Theoretical Analysis of Unidirectional Operation and Reflection Sensitivity of Semiconductor Ring or Disk Lasers

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***Abstract*— We theoretically and numerically analyze the unidirectional behavior of ring or disk lasers coupled to a bus waveguide with a relatively strong reflector on one side and find analytical expressions for the ratio of the powers in clockwise and counter clockwise modes. At low bias levels, this ratio depends on the coupling coefficients that determine the coupling between clockwise and counterclockwise modes, whereas at high bias levels it also depends strongly on the gain suppression. We also theoretically and numerically investigate the feedback sensitivity of such lasers and come to the conclusion that ring or disk lasers are generally much more sensitive to external reflections than traditional Fabry–Perot, DFB, or DBR lasers. At high bias levels, the feedback sensitivity also depends strongly on the gain suppression, and at high enough power levels, it can be better than that of traditional edge-emitting lasers.**

***Index Terms*— Ring lasers, microdisk lasers, reflection sensitivity, unidirectional operation.**

I. Introduction

SEMICONDUCTOR ring or microdisk lasers have been studied extensively in the past decade, a.o. because of their suitability as bistable lasers for optical switching or signal processing applications [1], [2], but also owing to their easy incorporation in photonic integrated circuits. Indeed, ring or disk lasers don't require reflecting facets or diffraction gratings and can be relatively easily fabricated. Using heterogeneous integration, microdisk lasers with very low threshold current and arrays of microdisk lasers, all coupled to the same bus waveguide, have been demonstrated, making these lasers good candidates for the light sources of e.g. on-chip optical interconnect [3].

Recently, there have been some reports about unidirectional operation of ring or disk lasers coupled to a bus waveguide with on one side a strong reflection and on the other side a weak or no reflection. In [4], such unidirectional operation has been qualitatively demonstrated using camera images of the light scattered by the waveguide roughness. In [5], a more detailed experimental and numerical analysis is presented for heterogeneously integrated microdisk lasers coupled to a bus waveguide on one side of which an almost 100% reflecting Bragg grating was designed.

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In this paper, we theoretically analyse the unidirectional behaviour starting from the coupled rate equations for the clockwise and counter clockwise mode and we demonstrate that, at low bias, the ratio of the powers (or photon numbers) in the clockwise and counter clockwise modes is equal to the ratio of the coupling coefficients that quantify the coupling between clockwise and counter clockwise modes. At high bias, this ratio is even larger and depends on the gain suppression.

From the same analysis, we can furthermore extract the reflection (feedback) sensitivity of such unidirectional ring lasers. We obtain that the change in threshold gain and optical frequency of ideal unidirectional ring or disk lasers, due to an external reflection is proportional with the square rooth of the external field reflection, in contrast with Fabry-Perot, DFB and DBR lasers for which the changes in threshold gain and frequency are proportional with the field reflection. Semiconductor ring lasers are therefore generally more sensitive to external feedback than Fabry-Perot or DFB/DBR laser diodes.

Below we first give a theoretical derivation that allows to derive the ratio of the powers in the clockwise and counter clockwise directions. We then proceed to derive, from the same analysis, some useful expressions for the feedback sensitivity of ring or disk laser diodes. Studies of the feedback sensitivity or ring or disk laser diodes have not been reported so far.

II. Unidirectionality of a Ring or Disk Laser Coupled to a Strong Reflector on One Side

A. Coupled Rate Equation Model

We start from the coupled rate equations for the complex field amplitudes E_{CW} and E_{CCW} of the clockwise and counter clockwise propagating laser modes respectively [6]:

$$\frac{dE_{CW}}{dt} = \frac{1}{2}(1+j\alpha)\left[G-\frac{1}{\tau_p}\right]E_{CW} + K_1 E_{CCW} \quad (1)$$

$$\frac{dE_{CCW}}{dt} = \frac{1}{2}(1+j\alpha)\left[G-\frac{1}{\tau_p}\right]E_{CCW} + K_2 E_{CW}. \quad (2)$$

