

Response to "Comment on 'Enhancement of the optical gain of semiconductors embedded in three-dimensional photonic crystals'"

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In our letter¹ we present results on the optical gain of semiconductor material embedded in three-dimensional photonic lattice. Observations, including the gain maximum at energies far below the electronic band gap of the semiconductor and orientation dependencies of the gain spectra, allow us to ascribe the observed effects to gain enhancement and lasing caused by multiple coherent Bragg scattering of light in the periodic photonic crystal. This conclusion was questioned by the author of the Comment,² who suggests that our observation is a consequence of a defect-related process in the CdS-impregnated opals.

First, we would like to stress that the conclusions in our letter arise from results obtained from the direct measurement of optical gain by a variable stripe length method (VSL). Therefore, unlike conventional photoluminescence (PL) methods, which deal solely with spontaneous emission (SE) processes, we studied stimulated or amplified spontaneous emission (ASE).³ The light amplification of SE from CdS quantum dots (optical gain) is clearly demonstrated in our experiments¹ from the observation of an exponential increase of ASE intensity measured in VSL geometry as a function of the stripe length [Figs. 2(a) and 2(b) of our letter]. The key point of our study is the observation of high optical gain at energies far below the absorption edge of the semiconductor. This long-wavelength band **B** can be found not only in the ASE spectra [Figs. 1(b) and 1(c) of the letter], but also in the optical gain spectrum (Fig. 3 of the letter). This is the gain spectrum (not the PL spectrum, as mistakenly stated in the Comment²), which strongly depends on the orientation of the stripe relative to the crystallographic directions of the photonic lattice (Fig. 3 of the letter). This observation clearly demonstrates that the enhanced gain at the energy of the B band arises due to constructive Bragg interference in the vicinity of the photonic stop band.

The author of the Comment² questions our assignment of the origin of band B suggesting, for example, that it can be caused by defect-related SE processes in the CdS-impregnated opals. We would like to stress, however, that, in general, the precise origin and spectral shape of SE is not important for the deduction of ASE. In the VSL method the

SE is used as a probe source. This dominates the spectra only in the initial linear region of the intensity increase (i.e., for very small stripe lengths D). Thus, the same conclusion about the role of the photonic lattice, giving rise to the gain enhancement, will hold whatever is the origin of PL in the linear regime.

Although it is apparent from the above discussion that we did not study the PL spectra of the opal/CdS, some conclusions can be drawn, however, from our measurements at very small stripe lengths D . We find that for stripe lengths smaller than 20 μm , where the SE dominates, the spectrum consists of a single band A with a shape very similar to that of spectrum 1 in Fig. 1(B) of our letter. No additional structured bands in the long-wavelength region are found. Note also that for $\langle 110 \rangle$ oriented stripes the B band does not appear in the ASE spectrum for any stripe lengths, which also indicates the absence of any additional electronic transitions at wavelengths longer than 500 nm. We, therefore, believe that the B band is composed mainly of ASE and it originates from the same intrinsic states as band A.

Although the criticism of the author of the Comment² regarding the directional dependency of the gain spectra is not very precise, we feel that our conclusions may, in fact, be consistent with the suggestions of the Comment in this respect. It is clear from the considerations of the magnitude of the wave vectors in reciprocal space, presented in the letter,¹ that the central frequencies of the stop bands for $\langle 111 \rangle$, $\langle 211 \rangle$, and $\langle 110 \rangle$ directions should increase in this order. Therefore, changing the direction of the collection of light from $\langle 211 \rangle$ to $\langle 110 \rangle$, defined in the VSL method by the direction of the stripe, should result in a blueshift of the stop band, which is also the conclusion of the Comment.² The optical gain being enhanced in the vicinity of the corresponding stop band gives rise to a band B, which strictly follows the blueshift of the stop band. Note also that our consideration takes into account the three-dimensional fcc photonic Brillouin zone and, therefore, we do not feel that the statement in the Comment that we employed an "oversimplified model of independent crystallographic planes" is justified.

¹Yu. A. Vlasov, K. Luterova, I. Pelant, B. Hönerlage, and V. N. Astratov, Appl. Phys. Lett. **71**, 1616 (1997).

²S. G. Romanov, Appl. Phys. Lett. **73**, 550 (1998).

³It is worthwhile noting that there exists a distinct difference between the mechanisms and spectra of SE, ASE, and optical gain, which can be found in any of the common textbooks. See, for example, A. Yariv, *Quantum Electronics* (Wiley, New York, 1967), Chap. 13.

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