Subject category:

Microphotonics

Title:

An out-of-plane experience

Standfirst:

Using clever device engineering, European researchers have created vertically-emitting microcavity lasers. The work could pave the way towards powerful THz sources and detectors useful for imaging and biological sensing.

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Main text:

One of the aims of the emerging field of microphotonics is to use advanced fabrication technology to create structures that provide tremendous control over the electromagnetic field[1]. Storing light for millions of optical cycles, confining it tightly to generate a large field intensity, and tailoring its dispersion are among the topics researchers have investigated. On page XXX of this issue[2], Mahler and co-workers show how such device engineering can be used to create vertically-emitting microcavity lasers, with possible applications for detection and imaging in the terahertz-frequency domain. In particular, they demonstrate this in a geometry and gain medium for which achieving out-of-plane emission is inherently challenging, but potentially quite valuable.

Put simply, a laser consists of two main parts: a gain medium that converts an external energy source into light emission, and an optical resonator that houses this gain medium and provides feedback for the emitted light. Most semiconductor lasers use a Fabry-Perot resonator, where end mirrors are created by cleaving facets into the laser material. Alternatively, microcavity geometries produced with planar fabrication techniques open up a number of exciting possibilities, both in the aforementioned control of the electromagnetic field within a single device, and also in opportunities for on-chip integration and creation of dense device arrays. The microdisk (Fig. 1a,b) is a geometry that has generated sustained interest since its use in semiconductor lasers in the early 1990s[3]. It supports whispering gallery modes (WGMs), where light circulates around its periphery (Fig. 1c) and is confined by total internal reflection at the curved interface formed between the disk and its surrounding. Provided that the disk diameter is sufficiently large compared to the wavelength of light propagating within it, WGMs suffer little optical loss from tunnelling of light outside the disk – loss in real-life experimental devices is instead usually dominated by fabrication-induced surface roughness or absorption. Moreover, the size requirement is not overly restrictive, with high quality factors (a measure of the optical loss) having been achieved in wavelength-scale structures[4].

However, one consequence of this azimuthally-symmetric geometry is that emitted light has no preferred direction within the plane of the microdisk. While better in-plane directionality has been achieved by coupling to a waveguide[5], modifying the geometry through etched gratings[6] and deforming the disk circularity[7], preferential vertical emission has seen less progress. Out-of-plane emission can be a defining characteristic for applications in chemical sensing and biomedical imaging, where the mid- and far-infrared regions of the spectrum are of particular importance. At these wavelengths (3-150 μm), quantum cascade lasers (QCLs) have assumed a leading role as a compact, semiconductor source of coherent radiation[8]. The creation of vertically-emitting microdisk QCLs is a technologically exciting step towards developing individually addressable, electrically-injected laser arrays for sensing applications.

In this issue, Mahler *et al.* produce their vertically-emitting microcavity lasers using a GaAs/AlGaAs quantum cascade heterostructure that emits light at a wavelength of 93.75 μm (a frequency of 3.2 THz). With a diameter of 180 μm and a thickness of 10 μm, they are wavelength-scale devices supporting a small number of optical modes, which can be classified according to their polarization and the number of radial and azimuthal lobes. To achieve vertical light emission, the authors fabricate a metallic grating on the top surface of the disk, along its periphery (Fig. 2). Surface emission is achieved through second order Bragg diffraction, where the grating mediates coupling to small wavevector components that radiate vertically. This grating breaks the azimuthal symmetry of the structure, producing non-degenerate pairs of modes whose electric field maxima are inside/outside the slit. The quality factors of the modes whose maxima lie inside the slit (designated as 'E' modes) are much higher, which means that these modes are excited above threshold. In a linear device such as a ridge waveguide, 'E' modes do not radiate light efficiently, since the alternating sign of the magnetic field on either side of the slits results in destructive interference in the far-field. In contrast, the curved nature of the disk used here means that the alternating sign of the magnetic field across the slits produces a net azimuthal magnetic field, which does lead to efficient vertical emission.

However, we are not finished yet, as further engineering is needed to improve the device performance, in particular the characteristics of the vertically emitted radiation pattern. If quality factor alone determined the lasing condition, 'E' modes with a single radial lobe would oscillate, which would be advantageous due to their relatively narrow far-field distribution. However, in the authors' initial devices, higher order modes with multiple radial lobes (and an accordingly more distributed emission pattern) lase, as they benefit from more uniform current injection and their quality factors are only slightly lower.

To favour the fundamental (single-lobe) mode, therefore, the authors do two things. First, they introduce a top ring contact (Fig. 2b), which reduces the pumping efficiency inside the device. Second, they change the number of grating periods so that the higher-order radial modes are no longer rotationally symmetric with respect to the grating, which degrades their quality factor. As a result of this engineering, the optimized devices exhibit a collected output power exceeding that of a grating-less microdisk by nearly two orders of magnitude.

The lasers devised by Devices in this work operate below 100 K. However, as with other THz QCLs, operation at higher temperatures is a goal for many applications. Moreover, optimization of the device geometry could produce additional increases in the collection efficiency. Regardless, this work represents an important advance in producing efficient, vertically-emitting lasers. The inter-subband transitions (i.e., transitions within the semiconductor conduction band) that create gain in quantum cascade structures are polarized with the electric field out-of-plane (called TM, or 'transverse magnetic' polarization). This means that light emission is primarily in-plane, which prevents the realization of the vertical cavity surface-emitting geometries often used in conventional lasers based on interband transitions (i.e., transitions between the conduction and valence bands). Methods to produce vertical emission therefore assume a particular significance within the context of QCLs.

