Whispering-gallery mode resonators for highly unidirectional laser action

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Published Version</td>
<td>doi:10.1073/pnas.1015386107</td>
</tr>
<tr>
<td>Citable link</td>
<td><a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:29074723">http://nrs.harvard.edu/urn-3:HUL.InstRepos:29074723</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA">http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA</a></td>
</tr>
</tbody>
</table>
Optical microcavities can be designed to take advantage of total internal reflection, which results in resonators supporting whispering-gallery modes (WGMs) with a high-quality factor (Q factor). One of the crucial problems of these devices for practical applications such as designing microcavity lasers, however, is that their emission is nondirectional due to their radial symmetry, in addition to their inefficient power output coupling. Here we report the design of elliptical resonators with a wavelength-size notch at the boundary, which support in-plane highly unidirectional laser emission from WGMs. The notch acts as a small scatterer such that the Q factor of the WGMs is still very high. Using midinfrared emission from WGMs, the notch acts as a small scatterer such that the Q factor of the WGMs is still very high. Using midinfrared emission from WGMs, the notch acts as a small scatterer such that the Q factor of the WGMs is still very high.

Whispering-gallery mode resonators for highly unidirectional laser action

Qi Jie Wang¹,², Changling Yan¹,³, Nanfang Yu¹, Julia Unterhinninghofen³, Jan Wiersig⁴, Christian Pflügl⁵, Laurent Diehl⁶, Tadataka Edamura⁷, Masamichi Yamanishi⁸, Hirofumi Kan⁹, and Federico Capasso⁴,¹⁰

School of Engineering and Applied Sciences, Harvard University, 9 Oxford Street, Cambridge, MA 02138; Instituto de Theoretische Physik, Universität Magdeburg, Postfach 4120, D-39016 Magdeburg, Germany; and Central Research Laboratory, Hamamatsu Photonics K.K., Hamamatsu 434-8601, Japan

Contributed by Federico Capasso, October 21, 2010 (sent for review August 1, 2010)

Optical microcavities can be designed to take advantage of total internal reflection, which results in resonators supporting whispering-gallery modes (WGMs) with a high-quality factor (Q factor). One of the crucial problems of these devices for practical applications such as designing microcavity lasers, however, is that their emission is nondirectional due to their radial symmetry, in addition to their inefficient power output coupling. Here we report the design of elliptical resonators with a wavelength-size notch at the boundary, which support in-plane highly unidirectional laser emission from WGMs. The notch acts as a small scatterer such that the Q factor of the WGMs is still very high. Using midinfrared emission from WGMs, the notch acts as a small scatterer such that the Q factor of the WGMs is still very high. Using midinfrared emission from WGMs, the notch acts as a small scatterer such that the Q factor of the WGMs is still very high.

Results and Discussion

We chose an elliptical resonator because it possesses WGMs with very high Q factors (29) for shapes with various long-to-short aspect ratio Y/X. A notch of size comparable to the wavelength in the material, suitably defined on the boundary, will diffract light toward the opposite boundary. Fig. 1A illustrates how the aspect ratio Y/X of the elliptical resonator (blue curve) was optimized to achieve maximum collimation. The notch is located at the intersection of the short axis and the boundary (point O). In order to achieve collimation of the majority of the light scattered by the notch, we exploit a well-known property of the ellipse: For any given refractive index n > 1, one can find an ellipse (auxiliary ellipse) such that all incoming parallel rays are collected into one of its foci (30); conversely in the reciprocal process light emerging from the left focus of the auxiliary ellipse in Fig. 1A is refracted by its right half-side into parallel rays. Note that the notch is located at one of the foci of the auxiliary ellipse (red dashed curve), but not at the focus of the elliptical resonator. The Y/X ratio of the elliptical resonator is now chosen such that its boundary best (i.e., over the largest possible angle 2θ) approximates that of the auxiliary ellipse.

