Intracavity difference-frequency generation in butt-joint diode lasers

V.Ya. Aleshkin[1], A.A. Dubinov[1], V.I. Gavrilenko[1], K.V. Maremyanin[1], S.V. Morozov[1], A.A. Biryukov[2], S.M. Nekorkin[2], B.N. Zvonkov[2], Vl.V. Kocharovsky[3]

[1]Institute for Physics of Microstructures RAS, 603950, Nizhny Novgorod, Russia
[2]Physico-Technical Research Institute, UNN, 603950, Nizhny Novgorod, Russia
[3]Institute of Applied Physics RAS, 603950, Nizhny Novgorod, Russia

Introduction

Compact mid-far-infrared semiconductor sources are now under active development stimulated by a variety of applications. The most significant progress has been achieved with quantum cascade (QC) lasers that work at and above room temperature in the continuous-wave regime in the mid-infrared range [1] and at cryogenic temperatures in the far-infrared range [2]. However, the perspectives of their room temperature operation in the far-infrared range are uncertain. Besides, QC lasers are quite complex devices including thousands of thin epitaxial layers. The intracavity difference-frequency generation (DFG) in semiconductor diode lasers provides an alternative way to room temperature injection-pumped source in the mid-far-IR range.

It would be very attractive to implement DFG process in the cavity of a laser diode generating radiation in the near-IR range [3]. In this work, we report the observation of DFG in a butt-joint diode lasers generating two wavelengths in the near-IR range that serve as a pump for the intracavity DFG process.

