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Increasing the coupling efficiency of a microdisk laser to waveguides by using well designed spiral structures

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In this article, we optimize the coupling efficiency from a GaAs microdisk resonator into a single mode spiral waveguide. A classical microdisk resonator coupling light into a nonevanescent straight waveguide reaches a typical coupling efficiency of 67%. We show that the introduction of a spiral waveguide that works both as a waveguide and circular Bragg reflector can improve such efficiency to almost 90%. The same structure with the addition of a taper can couple up to 80% of the generated power into a slot waveguide. © 2010 American Institute of Physics.

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I. INTRODUCTION

The development in integrated electronic circuits has allowed the integration of different devices on the same chip. If similar degree of integration is to be achieved for optical circuits, we need to confine light into small regions. Such confinement of light can be achieved by using three different physical mechanisms: the photonic bandgap effect,1–4 total internal reflection (TIR),5–12 and plasmonic propagation.13,14 Among these techniques, TIR based devices are very widely used, especially in microdisks which have high quality factors, cleavage-free cavity, and excellent wavelength selectivity.15

In principle, a single microdisk can emit light uniformly in all in-plane directions owing to its rotational invariance.11 Thus coupling light from a microdisk into waveguides can be a challenge. In general, light coming from (or likewise entering into) a given polygonal resonator (e.g., square and corner-cut square,16 microdisk and microring17,18) can be either nonevanescently or evanescently coupled into a waveguide. The waveguide can also be placed on the same18,19 or on a different plane20,21 from the resonator.

In this paper, we examine different schemes to couple light from a microdisk resonator into a straight waveguide. The main focus is to optimize the coupling efficiency inside the waveguide. In the first case, light is coupled from the microdisk to a spiral waveguide20 that has two functions: transporting the emitted power and acting as a Bragg reflector. In principle, well designed circular Bragg gratings could considerably reduce the lateral “losses” at a certain wavelength ($\lambda_B$) due to its photonic band gap effect. However, the power coupled into the spiral waveguide can also be lost due to the bend in the waveguide. Thus the coupling efficiency is determined by the competition between the confinement of light due to the presence of the circular gratings and the propagation and bending losses of the spiral waveguide. We analyze the effects in this paper and optimized the structure.

In the second case, we introduce a slot waveguide to the optimized structure described above. Slot waveguide is a newly developed class of waveguides that has received significant attention in the recent years and may lead to large reductions in size of optical waveguides.21–25 It usually consists of two strips of high refractive index material separated by a subwavelength low refractive index material.21 Due to large discontinuity of electric field at the high index contrast interfaces, this structure can enhance and confine optical field in the low index region (slot) even when the light is guided by TIR.21 Furthermore, the addition of a taper25 can lead to a significant coupling of light into the waveguide.

II. GENERAL DESCRIPTION OF THE DEVICES AND ANALYSIS OF REFERENCE STRUCTURES

The structure design used to fabricate the lasers is shown in Fig. 1. The core region consists of GaAs with three In$_{0.5}$Ga$_{0.5}$As quantum dot layers. The quantum dots provide a maximum gain at $\lambda = 1200$ nm (where $\lambda$ is the free space wavelength) and with a spectral linewidth of around 100 nm. The total thickness of the core region ($h_1 = \lambda/2n$ for the con-
structive interference, where \( \lambda \) is the peak wavelength of the quantum dot and \( n \) is the effective index of the core region) is about 170 nm. In order to provide better vertical confinement of light, the structure also incorporates a distributed Bragg mirror consisting of 25 pairs of alternating GaAs and AlAs layers under the core region. Therefore, the reflection components from successive interfaces can be constructively interfered and finally generate a very strong reflection in the vertical direction. In our case such a distributed Bragg mirror can provide in excess of 99\% (normal incidence reflectivity) reflection at \( \lambda = 1200 \) nm so that most of the generated light remains in the core region. This structure confines light adequately for transverse-electric (TE) modes (with main magnetic field in the \( y \) direction). Moreover, this structure is primarily designed for laser devices operating under optical pumping; electrically pumped sources would require a different slab structure with doped regions.

