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Nonlinear harmonic mixing in an InGaAs/InGaP/GaAs laser on a germanium substrate

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Abstract. **An InGaAs/InGaP/GaAs laser with quantum wells, grown on a lightly doped germanium substrate, is experimentally investigated. Generation on the second and sum harmonics is observed in this composite cavity laser, which confirms the possibility of efficient difference-harmonic generation.**

Keywords: *laser, germanium substrate, second harmonic, sum harmonic, difference harmonic.*

Currently, there is a need for compact semiconductor light sources in the far-IR range. Among these sources, the best characteristics were obtained for quantum-cascade lasers based on GaAs and InP [1]. Unfortunately, these lasers can generate only at cryogenic temperatures. In addition, there is a wavelength range (25–60 μm) in the far-IR region where they cannot work because of high phonon absorption in GaAs- and InP-based solid solutions [2].

A possible alternative far-IR source is a generator based on nonlinear optical conversion (difference-harmonic generation) of two near-IR wavelengths. The possibility of difference-harmonic generation due to the GaAs lattice nonlinearity in a dual-frequency near-IR laser containing two different quantum wells (QWs) was considered in [3]. To satisfy the phase-matching condition, it was proposed to excite a higher order mode for the shorter wavelength and the fundamental mode for the longer wavelength. This approach was justified for composite-cavity laser diodes, in which difference-harmonic generation at wavelengths of 8, 8.75 and 11.65 μm was implemented [4, 5]. However, the use of different-order modes to satisfy the phase-matching condition is inefficient for difference-harmonic generation in the far-IR range [6–8]. At the same time, application of a lightly doped germanium substrate for a GaAs-based laser allows one to fulfill the phase-matching condition for two fundamental modes and reduce significantly the phonon absorption in GaAs [9].

In this study, we investigated an InGaAs/InGaP/GaAs QW laser grown on a lightly doped Ge substrate. This laser allow for difference-harmonic generation in the composite-cavity mode.

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An InGaAs/GaAs/InGaP laser heterostructure was grown on a lightly doped Ge(100) substrate (with deviation from the [111] axis by 6°) by hydride–metal organic vapor phase epitaxy under atmospheric pressure. The active region was an array of two InGaAs QWs, located at the center of the $In_{0.01}Ga_{0.99}As$ waveguide. The parameters of the heterostructure layers are listed in Table 1. Based on this heterostructure, we fabricated a laser diode with an active-region width of 100 μm and a length of 1 mm by chemical etching of the contact layer beyond the active strip, with subsequent ion-implantation isolation. No anti-reflection and high-reflection coatings were deposited on the laser chip faces. Cleaved faces of the structures served as mirrors. To exclude overheating, the laser chip was soldered to a copper heat sink by indium solder. The heat sink was mounted on a Peltier element to change the laser temperature.

Table 1. Parameters of laser heterostructure layers.

Layer number	Layer	Layer doping and composition	Layer thickness/nm
1	Substrate	n-Ge	150000
2	Buffer	n^+-$In_{0.01}Ga_{0.99}As$	250
3	Limiting layer	n^+-InGaP	700
4	Waveguide	i-$In_{0.01}Ga_{0.99}As$	350
5	QW 1	i-$In_{0.2}Ga_{0.8}As$	8
6	Waveguide	i-$In_{0.01}Ga_{0.99}As$	135
7	QW 2	i-$In_{0.2}Ga_{0.8}As$	8
8	Waveguide	i-$In_{0.01}Ga_{0.99}As$	350
9	Limiting layer	p^+-InGaP	700
10	Contact layer	p^{++}-GaAs	220

As was shown in [10], the electrical properties of the Ge/GaAs structure are significantly affected by the Ge/GaAs heterointerface. Here, interdiffusion of Ge atoms to the GaAs layer and Ga and As atoms to the germanium substrate occurs, which may affect the current–voltage characteristic of the diode (Fig. 1). The light–current characteristics of laser diode at different temperatures were also shown in Fig. 1. The lasing threshold was 0.7–1 A, depending on temperature. The sharp decrease in the laser intensity upon heating is most likely caused by the structure overheating due to the high series resistance (0.2 Ω), which is much larger than the resistance of similar lasers based on a GaAs substrate [11].

