# A GaInAsP–InP Double-Ring Resonator Coupled Laser

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***Abstract*—A monolithic single-mode GaInAsP-InP double microring resonator coupled laser is demonstrated for the first time. The laser comprises two passive ring resonators, semiconductor optical amplifiers in the bus waveguides, and 3-dB codirectional couplers. The laser has an output power of 0.5 mW with a sidemode supression ratio of $>$35 dB. The tunability is demonstrated using integrated platinum resistors on top of the waveguides in the rings.**

***Index Terms*—Directional couplers, resonators, ring lasers, semiconductor optical amplifiers (SOAs).**

## I. INTRODUCTION

MICRORING resonators are of great interest. They are potential candidates for large-scale photonic integrated circuits for applications such as optical add–drop filters, signal processing, switching, modulation, wavelength conversion, and lasers. This is due to their merits both as compact devices and as high $Q$-resonators.

In the configuration of a racetrack ring resonator, the coupling strength can be adjusted by changing gap size and coupling region length. In order to make the free spectral range (FSR) large, either a small radius of curvature microring is needed [1] or a double-ring resonator (DRR) configuration has to be used, where the radii of the rings differ slightly from one another.

In a ring resonator coupled laser (RCL), the 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 and photon lifetime at the lasing wavelength. Thus, the laser linewidth and the frequency chirp can be greatly reduced. The first demonstration of a semiconductor microring RCL was done by Park *et al.* [2] using a single ring resonator made out of active material biased at transparency. In addition, a DRR configuration can be used to extend the wavelength tuning range using the vernier effect. The idea of wide tunable double-ring RCLs (DR-RCLs) comprising of passive ring resonators and active gain sections was proposed by Liu *et al.* [3]. A double-ring coupled laser has been demonstrated recently using a tunable polymer double microring filter and erbium-doped fiber amplifier gain [4].

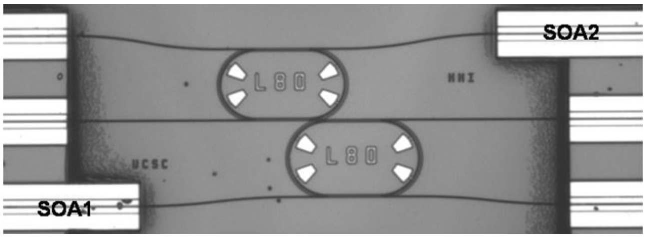

Fig. 1. Photograph of a DR-RCL.

In this letter, DR-RCLs with integrated semiconductor optical amplifiers (SOAs) on the basis of GaInAsP–InP have been fabricated and characterized.

## II. DESIGN AND FABRICATION

A detailed theoretical analysis of ring RCLs can be found in [5]. A standard ridge waveguide laser structure was used for the SOA section, which required an additional epitaxial growth step [6]. The width of the SOA is 2.2 $\mu$m. The bandgap wavelength of the quaternary material used for the passive waveguide is $\lambda_{\text{gap}} = 1.06$ $\mu$m. The waveguide ridge was deeply etched on the outer side of the ring to increase the light confinement and reduce the ring loss. The passive waveguide width is 1.8 $\mu$m. The design, fabrication, and layer sequence of the ring resonators, SOA, and passive waveguides are described in [6]. A photograph of a DR-RCL is shown in Fig. 1.

The ring resonators have a slightly different radius to increase the FSR and to achieve a single-mode operation. A DRR opens the possibility of expanding the FSR to the least common multiple of the FSR of individual ring resonators. This is done by choosing different radii in the DRR. In the case of different radii, the light passing through the DRR is launched from the drop port when the resonant conditions of the two single ring resonators are satisfied. The FSR of the DRR with two different radii is expressed by

$$\mathrm{FSR} = N \cdot \mathrm{FSR}_1 = M \cdot \mathrm{FSR}_2 \tag{1}$$

which leads to

$$\mathrm{FSR} = |M - N| \frac{\mathrm{FSR}_1 \cdot \mathrm{FSR}_2}{|\mathrm{FSR}_1 - \mathrm{FSR}_2|} \tag{2}$$

where $N$ and $M$ are natural and coprime numbers, $\mathrm{FSR}_1$ and $\mathrm{FSR}_2$ are FSRs of Rings 1and 2, respectively. The transfer functions are critically dependent on the coupling coefficients.

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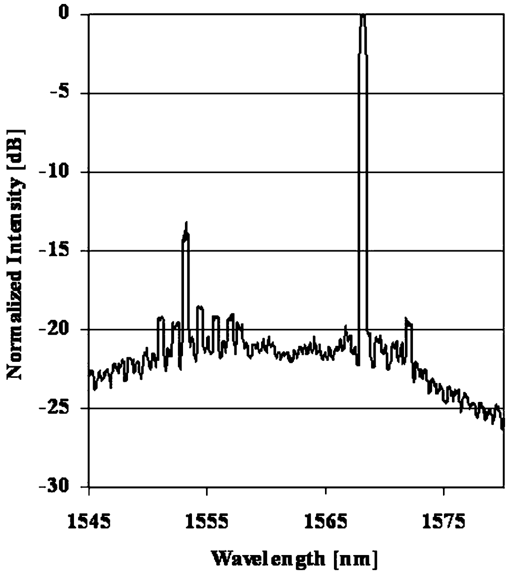

Fig. 2. Spectrum of a DR-RCL with an FSR of 15 nm.

