AMPLIFICATION IN PHOTONIC CRYSTAL HETEROSTRUCTURES WITH ACTIVE MEDIA FROM DOPING SUPERLATTICE LAYERS

D.V. Ushakov, V.K. Kononenko, and A.G. Smirnov

Stepanov Institute of Physics NASB
Fr. Scorina Pr., 70, 220072 Minsk, Belarus
Phone: 375(017)284-04-35, fax: 375(017)284-08-79, e-mail: lavik@dragon.bas-net.by

In the era of rapid progress in the Wavelength Division Multiplexing (WDM) technologies the cost-effective supercompact multiple-wavelength lasers that can be used as light sources in all-optical integrated circuits are in great demand. At present, two- or three-dimensional photonic crystals as well as one-dimensional (1-D) band-gap structures are generally recognized as a natural foundation of the future WDM photonics. This is due to their unique properties, such as spectral selectivity, high concentration of light intensity within small time-spatial volumes, and substantial lowering the speed of light, resulting in the alteration of the spontaneous emission rate of embedded atoms or clusters and gain enhancement [1-3]. Based on photonic band-gap (PBG) engineering, low threshold microlasers can be created.

In the paper, optical properties of one-dimensional heterostructures having optical forbidden gap are described and photonic structures with *n-i-p-i* superlattices as active media are designed for laser applications. As a possible candidate for active medium, *n-i-p-i* superlattices seem to be the best ones [4, 5]. They are feasible for integrating in optical circuits and, moreover, one can fabricate a crystal in a desirable manner to provide appropriate dispersion and emission properties in a wide spectral range. We would like to offer realistic design of the new band-gap microcavities and apply them for creation of low-threshold supercompact lasers.

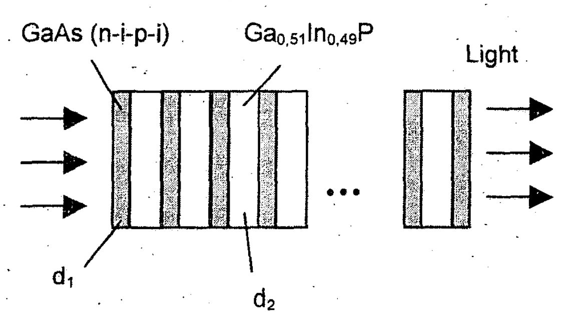


Fig. 1. One-dimensional PBG structure with the GaAs *n-i-p-i* active layers.

Our generic model of the laser crystal is depicted in Fig. 1. The active layers are made from *n-i-p-i* superlattices. They are controllable and their optical properties are modified due to electric or optical excitation [4]. The superlattice period is order of magnitude smaller than the period of the band-gap structure, therefore an approximation of effective refractive index may be applied for the description of the optical properties of active medium. The refractive index of *n-i-p-i* layers depends on the light wavelength and difference in the quasi-Fermi levels ΔF [6].

For constructing a composite band-gap material, we suggest heterostructures in the GaAs-$Ga_xIn_{1-x}P$ system, which are lattice-matched to the GaAs substrate. Superlattice layers are made as the GaAs *n-i-p-i* crystals with δ-doped *n-* and *p*-layers of the 2.8 nm thickness and with *i*-layers of the 6.8 or 11.3 nm thickness. Depending on the impurity concentrations and layer thickness, the effective band-gap of the doping superlattice changes from 0.04 to 0.53 eV under excitation. Accordingly, the refractive index and gain spectra are varied in a wide range. We have emanated from an opportunity of the growth of the band-

0-7803-7372-3/02/$17.00 ©2002 IEEE

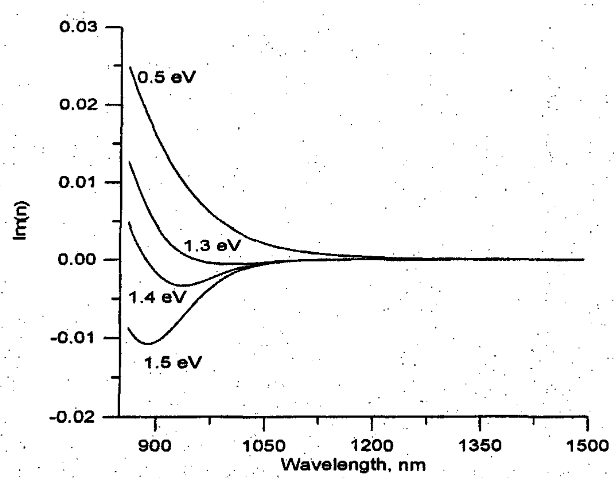


Fig. 2. Spectrum of the imaginary part of the *n-i-p-i* layer refractive index vs. the excitation level ΔF.