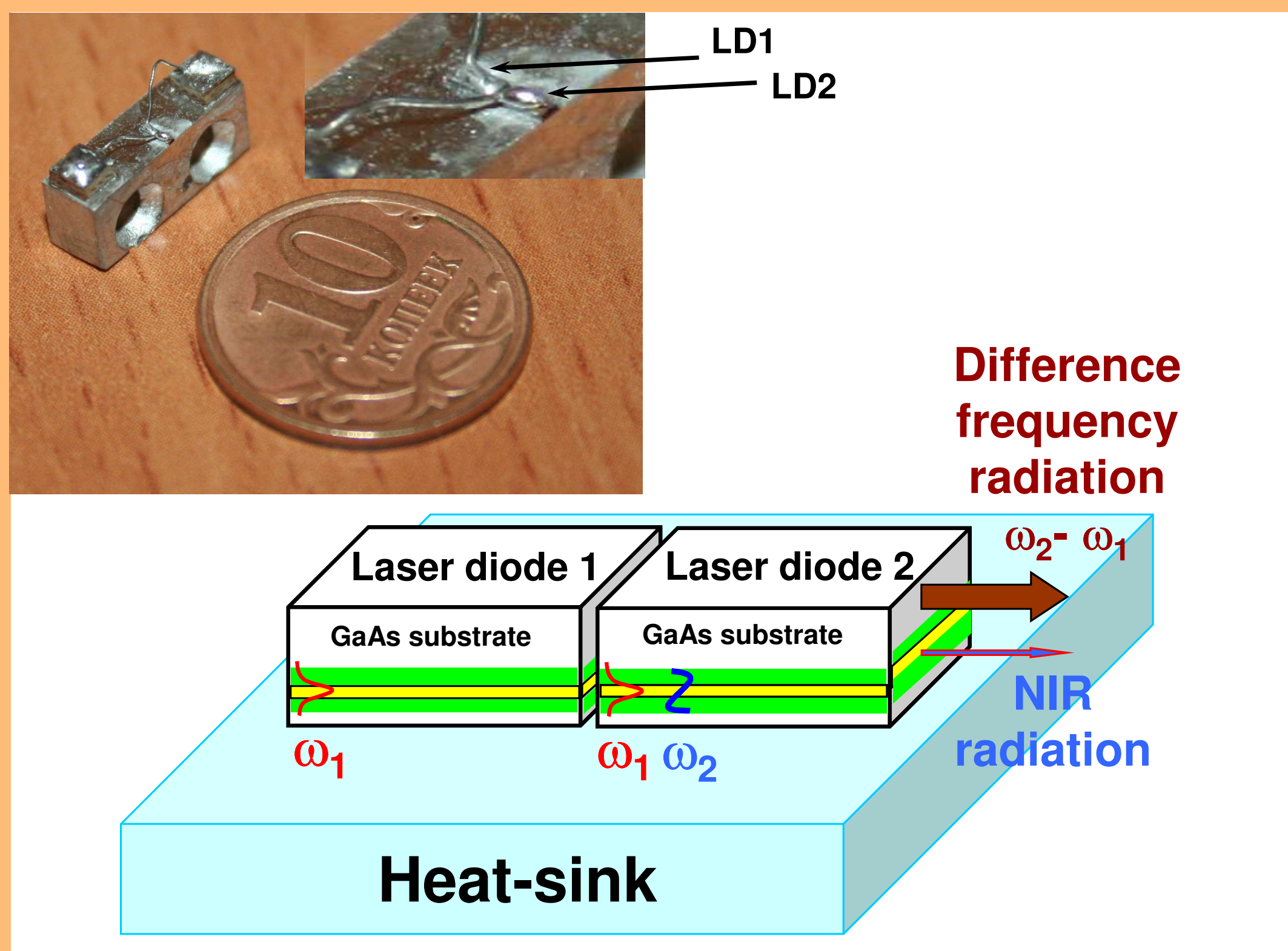


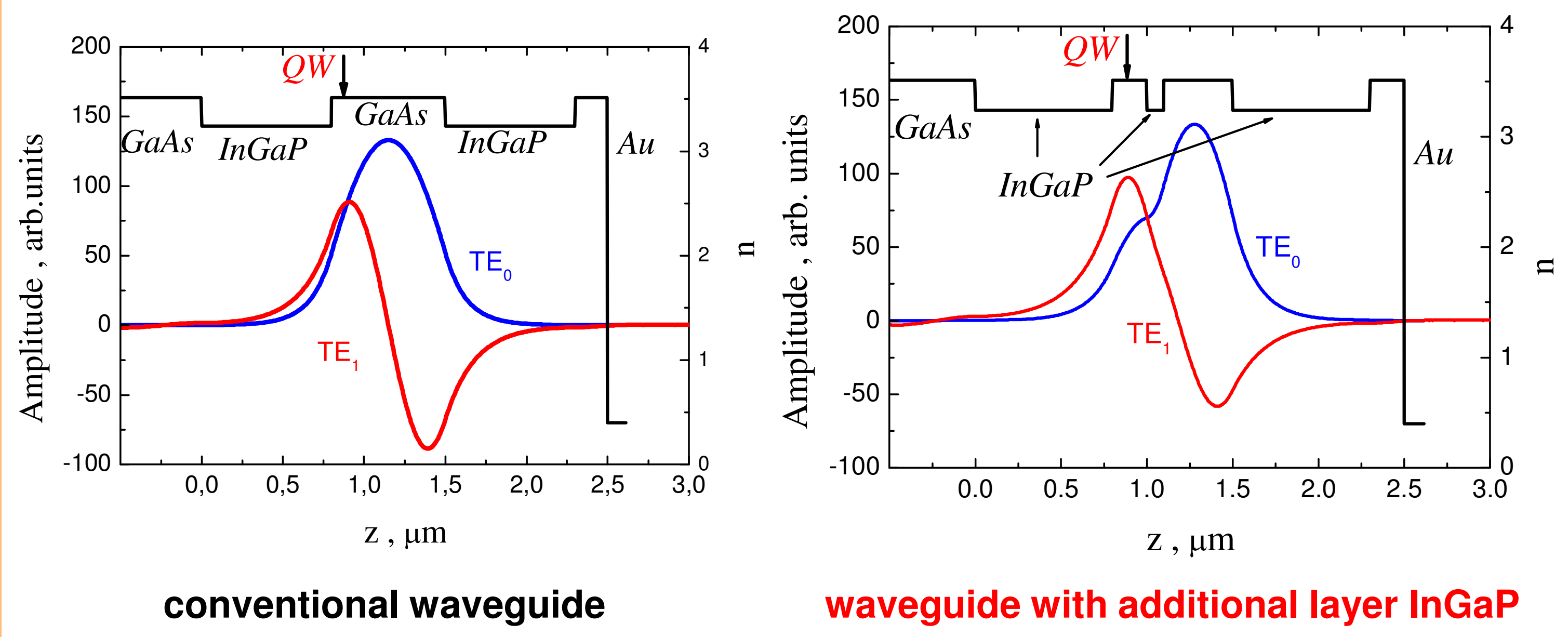
Fig.1. Butt-joint diode laser.

