Controlling a microdisk laser by local refractive index perturbation
Seng Fatt Liew, Li Ge, Brandon Redding, Glenn S. Solomon, and Hui Cao

View online: http://dx.doi.org/10.1063/1.4940229
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/108/5?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Active control of emission directionality of semiconductor microdisk lasers

Lasing properties of non-polar GaN quantum dots in cubic aluminum nitride microdisk cavities

Compact microdisk cavity laser with type-II GaSb/GaAs quantum dots
Appl. Phys. Lett. 98, 051105 (2011); 10.1063/1.3543839

Small optical volume terahertz emitting microdisk quantum cascade lasers
Appl. Phys. Lett. 90, 141114 (2007); 10.1063/1.2719674

CdSe quantum dot microdisk laser
Appl. Phys. Lett. 89, 231104 (2006); 10.1063/1.2402263
Controlling a microdisk laser by local refractive index perturbation

Seng Fatt Liew,1 Li Ge,2,3 Brandon Redding,1 Glenn S. Solomon,4 and Hui Cao1,a)
1Department of Applied Physics, Yale University, New Haven, Connecticut 06520, USA
2Department of Engineering Science and Physics, College of Staten Island, CUNY, Staten Island, New York 10314, USA
3The Graduate Center, CUNY, New York, New York 10016, USA
4Joint Quantum Institute, NIST and University of Maryland, Gaithersburg, Maryland 20899, USA

(Received 12 October 2015; accepted 7 January 2016; published online 3 February 2016)

We demonstrate a simple yet effective approach of controlling lasing in a semiconductor microdisk by photo-thermal effect. A continuous wave green laser beam, focused onto the microdisk perimeter, can enhance or suppress lasing in different cavity modes, depending on the position of the focused beam. Its main effect is a local modification of the refractive index of the disk, which results in an increase in the power slope of some lasing modes and a decrease of others. The boundary roughness breaks the rotational symmetry of a circular disk, allowing the lasing process to be tuned by varying the green beam position. Using the same approach, we can also fine tune the relative intensity of a quasi-degenerate pair of lasing modes. Such post-fabrication control, enabled by an additional laser beam, is flexible and reversible, thus enhancing the functionality of semiconductor microdisk lasers. © 2016 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4940229]

Semiconductor microdisk lasers have simple geometries, small footprints, and low lasing thresholds, making them attractive on-chip light sources for integrated photonics applications.1,2 Due to high refractive index contrast at the high-magnitude tilt-view SEM image [Fig. 1(b)] reveals the roughness of the disk sidewall created during the etching process. The fabricated microdisks are mounted in a low-temperature cryostat for the lasing experiment. The experimental setup is similar to the one described in Ref. 30 except that we added an additional CW green laser (λ = 532 nm) to introduce a local refractive index change by the photo-thermal effect. The InAs QDs were optically excited by a mode-
laser is a modification of the refractive index of the disk, suggesting the dominant effect of the green light on the microdisk laser when only the green laser beam is on. To further characterize the change of the lasing modes, we measured the emission intensity of each mode as a function of the red pump power, \( P \) with the green laser on or off. Figure 2(a) shows the data for mode ii, whose intensity decreases significantly with the green light on. In the absence of the green laser beam, mode ii displays a sharp increase in the growth rate of its intensity with pump at \( P \approx 3 \text{ mW} \), indicating the onset of lasing action. With the green beam on, mode ii starts lasing at slightly higher \( P \), but its emission intensity grows at a significantly reduced rate above the lasing threshold. Thus, the local perturbation introduced by the green light affects mostly the power slope of the lasing mode. Opposite of the behavior of mode ii, when the green beam is on, the intensity of mode iii grows faster after it lases, even though its lasing threshold also increases slightly [Fig. 2(b)].

