Photonic Crystal THz Lasers with Controllable Surface Emission Patterns

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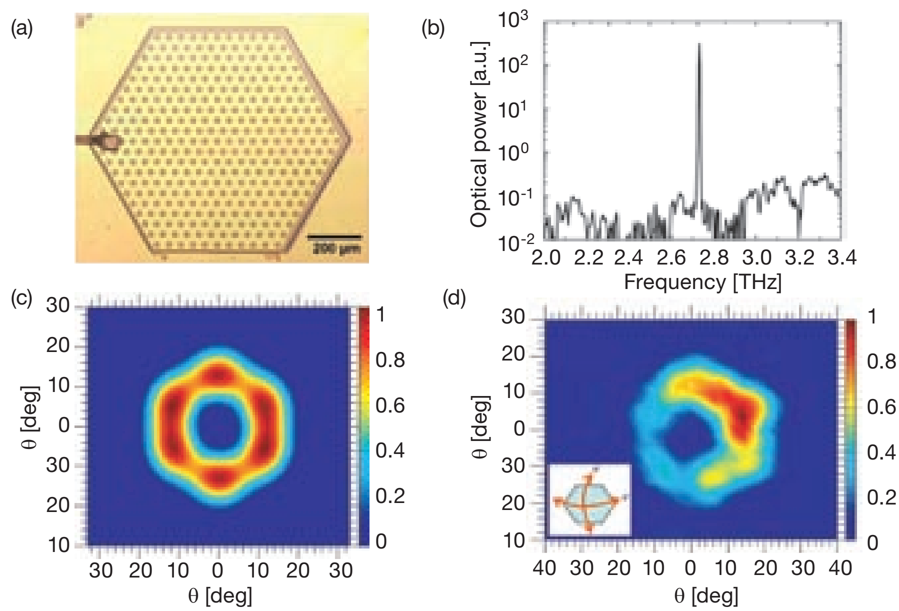
Semiconductor lasers based on two-dimensional photonic crystals generally rely on an optically pumped central area surrounded by unpumped and absorbing regions. This ideal configuration is lost when photonic-crystal lasers are electrically pumped—which is practically attractive since an external laser source is not required. In this case, the device area must be physically defined by semiconductor processing. This creates an abrupt change in the dielectric constant at the device boundaries, especially for lasers operating in the far-infrared, where the large wavelengths impose device thicknesses of several microns.

Such abrupt boundary conditions can dramatically influence the operation of electrically pumped photonic-crystal lasers. We have demonstrated a general technique to implement absorbing boundaries, which proves crucial to the excitation of proper photonic-crystal states.[1]

We fabricated photonic-crystal terahertz (THz) semiconductor lasers, where the photonic crystal is simply "written" in the device top metallization.[2] Single-mode laser action is obtained in the 2.55-2.88 THz range and is tunable with photonic lattice spacing. The emission far field exhibits a reduced angular divergence, thus providing a solution for the quasi-total lack of directionality typical of THz semiconductor lasers based on metal–metal waveguides.[3] The active laser materials used are GaAs/AlGaAs quantum cascade (QC) lasers.

Two-dimensional photonic-crystal lasers are classified as either defect mode or band-edge-mode lasers. The former operate at frequencies inside the bandgap by introducing a defect that supports localized modes. Band-edge mode lasers operate in regions of energy–momentum space that have a high photonic density of states. We implemented the latter device architecture to take advantage of the connected nature of the lattice, which greatly simplifies the processing. Furthermore, the spatial delocalization of band-edge modes allows for improved power extraction.



(a) Optical microscope image of the surface of a typical device. (b) Single-mode spectrum of photonic-crystal device (T=10K). Sidemode suppression ratio is at least 30 dB. (c) Calculated far-field profile for the hexapole mode. (d) Experimental far-field pattern for device operating on the hexapole mode. Measurement performed at 78 K by scanning a Golay cell detector at a constant distance from laser. Agreement with theory is good: The mode symmetry and angular values are correctly reproduced, although experimental far-field exhibits an asymmetric intensity. (Inset) The definition of the angles θ and φ.

We then demonstrated a framework to understand and predict far-field emission in THz photonic-crystal QC lasers.[4] We identified photonic-crystal band-edge states involved in the lasing process (hexapole and monopole modes at the Γ point of the photonic band structure, as designed). The theoretical far-field patterns, obtained via finite-difference time-domain simulations, are in very good agreement with experiment.

By using high-performance THz QC lasers, we obtained a maximum operating temperature of 136 K in pulsed mode for these lasers, as well as 7 mW peak output at 10K. This proves that the addition of new functionalities via photonic engineering comes at little detriment to the overall device performance, which could be further increased by optimizing the photonic-crystal resonators, in particlar the quality factor. This demonstration represents an important step in the development of photonic-crystal micro-cavity lasers for practical applications. ▲

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