In order to analyze the performance of devices, commercial finite-difference time-domain (FDTD) software “full-wave” is used.26 A Gaussian source with spot size diameter of 200 nm is placed close to the top edge of the microdisk resonator. Power/magnetic field monitors are placed in the middle of the waveguide. Perfectly matched absorbing layers are placed at the ends of the simulation region. The grid sizes in both \( x \) and \( z \) directions are 40 nm, while the grid size in the \( y \) direction is chosen as 20 nm. Finally, the time step is around \( 6.67 \times 10^{-17} \) s. We realize that the dynamic behavior and spectra of the devices may be changed when the devices are driven into lasing. However, it would be difficult to calculate coupling efficiencies if gain was added to the FDTD codes. Since when the device self-oscillates, there is not much control of the generated power in the cavity, making it considerably more difficult to estimate coupling efficiencies. Nevertheless, we believe that our study shows the potential of increasing the coupling efficiency by adding spiral waveguides.

We initially start the analysis of a stand-alone microdisk. Light is confined inside microdisk by TIR which occurs at the boundary between the high refractive index cavity and the low refractive index surroundings. This high index ratio is the key feature that strongly confines the optical mode to the plane of the microdisk so that a major fraction of the mode overlaps with the quantum dots.5 Among the possible modes propagating in the microdisk cavity, whispering gallery modes (WGMs) have high quality factors (Q). The resonant frequencies for the TE-like WGMs \( \text{TE}_{m,l} \) \((m \text{ and } l \text{ are angular and radial mode numbers})\) can be determined by solving the following eigenvalue equation:12

\[
J_m(n_{eq}kR)H_m^{(2)}(KR) = \eta J_m'(n_{eq}kR)H_m^{(2)}(KR),
\]

where \( J_m \) and \( H_m^{(2)} \) are the Bessel and second-kind Hankel functions of order \( m \), \( k \) is the free-space wave number, \( n_{eq} \) is the effective index of TE mode, and \( \eta \) equals to \( 1/n_{eq} \) for the TE-like WGMs.12 By solving this equation, we found that the main resonant mode (with the highest quality factor in the quantum dot gain linewidth) in our case is the \( \text{TE}_{22,1} \) mode.

Hereafter, the first case to be considered is the microdisk nonvanescently coupled with a straight waveguide [as shown in Fig. 2(a)]. This is the reference structure that will be used to compare different microdisk-waveguide configurations. The radius of the microdisk is 3.6 \( \mu \)m and the width of the single mode waveguide is 250 nm. In order to identify different resonant modes and their quality factors (in the absence of the quantum dots gain), we place a source with both spatial and temporal Gaussian profiles at the edge of the microdisk. A detector is placed in the middle of the waveguide to assess the performance of the combined waveguide-microdisk structure. The magnetic field spectrum \( (H_y) \) determines both resonant wavelengths and their quality

![Figure 2](image-url)
factors (Q). From laser theory, all the power that is generated from a laser resonator must exit through the cavity losses to avoid accumulation of energy in the cavity. Based on this fact, we can determine the coupling efficiency of the power generated into the waveguide.

The magnetic field spectrum ($H_y$) in the absence of quantum dots gain is shown in Fig. 2(b). The main peak occurs at $\lambda = 1.2112 \text{ } \mu m$ with $Q = 16822$. Due to the effect of coupling to a straight waveguide, the mode distribution at main peak is no longer WGM [as shown in Fig. 2(c)]. A power budget analysis indicates that about 67% of the power is coupled into the waveguide and less than 1% of the input power is lost downward into the distributed Bragg mirror while 4% escapes into the air region. All the remaining power is radiated in the lateral direction.

III. DEVICE DESIGN AND FIELD DISTRIBUTION ANALYSIS WITH CIRCULAR GRATINGS AND SPIRAL WAVEGUIDES

In order to increase the coupling efficiency into the straight waveguide, we initially add circular Bragg gratings to minimize the radiation losses in the lateral direction and concentrate light into the single-mode waveguide. These circular Bragg grating structures are designed to avoid light from escaping in the lateral direction since they operate in the photonic band gap region.

Based on Hankel functions, propagating waves in these circular gratings can be considered as inward and outward propagation cylindrical waves. As a result, the conventional coupled-mode theory is not suitable for the analysis of this structure. New coupled-mode theories have been used for so many years. And among them, the mth order coupling coefficient of the grating can be presented as

$$K_m = K_{-m} = \Gamma_g \left( \frac{\lambda}{2\beta} \right) \frac{\varepsilon_{(c)} - \varepsilon_{a}}{\pi m} \sin \left( \frac{\pi m d_2}{\lambda} \right),$$

where $k_0$ is the free space wave number, $\beta$ is the propagating constant, $\varepsilon_{(c)}$ and $\varepsilon_{a}$ are the permittivity of core region and air, respectively, $d_2/\lambda$ is the filling factor, and $\Gamma_g$ is the overlap integral which can be defined as

$$\Gamma_g = \left[ \int_{b1} |Z|^2 dz \right] \left[ \int_{-\infty}^{\infty} |Z|^2 dz \right]^{-1}.$$

Based on these formulas, power coupling of the basic grating structure can be affected by parameters such as filling factors, permittivity ($n = \sqrt{\varepsilon}$) of the grating material, grating height, and grating period ($\Lambda$). If the incident field has a wavelength close to the Bragg wavelength ($\lambda_B = 2n\Lambda$), it will be strongly reflected by the gratings.

