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LETTERS

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High-coupling distributed feedback lasers for the 1.55 μm spectral region

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Abstract. **A technique for the development of high-coupling distributed-feedback (DFB) lasers for the 1.55 μm spectral region is described. The lasers demonstrate stable single-frequency generation in a broad temperature range with a maximum side-mode suppression ratio of more than 30 dB.**

Keywords: *distributed feedback, single-frequency lasing, side-mode suppression ratio, semiconductor laser.*

1. Introduction

Single-frequency laser sources for the spectral region near 1.55 μm, based on distributed-feedback (DFB) semiconductor lasers, are key components of fibre-optic communication lines. The practical development of these lasers began as early as in the 1970s [1]. Despite the great progress in the DFB lasers at the end of the last century [2], the development of the DFB technology, which is of key importance for designing tunable single-frequency lasers in the aforementioned spectral region, still continues [3, 4]. This is primarily related to the application of a new concept of radiation sources for fibre-optic communication lines, which implies unification of the components in use [5], and to the development of modern spectroscopic systems [6]. There are a number of different approaches to the design of compact tunable lasers, including those based on application of miniature external cavities [7, 8], sampled grating distributed Bragg reflector [9], and DFB laser arrays [3, 4].

In this letter, we report the results of developing the technology of DFB lasers [10, 11] with a high coupling coefficient, emitting in the spectral range near 1.55 μm (the C-band). The heterostructures used as a basis for DFB lasers were grown by molecular-beam epitaxy (MBE) at the Connector Optics LLC (St. Petersburg, Russia) on a Riber 49 system. The heterostructure composition is given in Table 1.

Two-stage epitaxy (with overgrowth of DFB grating) was applied. After depositing layer 4, the epitaxial growth was stopped. Then diffraction gratings for DFB with periods of 468.6, 468, 467.4, and 466.8 nm were formed in layer 4 on a Raith Voyager electron-beam lithography system at the JSC OKB-Planeta (Velikii Novgorod, Russia). Gratings in the $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ layer were obtained by dry etching through a 50-nm-thick SiO_2 mask (formed by plasma-enhanced chemical vapour deposition) in combination with a 30-nm-thick Al layer. The topological mask in the Al layer for etching SiO_2 was made by explosive lithography using a two-layer resist based on LOR 1A and a positive electron resist PMMA 600K (a mask in the latter was formed by electron-beam lithography). The $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ layer was etched through a SiO_2-based mask in an inductively coupled plasma.

A scanning electron microscopy image of a typical grating in the $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ layer is presented in Fig. 1a. The etching depth was estimated by optical profilometry to be 80 nm. The gratings (formed on two-inch wafers) were MBE-overgrown with indium phosphide with the Riber 49 system at the Connector Optics LLC. As a result, upper emitter layer 5 and contact layer 6 were formed (Table 1). After the two-stage epitaxy, stripes ~5 μm wide were formed by liquid etching on the heterostructure surface using alignment marks. The shallow-mesa geometry (without etching the waveguide layer) was applied. After the wafer processing and thinning, experimental samples of DFB lasers with cavity lengths of ~0.5 and ~0.25 mm were pricked out and mounted on a primary heat sink.

The characteristics of DFB lasers were investigated in the pulsed regime. The pump pulse duration was 70–90 ns at a repetition frequency of 48 kHz. The characteristic threshold currents for the DFB samples under study were 300–600 mA at a temperature T = 288 K. A typical light–current characteristic of the laser with a cavity length of 0.25 mm at T =

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Table 1. Design of DFB laser heterostructure.

Layer number	Layer type	Layer composition	Doping type level/cm^{-3}	Layer thickness/nm
6	Contact	$In_{0.53}Ga_{0.47}As$	n, 5×10^{18}	150
5	Emitter	InP	n, 3×10^{16}	2000
4	Waveguide	$In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ (1.3 μm)*	–	200
3	Active region	$In_{0.58}Ga_{0.42}As_{0.91}P_{0.09}$ (1.55 μm)*	–	50
2	Waveguide	$In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ (1.3 μm)*	–	150
1	Buffer	$In_{0.52}Al_{0.48}As$	p, 2×10^{17}	3000
	Substrate	InP	p, 3×10^{18}	

*Compositions were chosen in correspondence with the specified interband-transition wavelength.

288 K is shown in Fig. 1b. The spectra were recorded with an MDR-23 monochromator using the lock-in detection technique. The size of the monochromator input and output slits during measurements was 0.1 mm; this size provided a spectral resolution of 0.26 nm, which is much smaller than the mode spacing of a Fabry–Perot cavity for the samples under consideration. The spectral measurements showed that the maximum side-mode suppression ratio (SMSR) exceeds 30 dB. A typical lasing spectrum is presented in Fig. 2a.

