

# A Semiconductor Tunable Laser Using a Wavelength Selective Reflector Based on Ring Resonators

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**Abstract:** We propose a tunable laser incorporating a cleavage-free wavelength selective reflector (WSR) formed by buried heterostructure (BH) microring resonators. Utilizing the proposed tunable reflector, a compact, 100-GHz-channel-spaced tunable laser is demonstrated.

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## 1. Introduction

A compact semiconductor tunable light source is needed for modern chip-scale wavelength division multiplexing (CSWDM) applications. Ring-coupled lasers that are based on semiconductor microresonator technologies have been suggested as devices to provide stable wavelengths and narrow spectral linewidths in photonic integrated circuits (PICs). Recently, a novel concept for wavelength selective reflectors (WSRs) based on coupled microring resonators was suggested [1]. The WSR is an attractive cleavage-free device that allows us to produce an in-plane optical feedback element with a simple fabrication process. In [1], a circular array, which consists of an odd number ( $N \geq 3$ ) of mutually coupled ring resonators, is coupled to a single bus line to form a WSR.

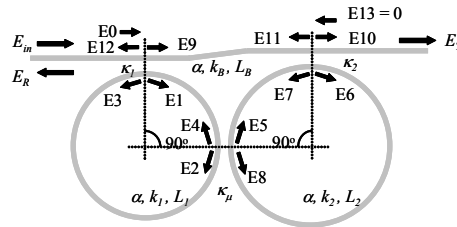


Fig. 1. A schematic drawing of a wavelength selective reflector (WSR)

In this paper, we propose a different layout for a tunable WSR that can be realized with fewer resonators ( $N = 2$ ) as depicted in Fig. 1. Here, two ring resonators having slightly different radii are coupled to a single bus waveguide and mutually coupled with each other. The layout in Fig. 1 utilizes Vernier effects that afford a wide spectral range of tuning by introducing small changes in the resonant wavelengths of the resonators. We analyze the proposed WSR and design a 100-GHz-channel-spaced tunable laser. The tunable WSR section is fabricated by using a buried heterostructure (BH) ring resonator technology [2-3], and offset quantum well (QW) techniques are employed to integrate a semiconductor optical amplifier (SOA) as the gain section [4].

## 2. Analysis and design of a microring wavelength selective reflector

We use the coupling of modes formalism to analyze and design the WSR. Solving the coupled linear equations is straightforward and the details will be omitted in this paper. The transmissivity ( $T$ ) and the reflectivity ( $R$ ) can be found from:

$$T = \frac{E_{10}}{E_m} = |T| \exp[j\phi_T], \quad R = \frac{E_{12}}{E_m} = |R| \exp[j\phi_R] \quad (1)$$

As stated earlier, we use BH ring resonators, where InGaAsP ( $n_{wg} = 3.40$ ) ring and bus waveguides are buried with InP ( $n_{clad} = 3.17$ ). The nominal radii of rings 1 ( $r_1$ ) and 2 ( $r_2$ ) are 130 and 140  $\mu\text{m}$ , respectively. When the BH waveguide has  $1 \times 0.4 \mu\text{m}^2$  cross-sectional area, the calculated effective indices of ring 1 ( $n_{eff1}$ ), ring 2 ( $n_{eff2}$ ) and the bus line segment connecting these rings ( $n_{effB}$ ) are 3.2831, 3.2900, and 3.3050, respectively, at  $\lambda = 1550 \text{ nm}$  for TE-polarization. The predicted free spectral range of rings 1 (FSR<sub>1</sub>) and 2 (FSR<sub>2</sub>) are 0.8 and 0.75 nm, respectively. The resultant FSR of the WSR is then 12 nm, the least common multiple (LCM) of FSR<sub>1</sub> and FSR<sub>2</sub>.

$R$  and  $T$  are specified by adjusting the coupling strengths for a given loss figure. When lossless ( $\alpha = 0$ ) waveguides are considered,  $|R|^2$  and  $|T|^2$  are complementary to each other (i.e.,  $|R|^2 + |T|^2 = 1$ ) at every wavelength. Since the reflective nature of a WSR originates from the ring-to-ring optical feedback,  $R$  and  $T$  are strongly affected by the strength of  $\kappa_\mu$  relative to the bus-to-ring couplings  $\kappa_1$  and  $\kappa_2$ : 1) when  $\kappa_\mu$  is comparable with  $\kappa_1$  and  $\kappa_2$ , the optical feedback is too strong and the resonant mode is split into two subpeaks. 2) As  $\kappa_\mu$  is weakened, the subpeaks are merged into one and the WSR becomes an ideal unity reflector with  $|R|^2 = 1$  and  $|T|^2 = 0$  at the resonance as shown in solid lines in Fig. 2 (a). 3) Further reduction of  $\kappa_\mu$  allows light to transmit through the bus, which consequently lowers  $|R|^2$  as given in dots in Fig. 2 (a). 4) When there is no feedback or  $\kappa_\mu = 0$ , all the light coupled into the resonators are coupled back to the bus line and the WSR becomes an all-pass filter ( $|R|^2 = 0$  and  $|T|^2 = 1$ ). Apparently, conditions 2) and 3) are of practical interest in lasers. In most semiconductor waveguides, however,  $\alpha$  is not negligible and  $|R|^2$  and  $|T|^2$  are not complementary to one another. Provided that BH ring resonators are used, a realistic WSR design is suggested in Table I. The assumed  $\alpha = 0.5 \text{ cm}^{-1}$  is the typical loss figure observed in BH ring resonators, which is lower than that of conventional air-guided resonators by several times [2-3].