In quantitative terms, let r(θ) be the distance between some point on the resonator boundary and point O, and R(θ) the distance between a corresponding point on the auxiliary ellipse and point O. Maximizing the range of angles θ where R(θ)−r(θ) is negligible (here we set |R(θ)−r(θ)|/R(θ)≈1% corresponding to the accuracy of fabrication), we find θ ≡ Y/X is ~1.2 for a refractive index n_{eff} = 3.2 for the laser material we used in the experiment.
Without considering the material optical losses, which are dominating property of the ellipse (auxiliary ellipse in red) to achieve optimal collimation: The boundary of the notched-elliptical resonator (blue curve) is designed to best approximate that of the auxiliary ellipse within the largest possible range of $\theta_{\text{max}} \sim 70^\circ$. The notch of the resonator is located at one of the foci of the auxiliary ellipse (red dashed curve). The optimal $Y/X$ ratio is 1.2 for $n_{\text{eff}} = 3.2$. (B) Ray simulation of the collimation effect: a number of rays are started at the position of the notch with different outgoing angles, simulating a scattering process. They travel inside the cavity until they hit its boundary, upon which they either are specularly reflected or, if the angle of incidence at the surface is smaller than the critical angle for total internal reflection, get refracted out. The red, solid rays, which leave the notch under relatively smaller outgoing angles, get collimated; the collimation is worse for higher outgoing angles (outermost red rays). The blue dashed ray leaves the notch at a high outgoing angle and is relaunched into a whispering-gallery mode. (C) Ray simulation of whispering-gallery mode dynamics. A single ray is started at some position along the resonator boundary with an initial condition such that the angle of incidence is larger than the critical angle. It is then specularly reflected many times, corresponding to a whispering-gallery-like mode, until at some point it hits the notch. It then gets reflected to the opposite boundary, is refracted out, and leaves the cavity parallel to the $x$ axis due to the collimation effect. A magnification of the dynamics near the notch is shown.

(see Materials and Methods). This optimal value $\epsilon = 1.2$ yields $2\theta_{\text{max}} = 70^\circ$; thus indeed the majority of the light is collimated by the elliptical resonator. It is also possible to derive an analytical expression in the paraxial ray approximation for the optimal $\epsilon$ by starting rays at the notch, using Snell’s law to find the far-field rays, and requiring that they are parallel. We find $\epsilon = (2 - 2/n_{\text{eff}})^{1/2} \approx 1.17$ for $n_{\text{eff}} = 3.2$, which agrees well with the numerical result of 1.2.

We first employed ray simulations to analyze the proposed resonator. Fig. 1B demonstrates the collimation effect of many rays scattered by the notch. Fig. 1C shows that a single ray travels inside the resonator and is reflected many times by the resonator boundary, corresponding to a high $Q$ factor WGM, until it hits the notch and escapes from the cavity at the opposite boundary.

We then calculated the optical modes in the cavity through wave simulations (see Materials and Methods). Fig. 2A shows the intensity distribution of the first-radial-order WGM, which is a transverse magnetic (TM) mode, as QCLs are TM polarized due to the intersubband transition selection rule (31), for a structure with $\epsilon = 1.2$ and an optimized, in terms of minimum beam divergence, notch size $o = 3\mu m$ and $d = 2\mu m$, where $o$ and $d$ refer to the width and the depth of the notch, respectively; see Fig. 3B. A $Q$ factor as high as 590,000 is calculated for this mode without considering the material optical losses, which are dominated at the midinfrared wavelengths of QCLs by free carrier absorption (32). Inclusion of such losses in the simulation, as discussed later in the paper, leads to a much reduced $Q$ factor.

Fig. 2B shows the near-field intensity distribution outside the cavity of this mode. To show the details of the light scattered by the notch inside the cavity, we plot the light intensity distribution in a logarithmic scale; see Fig. 2C. Only the outermost part of this mode has an overlap with the notch, thus giving a high $Q$ factor. Light is scattered by the notch to the right-hand-side boundary of the resonator (Fig. 2C). The refracted beams propagate almost parallel to the $\theta = 0^\circ$ direction, resulting in unidirectional emission (Fig. 2D). The weak backward refracted laser beams near position a in Fig. 2B are owing to the low transmission of light
out of the cavity through the notch. The two weak side peaks at positions b and c in Fig. 2B (corresponding to the two far-field peaks near ±120 deg in Fig. 2D), respectively, originate from a certain amount of light reflected toward b and c from different directions than from the notch, similar to the origin of the side peaks in TM Limaçon microcavity (see figure 3 in ref. 24 for elaboration). Higher-radial-order, lower Q factor, WG-like modes are also present (SI Text). Although the proposed scheme is demonstrated in a regime where the ratio of cavity size to wavelength in material $X/\lambda_{\text{eff}} \sim 26$ is relatively high, simulations show that the smallest notched-elliptical resonators with directional emission correspond to $X/\lambda_{\text{eff}} \sim 3$.

