Optimized surface-emitting photonic-crystal terahertz quantum cascade lasers with reduced resonator dimensions

Gregoire Sevin,1 Daivid Fowler,1 Gangyi Xu,1 Francois H. Julien,1 Raffaele Colombelli,1,a Suraj P. Khanna,2 Edmund H. Linfield,2 and A. Giles Davies2

1Institut d’Electronique Fondamentale, Univ. Paris Sud, UMR8622 CNRS, 91405 Orsay, France
2School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

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Terahertz frequency photonic-crystal quantum cascade lasers allow directional and controllable surface emission while at the same time functioning efficiently well above liquid nitrogen temperature. Through an in-depth understanding of the mechanism underlying surface emission, we demonstrate optimized devices with significantly reduced absolute threshold currents. We are able to reduce the device surface area by more than a factor of two, while maintaining angularly narrow, single-lobed surface emission with a divergence of \( \approx 10^\circ \times 10^\circ \). The devices emit at \( \sim 2.8–2.9 \) THz, with maximum operating temperatures in the range 80–150 K.

The GaAs/AlGaAs QC laser structure (wafer L207) used in this work has an emission frequency of \( \approx 2.7 \) THz. For details of the heterostructure growth and design, see Ref. 8. The device area in PhC QC lasers scales in proportion to the square of the number of PhC periods but the area required for wire bonding remains constant, as does the absorbing edge width. These constraints limit the extent to which the miniaturization of devices is possible. We designed and fabricated a series of small PhC THz QC lasers (12-, ten-, and eight-period, with device sizes 390 \( \mu m \times 390 \mu m \), 324 \( \mu m \times 324 \mu m \), and 260 \( \mu m \times 260 \mu m \), respectively). Three different bonding schemes [Figs. 1(a)–1(d)] were then tested. One obvious solution for miniaturization is to employ only one pad for wire bonding, as shown in Figs. 1(a) and 1(b). Figure 1(a), in fact, shows a 12-period PhC cavity, similar—although smaller and with only one bonding pad—to those developed in Ref. 10. However, a single bond-

Terahertz (THz) frequency quantum cascade (QC) lasers have become an extremely promising semiconductor laser source for the 1.2–5 THz frequency range (\( \lambda = 250–60 \mu m \)). Target applications include astronomy, biosensing/imaging and spectroscopy, inter alia. In this context, research is being focused not only on increasing the maximum operating temperature, \( T_{\text{max}} \), but also on “beam-shaping”\(^{3,4} \) since the extreme light confinement typical of THz resonators generally yields highly nondirectional emission patterns.\(^{3} \) Possible solutions include the use of horn-antennas,\(^{4} \) second and third-order distributed feedback gratings,\(^{5,6} \) and photonic-crystal (PhC) structures.\(^{7–9} \) The single frequency surface emission characteristics of PhC devices are particularly attractive, as they offer the prospect of implementation in arrays of high brilliance sources for Fourier-transform infrared spectroscopy.

We have shown in Ref. 7 that the operation of PhC THz QC lasers is critically dependent on the absorbing boundary conditions, which can be experimentally implemented at the edges of the PhC resonators using the highly absorbing, doped semiconductor top contact layers (absorbing edges). Furthermore, the resonator in-plane quality factor (\( Q_p \)), and thus the performance of PhC THz QC lasers, can be enhanced by grading the hole-radius across the lattice.\(^{10,11} \) Combining this technique with the introduction of a \( \pi \) phase-shift in the PhC structure leads to single-lobed surface emission.\(^{12,13} \) For example, the devices demonstrated in Ref. 10 had 14 and 18 PhC periods, were 454 \( \mu m \) and 584 \( \mu m \) wide, respectively, and led to single-lobed surface emission with a divergence of just \( \approx 12^\circ \times 8^\circ \).

In this paper, we show that we can reduce further the device surface area, by more than a factor of two, by implementing an optimized PhC resonator design. We are able to reduce the absolute threshold current, while maintaining highly directional emission. Furthermore, we demonstrate explicitly that the electromagnetic near-field in the central part of the device is not associated with the surface emission process, enabling this redundant region to be used for wire bonding, leading to a further size reduction.

\(^{a}\)Electronic mail: raffaele.colombelli@u-psud.fr.