We express the electric field amplitudes E_{CW} and E_{CCW} of clockwise and counter clockwise mode respectively and the coupling coefficients K_i in terms of their amplitude and phase:

$$E_{CW} = \sqrt{S}_{CW}\, exp\,(j\varphi_{CW}), \quad E_{CW} = \sqrt{S}_{CCW}\, exp\,(j\varphi_{CCW})$$
$$K_i = |K_i|\; exp\,(j\phi_i) \quad (3)$$

α is the linewidth enhancement factor, G the modal gain per unit time, and τ_p the photon lifetime of the cavity without

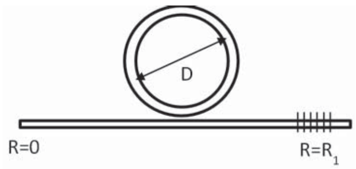

Fig. 1. Schematic structure of a ring laser coupled to a bus waveguide, with a reflecting Bragg grating on one side.

the coupling between clockwise and counter clockwise modes. We have normalized the optical fields such that their squared amplitude is equal to the photon number S.

The coupling coefficients K_i are the total field reflection (including phase) seen by the CW or CCW mode divided by the roundtrip time of the ring or disk under consideration. They include scattering due to sidewall roughness as well as reflections from facets or gratings in the bus waveguide. We can now decompose the equations for the complex electrical fields into an amplitude and phase equation. We consider the static case, for which the field amplitudes (and photon numbers S) are constant in time. Important in ring or disk lasers is that the gain for the CW and CCW mode experiences different gain suppression, i.e. [6]

$$\begin{aligned} G_{CW} &= G_0(N)/[1+\epsilon S_{CW}+2\epsilon S_{CCW}] \\ G_{CCW} &= G_0(N)/[1+2\epsilon S_{CW}+\epsilon S_{CCW}]. \end{aligned} \tag{4}$$

This gain suppression is typically symmetric around the laser line, such that there is no effect on the refractive index (or on the phase). Eqs, (1) to (4) can be combined to obtain (with $\Delta\phi = \phi_{CW}$-ϕ_{CCW} and $S_{CW}/S_{CCW} = \mu^2$):

$$G_0/[1+\varepsilon S_{CW}+2\varepsilon S_{CCW}] = \frac{1}{\tau_p} - 2\frac{|K_1|}{\mu} cos(\Delta\varphi - \phi_1) \tag{5}$$

$$G_0/[1+2\varepsilon S_{CW}+\varepsilon S_{CCW}] = \frac{1}{\tau_p} - 2|K_2|\mu cos(\Delta\varphi + \phi_2) \tag{6}$$

$$\frac{d\varphi_{CW}}{dt} = \Delta\omega = \frac{\alpha}{2}\left(G_0 - \frac{1}{\tau_p}\right) - \frac{|K_1|}{\mu} sin(\Delta\varphi - \phi_1) \tag{7}$$

$$\frac{d\varphi_{CCW}}{dt} = \Delta\omega = \frac{\alpha}{2}\left(G_0 - \frac{1}{\tau_p}\right) + |K_2|\mu sin(\Delta\varphi + \phi_2) \tag{8}$$

B. Unidirectionality Without Gain Suppression

In a ring/disk laser coupled to a reflector on one side of the bus waveguide, as shown schematically in Figure 1, one can assume that K_2 is due to sidewall roughness and residual facet reflection, while K_1 also includes reflection from the (e.g. Bragg) reflector in the bus waveguide and is thus much larger than K_2. With κ being the coupling between the ring/disk and the bus waveguide and r_1 the field reflection in the bus waveguide, one can write:

$$K_1 = K_2 + |\kappa|^2 \frac{r_1}{\pi D} v_g \tag{9}$$

D is the diameter of the ring/disk and v_g the group velocity in the laser cavity. r_1 should also include the phase delay due to propagation between the ring and the reflector (being a facet or Bragg grating e.g.).