Simulations (SI Text) demonstrate that the far-field profile of transverse electric (TE) polarized modes is also highly directional, implying that the proposed concept is broadly applicable also to diode lasers operating in the near infrared and visible. The Q factor of the whispering-gallery modes is still very high in these structures for the same wavelength-to-size ratio. At relatively short wavelengths, e.g., $\lambda \sim 1 \mu m$, free carrier absorption is negligible and optical losses are small (33) ($\sim 0.5 \text{cm}^{-1}$), limited by sidewall roughness of the cavity, and material absorption. This will lead to a much smaller Q-factor degradation than that at mid-IR wavelengths (optical loss is $\sim 15.6 \text{cm}^{-1}$ for our QCLs).

Thus we expect notched-elliptical resonators to be excellent for low-threshold, highly directional microcavity diode lasers. In support of this also note that for the same high Q ($\sim 1 \times 10^9$) Limaçon-shaped microcavity design (24), a Q factor of $\sim 2 \times 10^4$ was experimentally obtained for diode lasers emitting at $\lambda \sim 1 \mu m$ (28) as compared to $\sim 1,000$ of mid-IR QCLs (26).

Note that an optical mode with a calculated very high Q factor of $>5 \times 10^6$ does exist in the cavity (SI Text). It resembles the mode in Figs. 2A–C but with odd parity with respect to the short axis of the notched-elliptical resonator. However, due to its strongly reduced overlap with the notch, it has a much smaller output coupling than the even parity mode of Figs. 2A–C. In addition, due to the existence of unavoidable material optical losses, both odd and even parity modes start to lase at almost the same pumping current in experiments. Therefore, the odd parity mode is not observed in the far-field profile measurement but is visible in the measured spectra (as seen in Fig. 3D) because the spectrometer helps discriminate this weak signal from the background at low pumping currents.

Devices with different dimensions and notch sizes were fabricated and tested in pulsed mode operation at room temperature (Materials and Methods). Fig. 3A and B show, respectively, scanning electron microscope (SEM) images of a representative device and its vertical sidewall. Fig. 3C presents the light output power versus current (L-I) characteristics of this device. The measured Q factor of our devices is $\sim 1,260$, deduced from threshold current density and the gain coefficient measurements (32), which agrees well with the simulation value when the relative high optical losses at the midinfrared wavelengths (32) ($\sim 15.6 \text{cm}^{-1}$) for our devices, deduced from the measurements of threshold current densities versus cavity lengths of ridge laser devices) are included in the simulation. Thus for the QCL case, the threshold current density and Q factor of the notched-elliptical lasers are similar to those of Limaçon-shaped QCLs (25, 26), respectively, due to the high optical losses.

Fig. 3D presents the emission spectra of the notched-elliptical QCLs measured at different pumping currents. The laser operates in single mode at $\lambda \sim 10 \mu m$ near the threshold current (520 mA), corresponding to the mode with the highest Q factor ($>5 \times 10^6$) with odd parity. At a pumping current of 750 mA, two sets of optical modes appear, indicated by blue and red arrows, corresponding respectively to the first two highest Q factor WGMs with even and odd parities. The average mode spacing of each set is approximately 5.80 cm$^{-1}$, which agrees very well with the calculated value of 5.85 cm$^{-1}$ for both odd parity and even parity modes. At higher pumping current several additional modes appear, indicated by green arrows, corresponding to lower Q factor type of modes as the one described in the SI Text (Fig. SI4).

The schematic and the 2D far field of the device are displayed in Fig. 4A and B, respectively. A much narrower beam divergence angle of 6 deg in the plane of the laser cavity than previously reported in microcavity (26) and Fabry–Perot ridge QC lasers is demonstrated. As the vertical far-field emission distribution (due to diffraction at the small light-emitting aperture in the vertical direction of the resonator) does not affect the characteristics of WGM in the plane of the resonator, such as the mode intensity.
distribution in the resonator and the lateral far-field behavior, the employed 2D simulation method can well explain the measured 2D far-field profile. Thus, good agreement is observed between the experimental and simulated far-field intensity profiles (Fig. 4C). The measured vertical far-field divergence angle is about 20 deg. Further reduction of vertical beam divergence could be achieved by patterning integrated plasmonic collimators (34) on the sidewall of the cavity through soft lithographic techniques (35), which makes possible patterning arbitrary nanoscale metallic features onto nonplanar surfaces. All the far-field profiles are essentially the same at different pumping currents from 720 mA to 920 mA (Fig. 4D). The far-field profiles (Fig. 4E) are insensitive to variations of the notch sizes from 2 μm to 4 μm, a deviation well within fabrication uncertainties. We note that ref. 36 also briefly discussed numerical simulations of a notched ellipse but for the situation of microcavities with dimensions comparable to the free-space wavelength and that the lens effect of the ellipse was not discussed. A “point scatterer” (37) in circular shaped microresonators has also been proposed recently to achieve directional emission. However, the shape of the resonator is not optimized and the structure is difficult to fabricate as the “high-index scatterer” is placed inside the cavity.

