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Threshold current reduction and directional emission of deformed microdisk lasers via spatially selective electrical pumping

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We report on laser threshold current reduction and directional emission from quadrupole-shaped AlGaInAs microdisk diode lasers by selective electrical pumping. The directional emission results from breaking the 2-fold rotation symmetry of the system by the introduction of a triangle-shaped contact geometry, and the laser threshold reduction results from a small current injection area. Room temperature laser operation is achieved in both pulsed and continuous-wave operation for a microdisk radius of 50 μm and deformation constant of $\varepsilon = 0.09$, with optical output power of more than 8 mW and 3 mW, respectively. Under pulsed operation, the minimum measured threshold current for selectively pumped microlasers is 42 mA, significantly lower than the minimum measured threshold current for uniformly pumped microlasers (58 mA) and standard ridge lasers (80 mA) of the same device size and material. © 2015 AIP Publishing LLC.

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Microcavity lasers, such as microdisks, microcylinders, microrings, microtori, and microspheres have been intensely studied in the past decades for insights into fundamental physics such as cavity quantum electrodynamics,¹ optomechanics,² wave-chaos, and non-Hermitian phenomena,³ as well as for their potential applications in on-chip optoelectronics⁴ and optical biosensing⁵ due to their low power consumption and light confinement at the micrometer scale.

Light inside such laser resonators is confined by total internal reflection (TIR), which leads to a high quality (Q) factor and low radiation loss. For a highly symmetric cavity, such as a perfect microdisk, the laser emission is isotropic and leads to a low collection efficiency. To obtain a directional beam while maintaining a high Q value of the cavity, one approach is to use an asymmetric resonant cavity (ARC).^{6,7} It has been shown that a smooth deformation from circular symmetry produces directional light output.^{8–15} Usually, these cavities are pumped uniformly, and lasing occurs in the modes with the highest-Q values. These modes are generally whispering-gallery like and reside close to the cavity boundary. By optical pumping^{16,17} or current injection^{18–21} near the cavity boundary, one enhances the utilization of the pumped energy and leads to a reduction of threshold and an increase of output power. However, these whispering-gallery like modes have poor outcoupling coefficients, and if their thresholds are determined mostly by loss mechanisms other than radiation loss (such as material absorption and scattering loss), one would benefit by exciting the optimally outcoupled mode instead, which lowers the lasing threshold, increases the output power, reduces gain competition, and maintains a directional laser emission simultaneously.²² The geometry of the optimally outcoupled modes can differ significantly from that of the

cavity shapes, and one can excite them using a previously developed technique, known as selective pumping.^{17,23,24}

Here, we demonstrate directional emission and laser threshold current reduction from a selectively pumped ARC laser operating at room temperature in both pulsed and continuous wave (CW) operation with milliwatt range output power and at $\lambda = 1.31 \mu\text{m}$ wavelength. The ARC cavity geometry chosen for our work is a quadrupole, whose boundary is defined by $r(\Phi) = r_0 [1 + \varepsilon \cos(2\Phi)]$ in the polar coordinates, where r_0 is the radius, Φ is the polar angle, and ε is the deformation parameter. Quadrupoles with different deformations and refractive indices have been studied extensively.^{6–9,25,26} For diode lasers with their usual TE polarization, the dominant lasing modes in the quadrupole cavity are whispering-gallery-type modes at small deformation and short-periodic-orbit librational modes at high deformation.²⁵ At each deformation, the lasing modes that correspond to short periodic orbits exhibit multiple directional emission beams, and they satisfy the 2-fold rotation symmetry of the cavity itself. In our work, we break this 2-fold rotation symmetry by introducing a triangle-shaped contact (Figure 1(a)), which corresponds to a stable orbit (Figure 2(a)) at small deformations.²⁵ It aims to select a distinct set of modes that follows this periodic orbit, which have better outcouplings than the whispering-gallery modes closer to the cavity boundary. Due to the high refractive index in our samples ($n \sim 3.67$; see the discussion on the free spectrum range), the islands in the Surface of Section (SOS) corresponding to the triangular orbit is far above the critical angle ($\chi_c = \arcsin(1/n)$) (Figure 2(b)), and light emission from the cavity is caused by chaos-assisted tunneling.^{24,27–30} In this process, light first tunnels from the islands to the neighboring chaotic region in the SOS. It then undergoes chaotic diffusion, the general flow of which is determined by the unstable manifolds²⁶ of two other (unstable) triangular orbits; finally, it escapes refractively once its