We will first derive μ from the equations (5)-(8) for bias currents close to the threshold current, when the gain suppression can still be neglected. From (7) and (8), one finds that:

$$|K_1|\sin(\Delta\varphi - \phi_1) = -|K_2|\mu^2 \sin(\Delta\varphi + \phi_2) \tag{10}$$

While subtracting (5) and (6), for $\varepsilon = 0$, gives:

$$|K_1|\cos(\Delta\varphi - \phi_1) = |K_2|\mu^2 \cos(\Delta\varphi + \phi_2) \tag{11}$$

Dividing (10) and (11) then results in:

$$\begin{aligned} &\tan(\Delta\varphi - \phi_1) = -\tan(\Delta\varphi + \phi_2), \\ &\text{or } \Delta\varphi = \frac{\phi_1 - \phi_2}{2} + \mathrm{m}\pi \ (\mathrm{m} = 0, 1) \end{aligned} \tag{12}$$

Substituting $\Delta\phi$ in (10) or (11) readily gives:

$$\mu^2 = \frac{S_{CW}}{S_{CCW}} = \frac{|K_1|}{|K_2|} \tag{13}$$

Which shows that the powers in the clockwise and counter clockwise modes are in the same ratio as their respective field reflection coefficients. For the threshold gain, one easily finds:

$$G_0 = \frac{1}{\tau_p} - 2\sqrt{|K_1K_2|}\cos\left(\mathrm{m}\pi - \frac{\phi_1 + \phi_2}{2}\right) \tag{14}$$

The value for m (0 or 1) that gives a positive cosine has to be chosen as it is the solution that results in lowest threshold gain. For the frequency deviation, we find from (7) or (8):

$$\begin{aligned} \Delta\omega &= -\sqrt{|K_1K_2|}\left\{\alpha\, cos\left(\mathrm{m}\pi - \frac{\phi_1+\phi_2}{2}\right)\right. \\ &\qquad \left. + \sin\left(\mathrm{m}\pi - \frac{\phi_1+\phi_2}{2}\right)\right\} \\ \Delta\omega &= -\sqrt{|K_1K_2|(1+\alpha^2)}\sin\left(\mathrm{m}\pi - \frac{\phi_1+\phi_2}{2} + \tan^{-1}\alpha\right) \end{aligned} \tag{15}$$

A typical value for K_2 is 6.28 10^9 s^{-1} (see [2]). For a microdisk laser with a 10 μm diameter, a group index of 3 and 2% of coupling between the disk and the bus waveguide, we find for K_1 the value 0.02 $10^{14}\,\mu$m/s/($\pi\,10\mu$m) = 6.36 10^{10} s^{-1}. This gives a ratio $|K_1/K_2|$ of about 10.

C. Influence of Gain Suppression: Low Power Limit

At higher bias currents, one also has to include the gain suppression. Equation (10) doesn't change in this case, but equation (11) must be replaced by (with $\varepsilon' = \varepsilon/(1+3\varepsilon S_{CW})$):

$$\begin{aligned} \varepsilon' G_0 (S_{CW} - S_{CCW}) &= 2|K_2|\mu cos(\Delta\varphi + \phi_2) \\ &\quad - \frac{2}{\mu}|K_1| cos(\Delta\varphi - \phi_1) \end{aligned} \tag{16}$$

$$\begin{aligned} \varepsilon' G_0 (S_{CW} - S_{CCW}) &= 2|K_2|\mu \frac{sin[2\Delta\varphi + \phi_2 - \phi_1]}{sin[\Delta\varphi - \phi_1]} \\ &\approx \varepsilon' G_0 S_{CW} \end{aligned} \tag{17}$$

We now consider the case with $\mu \gg 1$, i.e. $|K_1| \gg |K_2|$, and thus can neglect S_{CCW}. To take into account the gain suppression, we introduce the approximations:

$$\mu^2 = \frac{|K_1|}{|K_2|}(1+\delta) \text{ and } \Delta\varphi = \frac{\phi_1 - \phi_2}{2} + \delta\varphi \tag{18}$$

