Lowering the threshold current of photonic crystal vertical-cavity surface-emitting lasers

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Reducing the oxide aperture diameter to match the central defect region leads to high single-fundamental-mode output devices.

In recent years, photonic crystal vertical-cavity surface-emitting lasers (PhC-VCSELs) have attracted significant attention. Characteristics such as single-mode operation in a large cavity area (which results in high single-mode output power), high-speed modulation, and a small circular divergence angle of the output beam profile make them suitable for optical communications and sensing applications. In addition, they are easy to design and fabricate, and polarization-stable devices with single fundamental-mode operation have been fabricated. However, the abnormally high PhC-VCSEL threshold current has puzzled researchers. Reducing the threshold current is necessary to reduce power consumption and thermal losses, and improve the PhC-VCSEL devices’ stability and reliability.

We used theory and experiment to optimize the relation between the oxide aperture and light emission aperture of the PhC-VCSELs so that we obtained both high single-mode output and low threshold current (see Figure 1). We used the full 3D (FDTD) method to analyze the effect of the oxide aperture diameter on the optical characteristics. FDTD takes not just the oxide aperture diameter into account but the whole structure. We used cavity mode loss analysis to investigate the single-mode operation of the laser and find the minimum oxide aperture required to maintain the single-mode performance of the device with a low threshold current.

The simulation results shown in Figure 2(a and b) show that the oxide aperture diameters in an appropriate range determine the threshold current and also, for those devices with a 7μm light emission aperture diameter, affect the higher-order modes. The oxide aperture provides additional transverse confinement to the transverse mode and reduces higher modes more significantly than the light emission aperture does. The oxide aperture reduces modal discrimination, finally deteriorating single-mode operation. However, as the oxide aperture diameter increases, the high-order mode losses quickly increase because of scattering from photonic crystal air holes, while the fundamental mode loss remains low: see Figure 2(c and d). The oxide aperture needs to be much larger than the emission aperture to be able to isolate the photonic-crystal-induced index changes.

Figure 1. Schematic 3D view of the photonic crystal vertical-cavity surface-emitting laser (PhC-VCSEL) containing 22.5 pairs of p-type top distributed Bragg reflectors (DBRs) and 34.5 pairs of n-type bottom DBRs. Both consist of aluminum gallium arsenide (Al0.9Ga0.1As and Al0.12Ga0.88As, except for a 30nm Al0.95Ga0.05As oxidation layer inserted in the base of the DBRs.)

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from those of the oxidized layer, because the optical confinement is provided mainly by the photonic crystal structure. While the oxide aperture provides only the electrical confinement, the photonic crystal structure can confine the fundamental mode, dissipate the high mode, and operate the device in single mode.\textsuperscript{7,8}

Experiments show the power-current/current-voltage and far-field distribution characteristics of our fabricated PhC-VCSEL: see Figure 3(a). The maximum output power is 3.1mW at a record low-threshold current of 0.9mA. The slope efficiency and differential series resistance of the device are 0.247W/A and 57.23Ω, respectively: see Figure 3(b), which demonstrates the optical spectrum of the PhC-VCSEL. We can see that the full width at half maximum of the device is less than 0.1nm (restricted by the resolution of the optical spectrum analyzer), and the side-mode suppression ratio is 35dB, at maximum power. The vertical and horizontal direction divergence angles are less than 10$^\circ$ and one intensity peak, illustrating that we improved beam quality by introducing the photonic crystal on the top DBRs.$^7$

In conclusion, we demonstrated, both theoretically and experimentally, a useful and reliable way to reduce the threshold current of PhC-VCSELs by reducing the oxide aperture and optimally matching it with the emission aperture. The oxide aperture should be larger than the emission aperture of the photonic crystal structure by one air hole diameter (1µm) of the photonic crystal to keep the PhC-VCSELs operating in single mode and with low threshold current. We obtained PhC-VCSELs with single-fundamental-mode continuous wave 3.1mW output and threshold current of 0.9mA. We are now building on these promising results by controlling the etching depth and quality to further improve PhC-VCSEL characteristics.

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