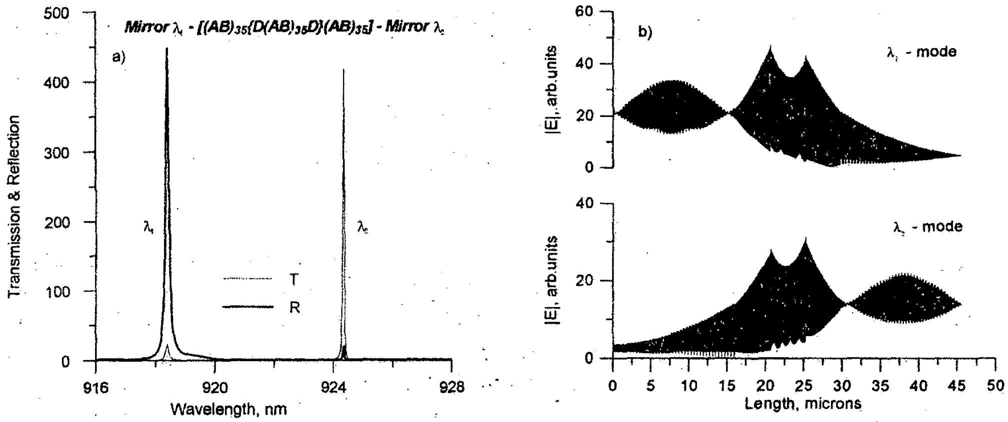
gap structures in the GaAs-$Ga_xIn_{1-x}P$ system considering the lattice constants and crystal matching. Therefore, thickness of the GaAs *n-i-p-i* layers is adjusted to the lattice constant of 0.565 nm, and the $Ga_xIn_{1-x}P$ layers make up is considered to have the mole fracture $x = 0.51$. Thus, the wide-band material is $Ga_{0.51}In_{0.49}P$ the forbidden gap of which is 1.89 eV.

We choose the *n-i-p-i* superlattice with *n*- and *p*-doped layers of the thickness $d_n = d_p = 2.83$ nm, *i*-layers of the thickness $d_i = 11.31$ nm and the concentrations of donors and acceptors of $N_d = N_a = 5.3\text{x}10^{19}$ cm^{-3}. The total thickness of the superlattice is 113 nm and covers four periods. The impurity surface concentration is equal to 1.5×10^{13} cm^{-2} and the effective band-gap of the superlattice falls up to $E_g = 0.04$ eV. As seen from Fig. 2, at the proper level of excitation ($\Delta F > 1.4$ eV) the imaginary part of the *n-i-p-i* layers refractive index becomes negative resulting in light amplification within certain spectral range (0.9 μm).

In order to attain high efficiency of lasing we have to tune our PBG material within amplification band of active medium. So we choose the following parameters of the generic $(AB)_N$ stack. Layer *A* is the *n-i-p-i* superlattice and layer *B* is the wide-gap semiconductor component $Ga_{0.51}In_{0.49}P$. Since the size of active layers is fixed in our PBG structure, $Ga_{0.51}In_{0.49}P$ layers are given of 16 nm thickness, that shifts the PBG to the 0.9 μm region. Difference between the refractive indices of *A* and *B* layers, $2(n_A - n_B)/(n_A + n_B) \approx 0.06$, is not very large, so the total number of layers in the band-gap structures proposed is about 100.

The model is considered where a pump excites uniformly the whole structure, and ΔF remains constant within all active layers. Active *n-i-p-i* superlattice layers can be pumped optically or electrically. Design of the whole photonic structure is similar to a configuration used for vertical-cavity surface-emitting lasers [7]. Because of high doping regions of *n-i-p-i* layers, suitable selective contacts [8] have enough low ohmic resistance and provide efficient injection of nonequilibrium current carriers into controlling layers of a photonic crystal heterostructure. For simplicity, it is also assumed that the PBG heterostructure is grown on the infinite GaAs substrate. In other words, no additional reflection occurs at end faces of the PBG crystal. Various schemes are possible, for example, antireflection coatings or Brewster-angle polishing to make the last condition true.