Butt-joint diode lasers

The four factors are important for the DFG efficiency. The first factor is the power of the short-wavelength pump radiation. The most powerful diode lasers are based on GaAs structures and operate at wavelengths around 1 μm. Therefore, we use GaAs/InGaAs/InGaP lasers operating in this wavelength range. The second factor is a relatively high optical nonlinearity of the laser waveguide material. The second order optical susceptibility of GaAs is 1.3 * 10^8 cm/V, which is a very high value. The third factor is phase matching, which can be satisfied for DFG in GaAs in the mid-IR range when near-IR pump modes have different transverse orders [4]. In butt-joint lasers we used the fundamental mode at a longer pump wavelength and the first order mode at a shorter pump wavelength. The fourth factor is the low losses for the difference frequency radiation. To minimize these losses, we used a low-doped substrate and a specially designed waveguide in chip where the DFG process took place.

To achieve simultaneous generation of two wavelengths around 1 μm, we used the butt-joint two-chip laser design [5] shown in **Fig. 1**. It provides independent control of power of the two modes by varying the corresponding currents in which diode. Such device promises a good degree of flexibility and spectral tunability. The chips are approximately 1 mm length and separated by no more than a 1 μm wide gap.

Laser structures were grown by metal-organic chemical vapor deposition epitaxy on GaAs substrates. Active regions are formed by $In_xGa1_{1-x}As$ quantum wells of 10 nm thickness with InAs fraction x=0.35, 0.32, 0.29 for radiation at wavelength λ_1 =1.13, 1.107, 1.077 μm and x=0.2 for radiation at wavelength λ_2=0.99 μm, respectively. Waveguide cladding is formed by $In_{0.49}Ga_{0.51}P$ layers lattice matched to GaAs. To minimize losses for the difference frequency radiation, we used a low-doped ~ (1-2) * 10^{17} cm^{-3} *n*-GaAs substrate of 150 μm thickness in front chip where the DFG process took place.



conventional waveguide

waveguide with additional layer InGaP

Fig.2. Laser cheap for the TE1 mode generation.

The waveguide of the LD1 laser that generates the fundamental mode at wavelength λ1 is of a standard design. Its facet facing the second laser. The waveguide of the LD2 laser generating at λ2 has a special asymmetric design (**Fig. 2**) with an extra InGaP layer to ensure laser operation at the first order transverse mode [6].

