High-Q whispering-gallery mode quantum-dot microdisk lasers

K. Solís Trápala, R. W. Smink, J. Molina Vázquez, B. P. de Hon and H. J. S. Dorren

COBRA Research Institute, Eindhoven University of Technology, P. O. Box 513, 5600 MB Eindhoven,
The Netherlands
k.s.t.solis.trapala@tue.nl

Abstract. *We compute the whispering-gallery modes for a microdisk laser with an InGaAsP/InP quantum-dot gain medium. We find that whispering-gallery modes in the 1.5 μm telecommunication window with* $Q>10^5$ *can be sustained in a microdisk laser with a diameter as small as 2.8 μm and a thickness of 200 nm.*

Introduction

To fulfill the demands of increasing speed of fibre-optic-based telecommunications, high speed, integrability and low-power consumption for the constituent devices are needed. Particularly, semiconductor microdisk lasers are attractive because of their small cavity volume, cleavage-free cavities, excellent wavelength selectivity, ultra-low threshold and high cavity quality (Q) factor due to the great confinement of whispering-gallery modes (WGMs) [1]. These characteristics can be enhanced with a quantum-dot (QD) active region offering fast response to external pumping [2] and the possibility for simultaneous excitation of multiple WGMs inside one microdisk over a wide spectral range [3].

At the surface of the microdisk laser, the modes are bound by total internal reflection. These whispering-gallery modes [4] are of special interest due to a very good confinement of the field which can be characterized by the cavity Q factor.

Recently, whispering-gallery modes in microdisk lasers have been theoretically and experimentally investigated [1;2;5-8]. The theoretical models in [5-7] simplify the problem to two dimensions by neglecting the wavevector dispersion in the axial direction. We investigate whispering-gallery modes through a three-dimensional model of a microdisk laser with a QD active region. We solve and compute the lasing modes for a quantum-dot microdisk laser by considering an approximate separation of Maxwell's equations in the axial and transverse directions, subsequently, we compute the Q factor in closed form for disk lasers with different dimensions. We find that large Q factors can be obtained for small disks.

Model

Figure 1 shows the device considered in our study, a disk with a dielectric-air boundary supported by a post with an active region consisting of ten QD layers. We are only interested in modes propagating along the edge of the disk and therefore the coupling of the field into the supporting post can be neglected. These are higher-order modes and correspond to the whispering-gallery modes. We labeled these modes with two numbers. The order of the resonance is N, where $N-1$ denotes the number of nodes in the radial variation of the field and M is the azimuthal-mode number, where $2M$ corresponds to the maxima in the azimuthal variation of the resonant field around the disk's circumference [4].

Due to the symmetry of the problem, we use a cylindrical coordinate system to solve the Maxwell's equations in three dimensions, for transverse-electric (TE) modes, using the

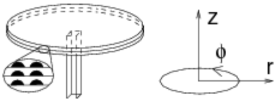

Figure 1: Multiple-layer quantum-dot microdisk laser in a cylindrical coordinate system.

method of Borgnis' potentials [9]. In the angular direction, we assume clockwise and counter-clockwise propagating waves. In the axial direction, the field consists of a cosine solution and decaying exponential functions inside and outside the disk, respectively. Lastly, the solution in the radial direction is expressed in terms of Bessel functions of the first kind and modified Bessel functions of the second kind, both of them of complex order k_φ, inside and outside the disk, respectively. The complex order k_φ, which corresponds to the complex wavevector for the field propagating in the angular direction, is a result of the losses due to the field radiating away from the disk. Simplified solutions consisting of Bessel functions of integer order, found for instance in [5-7], result in an over-estimation of the field confinement. Following the considerations above, we obtain expressions for the electric and magnetic field components inside and outside the disk. Modes are found by solving the continuity conditions at the microdisk radial and axial boundaries. For the QD gain and carrier-induced refractive index spectra we use the linear gain model described in detail in [10;11]. Finally, we compute the Q factor for the i-th mode using the following relation [9]:

$$Q = \omega_i \frac{W}{P}, \tag{1}$$

where ω_i denotes the natural angular frequency of the i-th mode, W is the time-averaged energy stored in the cavity and P denotes de power loss. Hence, we compute the time-averaged stored energy inside the cavity and we use the Poynting vector to compute the power loss.