In principle, we expect the maximum reflection to be achieved when the grating period is close to multiple integers of $\lambda/2$ (i.e., the air gap is $\lambda/4$ and grating width is $3\lambda/4n$). However, as mentioned by Scheuer and Yariv, for strong confinement the required circular gratings should exhibit a chirped and variable index profile. Due to this reason, we vary the dimension of both gap and solid regions to optimize the optical confinement in the microdisk region.

After going through an extensive optimization process (details are shown in Fig. 3), we determined that a high coupling efficiency can be achieved with five pairs of circular Bragg gratings [as shown in Fig. 4(a)]. The main peak in this case appears still at 1.2112 $\mu m$ and with a Q factor of 15318 as shown in Fig. 4(b). Figure 4(c) shows the magnetic field distribution at such peak. We can observe that most of the light is coupled into the waveguide. A power budget analysis indicates that about 88% of the generated power could be coupled into the waveguide, 5% of the generated power is lost into the vertical direction, mainly in the air region. From Fig. 3, the effect of parameter variation in the higher order gratings decreases due to the fact that the power which reaches the gratings further away from the microdisk exponentially decreases. Moreover, increasing the number of grating layers can further improve the efficiency, which is caused by greater amount of constructive interferences of the reflections.

Now what about if we use a spiral waveguide that works as both waveguide and Bragg reflector as shown in Fig. 5(a). When the spiral waveguide and microdisk resonator are merged, back reflections from the waveguide can occur, which may lead to the creation of additional resonant modes in the combined structure and a modification of the field profile of the main WGMs. These additional modes will compete with the main mode (main mode is the one with the...
highest quality factor) and can lead to an increase in the lasing threshold (the pumping power will be distributed among different modes), multiwavelength lasing and other undesirable behavior of the combined structure. Here we only consider the cases with up to three layers of spiral waveguides since further increase in the layer number will dramatically increase bending and radiation losses inside the waveguide, thereby reducing the coupling efficiency. From Fig. 5(b), the coupling efficiency increases significantly from 67% to 88% when we have one layer of spiral waveguide.

![FIG. 4.](image1)

![FIG. 5.](image2)

due to the reflection from spiral waveguide into the microdisk before being coupled into the waveguide. However, as the number of layers increases, power is also lost through
radiation in the curved waveguides. The net effect is a contradictory effect: more layers could lead to higher confinement of light in the microdisk but adding more curved waveguides will increase the bending losses.

The resonant peak in the case with one layer of spiral waveguide is almost at the same position as before [as shown in Fig. 5(c)] but the quality factor dramatically decreases to 3913 due to the relatively higher coupling efficiency into the waveguide. Although the Q is considerably lower, the structure can still reach lasing. Figure 5(d) shows the magnetic field distribution \( H_y \) at the main peak. Almost all in-plane light is coupled into the spiral waveguide. However, we can no longer claim that this main peak in the region where the quantum dots have high gain is TE\(_{22,1} \) and the mode is no longer a WGM mode anymore. Finally, a power budget analysis indicates that 88% of the light is coupled into the waveguide, less than 1% of light coupled downward to the distributed Bragg mirror region and approximately 4% of light emitted into the top air region with all remaining power lost in-plane.

\[
E_x = A \left\{ \begin{array}{ll}
\frac{1}{n_S} \cosh(\gamma_x x) & |x| < a \\
\frac{1}{n_H} \cosh(\gamma_a \cos[k_H(x-a)] + \frac{\gamma_a}{n_S^2 k_H} \sinh[k_H(x-a)]), & a < |x| < b \\
\frac{1}{n_C} \left\{ \cosh(\gamma_a \cos[k_H(b-a)] + \frac{\gamma_a}{n_C^2 k_H} \sinh(\gamma_a \sinh[k_H(b-a)] \right\} \exp[-\gamma_C(|x|-b)], & |x| > b
\end{array} \right.
\]

Here “a” and “b” are the slot and slab waveguide widths, respectively. \( k_H \) is the transverse wave number in high index slabs, and \( \gamma_x \) and \( \gamma_C \) are the field decay coefficients in the slot and cladding, respectively. \( A \) is the amplitude given by

\[
A = A_0 \frac{\sqrt{k_0^2 n_H^2 - k_H^2}}{k_0},
\]

where \( k_0 \) is the vacuum wave number. From these equations, we notice that at the interface, the value of \( E_x \) just inside of slot is \( n_S^2/n_H^2 \) higher than the value inside the slab.