To be more quantitative, we extract the lasing threshold and power slope of individual lasing modes from the dependence of their emission intensity on the pump power [Figs. 2(c) and 2(d)]. Without the green light, mode iii is the first to lase but the lasing thresholds of other modes differ only by a few percent. All the lasing modes experience an increase of lasing threshold with the green beam on, but the order of lasing remains the same. Opposite of the overall decrease of lasing thresholds, we observe a red-shift of the lasing modes, the mode ii displays a sharp increase in the growth rate of its intensity with pump at \( P \approx 3 \text{ mW} \), indicating the onset of lasing action. With the green beam on, mode ii starts lasing at slightly higher \( P \), but its emission intensity grows at a significantly reduced rate above the lasing threshold. Thus, the local perturbation introduced by the green light affects mostly the power slope of the lasing mode. Opposite of the behavior of mode ii, when the green beam is on, the intensity of mode iii grows faster after it lases, even though its lasing threshold also increases slightly [Fig. 2(b)].

To be more quantitative, we extract the lasing threshold and power slope of individual lasing modes from the dependence of their emission intensity on the pump power [Figs. 2(c) and 2(d)]. Without the green light, mode iii is the first to lase but the lasing thresholds of other modes differ only by a few percent. All the lasing modes experience an increase of lasing threshold with the green beam on, but the order of lasing remains the same. Opposite of the overall decrease of lasing thresholds, we observe a red-shift of the lasing modes, the mode ii displays a sharp increase in the growth rate of its intensity with pump at \( P \approx 3 \text{ mW} \), indicating the onset of lasing action. With the green beam on, mode ii starts lasing at slightly higher \( P \), but its emission intensity grows at a significantly reduced rate above the lasing threshold. Thus, the local perturbation introduced by the green light affects mostly the power slope of the lasing mode. Opposite of the behavior of mode ii, when the green beam is on, the intensity of mode iii grows faster after it lases, even though its lasing threshold also increases slightly [Fig. 2(b)].

To be more quantitative, we extract the lasing threshold and power slope of individual lasing modes from the dependence of their emission intensity on the pump power [Figs. 2(c) and 2(d)]. Without the green light, mode iii is the first to lase but the lasing thresholds of other modes differ only by a few percent. All the lasing modes experience an increase of lasing threshold with the green beam on, but the order of lasing remains the same. Opposite of the overall decrease of lasing thresholds, we observe a red-shift of the lasing modes, the mode ii displays a sharp increase in the growth rate of its intensity with pump at \( P \approx 3 \text{ mW} \), indicating the onset of lasing action. With the green beam on, mode ii starts lasing at slightly higher \( P \), but its emission intensity grows at a significantly reduced rate above the lasing threshold. Thus, the local perturbation introduced by the green light affects mostly the power slope of the lasing mode. Opposite of the behavior of mode ii, when the green beam is on, the intensity of mode iii grows faster after it lases, even though its lasing threshold also increases slightly [Fig. 2(b)].

To be more quantitative, we extract the lasing threshold and power slope of individual lasing modes from the dependence of their emission intensity on the pump power [Figs. 2(c) and 2(d)]. Without the green light, mode iii is the first to lase but the lasing thresholds of other modes differ only by a few percent. All the lasing modes experience an increase of lasing threshold with the green beam on, but the order of lasing remains the same. Opposite of the overall decrease of lasing thresholds, we observe a red-shift of the lasing modes, the mode ii displays a sharp increase in the growth rate of its intensity with pump at \( P \approx 3 \text{ mW} \), indicating the onset of lasing action. With the green beam on, mode ii starts lasing at slightly higher \( P \), but its emission intensity grows at a significantly reduced rate above the lasing threshold. Thus, the local perturbation introduced by the green light affects mostly the power slope of the lasing mode. Opposite of the behavior of mode ii, when the green beam is on, the intensity of mode iii grows faster after it lases, even though its lasing threshold also increases slightly [Fig. 2(b)].
increment of lasing threshold in Fig. 2(c), the power slope exhibits a different behavior in the presence of the green light [Fig. 2(d)]. In particular, the power slopes of modes i and iii increase while those of modes ii and iv decrease. The opposite change in the power slope is attributed to the non-linear interaction of the lasing modes, which is modified by the green laser beam. The power slope of one lasing mode depends not only on its own lasing threshold but also on the intensities of other lasing modes. The photo-thermal effect induces a local refractive index change, which modifies the quality ($Q$) factors of cavity resonances. The increase of the power slope for the first lasing mode (mode iii) and the decrease of the power slope for the second lasing mode (mode ii) can be predicted by the Steady-state Ab-initio Laser Theory (SALT), when the $Q$ of mode ii is reduced more than mode iii by the local refractive index change. In other words, the increase of power slope for mode iii is due to reduced gain competition from mode ii which lases less efficiently as a result of stronger $Q$ spoiling. Thus, the perturbation introduced by the green beam is not always detrimental to the lasing action, and it provides a simpler method to switch the dominant lasing mode from one to another.

