Widely Tunable Coupled-Ring Reflector Laser Diode

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***Abstract*—A coupled-ring reflector (CRR), which is composed of two coupled rings both of which are coupled with a straight waveguide, is applied to a widely tunable laser diode. When the radii of two rings are slightly different, the peak reflection wavelength of the CRR can be widely tuned over a few tens nanometers by a small amount of refractive index change. It is shown that a few tens nanometers of tuning with a sidemode suppression ratio exceeding 45 dB both for adjacent cavity mode and for adjacent ring mode is achievable in the widely tunable CRR laser diode.**

***Index Terms*—Integrated optics, ring resonators, tunable filters, tunable laser diodes.**

MICRORING resonators (MRRs) possess a wide variety of functionalities along with compact size. So far most common MRR applications have been transmission-type wavelength filters [1], [2]. However, it is also possible to create reflective elements using MRRs, and several approaches have been reported [3]–[5]. Such devices have a potential of replacing grating structures in realizing tunable single-mode laser diodes which in turn can be integrated with other functional devices such as modulators or amplifiers.

This letter proposes new widely tunable coupled-ring reflector (CRR) laser diodes in which the CRRs reported in [5] are incorporated as wavelength-selective reflectors. The CRRs with rings of identical radii could be used at each end of the laser to create periodic reflection spectra at both ends. In this case, a wide tuning of the lasing wavelength can be achieved by a small amount of refractive index change in one of the CRRs through the Vernier effect if the radii of the rings in one of the CRRs are slightly different from those in the other.

The same Vernier effect can also be obtained using a single CRR. When the radii of two rings in a single CRR are slightly different from each other, peak reflections appear only when the resonance wavelengths of two rings are aligned. The wavelength of peak reflection in a single CRR can be widely tuned by a small amount of refractive index change in one of the rings. That is, a single CRR with rings of slightly different radii can be used as a widely tunable reflector without the need for facets. The Vernier effect concept in the mentioned CRR laser diodes is similar to that reported in [6], where facets are required to create reflections and ring resonators are used as wavelength-selective transmission filters. However, the inherent reflection property of the CRR makes it possible to integrate the CRR laser diode with other components since there is no need for facets on one or both ends of the laser. In this letter, to discuss the feasibility of the proposed devices, CRR laser diodes with a single CRR and a facet are considered.

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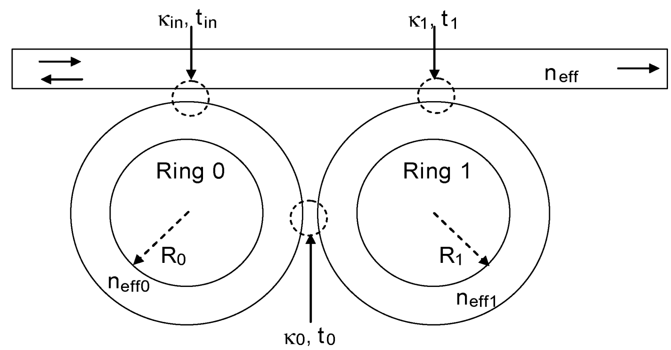

Fig. 1. Schematic configuration of CRR. Various κ's and t's are field coupling and transmission coefficients of various couplers.

The schematic configuration of the CRR is shown in Fig. 1. When the radii of two rings in the CRR are identical, a periodic reflection spectrum is observed [5]. If the radii of two rings in the CRR are slightly different, the resonance wavelengths of two rings could be misaligned at all the resonance wavelengths except certain wavelengths. By changing the refractive index of one of the rings in the CRR while maintaining that of the other, the peak reflection wavelength can be selected. The tuning range is given by

$$\Delta\lambda_{\mathrm{tune}} = \frac{\lambda_o^2}{2\pi n_g (R_1 - R_0)} = F\Delta\lambda_0 \tag{1}$$

where $\Delta\lambda_0$ is a free spectral range (FSR) for Ring 0 and F is a tuning enhancement factor, which is given by

$$F = \frac{R_1}{(R_1 - R_0)}. \tag{2}$$

When the radii of the rings in the CRR are $R_0 = 50$ μm and $R_1 = 52$ μm, respectively, corresponding to $F = 26$, the center wavelength is 1.55 μm, and the group refractive index (n_g) is 3.7, the tuning range could be as wide as 52 nm.

