LETTER

Vertical Cavity Surface-Emitting Laser Array for 1.3 μm Range Parallel Optical Fiber Transmissions

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SUMMARY Long-wavelength 1.3 μm GaInAsP/InP vertical cavity surface-emitting lasers (VCSELs) have been demonstrated in an array configuration. With the strong current confinement by a buried heterostructure and the efficient optical feedback by a dielectric cavity, five VCSEL elements in a 2×4 array operated at room temperature with 5 mW total power output and wavelength error within ±5%. The stacked planar optics including the VCSEL array is a promising optical transmitter in ultra large scale parallel optical communication systems.

key words: *surface-emitting laser, laser array, semiconductor laser, buried heterostructure, GaInAsP/InP, optical fiber communication*

Recently, the research on short-wavelength 0.63–0.98 μm range vertical cavity surface-emitting lasers (VCSELs) grown on GaAs substrates, aiming at applications to optical interconnects, has become active [1]–[4]. On the other hand, the performance of long-wavelength 1.3–1.55 μm VCSELs has been improved in the last few years, and their features acceptable for new optical communication network systems have been attracting much attention. We previously reported the first room-temperature continuous-wave (cw) lasing operation of a 1.3 μm VCSEL fabricated on InP substrate [5]. We also observed some lasing characteristics expected from VCSELs, i.e. appearance of a single spectrum and a small temperature dependence of lasing wavelength, as well as a circular spot profile and a small divergence of the output beam [6]. In this paper, we demonstrate these devices in an array configuration at room temperature.

Figure 1 shows the schematic of a 2×4 VCSEL array fabricated on an n-InP substrate. The VCSEL elements were arranged two-dimensionally with 500 μm pitch, which is four times the outer diameter of standard single-mode fiber. The p-GaInAsP bulk active region of each element was nearly circular and 0.7 μm thick, 12 μm in diameter and 1.37 μm in band-gap wavelength. The fabrication process is very similar to that described previously [7]. Liquid-phase epitaxy (LPE) was used for the growth process. The circular active region formed by chemical etching was buried by n- and p-InP current blocking layers by a maskless planar buried heterostructure (PBH) regrowth technique [7]. The substrate just above the active regions was etched through 300-μm-diameter windows of AuGe alloy. A pair of dielectric multilayer mirrors was evaporated on both surfaces of epitaxial layers to form a laser cavity. We employed eight and a half pairs of magnesia and amorphous silicon (MgO/Si) quarter-wavelength multilayers for the p-side surface, and six pairs of SiO_2/Si for the n-side surface. In the previous paper [8], we have shown that the thermally conductive MgO/Si mirror is effective for heatsinking under cw condition when the device is bonded p-side down on a metal submount. Since the light penetration depth into the multilayer mirrors is negligibly short, the cavity length is almost determined by the total thickness of epitaxial layers. It was nearly 4.5 μm in this experiment. The p-side mirror was covered with Au/Ni/Au metal as a common electrode. The current was introduced from the metal electrode to the ring contacts [7] of VCSELs and injected into the active regions.

Figure 2 shows the light output and voltage versus current characteristics measured at room temperature under pulsed condition. The light power increased rapidly above the current of 450 mA. From the observation of the near field pattern (NFP), it was confirmed that neighboring three elements started lasing oscillation with this current. Then the following two ele-

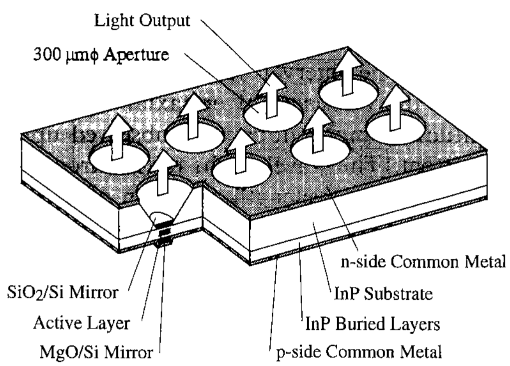

Fig. 1 Schematic of fabricated VCSEL array.

