Passive microring-resonator-coupled lasers

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In this letter, a passive microring-resonator-coupled semiconductor laser structure is proposed. The weakly coupled high-*Q* microring resonator provides a strong mode-selection filter and could considerably extend the effective cavity length of a conventional Fabry–Perot laser. The side-mode suppression ratio, the linewidth and the frequency chirp of this laser are dramatically improved comparing to distributed feedback and distributed Bragg reflector lasers. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1420585]

High-*Q* microring resonators have been recognized as compact and efficient passive and active optoelectronic devices for a while. Microring resonators are believed to be ideal channel-dropping filters[1–3] for dense wavelength division multiplexing applications, because they can potentially offer the narrowest linewidth for a given device size and can be integrated with other devices to yield more functional photonic components and circuits. Ring resonator semiconductor lasers[4,5] are thought to be an ideal source for photonic integrated circuit applications because of their cleavage-free cavity and small size. In this letter, a semiconductor laser structure is proposed where the active region in the conventional Fabry–Perot cavity is coupled with a passive microring resonator. This is different from conventional ring lasers, where the active traveling wave ring resonator replaces the standing wave Fabry–Perot cavity. With the help of the Lorentzian-type filter characteristics of ring resonators, the side mode suppression ratio, the linewidth, and the frequency chirp of this ring resonator coupled lasers (RCL) will be dramatically improved.

Figure 1 is the proposed laser structures integrated with a microring resonator, which has four regions: a gain region, a passive ring resonator, a passive straight waveguide, and an absorption region. The gain region provides light amplification; the absorption region extinguishes the filtered spontaneous light and the possible back reflections. The gain and the absorption regions have the same material structures with and without forward biases, respectively. The high-*Q* ring resonator is a mode selection filter, which only completely couples the light with the resonance wavelength (if no loss is in the ring) between the passive waveguides 1 and 2. The off-resonance light is absorbed by the absorption region. It is not necessary for the resonator to have a ring shape, any traveling wave supported high-*Q* resonators have the same effects. To form a laser cavity, the two facets of passive waveguide 1 and the gain region are cleaved as usual. The facets could be coated to increase the reflectivity. The ring resonator and passive straight waveguides could be used as coarse and fine tuning regions for matching the cavity mode with the resonance peak and for wavelength tuning. Essentially, this laser structure is quite similar to DBR lasers where the Bragg reflector is replaced with a ring resonator and a reflective facet. Compared to Bragg reflectors, the microring resonators have a very high-*Q*, which improves the laser performance dramatically as will be shown next.

By using the scattering matrix method[2] and assuming there is no coupling loss between the gain and the passive waveguide regions, it is easy to derive the transfer function:

$$t=\frac{E_0}{E_i}=\frac{t_1 t_2 |t_r| \exp(-j\varphi)}{1-r_1 r_2 |t_r|^2 \exp(-j2\varphi)}, \quad (1)$$

where E_i and E_0 are the amplitude of the input and output field. $t_{1(2)}$ and $r_{1(2)}$ are the amplitude transmission and refection coefficients of facet 1 and 2. φ is the overall roundtrip phase that will be described later. t_r is the amplitude transfer function of the single ring resonator.

$$t_r=\frac{-\kappa_1\kappa_2}{1-\sqrt{1-\kappa_1^2}\sqrt{1-\kappa_2^2}\exp(-j\beta_r l_r)}=|t_r|\exp(-j\phi), \quad (2)$$

where κ_1 and κ_2 are the amplitude coupling coefficients between the ring resonator and the passive waveguide 1 and 2. β_r is the propagation constant in the ring resonator. (β_r is replaced with $\beta_r - j\alpha_r/2$ if loss exists in the ring, α_r is the power absorption coefficient.) l_r is one round trip length of