In Fig. 2, the power reflectivity spectra for CRRs containing rings with the same and different radii are shown. For the analysis of the CRRs, the transfer matrix formalism [4] is used. Here, κ_{in} and κ_1 are 0.5, and κ_0 is 0.04. In Fig. 2(a), the reflectivity for $R_0 = R_1 = 50$ μm and $n_{\mathrm{eff0}} = n_{\mathrm{eff1}} = 3.29$ is shown. A periodic reflection response with an FSR of 2.17 nm is observed. In Fig. 2(b), the reflectivity in the case of different ring radii ($R_0 = 50$ μm, $R_1 = 52$ μm) are shown. Here, the refractive indexes are set to be $n_{\mathrm{eff0}} = 3.29$ and $n_{\mathrm{eff1}} = 3.29 + 1.9 \times 10^{-4}$. By changing the refractive index of Ring 1 by about 1.9×10^{-4} which is smaller by a factor of F than that required in the normal

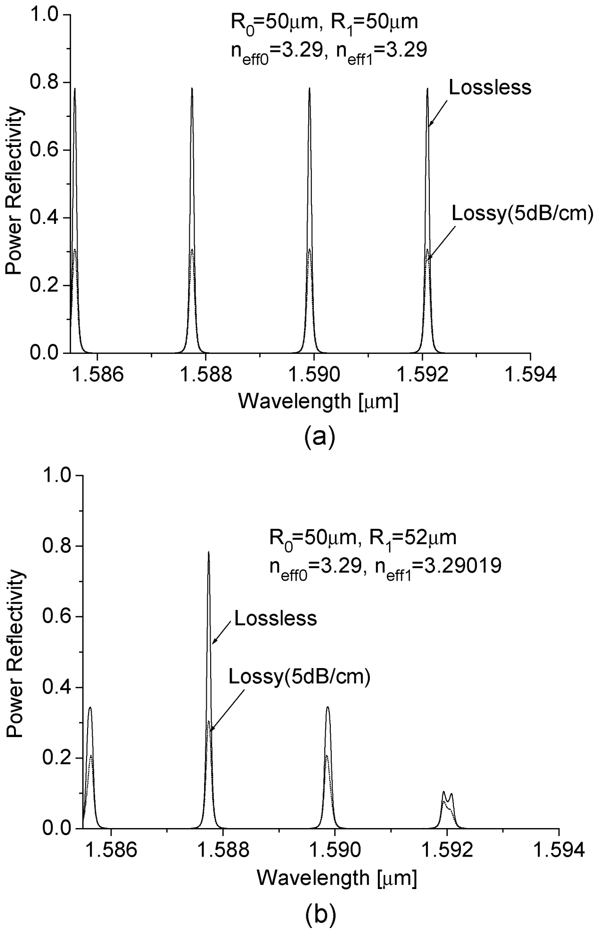

Fig. 2. Power reflectivity as a function of wavelength (a) for $n_{\mathrm{eff0}} = n_{\mathrm{eff1}} = 3.29$ at $\lambda = 1.55$ μm and $R_0 = R_1 = 50$ μm, and (b) for $n_{\mathrm{eff0}} = 3.29$, $n_{\mathrm{eff1}} = 3.29 + 1.9 \times 10^{-4}$, $R_0 = 50$ μm, and $R_1 = 52$ μm. κ_{in} and κ_1 are 0.5, and κ_0 is 0.04. The solid lines are for lossless case and the dotted lines are for 5-dB/cm propagation loss case.

tuning without a Vernier effect, the wavelength of peak reflection can be shifted by one FSR. The required refractive index change required to tune over a whole tuning range of 52 nm is only about 4.6×10^{-3}. In Fig. 2(a) and (b), it is observed that the peak reflectivity reduces from 0.78 to 0.31 as the propagation loss in the rings increases to 5 dB/cm. Especially, Fig. 2(b) indicates that the ratio of peak reflection value and the adjacent reflection maxima reduces significantly which would deteriorate the sidemode suppression for the adjacent ring modes as the loss in the rings increases. These issues will be discussed later.