In 2003, researchers produced microcavity QCLs with vertical emission using deeply-etched two-dimensional photonic crystals[9]. These 2D photonic crystals support low group velocity modes, which provide both the necessary feedback for lasing and also diffract light vertically. While 2D PCs can offer advantages in terms of the level of control over the electromagnetic field and the potential for intracavity integration with fluids and gases, the modified microdisks of Mahler *et al.* have their own advantages - specifically the ease of device fabrication and the more efficient current injection. Furthermore, the absence of a complete in-plane band gap for TM-polarized modes can ultimately limit the quality factors achievable in 2D PCs, while TM-polarized microdisks can be designed so that unwanted radiation is minimized and absorption and surface roughness are the only limitations.

Beyond the world of QCLs, efficient vertical emission can be beneficial for a number of microcavity-based applications[10], such as visible and near-infrared single photon sources**.** Operation at shorter wavelengths will be accompanied by fabrication challenges and, perhaps most importantly, absorption loss in metals will become a far more significant factor. Although addressing these challenges will require additional innovations, the design and methodology used in this work will likely serve as a valuable resource.

References

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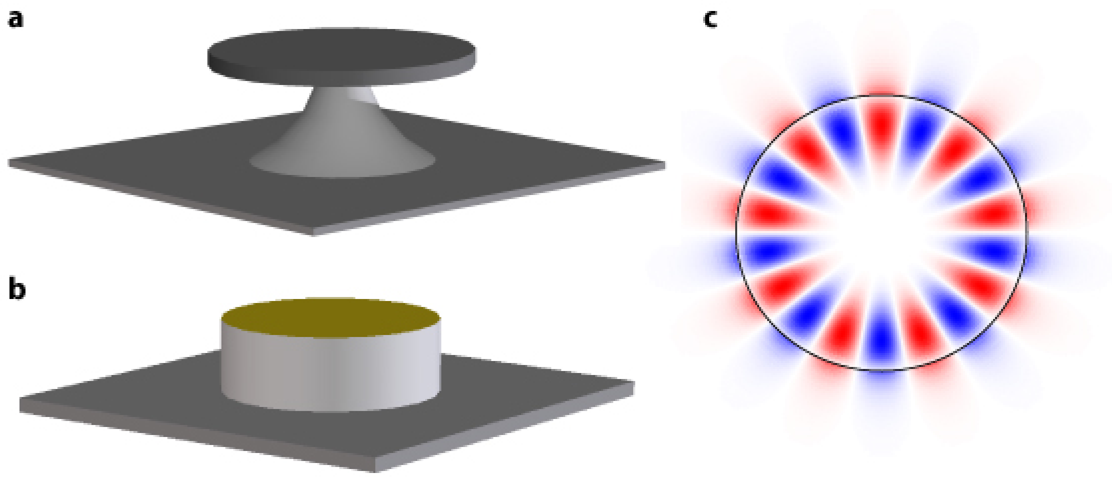

Figure 1. Microdisk cavities for typical (**a)** interband and (**b**) intersubband devices. Vertical confinement is provided by the surrounding air cladding in (**a**), while metal and/or highly-doped top and bottom layers are used in (**b**) to generate a double surface plasmon mode. (**c**) Top view of the electric field distribution for a microdisk WGM.

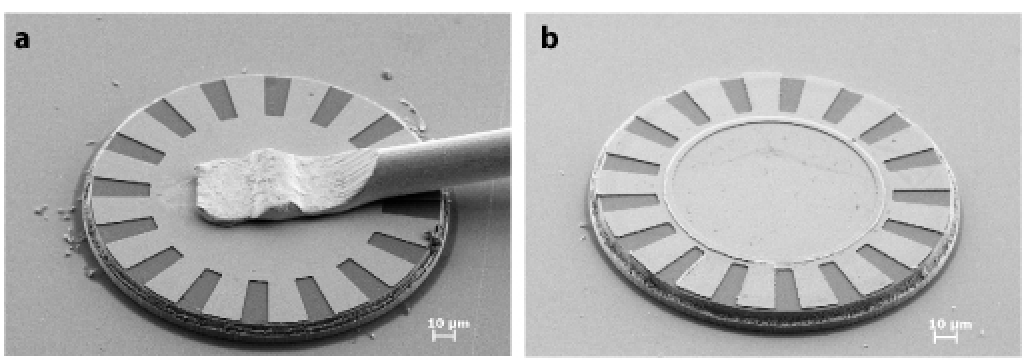

Figure 2. Scanning electron microscope images of the vertically-emitting microdisk lasers created by Mahler *et al.*[2]. The device in (**b**) has been optimized for lasing from the cavity's fundamental radial mode.

<u>**FOR ART EDITORS:**</u>

FIGURE 1A-C IS ORIGINAL ARTWORK FROM THE AUTHOR.

FIGURE 2A IS FIG 1A FROM THE MANUSCRIPT.

FIGURE 2B IS FIG 3C FROM THE MANUSCRIPT.