

Few-mode vertical-cavity surface-emitting laser: Optional emission of transverse modes with different polarizations

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The vertical-cavity surface-emitting laser (VCSEL), a key component for a variety of applications,1–4 can intrinsically support multiple transverse modes through its large transverse dimension, which is usually an undesirable property in most applications. However, for some applications where laser sources are employed in the form of an array,5–8 such as optical fiber communications using multiplexing technologies, including mode division multiplexing (MDM)6–8 this unwanted feature could instead be beneficial.

MDM technology, in which information is selectively loaded on different spatial modes and transferred in a single-core few-mode fiber (FMF),9 is expected to solve the problem that the capacity of commercial single-mode-fiber-based optical networks is reaching its limit. Like other multiplexing technologies, MDM requires multiplexers (MUXs) to convert multiple signals from a VCSEL array into a single fiber. Therefore, to ensure applicability to MDM communication systems, it is meaningful and feasible to develop a new type of VCSEL with multiple individually controllable modes, which can remove the need for a VCSEL array and greatly simplify or even eliminate the need for MUXs. Further, the polarization dynamics of the VCSEL are closely associated with the transverse modes.10–12 so this type of VCSEL could also provide orthogonal fiber modes for MDM.

Various types of densely packed VCSEL arrays for high-speed communication have been fabricated. These arrays must have a small footprint for efficient fiber coupling. However, some of them13,14 are not compact enough to be coupled into FMFs without sophisticated coupling optics. Ultrahigh-density VCSEL arrays with pie-shaped elements15,16 have been fabricated, but in the design, only up to three mesas can be fitted into one fiber core. Photonic crystal and proton-implanted coherently coupled VCSEL arrays17 with satisfactory properties have been reported. However, the need for complex fabrication limits the yield and potentially results in a high fabrication cost. Similar-looking devices with deeply etched petals have been presented,18 but these devices focus on high-power single-mode output and are not suitable for MDM.

In this work, we present VCSELs with several emission-controllable transverse modes obtained by directly etching a few air gaps from the top. The upper mesa is separated into several submesas acting as waveguides, each of which is deposited with p-type contacts. Two types of few-mode VCSEL with three and four submesas are fabricated. Single-mode emission control of each submese is achieved under certain driving current scales. Furthermore, polarization-controllable emission is achieved owing to the transverse-mode-related polarization of a VCSEL. The few-mode VCSELs with several pie-shaped submesas in a circle can naturally emit different transverse modes together with different polarization directions.

The three-dimensional structures of our few-mode VCSELs are schematically illustrated in Fig. 1. For example, in the three-mode VCSEL, the upper mesa is divided into three
of the submesa with a 120°-opening-angle lasing region are depicted in Figs. 2(d)–2(f). Owing to the region’s symmetry, they are all x-polarized. In the 95° one shown in Figs. 2(f) and 2(h), the polarization directions of the fundamental modes are \( \pm 6.15^\circ \) off of the x-axis because the shape is set to be nonsymmetric. In fact, each eigenmode of a certain lasing region in Fig. 2 has two solutions, both of which have almost the same intensity distribution but orthogonal polarizations, and we show only one of them. However, we can still refer to the simulation results to achieve manipulation of both the transverse modes and polarization of a single VCSEL device by properly controlling the size of the oxide aperture and the direction of the trenches.

The current flow inside our device was also simulated, and the normalized current density distributions on the active layer under different injection conditions are shown in Fig. 3; they indicate that current crosstalk between submesas is small. The carrier density of the active regions under the unbiased submesas should be far sufficient to excite the laser, guaranteeing independent emission control of each p-contact.

The main fabrication process of the few-mode devices is the same as that of a normal VCSEL, except for an additional step of air gap etching by inductively coupled plasma. To control the shapes and sizes of the trenches more precisely, trench etching was performed in the first step. The depth of the trench is approximately 2.3 \( \mu \)m, whereas the oxide layer and active layer are 2.65 and 2.79 \( \mu \)m deep, respectively. Because the trench bottom is so close to the oxide layer, the width of the air gaps can be designed to be as narrow as 2 and 3 \( \mu \)m, whereas they got about 0.2 \( \mu \)m widened.