The widely tunable CRR can be used to realize a widely tunable laser diode. The schematic configuration of the proposed widely tunable laser diode is shown in Fig. 3. The integration of the active region and the passive regions such as the phase control region and the ring waveguides can be achieved using various photonic integration techniques such as the offset quantum well or butt-coupling approaches [7], [8].

To investigate the applicability, we consider the reflection spectrum shown in Fig. 2(b). For the single-mode operation, the mode suppressions for the adjacent cavity mode and for the adjacent ring resonant modes should be checked. The penetration length of the CRR reflector is calculated to be 8800 μm in the

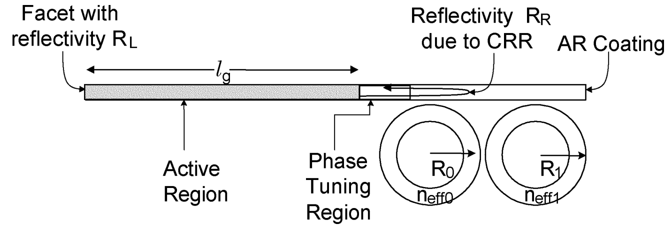

Fig. 3. Schematic configuration of a widely tunable CRR laser diode.

lossless case, which is much longer than the actual length of the laser diode [6]. Therefore, the cavity mode spacing is about 0.04 nm if the length of the active region is 400 μm. The reflectivity corresponding to the peaks of Fig. 2(b) is 0.78, and that 0.04 nm apart from the peak is 0.42. From the following sidemode suppression ratio (SMSR) formula [9]:

$$\mathrm{SMSR} = \frac{2P_0}{h\nu v_g n_{\mathrm{sp}} \alpha_m} \left[\frac{\Delta\alpha}{\Gamma g_{\mathrm{th}}} + \frac{\Gamma \Delta g}{\Gamma g_{\mathrm{th}}} \right] \tag{3}$$

the SMSR for the cavity mode is calculated to be 45 dB. In the above expression, the loss margin for the adjacent sidemode is given as $\Delta\alpha = (1/2l_g)\ln((R_R R_L)_0/(R_R R_L)_1)$, where $(R_R R_L)_0$ and $(R_R R_L)_1$ are the power reflectivity product for the main mode and that for the adjacent sidemode and l_g is the length of the gain region. In this calculation, the material gain variation Δg is assumed to be zero over the small wavelength change of 0.04 nm. In (3), P_0 is a power in the main mode, Γ a confinement factor, g_{th} a threshold gain, v_g a group velocity, α_m a mirror loss for the main mode, and $\Gamma g_{\mathrm{th}} = (\alpha_{\mathrm{act}} + \alpha_m)$. In the calculation, P_0 is assumed to be 5 mW, the waveguide loss (α_{act}) in the active region 30 cm^{-1}, the length of active region 400 μm, and the power reflectivity for left facet 0.3.

The sidemode suppression for the adjacent ring modes could be a major limitation because the material gain variation over an FSR might not be ignored. To investigate this effect, two sets of coupling ratios are considered: one set is $(\kappa_{\mathrm{in}}, \kappa_0) = (0.5, 0.04)$ and the other is $(\kappa_{\mathrm{in}}, \kappa_0) = (0.64, 0.08)$. The former has a sharper reflection spectrum shape than the latter and would give larger SMSR. The normalized gain variation is assumed to be 2.5% over an FSR and $\Delta g/g_{\mathrm{th}}$ is set to be -0.025 in the calculation of SMSR. The sidemode suppression for the adjacent ring mode is shown as a function of tuning enhancement factor in Fig. 4. To vary the tuning enhancement factor, R_0 is maintained to be 50 μm and R_1 is adjusted. The potential tuning range is also plotted. When 40-dB SMSR is enforced, the actual tuning range is limited to about 55 nm for $(\kappa_{\mathrm{in}}, \kappa_0) = (0.64, 0.08)$ and about 80 nm for $(\kappa_{\mathrm{in}}, \kappa_0) = (0.5, 0.04)$. The tolerance to error in refractive index control is also investigated. In case of $(\kappa_{\mathrm{in}}, \kappa_0) = (0.5, 0.04)$, the tolerance is estimated to be about 1×10^{-4} to ensure 40-dB SMSR.