When optimising the DFB laser technology, an important issue is to evaluate the coupling coefficient κ, because it determines the single-frequency lasing stability. This coefficient can be calculated from the expression [12]

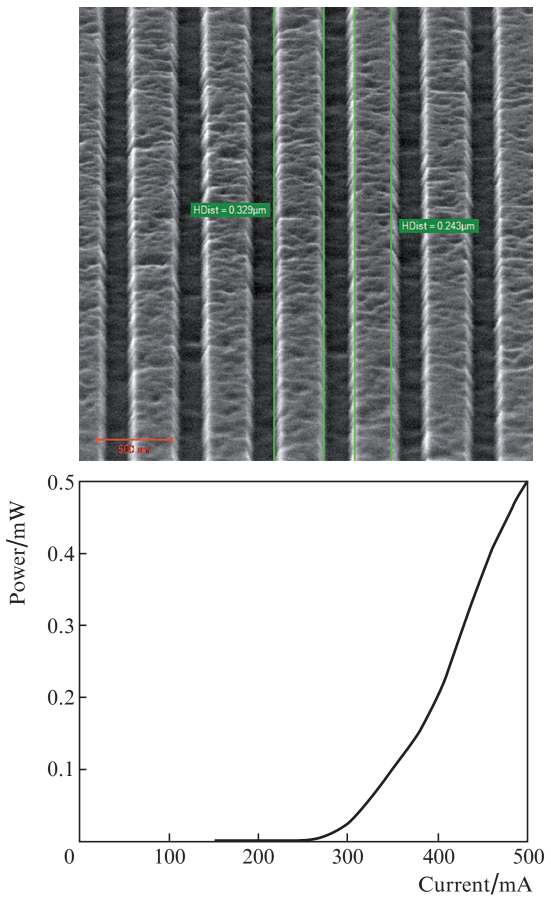

Figure 1. (a) SEM image of a typical grating and (b) a typical light–current characteristic of an experimental sample of DFB laser.

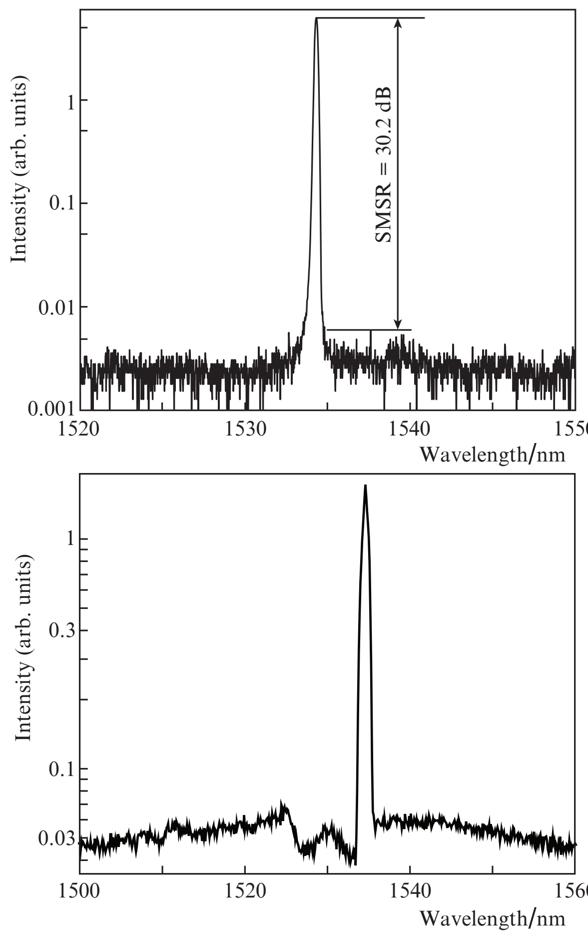

Figure 2. (a) Typical lasing spectrum of an DFB laser with a cavity length of 0.5 mm at $T = 288$ K and (b) the spectrum of the same laser at the same temperature but near the lasing threshold.

$$\kappa = \frac{\pi N \Delta\lambda_s}{\lambda_B^2}, \tag{1}$$

where N is the effective refractive index, $\Delta\lambda_s$ is the Bragg gap spectral width, and λ_B is the DFB lasing wavelength. The Bragg gap spectral width can easily be determined from the dip in the spontaneous-emission spectrum near the lasing threshold.

Figure 2b shows a spectrum of the same sample of DFB laser as in Fig. 2a but near the lasing threshold. One can observe well a dip in the spontaneous-emission spectrum, whose width $\Delta\lambda_s$ is ~9.5 nm. Substituting this value into formula (1), we find that $\kappa \sim 400$ cm^{-1}. Such a large coupling coefficient is indicative of high quality of the DFB diffraction gratings. The large value of the coupling coefficient and, therefore, the large Bragg gap width make it possible to tune the radiation wavelength in a wide temperature range without exciting a competing Bragg mode.