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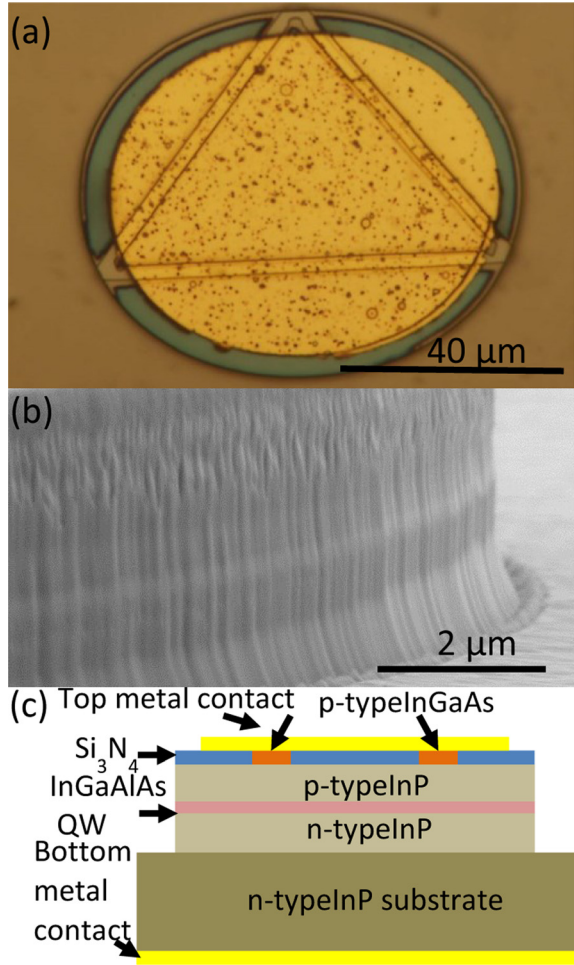


FIG. 1. (a) Optical microscope images of the selectively pumped ARC laser. (b) SEM image of the close up view of the dry-etched laser sidewall. (c) The schematic of the cross-section view of the selectively pumped ARC laser.

incidence angle χ on the cavity boundary falls below the critical angle. If there is an equal amount of light on the two unstable manifolds, the far-field emission pattern is shown by Figure 2(c) for clockwise light and counterclockwise light.

The commercial diode laser structure obtained from IQE Inc. used in our work consists of 26 nm thick AlGaInAs multiple quantum wells embedded in an InP waveguide. To fabricate selectively pumped ARC lasers, the highly doped top p-contact layer is chemically etched away except in the triangle-shaped contact pattern about $2\ \mu\text{m}$ wide defined by photolithography. Using plasma-enhanced chemical vapor deposition, we deposit Si_3N_4 which is used both as a hard mask for dry etching and as insulating layer. Dry etching is performed to fabricate the ARC cavity with $r_0 = 50\ \mu\text{m}$ and $\varepsilon = 0.09$. In order to electrically pump only the triangular mode, a contact window about $2\ \mu\text{m}$ wide is opened along the triangular pattern, formed by the highly doped p-contact layer (Figure 1(a)). Due to the lateral current spreading in the semiconductor, it is important to keep the contact opening as small as possible to achieve spatially highly selective pumping. The contact opening width of $\sim 2\ \mu\text{m}$ is the smallest we obtained from standard photolithography. The top view of the device, and contact geometry of a selectively pumped ARC laser, is given in Figure 1(a). Figure 1(b) shows the