The spectral characteristics and directional laser radiation patterns in the planes oriented perpendicular and parallel to the p–n junction plane (measured at room temperature) are

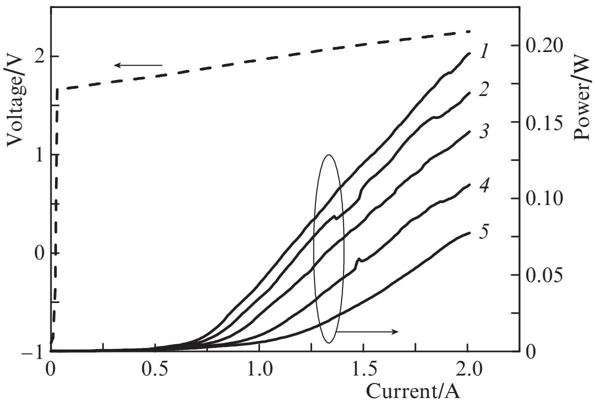

Figure 1. Current–voltage characteristic of the laser (T = 273 K) and its light–current characteristics at T = (*1*) 233, (*2*) 243, (*3*) 253, (*4*) 263 and (*5*) 273 K.

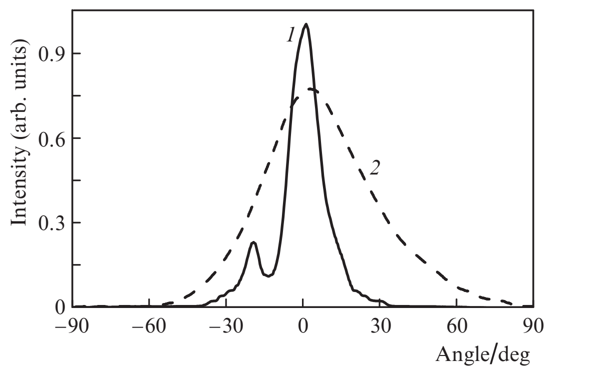

Figure 3. Laser radiation directional patterns in the planes oriented (*1*) parallel and (*2*) perpendicular to the p–n junction plane; T = 300 K, J = 2 A.

shown in Figs 2 and 3, respectively. The spectral dependences were recorded using an MDR-23 grating monochromator. To prevent the active region from heating, measurements were performed under pumping by 360-ns current pulses with a repetition rate of 1.5 kHz. As can be seen in Fig. 2, lasing was observed at a wavelength of 1 μm; the spectral line width was 4 nm. Figure 3 indicates that the directional radiation pattern in the plane parallel to the p–nn junction is broadened and has two maxima, which is caused, in our opinion, by the poor quality of the mirrors (formed by cleaving the structure on a germanium substrate).

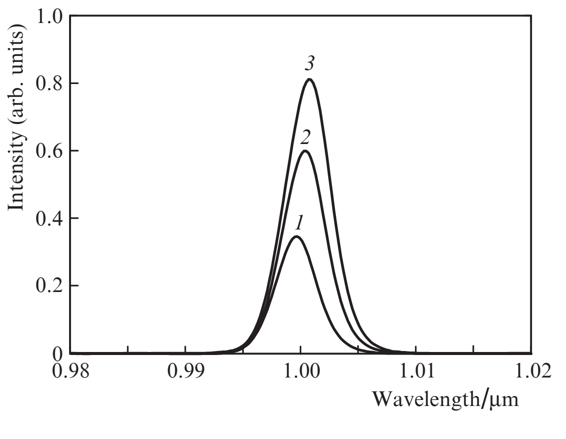

Figure 2. Emission spectra of a laser diode at pulse pump currents J = (*1*) 10, (*2*) 20 and (*3*) 30 A; T = 300 K.

To demonstrate nonlinear conversion of radiation into the second and sum harmonics, we used a design of a two-chip laser with a composite cavity, consisting of two cw QW lasers, mounted on the same heat sink in close proximity. Measurements were performed at liquid nitrogen temperature. In this scheme, both lasers generated at the fundamental transverse mode with different wavelengths, and the radiation of one of these lasers was launched into the waveguide of the other laser (along the normal to the transverse waveguide face). This design makes it possible to introduce a significant (~30%) part of radiation of one laser into the other laser [12]. The laser into which radiation was coupled was the above-described laser on a Ge substrate (λ = 0.93 μm and output power P_{out} = 0.8 W at T = 77 K), while the second laser was a conventional laser [13] on a GaAs substrate (λ = 1.03 μm, P_{out} = 1 W at T = 77 K and current 2 A). The emission spectra of the two-chip laser are shown in Fig. 4. They demonstrate the presence of second harmonics for the modes with wavelengths of 0.93 and 1.03 μm, and a sum-frequency signal of these modes at a wavelength of 0.488 μm. The power of the second and sum harmonics was approximately 0.5 μW, which can be explained by high absorption of radiation with these wavelengths in the $In_{0.01}GaAs$ waveguide layer and in the QWs. The observation of the sum harmonic is a direct proof of the possibility of frequency mixing in the laser cavity. Furthermore, it is expected to obtain difference-harmonic generation in the mid- and far-IR regions with an output power of ~10 μW [9], which is two orders of magnitude higher than the previously obtained result for a laser with higher order mode [4, 5].