Experimental results

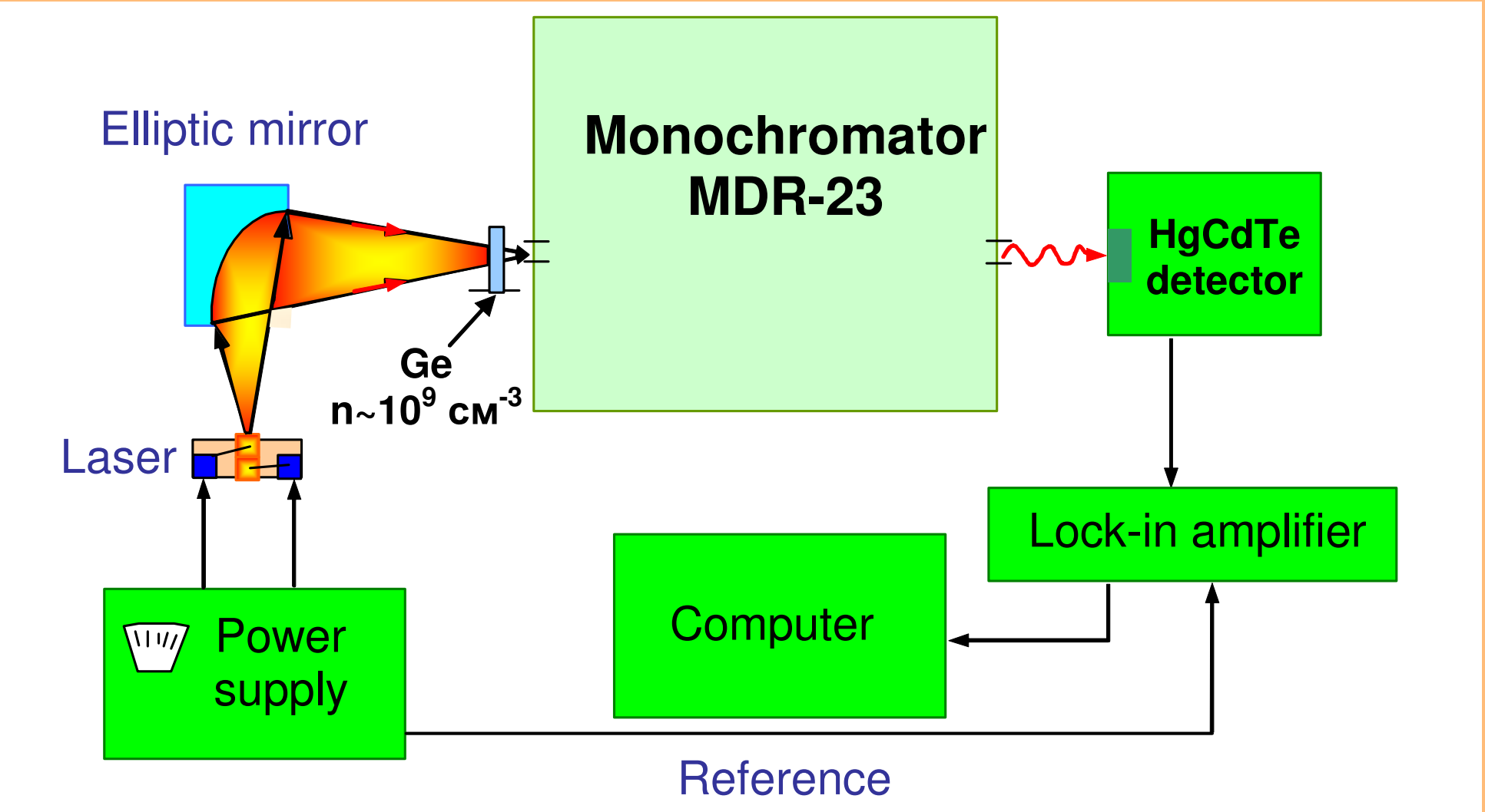


Fig. 3. Scheme of experimental setup for registration spectra of fundamental, second, sum harmonics and spectra in the mid-IR.

Radiation in the near-IR, mid-IR, and visible range was detected from the output facet of the LD2 laser (front). Scheme of experimental setup is shown in the Fig. 3. All spectra were measured in the pulsed regime with pulse duration of 500 μs and repetition rate of 1 kHz. **Figures 4 (A)** shows typical near-IR spectra. We have also detected the signals at the second harmonics and sum frequency at the nanowatt level. Their spectra are shown in the inset of **Fig. 4 (B)**. All spectra were measured by a diffraction grating monochromator. Mid-IR radiation at the difference frequency was detected by a liquid nitrogen cooled CdHgTe detector with bandwidth 2 - 12.5 μm. Spectra were measured by the same grating monochromator. Mid-IR radiation was filtered by a pure Ge filter. The observed difference-frequency spectra for three different lasers are shown in **Fig. 4 (C)** and **Fig. 5 (a)**. The estimated total power of the difference-frequency radiation is about 0.1 μW for line with peak around 8 μm and powers of two other lines are sufficiently lower, that good conformed with results of calculating power of DFG for our structures [7], which are shown in **Fig. 5 (b)**.

Thus we experimentally have demonstrated the possibility of difference frequency generation in mid-infrared region in butt-joint diode lasers at room temperature.