Table 1. Suggested design of a tunable WSR in the presence of optical losses

$\alpha$	$\kappa_1$	$\kappa_2$	$\kappa_\mu$	$ T ^2$	$ R ^2$
$0.5 \text{ cm}^{-1}$	4.5 %	4.5 %	1 %	0.2	0.5

The WSR can be tuned by introducing slight changes in the resonant wavelengths of the rings. Here, we consider the free carrier injection (FCI) method for tuning the system, in which the resonant wavelengths are blue-shifted by free carrier plasma effects [3]. When carriers are injected into ring 2 only, the resonance of a WSR is digitally tuned to the shorter wavelengths with 0.8 nm channel spacing (e.g.,  $\Delta f_{channel} = 100 \text{ GHz}$ ) that is FSR<sub>1</sub>. Figure 2 (b) shows the theoretical tuning characteristics of the WSR given in Table 1. However, for precise tuning, both resonators must be tuned in a synchronized fashion to compensate the errors caused by the dispersions.

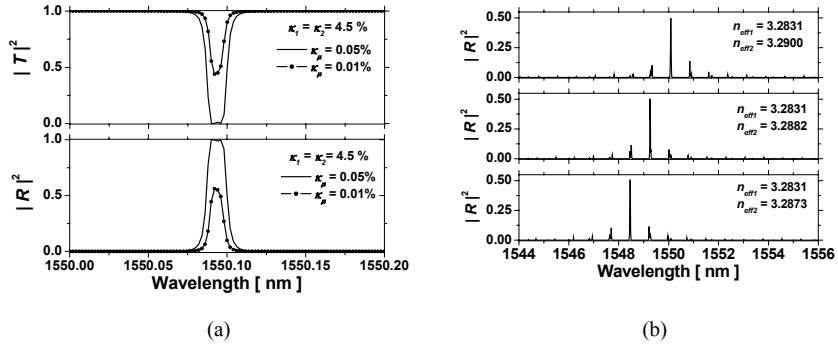


Fig. 2. (a) Theoretical  $|T|^2$  and  $|R|^2$  spectra of a lossless WSR (b) Calculated tuning characteristics of the WSR proposed in Table 1

### 3. Tunable laser design and fabrication

We design a tunable laser using a single WSR as illustrated in Fig. 3 (a). From the WSR design in Table I,  $|R_{WSR}| = \sqrt{0.5} = 0.707$  at the resonance. At the cleaved facet mirror, we find  $|R_{facet}| = 0.535$ . Following the notations provided in Fig. 3 (a), we track the accumulated changes in the field amplitude to express the threshold gain ( $g_{TH}$ ) as:

$$g_{TH} = \alpha \cdot \frac{L_p' + L_p}{L_G} + \alpha_G + \frac{1}{L_G} \cdot \ln \left[ \frac{1}{|T_{gain-trans}|^2 \cdot |R_{WSR}| \cdot |R_{facet}|} \right] \quad (2)$$

, where  $|T_{gain-trans}|$  is the amplitude transfer efficiency at the gain-to-transparent waveguide interface. Applying the parameters,  $\alpha = 0.5 \text{ cm}^{-1}$ ,  $\alpha_G = 5 \text{ cm}^{-1}$ ,  $L_p' = 80 \text{ }\mu\text{m}$ ,  $L_p = 100 \text{ }\mu\text{m}$ ,  $L_G = 700 \text{ }\mu\text{m}$ , and  $|T_{gain-trans}| = 0.9$  to (2) leads to  $g_{TH} = 22 \text{ cm}^{-1}$ . Note that  $g_{TH}$  can be reduced when the cleaved facet is replaced with another highly reflective WSR.