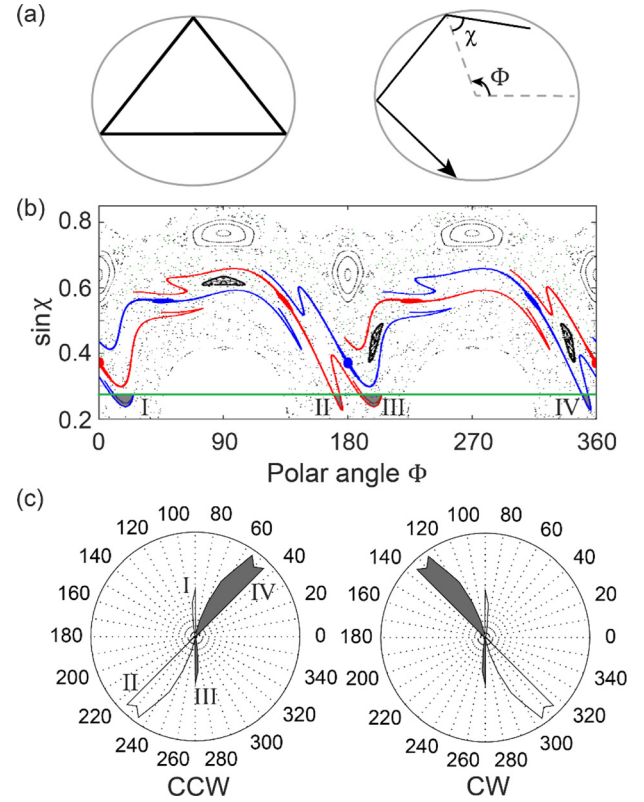


FIG. 2. (a) Left: A stable triangular orbit (solid black curve) in a quadruple cavity of deformation $\varepsilon = 0.09$. Right: Polar angle Φ and incident angle χ each time light is reflected from the cavity boundary. They form the two axes in the Surface of Section (SOS) shown in (b). (b) Part of the SOS for counterclockwise light propagation. Black thick lines delimit the three islands of the stable triangular orbit shown in (a). The unstable manifolds (blue and red lines) are represented by following 20 000 points in the two filled color disks in the SOS for 10 reflections. Horizontal green line shows the critical angle. (c) Far-field emission patterns calculated using Snell's law on 20 000 light rays starting just outside the islands of the triangular orbits. The four lobes are generated from the corresponding shadowed areas in (b), and the filled lobes III and IV agree well with experimental data. The emission pattern from the clockwise light (right) is the mirror image of that of the counterclockwise light (left).

vertical laser side wall formed by dry etching, and Figure 1(c) illustrates the schematic cross-sectional view of a selectively pumped ARC laser. The devices are mounted epitaxial-side up to copper heat sinks and wire bonded for optical and electrical characterization.

Room temperature far-field measurements are taken in pulsed mode operation with a HP 8152A power meter. Measurements are done with a 5° angle resolution and a 180° scanning range, covering one side of the symmetry line. Figure 3(a) shows the far-field patterns of five selectively pumped ARC lasers at 180 mA. The far-field angle values are defined with respect to the triangle shaped contact as shown in the inset in Figure 3(a). Three selectively pumped ARC lasers have directional emissions at $\sim 50^\circ$ angle from the top of the triangle along the minor axis, and one of them has an additional peak at 180° . These peaks correspond to ray escape from regions IV and III of the unstable manifolds shown in Figure 2(b), respectively, while those from regions I and II are missing, due to the break of the 2-fold rotation symmetry by the triangular contact. We observe that the majority of emission is at $\sim 50^\circ$ angle even though the emission along 180°

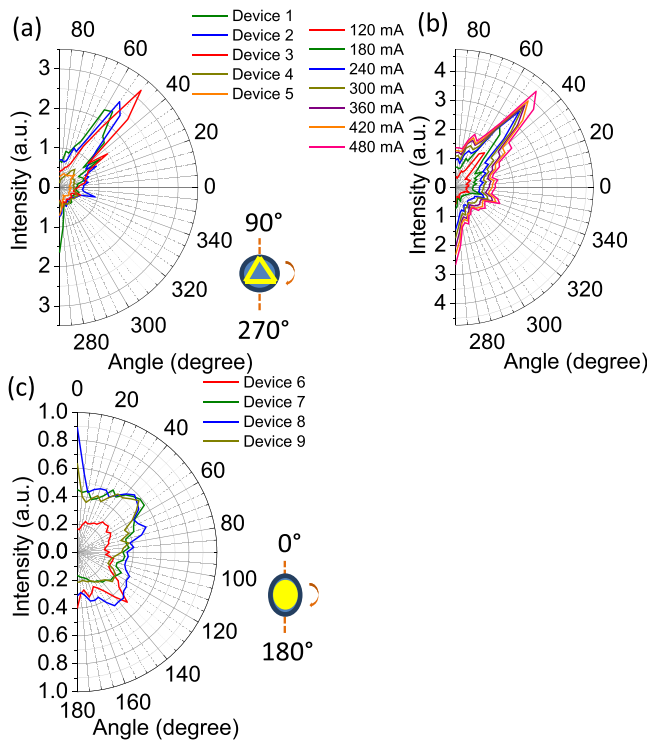


FIG. 3. (a) Far-field intensity pattern of selectively pumped ARC lasers at 180 mA and the schematic of far-field angles with respect to the device (inset). (b) Far-field intensity pattern of a selectively pumped ARC laser showing that directionality is maintained even at higher injection current. (c) Far-field intensity pattern of four uniformly pumped ARC lasers at 180 mA showing lack of directional emission.

angle becomes stronger at the higher current (Figure 3(b)). Figure 3(a) also shows that some of selectively pumped ARC lasers lack directional emission and have random far-field patterns similar to those of uniformly pumped ARC lasers (Figure 3(c)).