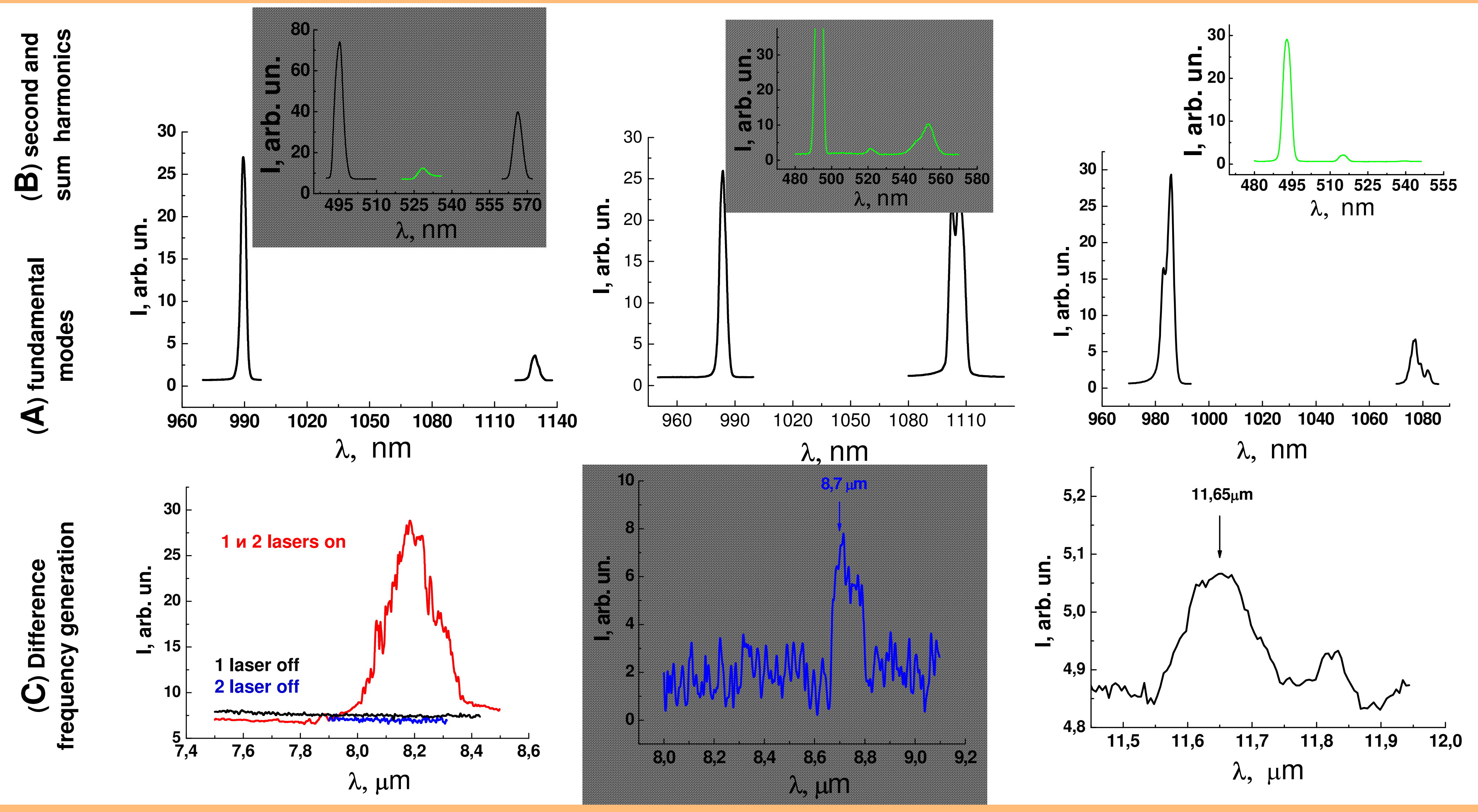


Fig.4. Measured emission spectra of three butt-joint diode laser: fundamental modes (A), second and the sum harmonics (B) and measured spectra of difference frequency generation (C) at room temperature.