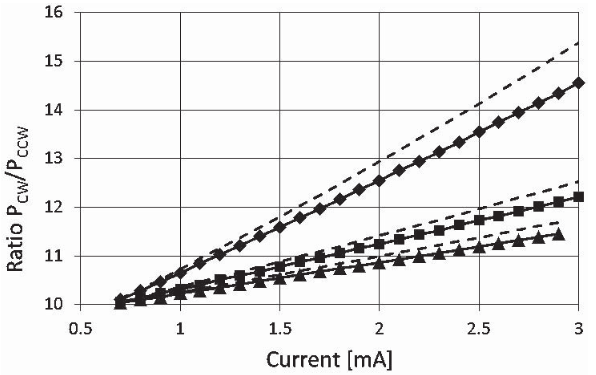

Fig. 2. Ratio of power in CW and CCW modes, obtained from a numerical solution of the coupled rate equations, for a microdisk laser with coupling coefficients $K_1 = 6\ 10^{10} s^{-1}$, and $K_2 = 6\ 10^9 s^{-1}$, (♦) for $(\phi_1,\phi_2) = (0, 0)$ and $\varepsilon = 2\ 10^{-18}$ cm^3, (■) for $(\phi_1,\phi_2) = (0, 0)$ and $\varepsilon = 1\ 10^{-18}$ cm^3, and (▲) for $(\phi_1,\phi_2) = (0, \pi/2)$ and $\varepsilon = 10^{-18}$ cm^3. The dashed lines are the approximation as obtained by (20).

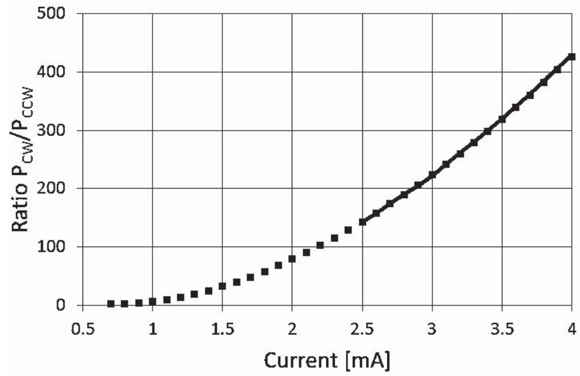

Fig. 3. Ratio of power in CW and CCW modes, (■) obtained from a numerical solution of the coupled rate equations, for a microdisk laser with coupling coefficients K1=6.36 $10^8 s^{-1}$, and 3.18 $10^8 s^{-1}$, and (−) obtained from expression (23). $\varepsilon = 10^{-18}$ cm^3.

with δ and $\delta\varphi$ being small. Substituting these expansions in (10) allows to express $\delta\varphi$ as

$$\delta\varphi = -\frac{\delta}{2}\tan(\frac{\phi_1+\phi_2}{2})$$

Substitution in (17) gives:

$$\varepsilon' G_0 S_{CW}\, cos\left(m\pi - \frac{\phi_1+\phi_2}{2}\right) = 2\delta\sqrt{|K_1||K_2|} \quad (19)$$

And thus:

$$\mu^2 = \frac{|K_1|}{|K_2|}\left(1+\frac{\varepsilon' G_0 S_{CW}\ \cos\left(m\pi - \frac{\phi_1+\phi_2}{2}\right)}{2\sqrt{|K_1||K_2|}}\right)$$
$$\Delta\omega = \varepsilon' G_0 S_{CW} - \sqrt{\frac{|K_1K_2|\left(1+\alpha^2\right)}{1+\delta}}\ \sin\left(m\pi - \frac{\phi_1+\phi_2}{2} + \tan^{-1}\alpha + \delta\varphi\right) \quad (20)$$

For a numerical example, we consider again the microdisk with a 10 μm diameter, for which $|K_1|$ and $|K_2|$ are 6.36 10^{10} s^{-1} and 6.36 10^9 s^{-1} respectively. In Figure 2, we plot the values of μ^2 obtained for two different values of ε, $\varepsilon = 1\ 10^{-18}$ cm^3 and $\varepsilon = 2\ 10^{-18}$ cm^3., and for $(\phi_1,\phi_2) = (0, 0)$ and $(\phi_1,\phi_2) = (0, \pi/2)$ respectively. The solid lines with symbols represent the values obtained from a numerical time domain simulation of the coupled equations (1), while the dashed lines represent the values obtaind using (20). The approximation can be made even better by replacing S_{CW} by $S_{CW}(1-|K_2/K_1|)$.