Fig. 5 shows the SMSR as a function of propagation loss in the rings. Here the tuning enhancement factor is 26. When $(\kappa_{\mathrm{in}}, \kappa_0) = (0.5, 0.04)$, the SMSR is maintained to be higher than 30 dB up to 9-dB/cm waveguide loss. When $(\kappa_{\mathrm{in}}, \kappa_0) = (0.64, 0.08)$, the SMSR decreases from 39.5 to 30 dB as the propagation loss increases to 5 dB. The intrinsic propagation loss of the passive undoped InGaAsP waveguide might be smaller than 9 dB/cm [7] and, thus, the intrinsic

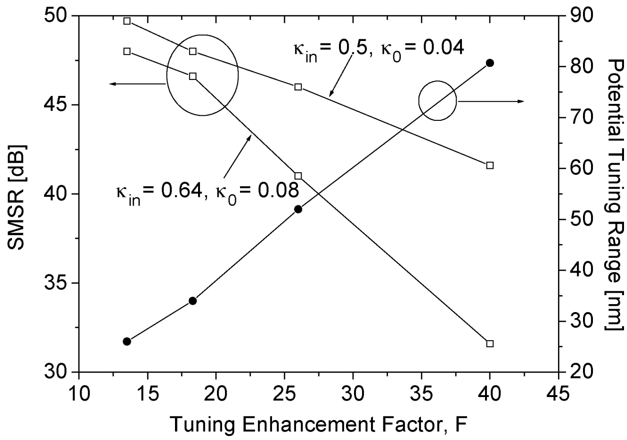

Fig. 4. SMSR for adjacent ring mode, and potential tuning range as a function of tuning enhancement factor. $n_{\rm eff0} = 3.29$, $n_{\rm eff1} = 3.29 + 1.9 \times 10^{-4}$.

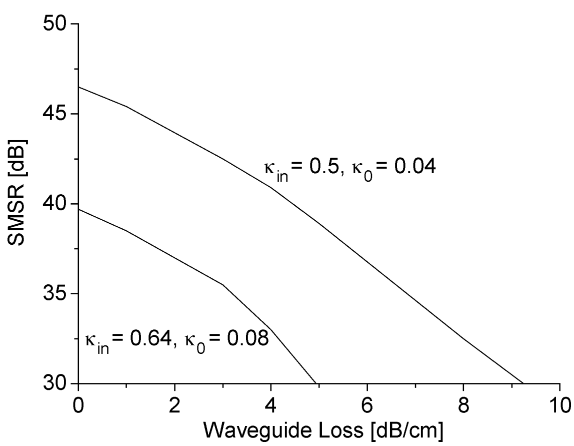

Fig. 5. SMSR for adjacent ring mode as a function of waveguide loss in the rings. $n_{\rm eff0} = 3.29$, $n_{\rm eff1} = 3.29 + 1.9 \times 10^{-4}$, $F = 26 (R_0 = 50\ \mu$m, and $R_1 = 52\ \mu$m).

loss would not significantly deteriorate the performance of the widely tunable CRR laser diode with properly chosen coupling ratio values. The required index change for 52-nm tuning is about 4.6×10^{-3} which can be obtained through a small amount of injection current corresponding to a carrier density of a few 10^{+17} cm^{-3} [10] or through quadratic electrorefractive effect accompanied by relatively small induced loss. When the propagation loss may be a problem, optical amplifier sections should be integrated within the rings to compensate the propagation loss [7], [8].

In conclusion, new widely tunable laser diodes composed of CRRs are proposed and their wide tuning characteristics are analyzed. The wide tuning characteristic of the CRR containing rings with slightly different radii is found to be useful in realizing widely tunable laser diode when the CRR is employed as a wavelength-selective reflector. The inherent reflection characteristic of the CRR is beneficial to integrate modulators or ampliers with the CRR laser diode. With a proper choice of coupling ratios, the tuning range ensuring 40-dB SMSR could reach 80 nm, and the ring waveguide loss up to 9 dB/cm could be tolerated to achieve 30-dB SMSR with 50-nm tuning range.

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