Results

We choose a QD gain medium with ten layers having a QD density of 4×10^{10} cm^{-2} and an average dot height of 5 nm. Figure 2 shows the QD gain and carrier-induced refractive index spectra. In our analysis, we consider microdisks with diameters in the range $2\ \mu\text{m} \leq D \leq 4\ \mu\text{m}$ and thicknesses in the range $50\ \text{nm} \leq L \leq 350$ nm.

In view of the two telecommunication windows, we are interested in modes in the range $1.3\ \mu\text{m} \leq \lambda \leq 1.7\ \mu$m. Figure 2 also shows the spectral positions of some of the lasing modes found in a disk with D=3 μm and L=200 nm. In addition, Figure 3 shows the mode wavelength dependence on the disk diameter and on the disk thickness for a fixed L=200 nm and for a fixed D=3 μm, respectively. We found that disks with D<2 μm or L<100 nm can only sustain low-order modes that have a low confinement inside the disk, and thus large losses. In contrast, disk diameters of $D \geq 2.8\ \mu$m and thicknesses of $L \geq 200$ nm show lasing of higher-order modes (M>10), i.e. WGMs in the 1.5 μm telecommunication window. We also observe that degenerate modes exist in the cavity. For instance, the modes in the 1.3 μm telecommunication window with M equal to 9 and 12. This situation does not occur in the 1.5 μm telecommunication window unless a thickness larger than 200 nm or a diameter larger than 3.6 μm is used. On the other

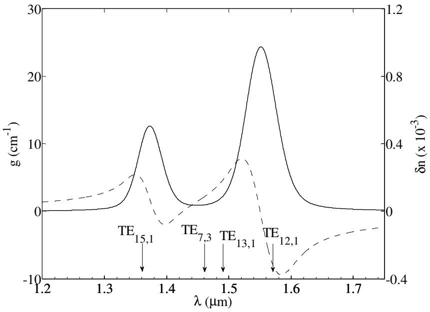

Figure 2: Quantum-dot gain (solid) and carrier-induced refractive index (dashed) spectra. Also shown are some of the lasing modes for a disk with D=3 μm and L=200 nm.

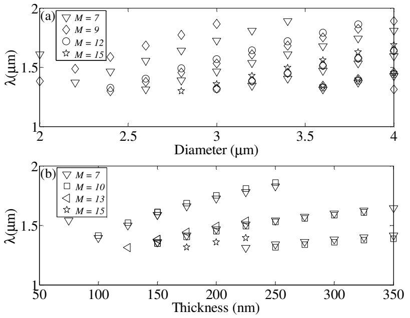

Figure 3: Mode wavelength dependence on the (a) disk diameter for a fixed L=200 nm, and on the (b) disk thickness for a fixed D=3 μm for the 7th, 9th, 10th, 12th, 13th and 15th modes.

hand, from Figure 3 (b), we observe that for $L \geq 250$ one can not sustain modes with M>12 since the cutoff wavelengths of these modes are reached.

We have computed the Q factor for all lasing modes M found during the variation of both the diameter and the thickness of the disk. Figure 4 shows the Q-factor dependence on the mode wavelength for the configuration of Figure 3 (a). We observe that the Q-factor behavior follows that of the QD gain but the other way around. That is, modes whose wavelengths coincide with the low part of the gain spectrum have also lower losses and as a consequence they achieve a higher Q factor (~10^7). On the other hand, modes having more gain are more amplified and consequently the losses, even when they are low, are greater than those in the previous case, resulting in Q factors which are still in the order of 10^5. Hence, we find that even when all of our modes have a positive net gain, only a few of them propagate with a field that is highly concentrated along the edge of the disk. To meet this condition, one should have a higher-order mode lasing at a wavelength with a high gain. It turns out that these modes present only one intensity peak in the radial direction, i.e. N=1. Higher-order modes, lasing at wavelengths with low gain, show more intensity peaks in the radial direction (N>1) which results in propagation along the edge of the disk but also inside the disk. An example of these two situations is illustrated in Figure 5, where the radial dependence of the field |V(r)|, for the 12th mode propagating in two different wavelengths is shown for a disk of D=3 μm and L=200 nm. We observe a similar behavior for the Q-factor dependence on the mode wavelength for the configuration of Figure 3 (b).

