Wide Tunable Double Ring Resonator Coupled Lasers

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***Abstract*—A double ring resonator coupled laser (DR-RCL) is proposed and analyzed in this letter. Benefiting from the uniform peak transmission, narrow bandwidth and other superior characteristics of traveling wave supported high-Q resonators, DR-RCLs offers many promising advantages over the conventional tunable lasers, including ultra wide wavelength tuning range, high side mode suppression ratio, uniform threshold and efficiency, narrow linewidth, low frequency chirp, and simple fabrication. A DR-RCL with a moderate optical loss ∼10 dB/cm in the ring resonators can achieve a wavelength tuning enhancement of ∼50. With such a large tuning leverage, DR-RCLs could utilize the electrooptic effects to achieve ultrafast tuning speed with a wide tuning range covering the material gain bandwidth.**

***Index Terms*—Laser tuning, resonant filters, ring lasers, semiconductor lasers.**

WAVELENGTH-TUNABLE lasers are very desirable for increasing the capacity, the functionality, and the flexibility of the current and next generation all-optical networks. The key issues for tunable lasers are the tuning range, side-mode suppression ratio (SMSR) and manufacturability. Several wide tunable lasers have been proposed and demonstrated [1]–[4]. So far, the most successful monolithic structures are sampled-grating distributed Bragg reflector (SG-DBR) lasers [2] and super structure grating (SSG) DBR lasers [3]. In this letter, a novel wavelength tunable source called double ring resonator coupled laser (DR-RCL) is proposed. This structure offers several promising characteristics, such as ultrawide tuning range, large SMSR, very narrow linewidth, low frequency chirp, and simple fabrication.

Fig. 1 is the proposed tunable double microring resonator coupled laser structure. This laser consists of four main regions: gain region, two passive microring resonators, passive waveguides, and absorption regions. The gain region provides light amplification. The two passive microring resonators have slight different radii (or effective indexes) providing the mode selection and wavelength tuning mechanism. Four passive waveguides connect the ring resonators and the gain region. They could also serve as fine tuning phase regions. The absorption regions extinguish the light possible back reflection from the facets and the rings. The front and back reflective facets form a laser cavity. The asymmetric double ring coupled laser is similar to the SG-DBR laser by replacing the front and back sampled gratings with two ring resonators. Compared to standing-wave supported SG-DBR structures, traveling-wave supported ring resonators have superior characteristics: very high-Q, narrow filter bandwidth and very large effective light traveling length.

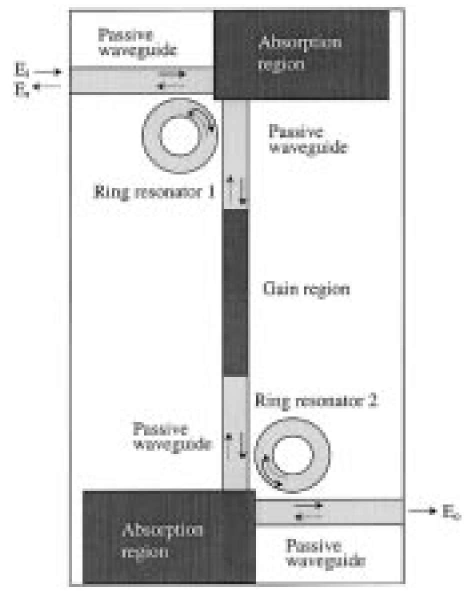

Fig. 1. Double ring resonator coupled laser structure.

The ring resonator provides a strong mode selection filtering. Only light at the resonance wavelength can be effectively coupled from the gain region to the front or back passive waveguides and reflected by one or both facets to the gain region via the ring resonators again. For the longitudinal single mode operation, single ring resonator is enough to obtain a high side-mode suppression ratio [5]. But in single ring resonator coupled lasers the wavelength tuning range is limited due to the small change of the refractive index. By adding the second ring, wavelength tuning range will be greatly enhanced via Vernier effect.