All measurements were performed under continuous-wave (CW) operation at room temperature. \( I_i \) (\( i = a, b, c, \) or d) indicates that only contact-\( i \) is biased. \( I_{ij} \) (\( i, j = a, b, c, \) or d, \( i \neq j \)) indicates that both contact-\( i \) and contact-\( j \) are biased, and so forth for \( I_{ijk} \) and \( I_{ijk} \). The measured near fields of the three-mode VCSEL are depicted in Fig. 4. The irregular profiles of the lasing regions and fluorescence from the trenches can be seen below threshold in Fig. 4(a). Although fluorescence from the trenches exists under all the types of injection, it is nearly invisible above threshold because neutral density filters with various extinction ratios were used to avoid saturation of the CCD camera by the laser. The near fields under \( I_a, I_b, \) and \( I_c \) injection are displayed in Figs. 4(b), 4(c), and 4(d), respectively. \( I_i \) injection successfully produced only mode \( M_i \) emission coinciding with the near fields under multicontact injection, which are shown in Figs. 4(e)–4(h). In summary, the three-mode VCSEL has seven types of operation: three types of single-mode operation, three types of two-mode operation, and one type of three-mode operation.

![Fig. 2. Mode analysis of various type of single lasing regions. (a) Infrared microscope image of the mesa after steam oxidation. Black areas are the oxide layer, and the three gray regions belong to the un-oxidized aperture. (b) Simulation geometry. The red pie-shaped area is the lasing region, the oxide layer, and the three gray regions belong to the un-oxidized aperture. (c) Annotation O, and the light purple region represents the high-loss area – (d)–(h) indicate the interface between the submesa and different sizes and shapes was performed. (d1)–(h1) Mode patterns of the total electric field \( E \).Intensity distribution of (d2)–(h2) the major polarization component \( E_x \) and (d3)–(h3) the minor polarization component \( E_y \). Lasing regions in (d), (e), and (f) are symmetric, whereas those in (g) and (h) are nonsymmetric. \( \varphi = \varphi + 90^\circ \). The white dashed lines in (d)–(h) indicate the interface between the submesa and air gap.](image)

lobes (submesas) by air trenches, and p-contacts are deposited above them. As mentioned in our previous work on the two-mode VCSEL, the air gaps provide extra current isolation and carrier-distribution guidance. Therefore, the trenches enable an inhomogeneous carrier distribution in the active region, where the laser can emit only if the carrier density is sufficient, because the optical modes in an oxide-confinued VCSEL are governed in part by the relationship between the optical field and carrier distribution. In addition, the air trench affords optical restriction. From the air gap \( r_{ex} \), only fluorescence is emitted because of the low reflectivity. Laser light is stimulated from lasing regions \( r_{ax}, r_{bx}, \) and \( r_{cx} \) when current is injected from the corresponding contact. These regions are located in the active layer, and their sizes and shapes are determined directly by the sizes and directions of the air trenches together with the oxide aperture. Because of the anisotropy of the oxidation speed of the oxide layer, the oxide aperture has an elliptical shape. Therefore, the pie-shaped lasing regions can be nonsymmetrical, as shown in Fig. 2(a).

To understand how the geometry of the lasing region affects the transverse mode, mode analysis of submesas with lasing regions of different sizes and shapes was performed using COMSOL Multiphysics. The first three eigenmodes
The polarization injection at each injection condition are summarized in Table I. Under single-contact injection, the main polarization directions of $M_a, M_b,$ and $M_c$ are $50^\circ,$ $-40^\circ,$ and $50^\circ,$ respectively. Because of the nonsymmetrical geometry, the polarization directions are neither along nor orthogonal to the angle bisector of the tip of $r_a$ and $r_b.$ The minor component of $M_a$ is relatively obvious, but its magnitude is still small compared to the major component, as shown in Fig. 5(a). Interestingly, it is the second-order mode [see Figs. 2(c) and 4(c)] rather than the fundamental mode that is the first excited mode of $r_a.$ As shown in Fig. 5(b), there are two peaks in the spectra of $M_b$ under $5 \text{ mA},$ but we can observe only the near field of the second-order mode, which is the major polarization component under full current scale. Further, only $I_c$ injection can achieve single-mode emission at full current scale, which is evident in Fig. 5(c). Therefore, every contact can be controlled to achieve single-mode, single-polarization emission at certain driving currents. Under multicontact injection, the polarizations of some transverse modes shifted. $I_{ab}$ injection was unstable, as the major polarization of $M_b$ switched between $50^\circ$ and $-40^\circ$ from time to time, whereas $M_a$ had stable polarization at $50^\circ.$ Under $I_{bc}$ injection, $M_a$ switched to stable polarization at $-40^\circ;$ and $M_b$ remained polarized at $50^\circ.$ Under $I_{bc}$ injection, both $M_b$ and $M_c$ were polarized at $50^\circ.$ $I_{ac}$ injection resulted in emission with two controllable orthogonal polarizations.