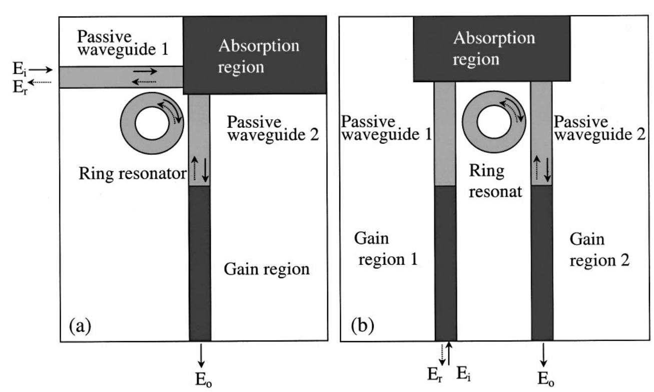

FIG. 1. Two examples of passive microring resonator coupled lasers. The structure (a) is analyzed more in detail in this letter. Structure (b) has similar mode selection behavior and it could be used when, e.g., single facet applications are important.

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the resonator. For a ring, $l_r = 2\pi r$, r is the radius of the ring resonator. The power transmission of a ring resonator is given by

$$T_r = |t_r|^2 = \frac{T_0}{1+\left(\frac{2}{\pi}F\right)^2 \sin^2\left(\frac{\beta_r l_r}{2}\right)}. \tag{3}$$

Here, T_0 is the transmission at resonance. (i.e., when $\beta_r l_r = M\times 2\pi$, M is an integer. The free spectral range (FSR) $=\lambda^2/n_r l_r$, n_r is the effective index of the ring waveguide.) F is the finesse of the ring resonator. For simplicity, we neglect the loss in the ring resonant here. Then $T_0=1$ when $\kappa_1=\kappa_2=\kappa$. The 3 dB bandwidth $\Delta\lambda_{3\,\mathrm{dB}} = [\kappa^2/(\pi\sqrt{1-\kappa^2})]$FSR and $F=\mathrm{FSR}/\Delta\lambda_{3\,\mathrm{dB}}$. In Eq. (2), we do not include the term $\exp(-ja\beta_r l_r)$ which has been added to the phase φ in Eq. (1).

$$\varphi = \beta_{w1} l_{w1} + a\beta_r l_r + \beta_g l_g + \beta_{w2} l_{w2} + \phi. \tag{4}$$

Here, al_r is the trip length in the ring between the in and out coupling points $(0<a<1)$. $a=1/4$ and $1/2$ in Figs. 1(a) and 1(b) respectively. β_{w1}, β_{w2}, and β_g are the propagation constants of the passive waveguides 1, 2, and the gain region; l_{w1}, l_{w2}, and l_g are their respective lengths.

Now, we can check the lasing characteristics. From Eq. (1), the lasing threshold gain and the phase condition could be expressed as (if there is no loss in the passive waveguides)

$$g_{\mathrm{th}} = \alpha_g + \frac{1}{l_g}\ln\left(\frac{1}{r_1 r_2 T_r}\right), \tag{5}$$

$$\varphi = N\times\pi, \tag{6}$$

where N is an integer. From Eq. (5), if the passive and the ring waveguides are lossless, the threshold gain is exactly the same as the conventional $F-P$ lasers at resonance. But the Lorentzian filtering mechanism from the high-Q ring resonator provides a strong mode selection, which is essential for dynamic single mode operation. The large loss margin between the main and side modes $\Delta\alpha l_g$ is necessary for a high mode suppression ratio (MSR).[6] From Eq. (5), $\Delta\alpha l_g = \ln(T_0/T_1)$, where T_0 and T_1 are the transmission of the ring resonator for the main and first side modes. Assuming the main mode is located at the ring resonance wavelength, the required minimum mode spacing between the main and first side modes for a certain loss margin is $\Delta\lambda_{\min} = \Delta\lambda_{3\,\mathrm{dB}}\sqrt{\exp(\Delta\alpha l_g)-1}/2$. The longitudinal mode spacing $\Delta\lambda_m$ needs to be bigger than $\Delta\lambda_{\min}$ to get the required MSR. From Eqs. (6), (4), and (2), we can get the mode spacing