Fig. 2 illustrates the basic tuning idea of double ring resonator coupled lasers. Each ring resonator has a set of transmission spectra and the wavelength period is the free spectral range $\mathrm{FSR} = \lambda^2/(n_r l_r)$, where n_r is the effective index of the ring and l_r is the roundtrip length in the ring. The two rings have slight different radii (or effective indices). Therefore, the two sets of transmission peak combs have small different peak spacing. Similar to SG and SSG-DBR lasers, wavelength tuning is achieved by aligning the peaks in the two sets of combs with the adjustment of index in one or both ring resonators in DR-RCLs. The wavelength tuning enhancement factor M [4] (To avoid the confusion with the finesse, we used M in this letter

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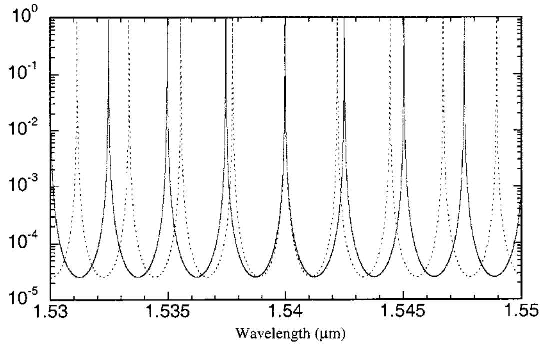

Fig. 2. The transmission spectra of two different rings. ($r_{r1} = 50\ \mu$m, $\Delta r = 6.536\ \mu$m, $\mathrm{FSR}_1 = 2.254$ nm, $M_1 = 612$, $\Delta M = 80$).

instead of F in [4]) is given by

$$M = \frac{1}{1 - \frac{r_{r1}}{r_{r2}}} \approx \frac{r_{r1}}{\Delta r} = \frac{M_1}{\Delta M} \tag{1}$$

where $r_{r1\ (2)}$ is the radius of the ring 1 (2), $r_{r2} = r_{r1} + \Delta r$ ($\Delta r \ll r_{r1}$) and $n_{r1} = n_{r2}$ without tuning. At resonance, $2\pi n_{r1} r_{r1} = M_1 \lambda_0$ and $2\pi n_{r2} r_{r2} = M_2 \lambda_0$, M_1 and M_2 are the resonance mode numbers of ring 1 and 2 at the center wavelength λ_0, and $M_2 = M_1 + \Delta M$ (ΔM is an integer). When $\Delta M = 1$, one may get the maximum tuning range of 0–$2\lambda_0$. For practical applications, the material gain bandwidth limits the possible maximum tuning range of $\lambda_0 - \Delta\lambda_g$ to $\lambda_0 + \Delta\lambda_g$, ($\Delta\lambda_g$ is the half bandwidth of the material gain), then $\Delta M = \lambda_0/\Delta\lambda_g$ and the corresponding tuning enhancement $M = \Delta\lambda_g/\mathrm{FSR}_1$. Compared to SG and SSG-DBR lasers, double ring resonant coupled lasers could offer a much larger tuning enhancement because of the inherent features of the ring resonators. First, ring resonators have the uniform peak transmission at all resonant peaks, which means the uniform thresholds and efficiencies between the mode hopping wavelengths. In contrast, the periodic peak power reflectivities decay with the number (N) of peaks as $1/N^2$ and $1/N$ in SG and SSG-DBR lasers [3], which limits the tuning enhancement to ~10. Second, the Lorentzian-type filtering of ring resonators provides an ultra narrow bandwidth with a very small device size. The peak spacing difference between two sets of transmission combs could be much smaller than that in the Sinc-type filters, and a high SMSR is still achievable.

The large tuning enhancement has many advantages. The available gain bandwidth in semiconductor is about 100 nm. Therefore, a tuning enhancement factor of ten is large enough to cover the whole bandwidth with the maximum index change $\Delta n/n \sim 1\%$ by carrier injection. Carrier injection is attractive for its large index change, but it also has several inherent disadvantages. First, the carrier injection causes the internal optical loss, which affects the uniformity of lasing thresholds and the efficiencies at different wavelengths. With a large tuning enhancement and a small index change requirement (~0.1% for $M = 100$), the tuning current is dramatically decreased and the internal loss is minimized. On the other hand, the switching time via carrier injection is in the range of tens of nanoseconds, not fast enough for some applications. For ultrafast tuning speed, electrooptic (EO) effect is preferred which has no induced loss. But the index change by EO effect is about one order magnitude smaller than the change by carrier injection, which means a large tuning enhancement factor of 50–100 is needed to cover the gain bandwidth. For example, if $\Delta\lambda_g = 50$ nm and $\mathrm{FSR} = 1.25$ nm, with a requirement of ~0.1% index change to cover this tuning range, one can find $\Delta M = 30$, $M = 40$ at $\lambda_0 = 1500$ nm. Such a large tuning enhancement is impossible with SG, SSG-DBR, but it is feasible with double ring resonator coupled lasers.