We initially optimize the parameters in the slot waveguide at \( \lambda = 1211.2 \) nm which is the main peak for the structure in Sec. III. Figure 6(b) shows the power inside the slot region when we change the slot width. The highest confinement of power is achieved when the slot width is 80 nm. As the width increases above this optimum value, the field decay gradually becomes obvious and the slot can no longer maintain a high field across the entire region. Figure 6(c) shows the power in slot region when changing the slab width. Maximum power is achieved when the slab width is around 120 nm. In addition the structure also presents very low wavelength sensitivity [as shown in Fig. 6(d)] as there is no interference involved in the guiding and confinement mechanisms.

IV. COMBINED MICRODISK AND SPIRAL WAVEGUIDE STRUCTURES DESIGNED TO COUPLE LIGHT INTO A SLOT WAVEGUIDE

In recent years, new structures have been designed to confine or enhance the optical field in the subwavelength-scale low refractive index material even when light is guided by TIR. An example of device that guides light in low refractive index material is the slot waveguide.

Figure 6(a) shows the basic structure for the slot waveguide in which \( n_{H}=3.521 \) (GaAs) is the refractive index for slab waveguide (red part) and \( n_L=n_C=1 \) is the refractive index in slot and cladding region, respectively, (white part). Here the devices are still operating in TE mode but the main field component is \( E_x \) (the electric field component normal to interface). Based on the paper by Almeida et al., the analytical solution for \( E_x \) in fundamental two-dimensional TM mode of slab-based slot waveguide (analogous to three-dimensional quasi-TE mode) is given by

However, tunneling light from a microdisk laser coupled with a single mode waveguide into a slot waveguide can be a challenge. Since the overall dimensions are very small, normally a lower coupling efficiency is obtained between our previous structure (microdisk and single spiral waveguide) and the slot waveguide that greatly limit the device performance. Direct coupling will result in high losses due to the large mode distribution difference between slot and strip waveguides.

To solve this problem, we use an ultracompact low-loss coupler similar to that employed by Wang et al. as shown in Fig. 7(a). The straight waveguide here has the same width as the spiral waveguide in Sec. III but is tapered at the end to couple to the slot waveguide. In order to optimize the coupling efficiency at \( \lambda = 1211.2 \) nm, different parameters are investigated. From Fig. 7(b), the coupling efficiency initially increases dramatically with the length of taper due to more effective coupling. However, after it reaches a certain point, the efficiency gradually decreases due to the large propagation losses in the taper. The maximum power coupling is achieved when the taper length is 9 \( \mu \)m. The taper-slot gap dependency [Fig. 7(c)] shows that as the taper-slot gap increases from zero, the coupling remains fairly constant but after a critical point (e.g., 0.5 \( \mu \)m) it drops quickly as there
are more losses inside the gap which has larger dimension. The effect of changing end slab width of slot waveguide is shown in Fig. 7(d). Initially, the power coupling is constant when the end slab width increases. However, after a certain point, the coupling efficiency dramatically drops which is caused by the multireflection. Based on Fig. 7(e), the coupling efficiency varies less than 5% in the wavelength range between 0.8 and 1.3 \( \mu \text{m} \), while it gradually decreases after 1.3 \( \mu \text{m} \). This phenomenon is probably due to that the strip waveguide is cut off for longer wavelength.

Finally, we couple the slot waveguide with the optimized spiral Sec. III by using this optimized taper coupler [as shown in Fig. 8(a), the coupled part is enlarged on the left top corner]. A power budget analysis shows the same light power distributions as before except that 76.2\% of light inside the slot waveguide. Figure 8(b) shows the electric field

FIG. 6. (Color online) (a) Top view of the single slot waveguide, (b) power coupling in the slot region when varying the slot width, (c) power coupling in the slot region when varying the slab width, and (d) power coupling in the slot region when varying the wavelength.

