Dielectric surrounding bleaches the optical bond between a microdisk resonator and a straight optical waveguide

A V Raskhodchikov, S A Scherbak, N V Kryzhanovskaya, A A Lipovskii, A E Zhukov
1 Department of Physics and Technology of Nanostructures, Alferov University, St. Petersburg 194021, Russia
2 International Research Laboratory of Quantum Optoelectronics, Higher School of Economics, St. Petersburg 194100, Russia
3 Institute of Physics, Nanotechnology and Telecommunications, Peter the Great St. Petersburg Polytechnic University, St. Petersburg 195251, Russia

Abstract. We performed a numerical study of a surrounding medium influence on coupling efficiency between a microdisk resonator supporting optical whispering gallery modes and a straight optical waveguide. Quality factors of the modes and relative optical power coupled to the waveguide were calculated using COMSOL Multiphysics environment. It was shown that the most efficient coupling takes place when propagation constants of the modes of the microdisk and the waveguide match. The coupling can be significantly strengthened by increasing the index of the surrounding medium.

1. Introduction

Semiconductor lasers with microdisk (MD) resonators are of interest for many areas of applied optics and photonics. They are very promising for all-optical interchip communications, particularly, because of their planar structure, temperature stability [1] and possibility of the integration in semiconductor circuits. Also, they are used in biosensing [2, 3], thermal and mechanical actuators [4, 5] and nonlinear optics [6]. The distinctive feature of MD resonators is the possibility to support optical whispering gallery modes (WGM), which have high quality factor, up to $10^{11}$ [7], and, therefore, narrow spectral peaks. Such high Q-factor is reached because of a strong electro-magnetic field localization inside MDs. Thus, optical communication channels with light sources based on MD lasers can provide significant information capacity. However, microlasers with WGMs as light sources lack of selective and directional optical power output, which complicates practical use of the lasers in optoelectronics. Many researches were aimed at providing directivity of MD lasers radiation, for example, this can be done by using plasmonic nanoantennas [8], or hole formation in the microdisk surface [9], or by MD sidewall periodical roughness [10]. All these methods require post processing of MDs that brings additional manufacturing difficulties. The solution we focus on is based on coupling a MD resonator with a bus optical waveguide (OW) [11,12]. This way, light output occurs in the same plane with the MD and such structures can be integrated in semiconductor circuits that simplifies their use in optoelectronics. As was mentioned above, MDs supporting WGMs have high quality factor and strong field localization inside, and the latter leads to weak coupling with external optical elements. Here we propose covering a MD with a dielectric to increase the fraction of the optical power transferred to the OW.
2. Approach
To analyze WGMs coupling with the OW we used numerical simulation in COMSOL Multiphysics environment via the finite element method. The model includes a MD with diameter of 6 μm and refractive index $n_{in}=3.4$ (close to GaAs) and an OW of the same material as the MD. The scheme of the problem is shown in Figure 1. The OW width $w$ was varied to find the condition of a resonant coupling. Also we studied the influence of the gap between the MD and the OW ($d$) and a surrounding medium index $n_{out}$ on the coupling efficiency. We considered 2D geometry (cylinder of infinite width) instead of 3D because this allows reducing required computation power while the coupling properties are qualitatively the same. Also we limited our consideration with TM-polarized (E-field in-plane, H-field out-of-plane) modes only.

We used an eigenfrequency solver to find WGMs of the MD, their Q-factor and the fraction of their optical power coupled to the OW in the near infrared wavelength region 1250-1300 nm. To match modeled Q-factor with Q-factor of typical MD lasing structures [13] imaginary part of the MD index $k_{in}$ was set to the value of $5\cdot10^{-5}$ that can be interpreted as internal loses.

3. Results and discussion
3.1. Definition of the resonant coupling
We simulated several WGMs of the isolated MD in air: TM(1,44) – wavelength 1263.1 nm, TM(2,39) – 1261.3 nm, TM(3,35) – 1258.0 nm (numbers in the brackets are radial and azimuthal orders of the mode, respectively). In particular, we considered TM(1,44) mode and the gap between the OW and the MD $d=200$ nm and varied the OW width to find the condition of the resonant coupling. Note that the OW width barely affects the WGMs eigenfrequencies, for the coupling is weak. The results of the calculations are shown in Figure 2. The dependences of the mode Q-factor on the OW width in Figure 2a have dips at certain OW widths. These dips correspond to the condition, when the effective propagation constant of the WGM matches the propagation constant of the waveguide and therefore more efficient (resonant) coupling occurs [11, 12]. The subsequent dips correspond to $TM_{m0}$ modes of the OW, where $m = 1, 2 \ldots$ is a number of the H-field maxima in the transverse direction of the OW. Spatial distributions of $H_z$ field of $TM_{01}$ and $TM_{02}$ modes are presented in Figures 2b and 2c ($w=240$ nm and $w=530$ nm, respectively).