The CW $L$–$I$–$V$ characteristics of the three-mode VCSEL are shown in Fig. 6. When laser modes propagate from the active layer to the output window, they suffer from scattering loss from the air trenches. Modes excited from lasing regions with a larger aspect ratio have a higher field intensity at the edges, resulting in more loss. However, the larger size can help complement the power. This behavior explains the differences among the power curves of $r_a, r_b,$ and $r_c.$

In agreement with our expectation, mode control of a four-mode VCSEL was also achieved, as shown in Fig. 7. By investigating the spectra under single-contact injection, we demonstrated single-mode emission from three submesas. Submesas a and b can maintain single-mode operation at full current scale, as shown in Figs. 7(a) and 7(b). From Fig. 7(c), we see that single-mode operation remained until the driving current reached $4.5 \text{ mA}$ for submesa c. The largest region, submesa d, exhibited two-mode emission at full scale, as illustrated in Figs. 7(d) and 7(h), implying that the direction of the air gaps can be modified. The peak of $M_b'$ for $M_d$ is higher than the $M_d$ values in the spectrum owing to differences in the coupling efficiency of different transverse modes; that is, the fundamental mode has better coupling than higher-order modes. The near fields and the corresponding polarizations are displayed in Figs. 7(e)–7(h). Independent control of three polarizations in a single device was realized, and two of the polarization directions are orthogonal. Although it is not demonstrated, the four-mode VCSEL can operate under 15 injection conditions, that is, in 15

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**Table I.** Major polarization angle under different types of injection.

| $I_a$ | $I_b$ | $I_c$ |
|---|---|---|
| $50^\circ$ | $M_a$: $50^\circ$, $M_b$: $50^\circ$ or $-40^\circ$, $M_c$: $50^\circ$ |
| $-40^\circ$ | $M_a$, $M_c$: $50^\circ$ |
| $-40^\circ$ | $M_a$, $M_c$: $50^\circ$ |
| $50^\circ$ | $M_a$, $M_c$: $50^\circ$ |

Fig. 4. Near fields of a three-mode VCSEL. (a) Near-field pattern below threshold, where lasing regions can be observed and are enclosed in dashed lines. (b)–(d) Near fields under $I_a, I_b,$ and $I_c$ injection, respectively. The arrows show the polarization directions of $M_a.$ (e)–(h) Near-field profiles under $I_{ab}, I_{bc},$ and $I_{ac}$ injection, respectively.

Fig. 5. Spectra of three-mode VCSEL under single-contact injection. (a) Spectra under $I_a$ injection from 5 to $7 \text{ mA}.$ Insets show the fundamental mode and a high-order mode. (b) Spectra under $I_b$ injection from 2 to $5 \text{ mA}.$ (c) Spectra under $I_c$ injection from 3 to $6 \text{ mA}.$

Fig. 6. CW $L$–$I$–$V$ performance of three-mode VCSEL.
transverse mode combinations. Finally, the $L$–$I$–$V$ curves are shown in Fig. 8, from which we can also differentiate the lasing regions by their geometries. Improved single-mode power compared to the three-mode device was achieved.

In summary, VCSELs with several independent contacts that can control the emission of certain transverse modes and different polarizations independently were demonstrated.

The shape and direction of each lasing region were proven to have a decisive impact on the transverse mode formation and polarization direction. The functionality of current guidance and optical field restriction of the air gap enable the independent emission control. Near-field profiles and spectra under single-contact injection and multicontact injection indicated that the emission status of the few-mode VCSEL can be manipulated by simply shifting the biased contact, and the VCSEL can be switched from single-mode operation to few-mode operation. We believe that our few-mode VCSEL prototype will contribute to future optical communication systems.

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