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Single-mode vertical-cavity surface-emitting laser with ring-shaped light-emitting aperture

Jin-Wei Shi\textsuperscript{a)}\textsuperscript{,b} and C.-H. Jiang
Department of Electrical Engineering, National Central University, Taoyuan 320, Taiwan, Republic of China
K.-M. Chen
Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan, Republic of China and Institute of Physics, Academia Sinica, Taipei 115 Taiwan, Republic of China
J.-L. Yen and Ying-Jay Yang
Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan, Republic of China

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In this letter, we demonstrate a single-mode vertical-cavity surface-emitting laser (VCSEL) with a ring-shaped light-emitting aperture, which is realized by the Zn diffusion technique, at a wavelength of 850 nm. Relative to the control VCSEL with an ordinary circular aperture and the same geometry and size, the demonstrated device can suppress the higher-order transverse mode more effectively without affecting the threshold current and output power. Compared with typical reported single-mode VCSELs, a larger light-emitting aperture and current-confined area with a smaller divergence angle of the output beam, and lower differential resistance are achieved with the present structure. © 2005 American Institute of Physics. [DOI: 10.1063/1.1997282]

Vertical-cavity surface-emitting lasers (VCSELs)\textsuperscript{1} have attracted much attention due to their advantages, such as low-threshold current, two-dimensional (2D) array formation,\textsuperscript{2,3} and inexpensive device fabrication. High output power of several milli-watts with optical single-mode or single-lobed output with a low divergence angle of VCSEL is much desired for several applications, such as free space optical interconnects,\textsuperscript{4} laser printing, and airborne light detecting and ranging (LIDAR) systems.\textsuperscript{5} Increasing the diameter of the circular light-emitting aperture of a VCSEL is necessary to achieve a high output power with a low divergence angle performance. However, due to the relatively large transverse dimension, it will exhibit several spatial transverse modes and lase at multiple wavelengths.\textsuperscript{6} Several methods have been developed for VCSELs with single-mode output and high optical power, such as the anti-resonant reflecting optical waveguide structure,\textsuperscript{7} surface relief structure,\textsuperscript{8,9} and the combined application of implant and oxide apertures.\textsuperscript{10} However, in order to implement these structures, a complex regrowth process or precise control of the etching depth of the top mirrors is necessary. Furthermore, the divergence angles of the output optical beams from the reported single-mode VCSELs with single-lobed far-field distributions are usually very large (>10°) due to small emitting areas.\textsuperscript{7,8,10} A large divergence angle of the output optical beam will not only increase the difficulty in beam collimation and the coupling of optical power, which play important roles in the application of free-space optical interconnects, but also degrade the spatial resolution of the LIDAR system.

In this letter, we demonstrate a VCSEL structure with a ring-shaped light-emitting aperture,\textsuperscript{11} which can achieve single-mode performance through the use of larger current-confined area and optical apertures that are possible with the typical single-mode VCSELs, without utilizing complex etching and regrowth processes. With a top partially disordered mirror formed by means of selective Zn diffusion\textsuperscript{12,13} through the top distributed Bragg reflector (DBR) and an ion-implanted current-confined area, the demonstrated device can achieve single-mode performance under continuous wave (cw) operation with 2 mW output power. Under single-mode operation, this device also exhibits smaller divergence angles (−5° vs. −10°) of output beams and lower differential resistance (−70 Ω vs. −200 Ω) than typical single-mode VCSELs do due to relatively large emission apertures of our device.

In order to characterize the performance of this structure, two types of devices were fabricated. Figures 1(a) and 1(b) show top and cross-sectional views of these two devices, respectively. Both devices share the same epilayer structure, which consists of a heavily carbon doped p-type GaAs cap layer as well as a 20-pair p-type and 30-pair n-type Al\textsubscript{0.3}Ga\textsubscript{0.7}As/AlAs (DBR). Three GaAs/AlGaAs quantum wells are sandwiched and serve as the active region, which has a center wavelength at 850 nm. Ion-implantation technique was used to define the circular current-confined area with the same 17 μm diameter of both devices. As shown in