Figure 1. Schematic illustration of a WGM resonator side-coupled to an optical waveguide.
3.2. Coupling efficiency vs gap

We studied strength of the MD and the OW coupling for different spacing $d$ between them. The WGM under consideration was $\text{TM}(1,44)$ and $n_{\text{out}}=1$. Calculated dependences of Q-factor of the mode on the OW width for different $d$ are presented in Figure 3a. As expected, the coupling strengthens when the optical elements are closer. Although it is obvious that the dips in Q-factor correspond to the raise in outcoupled optical power, it is convenient to calculate an actual optical power coupled to the OW. For an isolated MD Q-factor of a mode is defined as $Q_0=W_{\text{in}}/P_{\text{in}}$, where $W_{\text{in}}$ is an optical power stored in the MD and $P_{\text{in}}$ are both inner losses caused by $k_{\text{in}}$ and radiation losses from the MD surface. For the MD loaded with the waveguide: $Q=W_{\text{in}}/(P_{\text{in}}+P_{\text{out}})$, where $P_{\text{out}}$ is radiation loss through the waveguide. Thus, the fraction of the optical power coupled to the waveguide $\chi = P_{\text{out}}/W_{\text{in}}$ expressed through quality factors is: $\chi = 1/Q - 1/Q_0$. The $\chi$ dependence on $d$ is shown in Figure 3b.

Figure 2. Q-factor of the mode $\text{TM}(1,44)$ coupled to the straight optical waveguide vs its width (a), spatial distribution of $H_z$-field of the $\text{TM}(1,44)$ mode in MD and in OW with 260 nm width (b), the same mode in MD, coupled with OW with 530 nm width (c).

Figure 3. Q-factor of the mode $\text{TM}(1,44)$ coupled to the straight optical waveguide vs its width for different distance $d$ between them (a). Relative optical power resonantly coupled to the optical waveguide vs $d$ (b).

The $\chi$ dependence on the gap width shows exponential decrease for larger distances between the MD and the OW. This indicates that the interaction is determined by the exponentially decaying evanescent tail of the WGM field. As we mentioned above, WGMs are strongly localized, therefore an outer field tail rapidly decays and the coupling is weak – according to Figure 3b the relative output power does not exceed 0.4% even at 50 nm gap.
3.3. Coupling efficiency vs surrounding index $n_{out}$

Typically, MD-OW coupling is considered in air or vacuum with refractive index equals 1 [12, 13]. Here we study the influence of outer medium index on the coupling efficiency. Again, we considered the mode TM(1,44), the gap $d=200$ nm and calculated the dependences of Q-factor of the mode on the OW width for different $n_{out}$. Magnitude of the dips of Q-factor increases for higher $n_{out}$ that is shown in the Figure 4a. MD-OW coupling becomes stronger in an optically denser medium for two reasons. First, the MD mode becomes less localized and the evanescent tail outside the MD intensifies. Second, the evanescent tail decay length is longer in an optically denser medium (see Figure 4b, where H-field spatial distributions for different outer indices are compared). Thereby, coupling with the waveguide through the optically denser medium is more efficient. Note that the increase of the outer medium index causes noticeable red-shift of the mode wavelengths [14].

![Figure 4](image)

**Figure 4.** (a) Q-factor of the mode TM(1,44) coupled to the straight optical waveguide vs its width for different $n_{out}$; (b) spatial distribution of $H_z$-field of TM(1,44) mode in the case of resonant coupling with the OW in the surrounding medium with $n_{out}=1.0$ (upper) and $n_{out}=1.6$ (lower).

As we mentioned above, we simulated three modes of the given MD: TM(1,44), TM(2,39) and TM(3,35). Here we analyze and compare coupling efficiency of these first three radial modes depending on the outer index. The corresponding dependences are presented in Figure 5. Noteworthy that the relative optical power resonantly coupled to the waveguide is generally higher for the higher radial order modes. However, as was shown in [14], higher radial modes also suffer with considerable decrease of their Q-factor under increase of the outer medium index. The reason is that higher radial modes are less localized and, therefore, all in all more sensitive to any kind of nearest surrounding of a MD, whether it be dielectric covers, or bus waveguide, or other optical elements. Also noteworthy that the fraction of the optical power coupled to the OW significantly grows with the increase of the outer index: 10-fold gain can be reached for $n_{out}=1.5$ (close to many polymers) and more than 150-fold gain for $n_{out}=2.4$ (close to TiO$_2$). The growth is exponential that confirms that the coupling is driven by the evanescent tail of the mode field as was mentioned above. Essentially, an increase of the refractive index of the outer medium is qualitatively equivalent to the rapprochement of the MD and the OW: the both methods increase field overlap between optical elements. Though, technologically much easier to cover MD with, e.g., polymer, than making optical elements at very close distances without loss of quality.
4. Conclusion

We numerically simulated the coupling between the microdisk resonator and the bus optical waveguide and considered surrounding medium influence on the coupling strength. WGMs couple to the OW more efficiently when the structure covered with an optically denser medium. Moreover, the coupling strengthens exponentially under the increase of the index of an outer medium. Qualitatively the same strengthening occurs when the gap between the MD and the OW decreases. This indicates that the coupling is driven by exponentially decaying tail of the WGM field and the both methods similarly increase the field overlap between optical elements. However, the suggested method of covering a MD with a dielectric is easier in terms of technology. Also we showed that the WGMs of higher radial order couple with the waveguide more efficiently because they are less localized than first radial order modes and generally more sensitive to the surrounding.

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