The maximum tuning enhancement of DR-RCLs is limited by the required SMSR. Two different side competing modes need to be considered [2]. One is the adjacent cavity mode; the other is the adjacent resonant mode of the rings. We have analyzed the adjacent cavity mode suppression of single ring RCLs in [5] and shown that the loss margin in SR-RCLs is good enough to get >40–dB SMSR at 1-mW output. By introducing the second ring in DR-RCLs, the effective cavity length is almost doubled for weakly coupled double rings and the transmission is squared. One can find that the loss margin [6] between the resonance peak and first side cavity mode is about $2\ln\left(1 + \pi^2/4(1-\kappa^2)\right) \approx 2.49$ [5], where κ $(= \kappa_1 = \kappa_2)$ is the amplitude coupling coefficient between the lossless rings and the passive waveguides. Thus, >40-dB SMSR in DR-RCLs could be assured for 1-mW output power.

The ultimate limitation of the tuning leverage in DR-RCLs comes from the adjacent resonant mode of the rings. The transmission overlap could be significant between the two-ring resonance peaks adjacent to the aligned center peak with the increase of the tuning enhancement. The wavelength spacing $\Delta\lambda_r$ between the two adjacent resonance peaks can be expressed as

$$\Delta\lambda_r = \Delta\mathrm{FSR} \cdot \Delta M = \frac{\lambda}{M_1^2}\Delta M. \tag{2}$$

One could easily get the loss margin between the centered peak and the adjacent resonant mode without considering the material gain difference between the two peaks $\Delta\alpha l_g = 2\ln\left(1 + 2F^2/M\right)$, where F is the finesse of the ring resonator. For a conservative estimation, assuming there is a 3-dB material gain difference between the adjacent resonant modes and the minimum loss margin equals to the adjacent cavity mode loss margin in single ring coupled lasers, the maximum tuning enhancement factor is about $M \le 2(1-\kappa^2)^2/(\pi\kappa^4)$ to get >40 dB SMSR at 1-mW output power. Therefore, the wavelength tuning enhancement could be larger than 1000 for DR-RCLs without loss.

The loss is inevitable in microring resonators, which broadens the bandwidth and reduces the effective reflectivities of RCLs. The effects of the loss on SMSR of the adjacent cavity mode in double ring RCLs are quite similar to that in single ring RCLs, which has been investigated in [5]. Even with a 50-dB/cm loss, it is not difficult to achieve >30-dB SMSR at 1-mW power. The loss effect on SMSR of adjacent resonant modes is illustrated in Fig. 3. The tuning enhancement is limited by the loss and the coupling strength. The weak coupling needs a low loss to achieve a large tuning enhancement without increasing the threshold gain too much. If one could tolerate the extra threshold gain increase of 50 cm^{-1} and demands >30-dB SMSR at 1-mW output, <3-dB/cm loss is required to achieve a tuning enhancement factor of 40 for $\kappa_1 = 0.1$. But if $\kappa_1 = 0.2$ and 0.3,

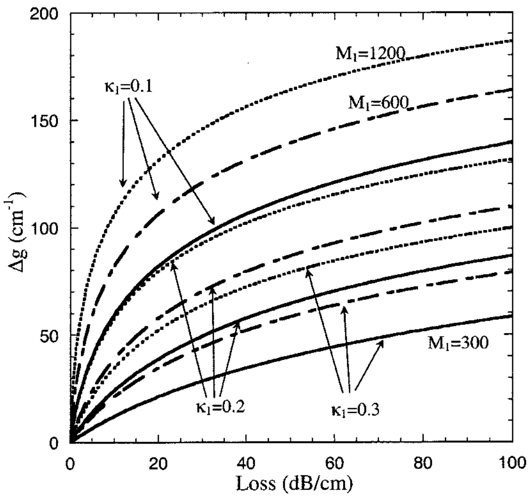

Fig. 3. The effects of loss on SMSR of the adjacent resonant mode at different tuning enhancements and coupling coefficients without considering the material gain difference. ($\Delta M = 30$, $l_g = 500$ μm, $n_g = 3.3$, $n_r = 3$, $\kappa_2 = \sqrt{1-(1-\kappa_1^2)/\exp(-\alpha_r l_r)}$ to get the maximum transmission, and the output power is 1 mW).