The room temperature emission spectra of selectively pumped and uniformly pumped ARC lasers as well as ridge lasers are measured by a Fourier Transform Infrared Spectrometer (FTIR) with 0.125 cm^{-1} spectral resolution. FTIR spectra are taken in pulsed-mode with a pulse width of 100 ns and a repetition rate of 80 kHz. Room temperature spectra are taken at 180 mA, well above laser threshold. A group refractive index of ~ 3.67 was obtained from the free spectral range of a $314 \mu\text{m}$ -long Fabry-Pérot laser fabricated on the same wafer. Average mode spacing for the microdisk lasers with triangular-shaped contact is measured to be $\sim 10.4 \text{ cm}^{-1}$ (Figure 4(a)). This corresponds to an optical path length of about $\sim 262 \mu\text{m}$, which is in excellent agreement with the geometric optical path length of the triangle mode. In comparison, the mode spacings are random when the cavities are uniformly pumped (Figure 4(b)). Figure 4(b) also illustrates a typical spectrum of the selectively pumped ARC laser that does not show directionality. The mode spacings are also random, and it is difficult to conclude what types of modes are lasing. One possible reason behind selectively pumped ARC lasers that do not show the directionality is the sidewall roughness introduced by dry etching, which affects the ray trajectory inside the cavity. Nevertheless, the far-field patterns and laser spectra of selectively pumped ARC lasers show that the majority of the fabricated ARC devices lase on the desired

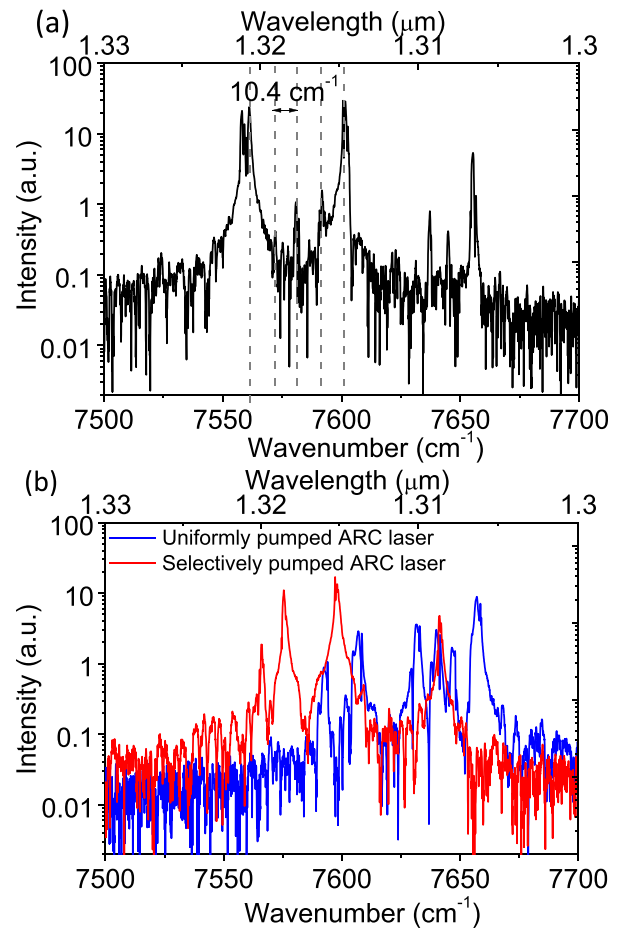


FIG. 4. High resolution emission spectra of (a) a selectively pumped ARC laser, showing the average mode spacing of 10.4 cm^{-1} that corresponds to the $262 \mu\text{m}$ optical path length of the triangular mode (an equidistant grid is overlaid), and (b) a uniformly pumped ARC laser (blue) and a selectively pumped ARC laser that lacks directionality (red), showing non-uniform mode spacings.

triangular modes. From the mode spacing of measured devices, we determine that about $\sim 70\%$ of our devices lase in the desired triangular mode.