Conclusions

We have used a three dimensional model to compute the whispering-gallery modes in quantum-dot microdisk lasers. The model accounts for the radiation of the field in the radial direction. We found that higher-order modes with high Q-factors (~10^5) propagating in the 1.5 μm telecommunication window can be sustained in disks with diameters from 2.8 μm and a thickness of 200 nm. It should be remarked though that the Q factors do not account for scattering losses at the disks edge. Also losses due to surface recombination have been neglected due to the nature of the quantum-dots. Accordingly, mode propagation with a highly concentrated field along the edge of the disk is determined by the quantum-dot gain and by a large azimuthal-mode number M.

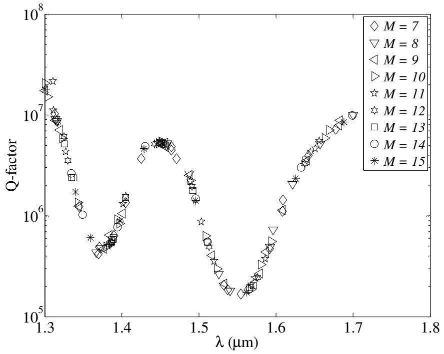

Figure 4: Q-factor dependence on the mode wavelength.

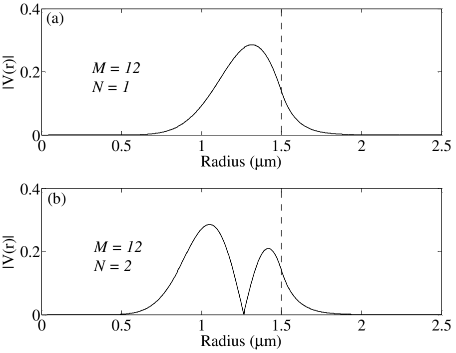

Figure 5: Radial dependence of the field for the (a) $TE_{12,1}$ mode and the (b) $TE_{12,2}$ mode propagating in a disk with D=3 μm (r=1.5 μm) and L=200 nm.

Therefore it is possible to engineer a quantum-dot gain medium having ground and excited state transition peaks centered at the lasing wavelength of the desired modes.

References

[1] M. Fujita, R. Ushigome, and T. Baba, "Continuous wave lasing in GaInAsP microdisk injection laser with threshold current of 40 μA", Electronics Letters, vol. 36, pp. 790-791, 2000.

[2] K. J. Luo, J. Y. Xu, H. Cao, Y. Ma, S. H. Chang, S. T. Ho, and G. S. Solomon, "Ultrafast dynamics of InAs/GaAs quantum-dot microdisk lasers", Applied Physics Letters, vol. 78, pp. 3397-3399, 2001.

[3] H. Cao, J. Y. Xu, W. H. Xiang, Y. Ma, S. H. Chang, S. T. Ho, and G. S. Solomon, "Optically pumped InAs quantum dot microdisk lasers", Applied Physics Letters, vol. 76, pp. 3519-3521, 2000.

[4] S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, "Whispering-gallery mode microdisk lasers", Applied Physics Letters, vol. 60, pp. 289-291, 1992.

[5] N. C. Frateschi and A. F. J. Levi, "The spectrum of microdisk lasers", Journal of Applied Physics, vol. 80, pp. 644-653, 1996.

[6] M. Fujita, A. Sakai, and T. Baba, "Ultrasmall and ultralow threshold GaInAsP-InP microdisk injection lasers: Design, fabrication, lasing characteristics, and spontaneous emission factor", IEEE Journal of Selected Topics in Quantum Electronics, vol. 5, pp. 673-681, 1999.

[7] E. I. Smotrova and A. I. Nosich, "Mathematical study of the two-dimensional lasing problem for the whispering-gallery modes in a circular dielectric microcavity", Optical and Quantum Electronics, vol. 36, pp. 213-221, 2004.

[8] P. Michler, A. Kiraz, L. D. Zhang, C. Becher, E. Hu, and A. Imamoglu, "Laser emission from quantum dots in microdisk structures", Applied Physics Letters, vol. 77, pp. 184-186, 2000.

[9] K. Zhang and D. Li, Electromagnetic theory for microwaves and optoelectronics Berlin: Springer, 1998.

[10] J. Molina Vázquez, H. H. Nilsson, J. Z. Zhang, and I. Galbraith, "Linewidth enhancement factor of quantum-dot optical amplifiers", IEEE Journal of Quantum Electronics, vol. 42, pp. 986-993, 2006.

[11] J. Molina Vázquez, J. Z. Zhang, and I. Galbraith, "Quantum dot versus quantum well semiconductor optical amplifiers for subpicosecond pulse amplification", Optical and Quantum Electronics, vol. 36, pp. 539-549, 2004.