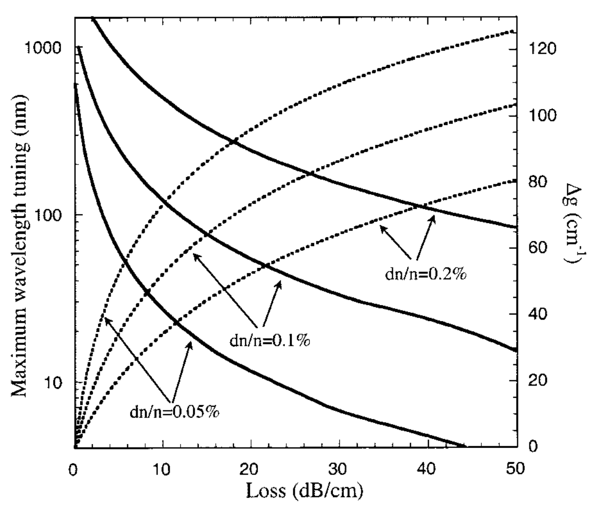

Fig. 4. The maximum wavelength tuning range (solid line) and the extra threshold gain (dashed line) as a function of the optical loss in rings. Here, the SMSR is set to 30 dB at 1-mW output, $\kappa_1 = 0.2$, $l_g = 500$ μm, $n_g = 3.3$, $n_r = 3$.

the loss could be 10 dB/cm to get this tuning enhancement. To achieve ~100 tuning enhancement will require the ring waveguides with an extremely low loss $(\sim 1$ dB/cm$)$. Fig. 4 shows the maximum wavelength tuning range and the extra threshold gain at different optical loss with the refractive index change of 0.05%, 0.1%, and 0.2%, where $\kappa_1 = 0.2$ and $\mathrm{SMSR} = 30$ dB at 1-mW output power, assuming no material gain bandwidth limitation exists. Clearly, the tuning range can be unbelievably extended even with only 0.1% index change. If the optical loss in microrings can be reduced to <2-dB/cm high-speed EO effect (~0.05$\%$ index change) will be enough to achieve a very wide wavelength tuning range of 100 nm.

As pointed out in [5], the effective cavity length in weakly coupled passive ring resonators can be extremely extended which makes the photon lifetime much longer. This is the biggest difference between the passive ring resonator coupled lasers and the conventional active ring and Fabry–Pérot (FP) lasers. In ring lasers, the traveling wave ring resonator replaces the standing wave FP cavity and the cavity loss is due to the coupling between the ring and the output waveguides. Therefore, to increase the photon lifetime one must increase the physical length of the ring and/or reduce the coupling. These will be limited by the device size and the output power. In the case of ring resonator coupled lasers, the ring resonator is used as a passive mode selector. Thus, a frequency-dependent passive mirror with complex amplitude reflectivity is formed by the combination of a coupled microring resonator with a reflection facet. This frequency dependent passive mirror can considerably extend the effective cavity length at the lasing wavelength. For a single lossless ring coupled laser, the effective cavity length is $l_{\mathrm{reff}} = (1-\kappa^2)/\kappa^2 \cdot l_r$ at resonance [5]. By adjusting the coupling strength, one can dramatically increase the effective cavity length. Thus, the laser linewidth and the frequency chirp can be greatly reduced [9]. By adding the second ring, the effective cavity length is almost doubled and the linewidth and frequency chirp are improved as well. In DR-RCLs, it is possible to achieve <100 kHz linewidth, even <1 kHz if the rings have a very small optical loss.

In conclusion, a double ring resonator coupled laser was proposed and analyzed. Because of the nature of traveling wave supported high-Q ring resonators, DR-RCLs offers many advantages: an ultrawide wavelength tuning range, high side-mode suppression ratio, very narrow linewidth, and low frequency chirp. Compared to grating-based tunable lasers, the fabrication of ring resonator coupled lasers is quite simple after no gratings and complicate multiple regrowths are required. Although a very low optical loss in microrings are essential to achieve >100 tuning enhancement, the moderate optical loss $(\sim 10$ dB/cm$)$ [8] in microrings is acceptable to get a ~50 wavelength tuning enhancement. In a tunable laser with this high tuning leverage, one could use more attractive electrooptic effects to tune the wavelength and realize ultra fast tuning speed for future optical network applications.

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