Fig. 5A shows the calculated directionality, defined as FWHM divergence angle, and the optical output power emitted into ±20 deg as a function of ε with the notch size/shape kept unchanged. The measured peak output power and the slope efficiency are plotted in Fig. 5B as a function of ε. Fig. 5C shows the measured far-field intensity profiles at different ε for \( X = 80 \mu m, o = 3 \mu m, \) and \( d = 2 \mu m. \) These calculations show that ε can be used as a design parameter to control the far-field profile. Beam profiles can also be manipulated by changing the notch size significantly (SI Text).

In summary, we have demonstrated highly unidirectional light emission from WGM lasers with in-plane beam divergence as small as 6 deg. The insensitivity of the device divergence to different notch sizes and to drive currents demonstrates the robustness of this type of resonator. To increase the output power of the device, one can choose to increase \( \varepsilon \) moderately (Fig. 5B) or change the notch size to scatter more power out of the cavity. Because our preliminary simulations show that the notched-elliptical resonator efficiently collimates also TE polarized modes that are typical for diode lasers this new resonator can also be used to achieve highly unidirectional near-infrared and visible WGM lasers. Furthermore, the successful realization of these simple-structured microcavity devices through standard photolithographic fabrication makes small-volume directional light sources possible for many important applications in, e.g., photonic integrated circuits, optical communications, and medical/biological high-sensitive sensors (8). It also allows an easy approach for studying microcavity physics (38) by coupling out light directly from the microcavities without external waveguides. We believe that the promising characteristics of notched-elliptical resonators, e.g., high Q factor, high directionality, robust fabrication, and wafer-based geometry, will lead to a previously undescribed phase of research and development on optical microcavities, where problems such as high-density chip-scale integration of collimated light sources in a lab-on-a-chip environment could be addressed.
Materials and Methods

Device Fabrication. We fabricated QCLs with different cavity sizes \( X = 50, 80, \) and 110 \( \mu \)m, and different axis ratio \( \epsilon = 1.0, 1.1, 1.15, 1.2, 1.25, 1.3, \) and 1.5. The QCL material is the same as the one used in ref. 26 designed by Wang et al. PNAS. We fabricated QCLs with different cavity sizes and 1.5. The QCL material is the same as the one used in ref. 26 designed by Wang et al. PNAS.

Simulations. Wave simulations for the cavities without considering gain were carried out by solving Maxwell’s equations numerically using the boundary element method (24). Our simulations show that the shape of the notch does not play a significant role; therefore, a Gaussian shape was chosen as it is numerically convenient. In the simulations, the equation used to describe the boundary of the notched-elliptical resonator is \( x = (1/\epsilon) - \exp(-0.5(\varphi - \varphi_0)^2)/(0.25\varphi^2)\cos(\varphi) \) and \( y = \sin(\varphi) \) in polar coordinates, where \( \varphi \) is the polar angle to the center of the notched ellipse; \( \epsilon = k/\lambda \); \( \lambda = 80 \mu \)m; \( \delta \) and \( \theta \) determine the depth \( d \) and width \( a \) of the notch. An effective refractive index \( n_{ref} = 3.2 \) for TM polarization is used in the simulations for \( j = 10 \mu \)m is the wavelength in free space), deduced from the measurement of the mode spacing of a Fabry–Perot-type ridge QCL fabricated from the same material that is used for the notched-elliptical resonators.

Measurements. The processed devices were electric pumped and tested in pulsed mode at room temperature with 125-ns current pulses at 80-kHz repetition rate. The far-field profiles of our devices were measured using a setup described in ref. 34. The tested device was mounted at the center of a motorized rotation stage with 0.5° resolution, and a midinfrared mercury–cadmium–telluride detector positioned 10 cm away from the devices was scanned to measure the output of the laser. Power measurements were carried out with a calibrated power meter. Devices with a smaller size of \( X = 50 \mu \)m exhibited continuous wave operation above cryogenic temperature (SI Text).

ACKNOWLEDGMENTS. The authors gratefully acknowledge fruitful discussions with Martina Hentschel. Margherita Maiuri helped measure the far-field profiles of some devices. Device fabrication was carried out at the Center for Nanoscale Systems at Harvard University, a member of the National Nanotechnology Infrastructure Network. The Harvard authors acknowledge financial support from the Air Force Office of Scientific Research. Financial support from the Deutsche Forschungsgemeinschaft research group 760 is gratefully acknowledged by J.U. and J.W.