Figures 5(a) and 5(b) show representative light-current (LI) characteristics of selectively pumped ARC lasers, uniformly pumped ARC lasers, and standard ridge lasers with the same device area at 300 K in pulsed and CW operation, respectively. Pulsed operation for LI measurements is taken with a pulse width of 250 ns and a repetition rate of 5 kHz. The light output from the ARC laser is collimated around the angle where the emission peak is located and focused onto the power meter by a pair of ZnSe lenses. In both pulsed and CW operations, selectively pumped ARC lasers have lower threshold than both uniformly pumped ARC lasers and ridge lasers. In addition, all measured selectively pumped ARC lasers with triangle modes have higher output power than uniformly pumped ARC lasers and ridge lasers in low injection current regimes, achieving more than 8 mW in pulsed operation and more than 3 mW in CW operation, which makes them suitable for on-chip application. In the higher current regime, the output power of uniformly pumped ARC lasers and ridge lasers dominates, due to the stronger gain saturation in selectively pumped ARC lasers resulted from its higher current density.

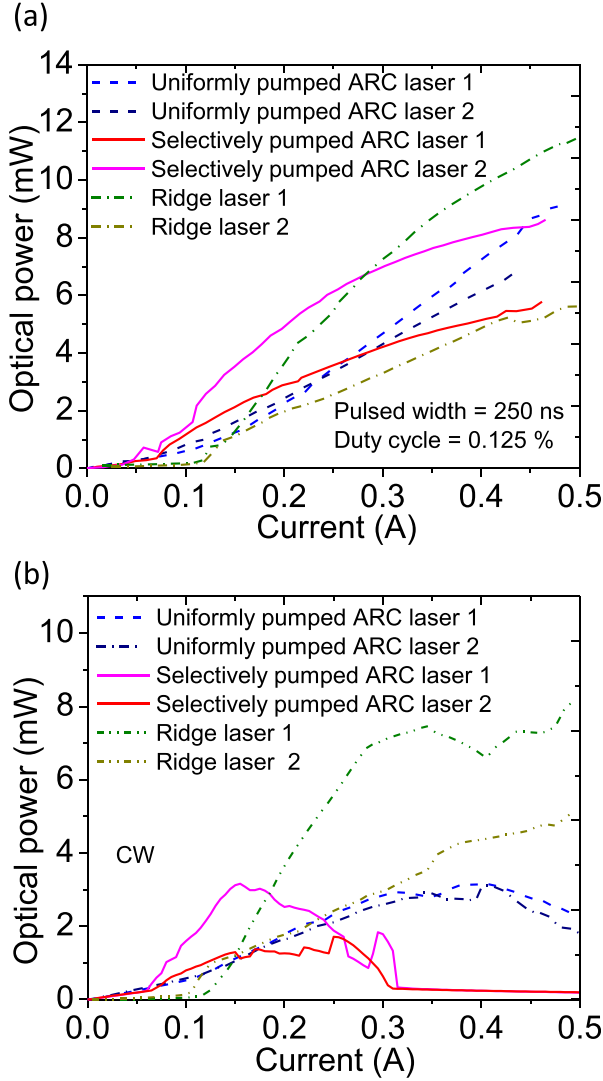


FIG. 5. (a) Output power vs. injection current characteristics for selectively pumped ARC lasers (solid lines), uniformly pumped ARC lasers (dashed lines), and ridge lasers (dashed dotted lines) with the same device area in pulsed mode operation at 300 K and (b) CW operation of the same devices.

Figure 6(a) demonstrates the distribution of laser threshold currents in pulsed operation for a full collection of selectively pumped ARC lasers, uniformly pumped ARC lasers, and 314 μm -long standard ridge lasers, all with the same device physical area. The laser thresholds are determined by spectra measurements using a FTIR. The threshold currents of selectively pumped ARC lasers are significantly lower than the other two types of lasers, with two thirds of the measured selectively pumped ARC lasers having threshold currents less than or equal to 54 mA. The minimum measured threshold current of selectively pumped ARC lasers is 42 mA, 28% lower than that for uniformly pumped ARC lasers (58 mA) and 48% lower than that for ridge lasers (80 mA). The average laser threshold current of selectively pumped ARC lasers is 57 mA, which is 32% and 40% lower than those of uniformly pumped ARC lasers (84 mA) and ridge lasers (96 mA). The wide spread of the threshold current maybe due to surface recombination and scattering loss introduced by the roughness on the sidewall. Some of the selectively pumped lasers have higher laser threshold than the uniformly pumped ARC lasers. This may be due to the