$$\Delta\lambda_m = \frac{\lambda^2}{2(n_{w1}l_{w1} + a n_r l_r + n_g l_g + n_r l_{\mathrm{reff}})}, \tag{7}$$

where l_{reff} is the effective length of the ring resonator and is given by $l_{\mathrm{reff}} = -\lambda/\beta_r \partial\phi/\partial\lambda$. At resonance, $l_{\mathrm{reff}} = [(1-\kappa^2)/\kappa^2] l_r$, which depends on the coupling strength and the radius of the ring. For a weakly coupled ring ($\kappa \ll 1$), the effective length will be largely extended ($l_{\mathrm{reff}} \gg l_r$) and dominate the total cavity length. This is a big difference from DBR lasers, where the effective length is always smaller than the physical length. In the weak coupling case, we could neglect the straight waveguide and the gain region lengths.

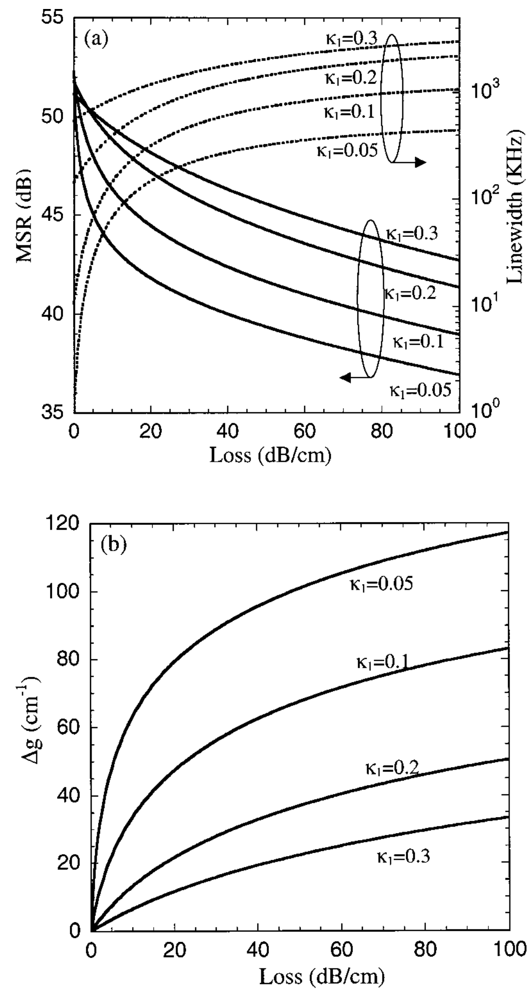

FIG. 2. (a) MSR and linewidth of an InGaAsP/InP passive ring resonator coupled laser. ($l_g=400$ μm, $n_g=3.3$, $r=20$ μm, $n_r=3$, and $\kappa_2 = \sqrt{1-(1-\kappa_1^2)\exp(-\alpha_r l_r)}$ to get the maximum transmission, the threshold gain is 50 cm^{-1} without the ring and the output power is 5 mW.) (b) The extra threshold gain to compensate the loss in the microring resonator.

The loss margin between the resonance peak and first side mode is about $\ln(1+\pi^2/(1-\kappa^2))\approx 2.39$. This loss margin is good enough to get >40 dB MSR at 1 mW output for a typical semiconductor laser. Besides the cavity modes, suppression of the adjacent resonance modes of a ring resonant could be another concern for single mode operation. This will require a large FSR ($>$ the material gain bandwidth), which means a small radius of the ring. This could be achieved by using high index contrast waveguides[7] or cascading two slightly different large rings together[2] if the loss is an issue in a very small ring. Integration of other filters such as gratings is also a possibility.