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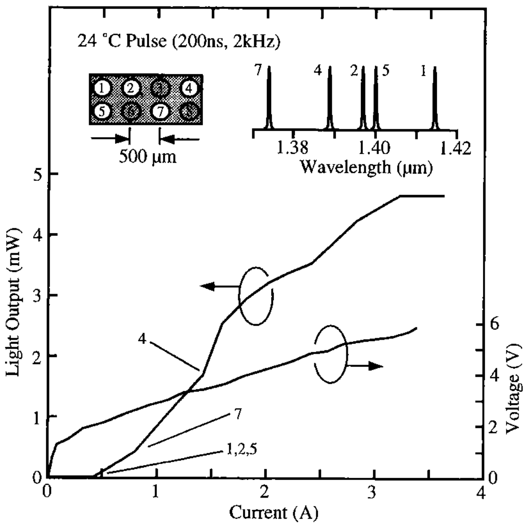

Fig. 2 Measured light output and voltage versus current characteristics with positions and wavelengths of lasing elements.

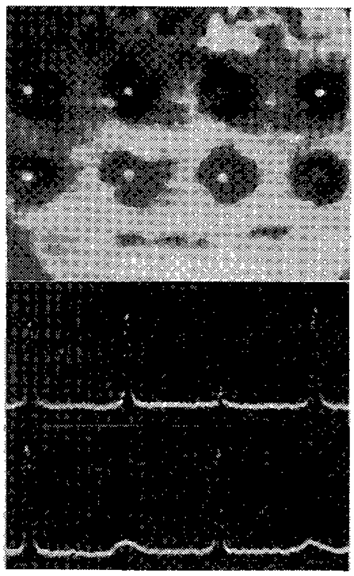

Fig. 3 Observed near-field pattern above threshold and corresponding field profiles.

ments reached threshold condition at nearly 800 mA and 1450 mA, respectively. The light power increased monotonically with current, and saturated above 3300 mA. The NFP and its profiles at 2500 mA were observed by a bisicon camera, as shown in Fig. 3. Other three elements could not lase although they exhibited the spontaneous emission of a relatively broad NFP. The total light power showed a maximum value of 5 mW. This value is the highest among the long wavelength VCSELs so far reported operating at room temperature. However, the differential quantum efficiency η_d was estimated to be 0.03%. Owing to the extremely high reflectivity of multilayer mirrors, η_d of a single device was typically as low as 0.18% [6]. Even comparing with this value, the value of η_d in this experiment is lower by a factor 6. This seems to be caused by a noticeable leakage current not only around the active regions but also through pinholes of the current blocking layers, which are relatively wide compared with those of a single device.

The position of the lasing elements is indicated by open circles in the inset of Fig. 2. Also, the lasing wavelengths of the corresponding elements are shown. In VCSELs, the lasing wavelength is almost only dependent on the cavity length, i.e., the total thickness of epitaxial layers. The interval of longitudinal modes estimated from the thickness of epitaxial layers is 50 nm. No longitudinal mode hops were observed upon varying the current. The wavelengths ranged from 1.374 μm to 1.414 μm. The wavelength variation of nearly $\pm$ 5% seems to be caused by the inhomogeneous thickness of epitaxial layers of the same order within $1500 \times 500\,\mu\text{m}^2$ area.

Under the cw condition, lasing operation could not be achieved in the VCSEL array. This is due to the relatively high injection level over 1 A, which causes large heat generation inside the device, and also to the degradation of electrical characteristics. Figure 4 shows the simulated temperature increase ΔT inside the device under cw condition. Here, we did not take into account the excess leakage current caused by the imperfection of the fabrication process, and assumed the ideal single device as the calculation model. We used a finite-element method with the cylindrical coordinate system. Since the series resistance of our device is typically less than 10 Ω, we neglected the Joule heat by the resistance. We assumed the heat uniformly generated inside the active region to be 20 mW, which corresponds to the product of the band-gap energy 0.9 eV and the threshold current of the previously obtained cw device, i.e., 22 mA. The highest ΔT is calculated to be 18 K at the center of the active region. The area inside which ΔT is greater than 1 K is 22 μm in radius. Therefore, the cw lasing threshold will not be affected by other operating elements, although the pitch between elements is reduced to 45 μm. However, in an actual device, the pitch must be much larger than this value since a large amount of heat is generated even above threshold in devices showing low differential quantum efficiency.