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{(a) Top views of devices A and B; (b) cross-sectional view of device B. Device A is a conventional broad-area VCSEL and device B is a VCSEL with a ring-shaped light-emitting aperture. The shaded regions indicate Zn-diffused areas.}
\end{figure}
Fig. 1(a), the only difference between A and B is that device B has a center circular optical lossy region formed by Zn diffusion.\textsuperscript{12,13} The Zn-diffused DBR region requires a larger threshold gain for lasing than the other regions due to its larger optical loss from the free-carrier absorption and the reflectivity reduction caused by disordering.\textsuperscript{12,13} The inside and outside diameters of the ring-shaped emitting area are 5 and 15 μm, respectively. We expect that the devices A and B will behave like a 2D and an annular one-dimensional (1D) VCSEL array, respectively. Every ~5 μm-diam emitting spot will be formed in a broad area VCSEL mainly due to the filament formation,\textsuperscript{6} which results in a 2D and 1D like VCSEL array in the devices A and B, respectively. Furthermore, the typical diameter of a light-emitting area of a single-mode VCSEL is around 5 μm;\textsuperscript{5,7} an annular single-mode 1D like VCSEL array with such mode size elements is thus expected to be formed in a 5-μm-wide ring cavity in device B. The ring cavity formed in the partially disordered mirror is designed to have single-mode elements with coherent coupling, which will result in a fundamental supermode emission. Although devices A and B have different near-field distributions\textsuperscript{11} due to the different shapes of their light-emitting apertures (circular plate versus ring), they should have almost the same theoretical far-field pattern with single-lobed distribution under the case of single-mode operation and the same outer diameter (15 μm) of their optical apertures.\textsuperscript{11} The detailed far-field calculated results of these two near-field distributions (circular plate versus ring) of VCSEL are reported in the previous work on a VCSEL with a ring-shaped microcavity.\textsuperscript{11}

The procedure used to fabricate these two devices can be described as follows. First a Si3N4 mask was formed through photolithography on the sample to define the ring shape. Then the masked sample with a Zn2As3 source was sealed in an evacuated quartz ampoule and heated to 650 °C for 15 min. This resulted in a Zn-diffused region with a diffusion depth (~1 μm) outside the Si3N4 masked area, which formed a higher-order mode absorber. After Zn diffusion, using a photore sist layer as a mask, we conducted ion implantation on the Zn-diffused sample to form a circular current-confined area. After that, a Ti/Au film with an opening window and Au/Ge/Ni film were deposited on the top and bottom of the sample to form a p- and n-type electrode.

Figure 2 shows the light output versus current (L-I) characteristics of the two fabricated devices operated at room temperature. The light output power was measured by a calibrated Newport silicon p-i-n photodetector. One can clearly see that both devices exhibited quite similar threshold current and L-I curves. Based on the measurement results, we can conclude that the optical absorption aperture in our demonstrated structure does not cause the optical power or threshold current performance to degrade significantly. We also measured the output optical spectrum of both devices under different current operation. Device B exhibited single-mode performance when the injected current was below 5 mA, which corresponded to 2 mW output power. A multimode spectrum was observed when the optical power exceeded 2 mW. On the other hand, device A exhibited very poor performance in terms of optical mode stability. It exhibited multi-mode behaviors when the injected current just exceeded the threshold (2.8 mA). The insets in Fig. 2 show the measured spectra of the two devices under the same operating current (~5 mA). The corresponding differential resistance of device B was about 70 Ω. Compared with the differential resistance (~200 Ω) of typical single-mode VCSELs,\textsuperscript{12,14} our structure exhibits a much lower differential resistance due to its larger current-confined area.

The measured far-field profiles in the x direction of both devices A and B under different operating currents are shown in Figs. 3(a) and 3(b), respectively. The measured far-field patterns exhibited quite similar shapes and divergence angles in both the x and y axes. Device B exhibited a single-lobed pattern with a narrow divergence angle defined by the full width at half maximum, even under multi-mode operation with optical power of 5.4 mW (8 mA injected current). As device A, its far-field pattern and divergence angle changed rapidly with the injected current. It started with a Gaussian-like single mode at the threshold current, and then progressed to higher-order modes with two main peaks as the injected current increased. This phenomenon is mainly attributed to the spatial hole burning effects\textsuperscript{15,16} in the cavity without mode confinement. Table I lists the measured divergence angles in the x and y directions of both devices at various drive-current levels. Device B exhibited much more stable single-lobed performance and a narrower divergence angle than device A did. The demonstrated single-lobed, high output power (5.4 mW) performance is comparable to the performance of a 2D array of VCSELs\textsuperscript{2,3,17} and of VCSELs with triangular hole structures in their DBR mirrors,\textsuperscript{6} which are
The measured divergence angles of devices A and B under different levels of injected current. The values in the “Average” column were calculated by averaging the measured divergence angles in the X and Y directions.

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Divergence angle of device A</th>
<th>Divergence angle of device B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X axis (deg)</td>
<td>Y axis (deg)</td>
</tr>
<tr>
<td>4</td>
<td>7.1</td>
<td>6.6</td>
</tr>
<tr>
<td>6</td>
<td>7.5</td>
<td>6.6</td>
</tr>
<tr>
<td>8</td>
<td>9.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

In conclusion, we have fabricated and investigated the characteristics of a VCSEL with a ring-shaped light-emitting aperture. The optical aperture and current-confined path of the demonstrated device were obtained using Zn diffusion and ion-implantation techniques, respectively. This newly designed structure is expected to exhibit single-mode output with higher power, a narrower divergence angle, and lower resistance than can be achieved with typical single-mode VCSELs due to relatively large optical apertures and the diameter of current-confined area of our device. The measured far-field patterns also reveal excellent single-lobed performance with high power and a low divergence angle, which are suitable for LIDAR and free-space optical interconnect applications.

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