We initiate the epitaxy using metal-organic chemical vapor deposition (MOCVD) by growing an undoped 0.4- $\mu\text{m}$ -thick InGaAsP ( $\lambda_{wg} = 1250 \text{ nm}$ ) waveguide layer that is followed by six compressively-strained (0.5 %) quantum wells (6-MQWs) with  $\lambda_{QW} = 1560 \text{ nm}$ . Transparent waveguides are formed by selectively etching off the MQWs with wet chemical solutions. Once the gain and transparent sections are identified, we deposit a  $\text{SiN}_x$  layer onto which ring and bus waveguide designs are transferred by contact photolithography. Smooth and vertical, 0.8- $\mu\text{m}$ -deep waveguide mesas are dry-etched in a  $\text{BCl}_3$ -based inductively coupled plasma (ICP) discharge. After the mesa etching, the  $\text{SiN}_x$  mask on transparent sections is selectively removed. Then, a 0.7- $\mu\text{m}$ -thick, undoped InP

layer is overgrown to bury the quaternary waveguide mesa structures. The burying material is undoped to prevent the optical mode from being in contact with the absorptive p-materials that follow. The SiN<sub>x</sub> mask remaining on the gain areas is removed after the InP overgrowth. Finally, a 1- $\mu\text{m}$ -thick p-type InP and a 0.1- $\mu\text{m}$ -thick p-InGaAs layer are grown. The active region is patterned in a rib-type waveguide layout, where the top p-type layers are removed by aligning a pair of dry-etched trenches along the MQW-containing waveguides. In the ring resonator section, the trenches are 3  $\mu\text{m}$  away from the resonator core such that we maintain the waveguides buried in InP. After the wafer is planarized by polyimide, electrodes are formed and the device is cleaved for measurement. The WSR end facet is AR-coated. Fig. 3 (b) is a micrograph of the fabricated tunable laser device.

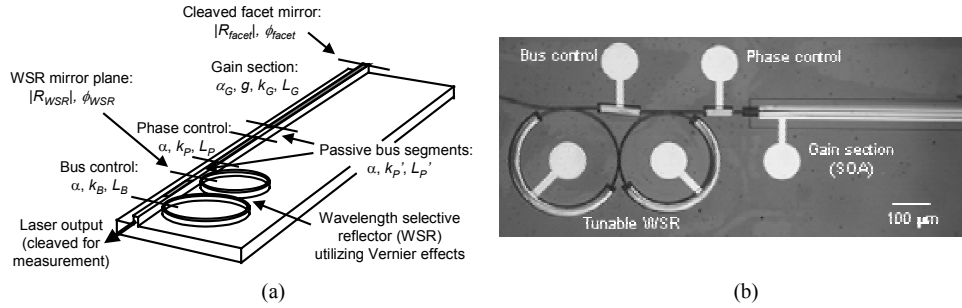


Fig. 3. (a) A schematic illustration of the suggested tunable laser (b) A micrograph of the fabricated device

#### 4. Results and discussions

We first measure the transmission characteristics by coupling an external TE-polarized light source into the cleaved mirror facet and collecting the output signal from the AR-coated WSR terminal, for which the gain section is pumped at  $I_G = 15$  mA up to transparency. For simplicity, only ring 2 is tuned (i.e.,  $I_{R1} = 0$  mA,  $I_{R2} > 0$  mA) in searching the resonance of the Vernier filter, and the first resonance is observed at  $\lambda = 1568.7$  nm when  $I_{R2} = 0.3$  mA. Now we remove the external light source and increase the current injection of the gain and bus/phase control ( $I_B/I_P$ ) sections to measure the laser. A single mode laser is observed at  $\lambda = 1568.7$  nm when  $I_G = 90$  mA,  $I_B = 4$  mA, and  $I_P = 0$  mA as shown in the inset of Fig. 4. The measured output intensity and side mode suppression ratio (SMSR) are  $-19$  dBm and  $-22$  dB, respectively. It is believed that greater output power at lowered driving current is achievable when the monolithic integration technique of gain and transparent waveguides is modified properly. Also, we expect the SMSR to be greatly improved when the cleaved facet mirror is replaced with another WSR.

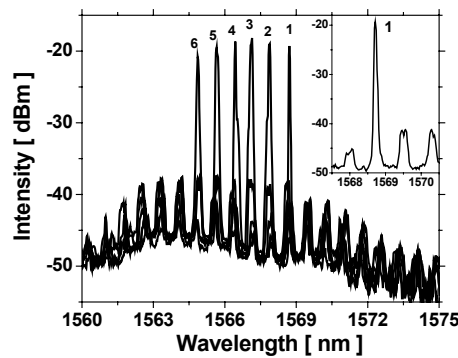


Fig. 4. Measured tuning characteristics of a 100-GHz-spaced, digitally tunable CW laser

Figure 4 shows the measured tuning characteristics of a 100-GHz-channel-spaced CW tunable laser, where  $I_{R1} = 0 \sim 0.4$  mA,  $I_{R2} = 0.3 \sim 5.4$  mA,  $I_B = 0 \sim 4.5$  mA, and  $I_G = 90 \sim 95$  mA are applied to demonstrate the digital tuning of the lasing wavelength for 6 channels. The current injection efficiency, and the consequent FCI tuning efficiency, can be improved when the BH ring resonators incorporate an appropriate current blocking structure.

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