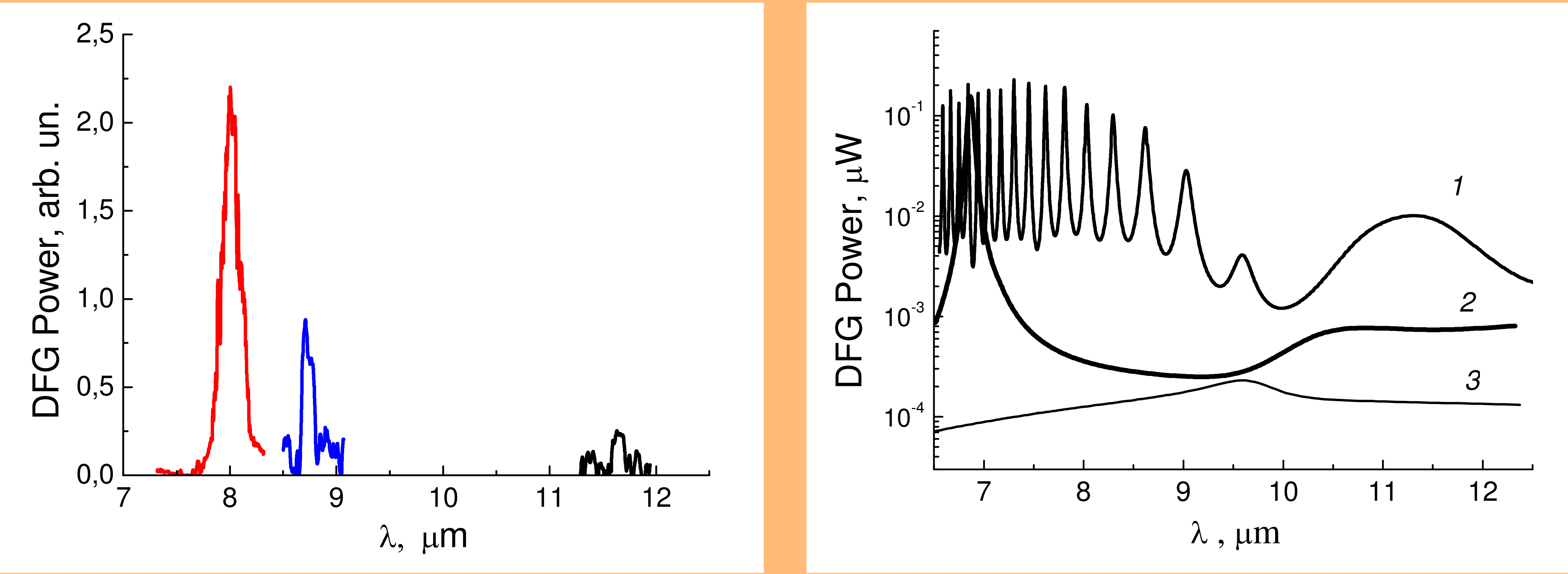


Fig.5. a - Measured spectra of difference frequency generation in three butt-joint lasers. Power radiation with peak 8μm is ~ 0.1μW; b - Calculated power of DFG for three doping levels of substrate: 1 - n=10^{17}cm^{-3}, 2 - buffer layer 3 μm with n=10^{17}cm^{-3} and substrate with n=2*10^{18} cm^{-3}, 3 – n=2*10^{18}cm^{-3}.

References

[1] A. Evans, J.S. Yu, S. Slivken and M. Razeghi, *Appl. Phys. Lett.* **85**, 2166 (2004).
[2] B. S. Williams, *Nat. Photonics* **1**, 517 (2007).
[3] V.Ya. Aleshkin, A.A. Afonenko and N.B. Zvonkov, *Semiconductors* **35**, 1203 (2001).
[4] M. Jager, G.I. Stegeman, M.C. Flipse, M. Diemeer, and G. Mohlmann, *Appl. Phys. Lett.* **69**, 4139 (1996).
[5] A.A. Biryukov, S.M. Nekorkin, B.N. Zvonkov, V.Ya. Aleshkin, A.A. Dubinov, V.I. Gavrilenko, K.V. Maremyanin, S.V. Morozov, A.A. Belyanin, V.V. Kocharovsky and Vl.V. Kocharovsky, *Laser Phys.* **17**, 684 (2007).
[6] A.A. Biryukov, B.N. Zvonkov, S.M. Nekorkin, V.Ya. Aleshkin, A.A. Dubinov, V.V. Kocharovsky and Vl.V. Kocharovsky, *Semiconductors* **41**, 1364 (2007).
[7] V.Ya. Aleshkin, A.A. Afonenko, A.A. Dubinov, *Technical Physics* **76**(9), 98 (2006).