The presence of sidewall roughness breaks the rotational symmetry of the microdisk, making the photo-thermal effect on the lasing modes depend on the position of the focused green laser beam. Next, we investigate the change of lasing modes when the focused green beam is moved along the disk boundary [Fig. 3(a)]. While the spot size of the green beam is 1.8 µm, the heat it generates spreads to a larger area. Experimentally, we observe a notable variation of the lasing spectra when the azimuthal angle $\theta$ of the green spot is changed by 36°, which corresponds to an arc length of 5.8 µm. Figure 3(b) shows the lasing spectra as the green beam spot is moved azimuthally across the perimeter of the disk. Individual lasing modes change in different ways, for example, the intensity of mode ii first increases and reaches the maximum at $\theta = 72^\circ$, then it decreases and reaches the minimum at about $\theta = 180^\circ$ before rising again. Mode iv displays a more dramatic change, its lasing is turned off at $\theta = 180^\circ$. In contrast to modes ii and iv, mode iii has the maximal emission at about $\theta = 180^\circ$.

In the following, we take a closer look at the lasing mode iii, whose line shape also changes with the position of the green beam. Figures 3(c) and 3(d) show the spectral line of mode iii when the green beam spot is at $\theta = 0^\circ$ and 180°, respectively. At $\theta = 0^\circ$, the line shape differs from a symmetric Lorentzian curve, indicating the peak consists of two sub-peaks. The whispering-gallery modes in a perfect circular disk are degenerate, however, due to the roughness of the disk sidewall, the frequency degeneracy is lifted and the quasi-degenerate modes are formed. We decompose the spectral line to recover the two quasi-degenerate modes $L_1$ and $L_2$, and also include an additional peak $L_3$ from a nearby resonance that has significantly weaker emission. At $\theta = 0^\circ$ [Fig. 3(c)], the two quasi-degenerate modes $L_1$ and $L_2$ have similar emission intensity, but at $\theta = 180^\circ$ only one of the quasi-degenerate modes, $L_1$, lases, and the spectral line becomes narrower and symmetric [Fig. 3(d)].

Figure 3(e) plots the intensities of the two quasi-degenerate modes, $L_1, L_2$, as a function of the position of the green beam $\theta$. While $L_1$ and $L_2$ have similar intensity at $\theta = 0^\circ$, $L_1$ is enhanced and $L_2$ is suppressed as the green spot moves towards 180°. Their difference becomes the largest at $\theta \approx 180^\circ$, where $L_2$ nearly disappears and $L_1$ has the maximal intensity. With a further increase of $\theta$ beyond 180°, $L_1$ goes down while $L_2$ grows, eventually $L_2$ becomes stronger than $L_1$. Their difference diminishes as $\theta$ approaches 360°. In contrast to the drastic change of $L_1$ and $L_2$, $L_1$ exhibits only slight fluctuation of its intensity around the mean value (not shown), when the green spot moves to different locations. This result shows that by focusing the green laser beam on different locations, we can tune the relative intensity of the quasi-degenerate modes and even switch off lasing in one of them.

