the radiation pattern, and the relaxation (Sapienza et al. (2011),

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Kuroda et al. (2010)). Photonic crystals, that are periodically structured optical media, are used to control the radiative properties of these light sources. The use of photonic crystals based on the presence of forbidden zones in which there is suppression of the spontaneous emission (Yablonovitch (1987)). In the one-dimensional photonic crystal, a sharp increase in output power at frequencies close to the edges of the band gap is observed (Tocci et al. (1996)).

The local density of states (LDOS) (Moroz (1999), Wubs and Lagendijk (2002), Yeganegi et al. (2014)) is an essential characteristic of inhomogeneous media. In the work (Moroz (1999)) the LDOS was calculated for the superlattice with a rectangular profile of modulation of the dielectricpermeability (a one-dimensional photonic crystal). It is known that the spontaneous emission rate of atoms and molecules embedded in a photonic crystal is directly proportional to the LDOS (Novotny and Hecht (2012)).Therefore, the spontaneous emission can either be reduced down to zero (at zeroes of the LDOS) or substantially enhanced at points which correspond to the maxima of the LDOS) with respect to the vacuum case. Suppression of the spontaneous emission may have applications for semiconductor lasers, solar cells, heterojunction bipolar transistors, and thresholdless lasers.

The aim of this work is to study changes of the LDOS depending on the position of the radiation source relative to the profile of the superlattice dielectricpermeability $\varepsilon(z)$, as well as a comparison of the LDOS for superlattices with the rectangular and the sinusoidal profiles of modulation of $\varepsilon(z)$.

2. Green's function and LDOS

In the sinusoidal superlattice the scalar Green's function satisfies the equation

$$\nabla^2 G(\mathbf{r}, \mathbf{r}_0) + \left(\frac{\omega}{c}\right)^2 \left[\varepsilon + \Delta\varepsilon \cos(qz + \psi)\right] G(\mathbf{r}, \mathbf{r}_0) = -\delta(\mathbf{r} - \mathbf{r}_0) \,, \tag{1}$$

where $q = 2\pi / l$, l is the superlattice period, ψ is the phase, ε is the dielectricpermeability, ω and c are the frequency and speed of light, respectively.In the work (Ignatchenkoand, Tsikalov (2015), Ignatchenko and Tsikalov (2016)) we obtain an analytic expression for the Green's functions inthe $\mathbf{k}$-space in the form of continued fractions, which have fast convergence, so that expression is useful in the study of the Green's function in the $\mathbf{k}$-space and in the $\mathbf{r}$-space.

$$G(\mathbf{k}_\perp, k_z, z_0) = -\frac{\exp(-ik_z z_0)}{(2\pi)^3} \frac{1 + P_1^+ + P_1^-}{L_0} \,. \tag{2}$$

Here $P_1^\pm$ are ascending continued fractions, determined by the recursive formula

$$P_n^\pm = -\frac{\Delta\varepsilon}{2}\left(\frac{\omega}{c}\right)^2 \exp(\pm i\psi) \frac{\exp(\pm inqz_0) + P_{n+1}^\pm}{L_n^\mp} \,, \tag{3}$$

and L_0, $L_n^\pm$ are ordinary continued fractions defined by the formulas

$$L_0 = \varepsilon\left(\frac{\omega}{c}\right)^2 - k^2 - \frac{\Delta\varepsilon^2}{4}\left(\frac{\omega}{c}\right)^4\left[\frac{1}{L_1^+} + \frac{1}{L_1^-}\right], \; L_n^\pm = \varepsilon\left(\frac{\omega}{c}\right)^2 - k_\perp^2 - (k_z \pm nq)^2 - \frac{\Delta\varepsilon^2}{4}\left(\frac{\omega}{c}\right)^4 \frac{1}{L_{n+1}^\pm} \,. \tag{4}$$

The function of the LDOS is proportional to the imaginary part of the Green's function at the point of the radiation source, and is defined by expression (see., e.g. Tocci et al. (1996), Moroz (1999), Wubs and Lagendijk (2002), Yeganegi et al. (2014))