Proton-implantation technique for high-power laser light

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An arrayed configuration with proton-implanted current apertures creates the potential for more reliable, higher-powered vertical-cavity surface-emitting lasers.

Vertical-cavity surface-emitting lasers (VCSELs) have recently become very attractive as high-power light sources. Their high output power makes them suitable for use in a wide range of optical applications, including materials processing, optical pumping, medical treatment, and sensing. VCSELs are not subject to catastrophic optical damage, which occurs when a semiconductor junction is overloaded by exceeding its power density and is a major limiting factor in the maximum achievable output power for edge-emitting lasers. The output power of VCSELs can also be increased using two-dimensional arrays. The reliability of VCSELs is increasingly important for high-power operation. While the selective-oxidation technique that is generally employed to form current apertures does provide optical confinement, reducing the energy lost by diffraction, it also introduces defects into the crystal.

A proton-implantation technique enables the formation of small current apertures that are free from crystal defects. Previously, the detailed characteristics of proton-implanted VCSELs have only been researched using output powers in the 10mW class because the implantation technique is unable to provide optical confinement, which makes high-efficiency operation of VCSELs with small current apertures challenging. However, the importance of optical confinement decreases as the size of the current aperture increases. Hence, proton-implanted VCSELs with large current apertures provide a possible route toward high-power operation.

To explore the possibility of efficient operation of proton-implanted VCSELs with large current apertures, we prepared a proton-implanted VCSEL with a current aperture of 100μm. Figure 1 shows a schematic diagram and a cross-sectional scanning electron microscopy image of the bottom-emitting type VCSEL with a proton-implanted current aperture. The proton-implanted region can be clearly observed due to the strong contrast in the image: see Figure 1(b). We fabricated
two devices: one with a single emitter, and another with seven hexagonally arrayed emitters with a spacing of 150μm.

Figure 2 shows the injection current and output power characteristics of the single-emitter device under continuous wave operation at 15°C. We achieved a maximum output power and a maximum slope efficiency of over 380mW and 0.96W/A, respectively. The output power density of the 100μm single emitter device was therefore estimated to be 4.9kW/cm². To the best of our knowledge, this value is higher than all previous reports on high-power single VCSELs, and confirms the efficient operation of proton-implanted VCSELs with large current apertures. Moreover, the output characteristics are superior compared to all other proton-implanted VCSELs.

Figure 3 shows current injection pulse and peak output power characteristics of the arrayed device at 20°C. The width and repetition frequency of the current injection pulse were 100ns and 10kHz, respectively, and the peak output powers were estimated from time-dependent and time-averaged output powers. We achieved a peak output power of 40.6W at the pulsed current of 50A. This is the first demonstration of 10W-class output power from a proton-implanted VCSEL. The previously reported maximum power density of oxide-confined VCSELs was 24.6kW/cm² with a pulse width of 60ns and a repetition frequency of 100Hz. Our fabricated device has an output power density three times greater, in spite of harder drive conditions.

In summary, we have developed high-power VCSELs using proton-implantation techniques and a large current aperture (100μm). Using an arrayed device under 100ns pulse operation at 20°C, a peak output power of 40.6W was achieved. The corresponding power density is estimated to be 73.8kW/cm², a value three times greater than the reported record for oxide-confined VCSELs. In the future, we hope to improve the thermal management and electrical properties of the device to further increase power and reliability.

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Continued on next page
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