High-power limitation of passive ring-resonator-coupled lasers in the presence of material nonlinearity

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We investigate the high-power limitation and stability of a passive ring-resonator-coupled laser (RCL). A detailed numerical analysis of the bidirectional transmission of the microring resonator in the presence of material nonlinearity is presented. The two-photon absorption is the limiting factor for high-power operation of the RCL. © 2004 American Institute of Physics.

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Passive ring-resonator-coupled lasers (RCL) offer great promise for reducing the linewidth, improving the side mode suppression, and extending the wavelength tuning range. Many of these benefits come from the low-loss and high finesse microring. However, nonlinear optical absorption and refraction cannot be neglected due to the cavity enhancement of light intensity in the microring. Nonlinear optical absorption adds extra loss in the ring, which increases the threshold current and degrades the emission linewidth and side mode suppression. Furthermore, the nonlinear optical refraction shifts microring resonance wavelength and laser cavity modes, and may cause operation bistability. In this work, we investigate the high power limitation of RCL.

Two-photon absorption (TPA) and the corresponding nonlinear refraction are the dominant factors influencing the transmission in the waveguide at large light intensities. The light intensity enhancement and the optical nonlinearity in a microring resonator have been used in applications such as all-optical switching. The dispersion of the two-photon absorption coefficient $\beta$ obeys Van Stryland’s scaling law. The nonlinear refraction coefficient $n_2$ can be derived from the two-photon absorption spectra by Kramers–Kronig relations. It was shown that the nonlinear refraction coefficient got a positive peak close to the two-photon absorption edge and then decreased, turning negative in the middle of the two-photon and single-photon absorption edge. Thus, the amplitude of the nonlinear refraction coefficient may have a small absolute value where it turns the sign. We use the ring ridge-waveguide structure described in Ref. 3, with a GaInAsP core layer ($\lambda_{gap} = 1.06 \mu m$), which has a small nonlinear refraction coefficient. The waveguide width is 1.4 $\mu m$ and the microring radius is 100 $\mu m$. The effective area of the waveguide mode is 1.257 $\mu m^2$ by beam propagation simulation. We assume a constant $\beta \sim 20 \text{cm/GW}$ and a constant $n_2 \sim 1.7 \times 10^{-13} \text{cm}^2/\text{W}$ at wavelength 1550 nm in the simulation.

Figure 1 is the proposed structure of the passive microring-resonator-coupled laser. Since the transmission in the ring is bidirectional, the TPA and nonlinear refraction due to the interaction between clockwise and counterclockwise beams should be included. Assuming the light beam propagating along clockwise direction is denoted by subscript 1, and that along the counterclockwise direction is 2, then the coupled propagation equations can be written as

$$\frac{\partial A_1}{\partial z} + \frac{n_0}{c} \frac{\partial A_1}{\partial t} - j \frac{2\pi n_{f1}}{\lambda} A_1 + \frac{\alpha_{f1}}{2} A_1 = 0,$$

$$\frac{\partial A_2}{\partial z} + \frac{n_0}{c} \frac{\partial A_2}{\partial t} - j \frac{2\pi n_{f2}}{\lambda} A_2 + \frac{\alpha_{f2}}{2} A_2 = 0,$$

(1)

where $A$ is the normalized electrical field. The absorption and refractive index for light intensity $I_1$ are

$$\alpha_{f1} = \alpha_0 + \beta_2 (I_1 + 2I_2),$$

$$n_{f1} = n_0 + n_2 (I_1 + 2I_2).$$

(2)