FIG. 1. (Color online) Images of typical devices (top view). The PhC period is 32.4 \( \mu m \), the hole radius is graded to improve the in-plane Q-factor (\( Q_p \)), and a \( \pi \) phase-shift is included. Areas assigned for wire-bonding are enclosed within dashed lines. (a) 12-period PhC with one bonding pad placed in the device corner, (b) ten-period PhC with one bonding pad placed on the device side, (c) 12-period PhC with central bonding pad, and (d) ten-period PhC with central bonding pad, and an actual wire-bond shown.

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period 

features which do not have

for each device. Results are also shown, for comparison, from PhC struc-

tures measured from such devices are more angularly diver-

ing pad reduces the device symmetry. Far-field emission pat-

terns demonstrated that the lowest measured $I_{th}$ is $1.35$ A at

78 K, for the ten-period device. This is a significant improve-

ment on previous, larger device designs which had $I_{th} =

2.4$ A (3.7 A), for 14-(18)-period devices. All lasers ex-

hibit single frequency emission [Fig. 2(a), inset], which con-

firms that the PhC resonator mode is correctly selected.

The absolute current threshold ($I_{th}$) scales well with the

device surface area as demonstrated in Fig. 2(b) where the
data in Fig. 2(a) is replotted in terms of current density for
ten and 12 period PhCs. The $V$-$J$ curves superpose almost
perfectly, suggesting that current dispersion problems are in-

significant. The $L$-$J$ characteristics provide qualitative

information on the relative device $Q_{th}$ as $J_{th}$ is inversely propor-
tional to the total $Q$-factor. Assuming that the material $Q$-factor is the same for all structures, and the radiative

$Q$-factor is negligible, a higher $J_{th}$ corresponds to a lower $Q_{th}$.

In qualitative agreement with simulations, Fig. 2(b) shows

that the $J_{th}$ increases slightly when the size is reduced. This
demonstrates that the lowest size for a THz PhC QC laser is

limited by the $Q_{th}$-factor, which decreases with reduction in

size. $J_{th}$ is plotted as a function of heat-sink temperature in

Fig. 2(c) for several devices with different dimensions. To

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bonding pad [Figs. 3(e) and 3(f)], avoids degradation of the far-field pattern with device size reduction. Almost ideal, single-lobed angularly-narrow emission patterns are obtained, in very good agreement with the numerical finite difference time domain (FDTD) far-field simulations of PhC devices which include a central π-shift, as described in Refs. 8 and 10. Remarkably, in this improved design the emission pattern is affected only slightly by the device size. There is, therefore, no direct connection between the $Q_i$ optimization/$I_{th}$ reduction and the far field quality. In contrast, it is clear that the conventional ten-period and 12-period PhC devices exhibit far-fields with abnormally strong lateral lobes [Figs. 3(a)–3(d)], possibly a result of the presence of only one bonding pad.

The angular divergence of devices with a central bonding pad is narrow, with an approximate full width at half maximum of $10^\circ \times 10^\circ$. Directivity, $D$, can be used as figure of merit,$^{10,14}$ defined as $D = 10 \log_{10}(2 \pi I_{\text{peak}} / I_{\text{total}})$, where $I_{\text{peak}}$ is the peak intensity (in watts per steradian) in the far-field, and $I_{\text{total}}$ is the total emission power (in Watts) into half space. We obtain $D \approx 19–20$ dB for both the 12-period and the ten-period lasers with a central bonding pad. This value is slightly higher than that reported in Ref. 10 (16 dB) for larger devices but most importantly, it does not degrade with reduction in the surface area.

The counterintuitive result that the central bonding pad does not perturb the emission pattern can be explained by analyzing the near-field emission of the device. These devices operate on monopolar modes at the light cone, which do not contribute to surface radiation. Calculations were undertaken using two-dimensional FDTD simulations—as in Ref.8—followed by MATLAB postprocessing. The negligible contribution of the central part of the PhC resonator [Fig. 4(c)] explains why the device architecture presented in this paper works so efficiently. Removing the central holes does not change the distribution of the slow components [Fig. 4(d)], and thus the central wire bonding can be applied without affecting the far-field distribution.

In summary, we have demonstrated optimized surface-emitting THz PhC QC lasers with both a reduced device surface area, and a reduced threshold current. The resulting emission patterns show a high directivity, which does not decrease with reduced device dimensions.