FIG. 7. (Color online) (a) Top view of the strip and slot waveguide coupling with taper coupler, (b) coupling efficiency in the slot waveguide changes with taper length, (c) coupling efficiency in the slot waveguide changes with gap between taper and slot waveguide, (d) coupling efficiency in the slot waveguide changes with end slab width, and (e) coupling efficiency in the slot waveguide when varying the wavelength.
distribution (E_x) at the wavelength of 1.2112 µm. The field distribution inside the microdisk is similar as the magnetic field distribution shown in Fig. 5(d) but with weaker intensity. From the enlarged figure of the taper-slot section, we notice that most of the light from the spiral waveguide output is coupled into the slot waveguide.

V. STEADY-STATE ANALYSIS

The rate equations of both carriers and photon densities can be expressed by Eqs. (6)–(8).35,36 We assume that the devices are optically pumped in the vertical direction by an external laser with a wavelength of 637 nm and a spot size diameter of 6 µm.

\[
\frac{dN_w}{dt} = \eta \frac{P_m \lambda_p}{\hbar c V_a} - \frac{N_w}{\tau_w} - \frac{N_w}{\tau_c},
\]

\[
\frac{dN_g}{dt} = \frac{N_w}{\tau_c} - \frac{N_g}{\tau_{sp}} - \frac{N_g}{\tau_{tr}} - \text{GP},
\]

\[
\frac{dP}{dt} = \Gamma \text{GP} + \Gamma \beta \frac{N_g}{\tau_{sp}} - \frac{P}{\tau_p},
\]

where N_w is the wetting layer carrier density, N_g is the quantum dot ground state carrier density, and P is the photon density. P_m is the external laser pump power and \lambda_p is the pump wavelength. The active pump volume V_a is given by,35,36

\[
V_a = h_a \frac{\phi_s^2}{4},
\]

where h_a is the thickness of the active region and \phi_s is the spot size diameter of the external pump laser.

The time constant \tau_p is given by,35,36

\[
\tau_p = \frac{Q \lambda_e}{2 \pi c},
\]

where \lambda_e is the emitting wavelength and Q is the quality factor of the resonant mode.

The gain G of the quantum dots can be expressed as,36

\[
G = G_0 (N_g - N_{tr}),
\]

where G_0 is the linear gain coefficient with the value of 8.2 \times 10^{-6} s^{-1} in our case and N_{tr} is the transparency carrier density with a typical value of 3.2 \times 10^{23} m^{-3}.

In the steady-state regime all derivatives are zero. By solving these equations, we will be able to determine the threshold values of N_w, N_g, and P. We can also determine the output power by using the equation below35,36

\[
P_{out} = \eta \frac{\hbar c V_{mode}}{\lambda_e} \frac{V_{mode}}{\tau_{mirror}},
\]

where \eta is the coupling efficiency into the waveguide, \tau_{mirror} is the mirror lifetime which has got the same value as \tau_p, and V_{mode} (the optical mode volume) can be expressed as

\[
V_{mode} = h_p \pi r^2,
\]

where h_p is the thickness of the optical core and r is the radius of the microdisk resonator. All remaining parameters are summarized in Table I.

Although the microdisk structure can lase at different peaks, we are only concerned with the steady-state laser characteristics of the main peak within the quantum dot gain linewidth. In Fig. 9 we compare the light output versus pump power for the above three cases which are (a) microdisk directly coupled with a straight waveguide (dotted line), (b)

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<th>Table I. Typical parameter values in steady-state laser analysis.</th>
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<td>Symbol</td>
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microdisk directly coupled with a one-layer optimized spiral waveguide (solid line), and (c) microdisk coupled with a one-layer optimized spiral waveguide and a slot waveguide (dashed line). All three cases have the same threshold but differential quantum efficiency in case (b) and (c) are much higher than (a). Although the quality factors in these two cases [(b) and (c)] decrease substantially, the overall coupling efficiencies have been greatly improved compared to case (a) which ultimately results in higher differential efficiency.

VI. CONCLUSIONS

In this article, we analyze the coupling efficiency of a microdisk laser under three different situations: nonevanescently coupled with a straight waveguide, directly coupled with a spiral waveguide and coupled with a spiral and a slot waveguide. Among these schemes, directly coupling with a one-layer spiral waveguide can lead to a significant improvement in the coupling efficiency from 67% (reference scheme) to 88% and is the best coupling scheme investigated in this paper. Furthermore the combination between the spiral and a slot waveguide by using a well designed taper coupler can almost avoid the coupling losses and reach 76.2% efficiency in the slot waveguide.

ACKNOWLEDGMENTS

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