In summary, we obtained the room temperature lasing oscillation of five elements in 2×4 VCSEL array with $\pm$ 5% variation of the lasing wavelength. Further flat epitaxy and uniform process will reduce the variations of the wavelength. In addition, the cw operation will be achieved by reducing further the pulsed threshold current in each element. It was indicated from the numerical calculation that the array pitch between elements can be reduced to 45 μm. However, the improvement of the differential quantum efficiency will also be required to avoid the thermal interaction above thresh-

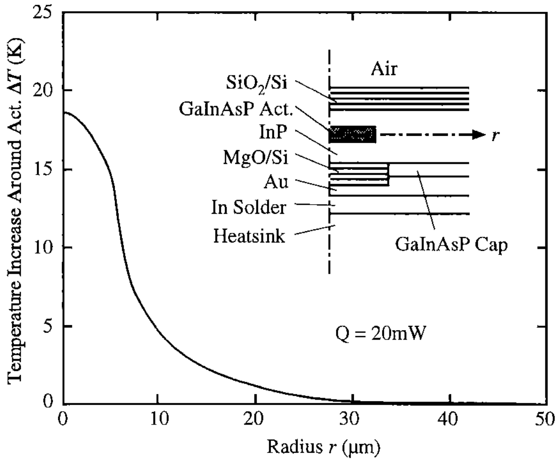

Fig. 4 Calculated temperature increase inside a single device with cw current of 22 mA.

old. In any case, the VCSEL array will be a promising transmitter in ultralarge scale optical parallel communication systems by integrating with stacked planar optics [9] including planar microlens array [10], put-in microconnectors [11], fiber guides [12], and fiber array.

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References

[1] Iga, K., "Surface emitting lasers and parallel operating devices – fundamentals and prospects –," *IEICE Trans. Fundamentals*, vol.E75-A, no.1, 1992.

[2] Peters, F.H., Peters, M.G., Young, D.B., Scott, J.W., Thibeault, B.J., Corzine, S.W. and Coldren, L.A., "High-power vertical cavity surface emitting lasers," *Electron. Lett.*, vol.29, pp.200–201, 1993.

[3] Numai, T., Kurihara, K., Ogura, I., Kosaka, H., Sugimoto, M. and Kasahara, K., "High electronic-optical conversion efficiency in a vertical-to-surface transmission electro-photonic device with a vertical cavity," *IEEE Photon. Tech. Lett.*, vol.5, pp.136–138, 1993.

[4] Wipiejewski, T., Panzlaff, K., Zeeb, E. and Ebeling, K.J., "Submilliamp vertical cavity laser diode structure with 2.2 nm continuous tuning," *Proc. European Conf. Opt. Commun.*, no.Th PD II.4, 1992.

[5] Baba, T., Yogo, Y., Suzuki, K., Koyama, F. and Iga, K., "First room temperature cw operation of GaInAsP/InP surface emitting laser," *IEICE Trans. Electron.*, vol.E76-C, no.9, pp.1423–1424, 1993.

[6] Baba, T., Yogo, Y., Suzuki, K., Koyama, F. and Iga, K., "Near room temperature continuous wave lasing characteristics of GaInAsP/InP surface-emitting laser," *Electron. Lett.*, vol.29, no.9, pp.913–914, 1993.

[7] Baba, T., Suzuki, K., Yogo, Y., Iga, K. and Koyama, F., "Threshold reduction of GaInAsP/InP circular buried heterostructure surface emitting laser by a single step PBH regrowth," *Electron. Lett.*, vol.29, no.4, pp.331–332, 1993.

[8] Baba, T., Yogo, Y., Suzuki, K., Koyama, F. and Iga, K., "Continuous wave GaInAsP/InP surface emitting laser with a thermally conductive MgO/Si multilayer mirror," *Jpn. J. Appl. Phys.*, vol.33, no.4A, pp.1905–1909, 1994.

[9] Iga, K., Oikawa, M., Misawa, S., Banno, J. and Kokubun, Y., "Stacked planar optics: an application of planar microlens," *Appl. Opt.*, vol.21, pp.3456–3460, 1982.

[10] Oikawa, M., Iga, K., Sanada, T., Yamamoto, N. and Nishizawa, K., "Array of distributed-index planar microlens prepared from ion exchange technique," *Jpn. J. Appl. Phys.*, vol.20, pp.L296–L298, 1981.

[11] Sasaki, A., Baba, T. and Iga, K., "Put-in micro-connector for alignment-free coupling of optical fiber array," *IEEE Photon. Technol. Lett.*, vol.4, no.8, pp.908–911, 1992.

[12] Konishi, H. and Iga, K., "Interconnect of semiconductor laser and optical fiber array using planar microlens and Si guide holes," *Trans. IEICE*, vol.J75-C-II, no.1, p.46, 1991.