On the basis of PBG layouts discussed above we propose 1-D microresonator which is attractive for simultaneous lasing at two wavelengths. The resonator presented is a system of two mixed microcavities. Then, lasing is realized simultaneously at two separate mixed-cavity (MC) modes (wavelengths λ_1 and λ_2). The extra feature of this laser system is the possibility to guide the generated radiation in different output directions depending on operating wavelength. The solution is possible owing to additional selective Bragg mirrors blocking the light output at the resonator end faces. The blocking Bragg mirrors can be also constructed in the GaAs-$Ga_xIn_{1-x}P$ system. We offer the following design, i. e., $(Gc)_{40}[(AB)_{35}\{D(AB)_{35}D\}(AB)_{35}](GC)_{40}$, where "*G*" is the GaAs layer of the 0.209 μm



(a) (b)

Fig. 3. Lasing PBG MC-structure with active *n-i-p-i* layers ($\Delta F = 1.42$ eV). (a) Transmission and reflection spectra for two lasing modes and (b) distribution of the light amplitude inside the resonator for two different modes.

thickness, "*D*" is a "defect" layer, "*C*" is the 0.188 μm $Ga_{0.51}In_{0.49}P$ layer, and "*c*" is the $Ga_{0.51}In_{0.49}P$ cell of the 0.193 μm length. Fig. 3 depicts transmission and reflection spectra as well as light patterns for different MC-modes calculated for the case of pump being close to the lasing threshold. It is clearly seen that lasing occurs simultaneously at opposite directions, backward at λ_1 and forward at λ_2 wavelength.

Thus, computer simulation demonstrates that asymmetric photonic crystal heterostructures with defect layers provides lasing at two different wavelengths and in opposite output directions. The light field distribution and radiation transport in the photonic structures are strongly affected by the *n-i-p-i* layers periodicity, dispersion characteristics of the components, and conditions at the interfaces. Described photonic crystal heterostructures can be attractive for a wide variety of applications. In particular, they can be used as single-mode laser sources or amplifiers at the near-infrared spectral region.

References

1. J. Dowling, M. Scalora, M. Bloemer, and C. Bowden, "The photonic band edge laser: A new approach to gain enhancement," J. Appl. Phys. **75**, 1896–1899 (1994).
2. Yu. Vlasov, K. Luterova, I. Pelant, B. Hönerlage, and V. Astratov, "Enhancement of optical gain of semiconductors embedded in three-dimensional photonic crystals," Appl. Phys. Lett. **71**, 1616–1618 (1997).
3. Y.C. Tsai, K.W. Shumg, and S.C. Gou, "Impurity modes in one-dimensional photonic crystals-analytic approach," J. Mod. Opt. **45**, 2147–2157 (1998).
4. V.K. Kononenko, I.S. Manak, and D.V. Ushakov, "Optoelectronic properties and characteristics of doping superlattices," Proc. SPIE **3580**, 10–27 (1998).
5. I.S. Nefedov, V.N. Gusyatnikov, M. Marciniak, V.K. Kononenko, and D.V. Ushakov, "Optical gain in one-dimensional photonic band gap structures with *n-i-p-i* crystal layers," J. Telecommun. Inform. Technol. 1, 60–64 (2002).
6. D.V. Ushakov, V.K. Kononenko, and I.S. Manak, "Nonlinear optical processes in doped semiconductor superlattices," J. Appl. Spectrosc. **68**, 656–662 (2001).
7. L. Jewel, J.P. Harbison, A. Scherer, Y.H. Lee, and L.T. Florez, "Vertical-cavity surface-emitting lasers: design, growth, fabrication, characterization," IEEE J. Quantum Electron. **27**, 1332–1346 (1991).
8. H. Döhler, G. Hasnain, and J.N. Miller, "In situ grown-in selective contacts to *n-i-p-i* doping superlattice crystals using molecular beam epitaxial growth through a shadow mask," Appl. Phys. Lett. **49**, 704–706 (1986).