For the special case $\phi_1 + \phi_2 = \pi$, and for $\varepsilon = 0$, one finds from (11) that $\Delta\phi - \phi_1 = \pm\ \pi/2$ and thus $\cos(\Delta\phi - \phi_1) = 0$. Although one finds from (10) that $\mu^2 = |K_1/K_2|$, we obtain from the time domain numerical analysis a self-pulsating behaviour irrespective of the value of ε.

It is emphasized that the above approximations are only valid as long as δ is small, i.e. as long as $\varepsilon G_0 S_{CW} < (2\sqrt{|K_1||K_2|})$.

D. Influence of Gain Suppression: High Power Limit

For high power levels or low coupling constants K_1 and K_2, one has $\varepsilon G_0 S_{CW} \gg (2\sqrt{|K_1||K_2|})$, and in this case we can assume that $\mu^2 \gg |K_1|\,/\,|K_2|$. From (10), it then follows that:

$$\Delta\varphi + \phi_2 = 0 \text{ and } \Delta\varphi - \phi_1 = -\left(\phi_1+\phi_2\right) \quad (21)$$

Substitution in (16) gives:

$$\varepsilon' G_0 S_{CW} = 2\,|K_2|\,\mu - \frac{2}{\mu}\,|K_1|\,cos\left(\phi_1+\phi_2\right) \quad (22)$$

with solution in (23), as shown at the bottom of the page.

Figure 3 shows μ^2 obtained from a time domain numerical solution of the couled wave equations (1) up to higher current levels for the case, $K_1 = 6.36\ 10^8$ s^{-1}, $K_2 = 3.18\ 10^8$ s^{-1}, and $\varepsilon = 10^{-18}$ cm^3 as well as the results for currents above 2.5mA obtained using (23). Although the ratio K_1/K_2 is only 2, one obtains much higher μ^2 values and they correspond quite well to the values obtaind using (23).

III. Reflection Sensitivity of Ideal Ring or Disk Lasers

In a Fabry-Perot or DFB laser of length L, with one 100% reflecting facet and one partly or non-reflecting facet, the feedback sensitivity parameter C can be expressed as [7], [8]:

$$|C| = \frac{2}{\tau_L}\alpha_{end} L\sqrt{K_z} \quad (24)$$

$$\mu = \frac{\varepsilon' G_0 S_{CW} + \sqrt{(\varepsilon' G_0 S_{CW})^2 - 8|K_2|\varepsilon' G_0 S_{CW} + 16|K_2K_1|cos(\phi_1+\phi_2)}}{4|K_2|} \approx \frac{\varepsilon' G_0 S_{CW}}{2\,|K_2|}$$
$$\Delta\omega = \varepsilon' G_0 S_{CW} + \frac{2\,|K_1K_2|}{\varepsilon' G_0 S_{CW}}\sqrt{\left(1+\alpha^2\right)}\sin\left(\phi_1+\phi_2-\tan^{-1}\alpha\right). \quad (23)$$

with $\alpha_{end}L$ being the normalized facet loss and K_z the longitudinal Petermann factor. For a Fabry-Perot laser with one 100% reflecting facet, one can write:

$$\frac{|C|\,\tau_L}{\alpha_{end}L} = \frac{1-(r_2)^2}{-r_2\ln(r_2)} \tag{25}$$

The change in optical pulsation $\Delta\omega$ due to an external field reflection r_e is given by:

$$\Delta\omega = |C|\,|r_e|\sqrt{1+\alpha^2}\sin\left(\omega\tau_e - \tan^{-1}\alpha\right) \tag{26}$$

Obviously, (24) implies that the reflection sensitivity of a DFB laser is, apart from a possibly different K_z factor, identical to that of a Fabry-Perot laser with identical facet loss. In what follows, we will therefore only compare the reflection sensitivity of ring lasers with that of Fabry-Perot lasers.