Given that the quasi-degenerate modes have a similar spatial field profile, it is surprising that the focused green laser beam, whose spot size is much larger than the wavelength, can induce a different response from them. To understand such phenomena, we perform a numerical simulation on a 2D dielectric disk without gain or loss. Random harmonic perturbations are added to the disk boundary to emulate the sidewall roughness on the fabricated disk. To reduce the computing time, we set the disk radius to be $R = 3 \mu m$. The presence of sidewall roughness breaks the rotational symmetry of the microdisk, making the photo-thermal effect on the lasing modes depend on the position of the focused green laser beam. Next, we investigate the change of lasing modes when the focused green beam is moved along the disk boundary [Fig. 3(a)]. While the spot size of the green beam is 1.8 µm, the heat it generates spreads to a larger area. Experimentally, we observe a notable variation of the lasing spectra when the azimuthal angle $\theta$ of the green spot is changed by 36°, which corresponds to an arc length of 5.8 µm. Figure 3(b) shows the lasing spectra as the green beam spot is moved azimuthally across the perimeter of the disk. Individual lasing modes change in different ways, for example, the intensity of mode ii first increases and reaches the maximum at $\theta = 72^\circ$, then it decreases and reaches the minimum at about $\theta = 180^\circ$ before rising again. Mode iv displays a more dramatic change, its lasing is turned off at $\theta = 180^\circ$. In contrast to modes ii and iv, mode iii has the maximal emission at about $\theta = 180^\circ$.
smaller than the measured one. The effective index of refraction of the disk is computed from the thickness of the fabricated disk, and its value is \( n = 3.13 \). As mentioned earlier, the dominant effect of the green laser beam is an increase of the local refractive index of the disk via the photo-thermal effect. To match the ratio of the green beam spot size to the microdisk dimension in the experiment, we increase the refractive index of the disk within a circular region of diameter \( d = 600 \text{ nm} \) in the simulation. Based on the experimentally observed wavelength shift \( \delta \lambda \) of the lasing peaks, we set the change of refractive index to be \( \delta n = (\delta \lambda / \lambda) (2 \pi R / d) \approx 0.01 \). We calculate the resonant modes of the passive microdisk using the finite-difference frequency-domain (FDFD) method with and without the perturbation of the green light. Figure 4(a) shows the spatial field distribution for one pair of high-\( Q \) quasi-degenerate modes in the absence of the perturbation. Although their spatial field profiles look very similar, their \( Q \) factors and center wavelengths \( \lambda \) are slightly different due to the roughness of the disk boundary. The perturbation of the green beam causes further changes in \( Q \) and \( \lambda \). As shown in Figs. 4(b) and 4(c), with the green beam focused on different locations on the disk, the \( Q \) values of the quasi-degenerate modes 1 and 2 can either approach each other or move further apart. Next we introduce optical gain to the microdisk, and compute the lasing intensity as a function of the pump strength using the SALT.\(^{37,38} \) Figure 4(d) plots the emission intensities of modes 1 and 2, when the “green beam spot” is at two spatial locations shown in Fig. 4(b). Their intensities get closer when the difference in their \( Q \)’s is reduced by the green beam. However, when the green beam is moved to another location, the \( Q \) difference is increased, and so is the intensity. The numerical results, which agree qualitatively with the experimental data, illustrate the sensitivity of quasi-degenerate lasing modes to the spatial-dependent perturbation of the green laser beam.

In conclusion, we demonstrate a simple yet effective method to control the lasing modes in a semiconductor microdisk using an additional laser beam at a different wavelength. By moving the beam spot on the disk, we can either enhance or suppress lasing in individual modes by modifying the power slope. Different lasing modes display a distinct or even opposite response to the perturbation of the additional laser beam, allowing us to switch the dominant lasing mode. Moreover, we can tune the relative intensity of the quasi-degenerate lasing modes. All the changes induced by the additional laser beam, which is a low-power continuous wave, are reversible. The microdisk boundary roughness is essential to controlling the lasing process by varying the green beam position, which would otherwise be impossible for a perfectly circular microdisk. Such post-fabrication tuning of lasing modes is flexible and sensitive, thus enhancing the functionality of semiconductor microdisk lasers.

This work was supported by the MURI Grant No. N00014-13-1-0649 from the U.S. Office of Naval Research and by the National Science Foundation under the Grant Nos. DMR-1205307 and DMR-1506987. Facilities use was supported by YINQE and NSF MRSEC DMR-1119826.