It is well known that increasing the effective cavity length[6] which makes photon lifetime longer is the most effective way to reduce the linewidth and frequency chirp of semiconductor lasers. Therefore, the reduction of linewidth and chirp could be predicted in a weakly coupled ring resonator integrated semiconductor laser because of the dramatic effective cavity length increase. The combination of a microring resonator with a reflection facet and passive waveguides could be thought as a frequency-dependent passive mirror with complex amplitude reflectivity $r(\omega)$, which is expressed as $r(\omega) = r_1 T_r \exp(-j2\phi_p)$, here $\phi_p = \phi$

$m + a\beta_r l_r + \beta_{w1} l_{w1} + \beta_{w2} l_{w2}$. The linewidth for this laser structure is given by[6,8,9]

$$\Delta\nu = \frac{\Delta\nu_0}{(1+A+B)^2} \times \frac{2r_1 T_r(1-r_2^2)}{(r_1 T_r + r_2)(1-r_1 T_r r_2)}, \tag{8}$$

where $\Delta\nu_0$ is the linewidth of the solitary laser,

$$A = 2/\tau_g \times \partial\phi_p/\partial\omega$$
$$= (n_r l_{\mathrm{reff}} + a n_r l_r + n_{w1} l_{w1} + n_{w2} l_{w2})/(n_g l_g),$$
$$B = \alpha/\tau_g \times \partial \ln T_r/\partial\omega.$$

τ_g is the round-trip group delay time in the gain region and α is the linewidth enhancement factor. $B=0$ at resonance and the second term in Eq. (8) is about unity for a lossless ring. So the linewidth will be reduced by $(1+A)^2$. For a weakly coupled ring resonator and neglecting the passive straight waveguides, $(1+A)^2 \approx [(n_g l_g + n_r l_{\mathrm{reff}})/(n_g l_g)]^2 \approx (1-\kappa^2)/\kappa^4 \times (n_r l_r/(n_g l_g))^2$. A linewidth reduction by more than three orders can be achieved. Therefore, without a long external cavity, <100 kHz linewidth is possible by using a weakly coupled ($\kappa \approx 0.1$) high-Q microring resonator in a conventional $F-P$ semiconductor laser. Such a narrow linewidth could only be realized in a very long external cavity laser before.[10] As pointed out in Ref. 9, the frequency chirp for a laser cavity with a frequency-dependent reflection coefficient $r(\omega)$ is reduced by a factor of $(1+A+B)$. Thus, the chirp of a weakly coupled ring resonator laser could be one order magnitude better than the conventional semiconductor lasers, which is crucial for high bit-rate transmission in future optical communication systems.

The loss in microrings will limit the ultimate performances of ring RCLs. Figure 2(a) is the calculated MSR and linewidth for a RCL at different losses. Even with a loss of 100 dB/cm, RCLs still can reach >35 dB MSR and <1 MHz linewidth at 5 mW output for $\kappa \leqslant 0.1$. These data are far better than conventional DBR/DFB lasers. But if the loss is too high, the threshold gain will also increase considerably. Figure 2(b) shows the threshold gain increase as a function of loss in the ring. If one can tolerate the doubling of the threshold current density, the required maximum loss in the rings is about 20 dB/cm for $\kappa=0.1$. With advanced material growth, patterning and etching, recently high index contrast waveguides for microring resonators with loss <20 dB/cm have been achieved.[11,12]

In conclusion, a semiconductor laser structure integrated with a passive high-Q ring resonator is proposed. Incorporation of a weakly coupled ring resonator in a $F-P$ laser cavity will dramatically improve the laser performances. Large side mode suppression ratio (>40 dB at 1 mW power), very narrow linewidth (<100 kHz) and reduced frequency chirp can be achieved. Even with moderately large loss in the ring resonators, RCLs still could offer promising performances. This laser could be an attractive source for future high bit rate DWDM system and sensing applications. Other advantages of ring resonator coupled semiconductor lasers include the wide and continuous wavelength tuning range,[6] the simple fabrication and the integration capability. Compared to DFB and DBR lasers, no grating and no multiple regrowths are required. However, gratings and other ring resonators can be easily integrated with a single ring RCL to improve the performances further.

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