Shenzhen 518055, China
e-mail: huanglq@sz.tsinghua.edu.cn
†School of Life Sciences, University of Science & Technology of China, Hefei 230027, China
‡The National Orchid Conservation Center, Shenzhen 518114, China
§College of Forestry, South China Agricultural University, Guangzhou 510642, China

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PHOTONICS

Lasers producing tailored beams

Compact lasers that can produce a range of beam patterns are important for progress in several areas, including the improvement of optical tweezers[1], ultra-high-density optical memory[2] and microfluidics[3]. Here we engineer photonic crystals to generate semiconductor lasers that produce a range of beam patterns while maintaining stable single-mode oscillation. Our results could contribute to the realization of compact lasers that are capable of producing diverse beam patterns on demand.

The beam (far-field) pattern emitted by a semiconductor laser is determined by the Fourier transformation of the electromagnetic field distribution in its output plane. It is therefore important to find a method of controlling the electromagnetic field while maintaining stable single-mode oscillation. An array of vertical-cavity surface-emitting lasers has been investigated[4], but without achieving stable and flexible control of the field distribution. The use of a band-edge effect in two-dimensional photonic crystals[5–8], in which the refractive index is changed periodically, is a promising way to get this control. The group velocity of light becomes zero at the band edge, which gives rise to the formation of a large and stable two-dimensional single-cavity mode, and the output beam is emitted in the direction normal to the crystal plane, using the crystal itself as a diffraction grating.

We therefore developed photonic-crystal lasers based on the band-edge effect by engineering lattice points[7] and/or lattice phases[9,10] in the crystal structure in order to control the internal field distribution (see supplementary information). Scanning electron micrographs of the fabricated photonic crystals are shown in Fig. 1 (a–f, left panels). The engineered photonic-crystal lasers all display stable single-mode oscillation at room temperature; the maximum output power exceeds 45 mW under continuous-wave conditions.

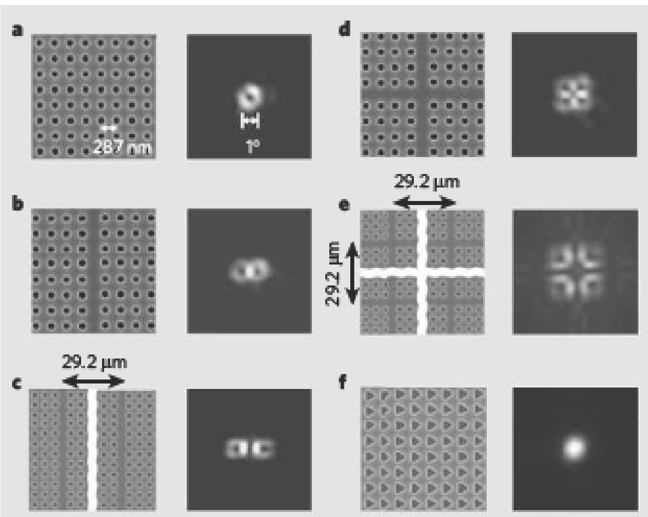

Figure 1 | A range of beam patterns produced by photonic-crystal lasers with engineered lattice points and/or lattice phases. a–f, Scanning electron micrographs of crystal structures (left panels) and observed beam patterns (right panels) for circular lattice points with no lattice shifts, with one shift, with parallel double shifts, with crossed shifts and with double-crossed shifts, and for triangular lattice points with no shifts, respectively. Details, including those of the device structure and of beam-pattern control, are explained in supplementary information.

The surface-emitted beams had a variety of shapes, including single, twin and quadruplet doughnuts, either separated or touching, and circular single-lobed forms (Fig. 1, right panels). Divergence angles of these beams were less than 2°, reflecting the large area (about 50 × 50 μm^2) of coherent oscillation. An even larger area of coherent oscillation can be achieved by adjusting the distance between the photonic crystal and the active layer in the device's structure (see supplementary information).

The mechanisms by which the individual beam types are produced can be explained qualitatively. The beam patterns reflect the field distribution within one unit cell of the crystal lattice. Circular lattice points give rise to a rotationally symmetrical field distribution (see supplementary information). Interference in the far field produces a doughnut-shaped beam (Fig. 1a), which can have either tangential or radial polarization (see supplementary information). Shifts of the crystal lattice by half of the lattice constant produce phase shifts in the field distributions: the resultant far-field interactions are reversed, leading to the formation of various types of doughnut beam (Fig. 1b–e, and see supplementary information).

When the structure of the lattice points is modified, the field distribution within one unit cell is altered: for example, with triangular lattice points, destructive interference in the far field does not occur in the x-direction, which reflects the asymmetry around the lattice point in this direction; as a result, a circular single-lobed beam can be obtained (Fig. 1f, and see supplementary information).

Further engineering of the photonic crystal structures described here should allow novel beams to be generated. This will define a new direction for semiconductor lasers and could lead to the realization of compact lasers with on-demand beam characteristics.

Eiji Miyai*, Kyosuke Sakai*, Takayuki Okano*, Wataru Kunishi*†, Dai Ohnishi*†, Susumu Noda*
*Department of Electronic Science and Engineering, Kyoto University, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto 615-8510, Japan
e-mail: snoda@kuee.kyoto-u.ac.jp
†Optical Device Research and Development Center, ROHM, 21 Mizosaki-cho, Saiin, Ukyo-ku, Kyoto 615-8585, Japan

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