By exchanging the subscripts, we can get the absorption and refraction coefficients for $I_2$. The scattering matrix method is used to describe the coupling between the ring and the straight waveguides. Clockwise and counterclockwise beams are connected by the boundary condition that assumes a unity reflection at $r_1$. We also assume that the power reflectivity at the output facet is 80%. The coupling coefficient $k$ is 0.3 and the linear propagation loss in the ring is 1.387/cm. The ring is divided into 10,000 grids and a one-dimensional finite difference time domain method was used for the simulation.
At a steady low power input of 1 μW, the transmission $A_{\text{out}}/A_{\text{in}}$ and intensity enhancement factor $A_{\text{ring}}/A_{\text{in}}$ are plotted in Fig. 2, where $A_{\text{in}}$ represents input amplitude to the ring from the gain region, $A_{\text{out}}$ is that to the gain region from the ring, and $A_{\text{ring}}$ is the root mean square of the amplitude of the clockwise beam in the ring. It shows a free spectral range of 1.2 nm and light intensity enhancement of 7.2 dB at resonance. When the power input to the microring increases, the two-photon absorption takes effect and the total loss coefficient in the microring increases, which reduces both transmission and finesse. Thus, the threshold gain of the RCL increases, the side mode suppression ratio decreases, and the laser emission linewidth increases, when compared to lasers without nonlinear absorption. The dependence of microring transmission and light intensity enhancement is shown in Fig. 3 for two different wavelengths. One is termed fixed wavelength and is the resonance wavelength without nonlinear refraction. Another is the corresponding resonance wavelength including nonlinear refraction. The transmission loss at the fixed wavelength deviates from that at resonance to the larger with the increasing of power. The light enhancements for both clockwise and counterclockwise beams are plotted at the fixed wavelength. The clockwise propagation beam has a larger intensity enhancement than the counterclockwise one due to the cross-TPA. It can be seen that there is an input power limitation due to transmission degradation. At an input power of 18.5 dBm the ring transmission degrades by 3 dB. At the same point, the finesse is reduced by about 15% from the intensity enhancement. The one-way threshold gain of the gain region to compensate the ring loss and the RCL output power are shown in Fig. 4. It is obvious that the threshold current increases with the operation power in the presence of TPA. The output power drops from linear relation to the incidence power to the ring at high power. At 3 dB degradation of ring transmission, it gives RCL output 5.1 mW and one-way excess gain of 1.5 dB. The resonance wavelength shift with the increasing of the output power is plotted in Fig. 5. It is shown that the resonance wavelength shift is less than 0.006 nm when the output power is less than 10 mW. The resonance wavelength shift with output power indicates that the wavelength is stable at low power in the presence of the nonlinear refraction. It is possible there are two stable states, with two different cavity enhancements and transmission rates, depending on the operation wavelength. However, the cavity enhancements and transmission rates of...
both the stable states are lower than those of the resonance wavelength. The effective wavelength difference of the bistates due to nonlinear refraction detuning is less than a resonance wavelength shift of 0.006 nm when the output is less than 10 mW. For the same reason, the transmission loss difference between the bistates is less than that between the fixed and resonance wavelength, which is 0.17 dB from Fig. 3, when the output is less than 10 mW. Thus, the bistability operation of the RCL does exist but is negligible at a laser output below 10 mW. On the other side, the bistability operation can be utilized at high power operations.

It is also noticed that there are several ways to release the high power restrictions of a RCL subjected to nonlinear effects. One is to use a larger effective mode area, which can generally be implemented by a thicker or wider waveguide core. Increasing the band gap of core materials a little can also reduce the nonlinear absorption, although this may increase the absolute nonlinear refraction, which is less serious in our calculations. Another way to drain more power out of the RCL without changing the operation condition of the microring is to reduce the output mirror reflectivity. However, doing so sacrifices threshold gain.

In conclusion, we analyze the bidirectional transmission of the microring resonator in the presence of material nonlinearity numerically. For the given InP-based ridge-waveguide RCL, the optical nonlinearity gives a laser output limit of 5.1 mW considering the threshold, side mode suppression and linewidth degradation. Below an even higher output of 10 mW, the bistability of the RCL is negligible. There are several ways to increase the output power limit by using a larger effective mode area, increasing the band gap of the core materials, or reducing the output mirror reflectivity.