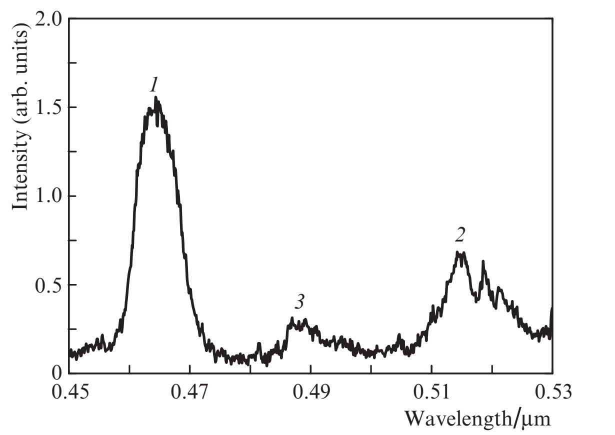

Figure 4. Emission spectrum of a two-chip composite cavity laser in the visible wavelength range at T = 77 K: (*1*) the second harmonic of a laser on a germanium substrate, (*2*) the second harmonic of a laser on a GaAs substrate and (*3*) the sum harmonic.

Thus, we have developed and investigated an InGaAs/InGaP/GaAs laser with QWs, grown on a lightly doped germanium substrate and designed for difference-harmonic generation. The observed generation of the sum and second harmonics indicates that nonlinear frequency conversion can be implemented in this laser.

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References

1. Williams B.S. *Nat. Photonics*, **1**, 517 (2007).
2. Ohtani K., Beck M., Faist J. *Appl. Phys. Lett*., **105**, 121115 (2014).
3. Aleshkin V.Ya., Afonenko A.A., Zvonkov N.B. *Fiz. Tekh. Poluprovodn*., **35**, 1256 (2001) [*Semiconductors*, **35**, 1203 (2001)].
4. Zvonkov B.N., Biryukov A.A., Ershov A.V., Nekorkin S.M., Aleshkin V.Ya., Gavrilenko V.I., Dubinov A.A., Maremyanin K.V., Morozov S.V., Belyanin A.A., Kocharovsky V.V., Kocharovsky Vl.V. *Appl. Phys. Lett*., **92**, 021122 (2008).
5. Zvonkov B.N., Biryukov A.A., Nekorkin S.M., Aleshkin V.Ya., Gavrilenko V.I., Dubinov A.A., Marem'yanin K.V., Morozov S.V. *Fiz. Tekh. Poluprovodn*., **43**, 220 (2009) [*Semiconductors*, **43**, 208 (2009)].
6. Afonenko A.A., Aleshkin V.Ya., Dubinov A.A. *Fiz. Tekh. Poluprovodn*., **38**, 244 (2004) [*Semiconductors*, **38**, 239 (2004)].
7. Afonenko A.A., Aleshkin V.Ya., Dubinov A.A. *Semicond. Sci. Technol*., **20**, 357 (2005).
8. Aleshkin V.Ya., Dubinov A.A. *Kvantovaya Elektron*., **38** (2), 149 (2008) [*Quantum Electron*., **38** (2), 149 (2008)].
9. Aleshkin V.Ya., Dubinov A.A. *Kvantovaya Elektron*., **38** (9), 855 (2008) [*Quantum Electron*., **38** (9), 855 (2008)].
10. Galiana B., Rey-Stolle I., Algora C., Volz K., Stolz W. *Appl. Phys. Lett*., **92**, 152102 (2008).
11. Ladugin M.A., Koval' Yu.P., Marmalyuk A.A., Petrovskii V.A., Bagayev T.A., Andreev A.Yu., Padalitsa A.A., Simakov V.A. *Kvantovaya Elektron*., **43** (5), 407 (2013) [*Quantum Electron*., **43** (5), 407 (2013)].
12. Biryukov A.A., Aleshkin V.Ya., Nekorkin S.M., Kocharovsky V.V., Kocharovsky Vl.V., Zvonkov B.N., Scully M.O. *J. Mod. Opt*., **52**, 2323 (2005).
13. Avrutskii I.A., Batukova L.M., Dianov E.M., Zvonkov B.N., Zvonkov N.B., Maksimov G.A., Malkina I.G., Medvedeva L.V., Yan'kova T.N. *Kvantovaya Elektron*., **21** (10), 921 (1994) [*Quantum Electron*., **24** (10), 859 (1994)].