A. The Low Power Limit

From (20), we can derive that for a perfect ring or disk laser (i.e., without any scattering or residual facet reflection) without gain suppression, the equivalent of (26) is (using $K_2 = |\kappa|^2 r_e/\tau_L$)

$$\Delta\omega = \sqrt{\left|K_1\frac{\kappa^2}{\tau_L}r_e\right|}\sqrt{1+\alpha^2}\sin\left(\frac{\phi_1+\omega\tau_e}{2} - \tan^{-1}\alpha\right). \tag{27}$$

Assuming a 100% reflection on one side of the bus waveguide, we have $K_1 = |\kappa|^2/\tau_L$ and (27) can be transformed into:

$$\Delta\omega = \frac{|\kappa|^2}{\tau_L}\sqrt{|r_e|}\sqrt{1+\alpha^2}\sin\left(\frac{\phi_1+\omega\tau_e}{2} - \tan^{-1}\alpha\right) \tag{28}$$

For such a ring laser, the normalized facet loss is (for relatively small κ):

$$\alpha_{end}\pi D = \ln\left(\frac{1}{1-|\kappa|^2}\right) \approx |\kappa|^2 \tag{29}$$

Hence, we can write in analogy with (24) and with $L = \pi D$:

$$\begin{aligned}\Delta\omega &= |C|\sqrt{|r_e|}\sqrt{1+\alpha^2}\sin\left(\frac{\phi_1+\omega\tau_e}{2} - \tan^{-1}\alpha\right)\\ \frac{|C|\tau_L}{\alpha_{end}L} &= \frac{\kappa^2}{-\ln\left(1-\kappa^2\right)} = \frac{1-t^2}{-2\ln(t)},\ t = \sqrt{1-\kappa^2}\end{aligned} \tag{30}$$

The normalized values of $|C|$ given by (25) and (30) are plotted in Figure 4 as a function of r_2, resp. t. Although the normalized values are seen to be smaller for ring lasers, the square root dependence on the external reflection r_e, implies that ring lasers will generally have a higher feedback sensitivity. This is especially the case for external reflections of −40dB or less, for which $r_e < 0.01$ and thus sqrt(r_e) > 10 r_e. The expression (30) also holds for non-ideal ring lasers, provided that the coupling K_2 due to scattering (or residual facet reflections) is much smaller than that due to the external reflection. For microdisk lasers as in [2], the value of t is typically of the order of 0.98 – 0.99.

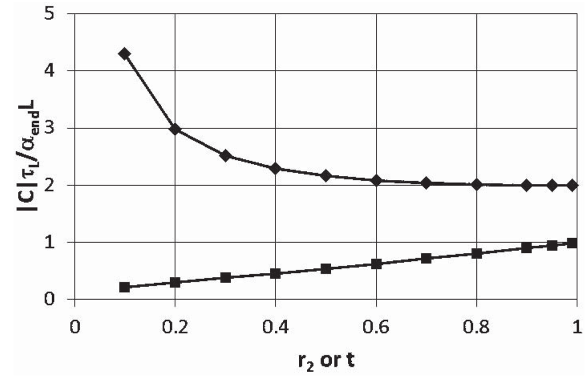

Fig. 4. Normalized external reflection sensitivity of a Fabry-Perot laser with one 100% reflecting facet and one facet with field reflection r_2 (♦) and of a ring laser with one perfectly AR-coated facet, one 100% reflecting facet and a coupling κ ($t^2 = 1-\kappa^2$) between ring and bus waveguide (■).

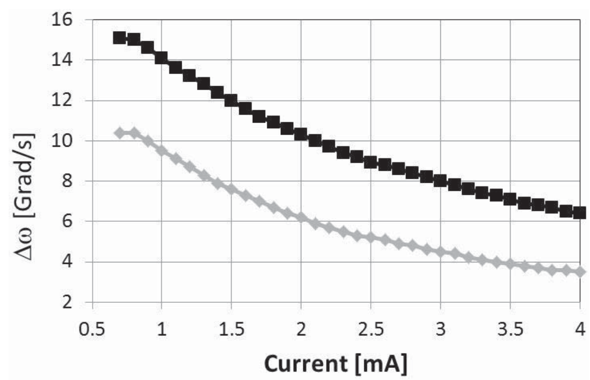

Fig. 5. Change in optical pulsation ($\Delta\omega$) due to external reflections as a function of bias current. Black curve: $r_e = 10^{-2}$, grey curve: $r_e = 5\ 10^{-3}$.