We studied the temperature tuning of experimental samples of DFB lasers. Figure 3 shows the temperature dependences of the lasing wavelength and SMSR for a DFB laser with a cavity length of 0.5 mm in the temperature range of 15–35 °C (288–308 K). The spectral tuning range was found to be 2.1 nm, a value corresponding to the lasing line temperature shift $d\lambda/dT \approx 0.1$ nm K^{-1}.

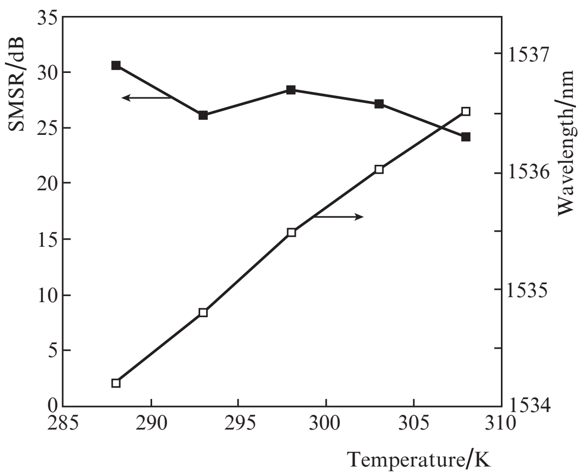

Figure 3. Temperature dependences of the lasing wavelength and SMSR.

The data presented in Fig. 3 are indicative of stable single-frequency lasing at large SMSR values in the entire temperature range under study. The maximum SMSR value exceeded 30 dB. This result demonstrates that tunable DFB laser arrays can be formed based on the developed technology; the latter can also be scaled to design wide-aperture DFB lasers with curved grating lines, which provide output beam focusing [13, 14].

Thus, we have developed a technology of fabricating DFB lasers with a high coupling coefficient for the spectral region near 1.55 μm. The fabricated samples of DFB lasers exhibit stable single-frequency lasing. The maximum side-mode suppression ratio exceeds 30 dB. Stable single-frequency lasing in a wide temperature range has been demonstrated, which indicates that the developed technology can be used to form tunable DFB laser arrays on one chip.

References

1. Alferov Zh.I., Gurevich S.A., Klepikova N.V., Kuchinskii V.I., Mizerov M.N., Portnoi E.L. *Pis'ma Zh. Tekh. Fiz*., **1**, 645 (1975).
2. Baryshev V.I., Golikova E.G., Duraev V.P., Kizhaev K.Yu., Kuksenkov D.V., Kuchinskii V.I., Portnoi E.L., Smirnitskii V.B. *Sov. J. Quantum Electron*., **18**, 1376 (1988) [*Kvantovaya Elektron*., **15**, 2196 (1988)].
3. Gotoda M., Takabayashi Y., Horiguchi K., Matsumoto K., Ishimura E. *IEEE J. Sel. Top. Quantum Electron*., **23**, 6000406 (2017).
4. Pezeshki B., Vail E., Kubicky J., Yoffe G., Zou S., Heanue J., Epp P., Rishton S., Ton D., Faraji B., Emanuel M., Hong X., Sherback M., Agrawal V., Chipman C., Razazan T. *IEEE Photon. Technol. Lett*., **14**, 1457 (2002).
5. http://www.oiforum.com/wp-content/uploads/OIF-ITLA-MSA-01.3.pdf.
6. Yang R., Dong X., Bi Y., Lv T. *Opt. Commun*., **410**, 782 (2018).
7. Sato K., Mizutani K., Sudo S., Tsuruoka K., Naniwae K., Kudo K. *J. Lightwave Technol*., **25**, 2226 (2007).
8. Liu A.Q., Zhang X.M. *J. Micromech. Microeng*., **17**, R1 (2007).
9. Yagi H., Kaneko T., Kono N., Yoneda Y., Uesaka K., Ekawa M., Takechi M., Shoji H. *IEEE J. Sel. Top. Quantum Electron*., **24**, 6100411 (2018).
10. Kazarinov R.F., Suris R.A. *Fiz. Tekh. Poluprovodn*., **6**, 1359 (1972).
11. Kogelnik H., Shank C.V. *J. Appl. Phys*., **43**, 2327 (1972).
12. Hillmer H., Hansmann S., Burkhard H. *Appl. Phys. Lett*., **57**, 534 (1990).
13. Sokolovskii G.S., Rafailov E.U., Birkin D.J.L., Sibbett W. *J. Opt. Quantum Electron*., **31**, 215 (1999).
14. Sokolovskii G.S., Rafailov E.U., Birkin D.J.L., Sibbett W. *IEEE J. Quantum Electron*., **36**, 1412 (2000).