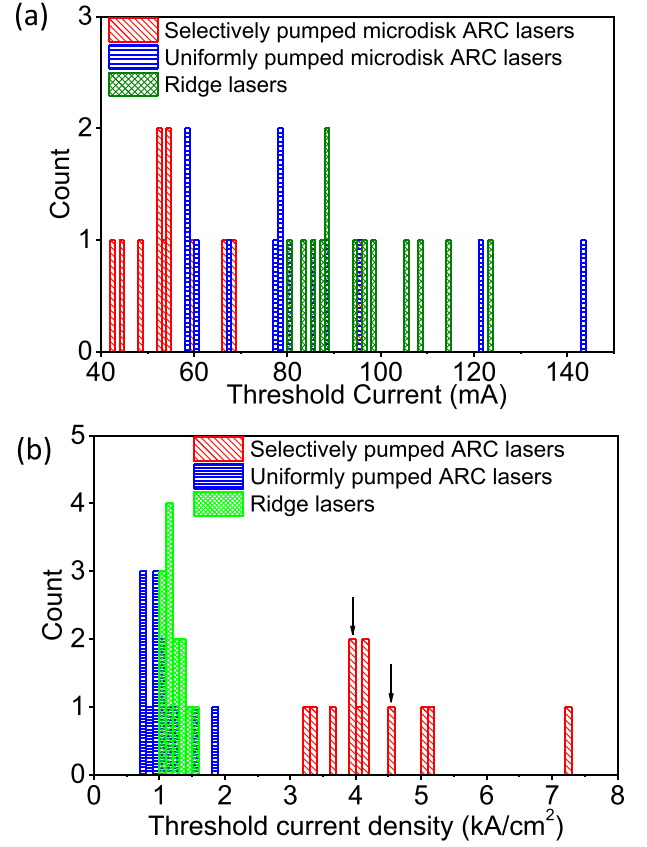


FIG. 6. Room temperature threshold current (a) and threshold current density (b) distribution of selectively pumped ARC lasers, uniformly pumped ARC lasers, and standard ridge lasers with the same device area in pulsed mode operation, showing the relatively low laser threshold of selectively pumped ARC lasers.

serious lateral current spreading in these selectively pumped devices in addition to the variation in scattering loss introduced by the roughness on the sidewall. The threshold current density for selectively pumped ARC lasers (Figure 6(b)) is calculated by dividing the threshold current with the geometric optical path length of 262 μm and the width of 5 μm ; the latter is the calculated FWHM of the current distribution in the active core of diode laser with 2 μm contact width, using the model presented in Ref. 31. From the threshold current densities, we determine the Q-factor of our selectively pumped ARC laser using the relation given by Ref. 32

$$Q = \frac{2\pi n_{\text{eff}}}{\lambda J_{\text{th}} g \Gamma},$$

where n_{eff} is the group refractive index, λ is the wavelength of the laser, J_{th} is the threshold current density, g is the gain coefficient, and Γ is the mode confinement factor. The value of $g\Gamma$ at 300 K is experimentally measured to be 28.4 cm/kA. Our selectively pumped ARC lasers achieve the Q-factor as high as ~ 1844 , while uniformly pumped ARC laser achieve the Q-factor of ~ 7600 . Therefore, we conclude that we are indeed selectively pumping an optimally outcoupled mode, with a lower Q than the whispering-gallery-modes, which increases the output and lowers the laser threshold current.

In conclusion, we have demonstrated directional emission and 28% reduction in threshold current from AlGaInAs ARC microdisk diode lasers by inhomogeneous electrical pumping.

The geometric optical path length of $262\ \mu\text{m}$ derived from the free spectral range indicates that the device is lasing on the triangular modes excited by the triangular shaped electrical contact. Room temperature operation in both pulsed mode and CW mode is achieved with a peak optical power of more than 8 mW in pulsed and 3 mW in CW mode. In particular, we have showed that selectively pumped ARC lasers have higher optical power than conventional uniformly pumped ARC lasers in low injection current regimes, making the former more attractive over the latter for on-chip applications.

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