B. The High Power Limit

In this case, we can make use of (23). We first consider an ideal ring or disk laser, for which $K_2 = 0$ and $K_1 = |\kappa|^2/\tau_L$ and without the external feedback. From (23) we find:

$$\begin{aligned}\Delta\omega &= |C|r_e\sqrt{1+\alpha^2}\sin\left(\phi_1+\omega\tau_e - \tan^{-1}\alpha\right)\\ \frac{|C|\,\tau_L}{\alpha_{end}L} &= \frac{2\kappa^4}{-\ln\left(1-\kappa^2\right)\tau_L}\frac{1}{\varepsilon' G_0 S_{CW}}\\ &= \frac{\left(1-t^2\right)^2}{-2\ln(t)}\frac{1}{\varepsilon' G_0 S_{CW}\tau_L}.\end{aligned} \tag{31}$$

Since τ_L is typically of the order of ps or sub-ps, and $\varepsilon' G_0 S_{CW}$ is of the order of $10^{10}s^{-1}$, the last factor in (31) is 100 or more. For values of t^2 larger than 99% (i.e. κ^2 smaller than 1%), the normalized value of C can be smaller than that of an equivalent Fabry-Perot laser (in both cases at the expense of the efficiency). For larger values of κ, ring or disk lasers will have a worse feedback sensitivity though. The approximation (31) is valid as long as $r_e < (\varepsilon G_0 S_{CW}\tau_L/2\kappa^2)^2$. For a microdisk laser with $\kappa^2 = 1\%$, 10μm diameter and $\varepsilon G_0 S_{CW} = 10^{10}s^{-1}$, this gives $r_e < 0.025$ or $R_e < 6.\ 10^{-4}$.

Figure 5 shows $\Delta\omega$ obtained from a numerical time domain solution of the rate equations as a function of the bias current for microdisk lasers with a 10μm diameter and $\kappa^2 = 0.01$.

The bus waveguide has on one side a 100% reflecting facet and on the other side a perfectly AR-coated facet. Two values for r_e are considered: $r_e = 10^{-2}$ and $r_e = 5\ 10^{-3}$. We used $\phi_1 = \phi_2 = 0$ and an α-factor of -5 to obtain maximum $\Delta\omega$. One can see that the reflection sensitivity decreases with increasing bias current (or power) in both cases, and that at low bias $\Delta\omega$ increases proportional with the square root of r_e while at higher bias $\Delta\omega$ is rather proportional with r_e. For values of r_e of 10^{-2} or below, there is of course an order of magnitude or more difference between r_e and its square root.

It can also be remarked that since $\Delta\omega$ is proportional with K_1K_2 at higher power levels, one can also decrease the feedback sensitivity of these ring or disk lasers (without affecting the unidirectionality) by decreasing K_1, i.e. by decreasing the reflection R_1 (which we assumed to be 100%) so far.

In the case of a non-negligible K_2 (e.g. caused by a facet reflection r_2), a reflection sensitivity can be derived by expanding K_2 as:

$$K_2 = \frac{|\kappa^2|}{\tau_L}\left[r_2 + \left(1 - |r_2|^2\right) r_e \exp\left(-2j\omega\tau_e\right)\right] \tag{32}$$

IV. Conclusion

We have shown theoretically that ring or disk lasers with a strong reflection from one side and a weak reflection from the other side can be operating in a unidirectional mode. At low power levels, the ratio of powers in clockwise and counter clockwise mode is approximately equal to the ratio of the coupling coefficients between clockwise and counter clockwise mode, while at high power levels this ratio is determined by gain suppression and the lowest coupling coefficient.

Using the same analysis, we were also able to derive the external feedback sensitivity of unidirectional ring lasers with different configurations and compare it to the feedback sensitivity of Faby-Perot lasers with one 100% reflecting facet and one partially reflecting facet. In general, ring laser diodes seem to be more sensitive to external feedback than Fabry-Perot or DFB/DBR laser diodes. At high power levels though, the feedback sensitivity of ring/disk lasers decreases considerably due to gain suppression and under certain conditions it can be better than that of conventional edge-emitting laser diodes.

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