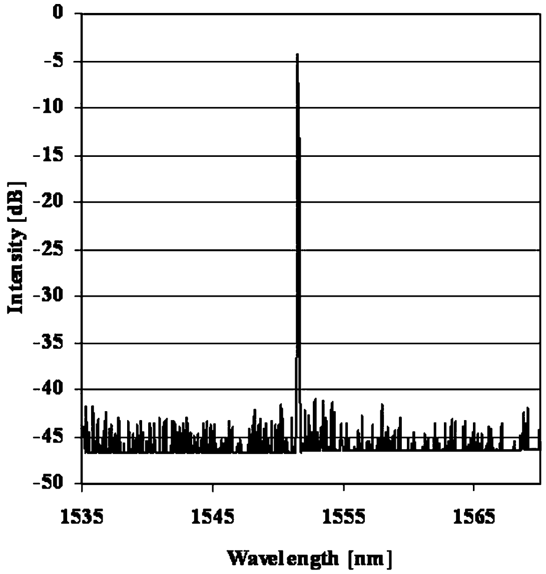

Fig. 3. Spectrum of a DR-RCL with an FSR of 30 nm.

Two configurations of DR-RCLs are investigated and the radii of the rings are 100/108 and 100/104 $\mu$m. The cavity lengths of the racetrack-shaped rings for the first configuration are $L_1 = 1628.32$ $\mu$m and $L_2 = 1678.58$ $\mu$m, for the second configuration $L_1 = 1628.32$ $\mu$m and $L_2 = 1653.45$ $\mu$m, which lead to an FSR of the double ring of about 15 and 30 nm, respectively, using (2).

One of several advantages of using a DRR is the possibility of a higher tuning enhancement factor using the vernier effect. This is given by

$$T = \frac{1}{1 - \frac{L_1}{L_2}} \tag{3}$$

where $L_1$ and $L_2$ are the cavity lengths of each ring. The tuning range of the DRR is $T$ times the tuning range of a single ring. The tuning enhancement factors of the two fabricated DR-RCLs are 33 and 66.

The coupling between the bus waveguides and the ring resonators is realized by a codirectional coupler with a length of 500 $\mu$m and a coupling gap of 1 $\mu$m. The coupling from the bus waveguide to the ring depends critically on the separation. The achieved splitting ratio is 3 dB. The laser cavity consists of SOA1 and SOA2 (see Fig. 1) which have a length of 500 $\mu$m each and the two ring resonators. The chip length is 2 mm. The remaining SOAs are not biased and they are used as absorbers to supress the lasing of subcavity modes. The end facets of the chip are as-cleaved and have not been coated, which could be improved to increase the performance in the future. The output of the DR-RCL is collected using a tapered fiber at SOA2.

## III. MEASUREMENT

### *A. DR-RCL With an FSR of 15 nm*

The spectrum of the DR-RCL with an FSR of 15 nm is shown in Fig. 2 when the driving currents for SOA1 and SOA2 are 110 and 90 mA, respectively. Due to the not large enough FSR of the DRR, another lasing mode is present. The power difference between the two lasing modes is 13 dB. The threshold of the DR-RCL is about 30 mA when SOA1 is biased above 40 mA.

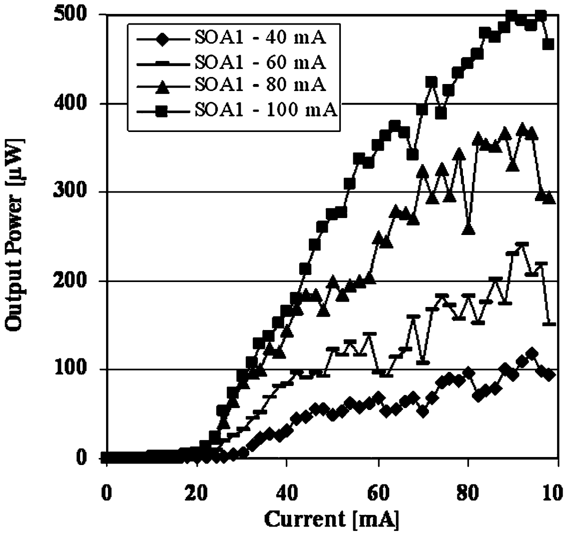

Fig. 4. Power versus current (*P-I* characteristics) of the DR-RCL with an FSR of 30 nm changing the current at SOA2.

### *B. DR-RCL With an FSR of 30 nm*

The spectrum of the DR-RCL with an FSR of 30 nm is shown in Fig. 3. A sidemode supression ratio of >35 dB is obtained which is limited by the dynamic range (−35 dB) of the optical spectrum analyzer (OSA). The linewidth of the lasing wavelength is also limited by the bandwidth of the OSA which is 0.06 nm in our case. From calculations, the linewidth is estimated to be <2 MHz. The driving currents for SOA1 and SOA2 are 100 and 90 mA, respectively.

The output power varies with the currents supplied to SOA1 and SOA2 (Fig. 4). The threshold of the DR-RCL is about 25 mA when SOA1 is biased above 40 mA.

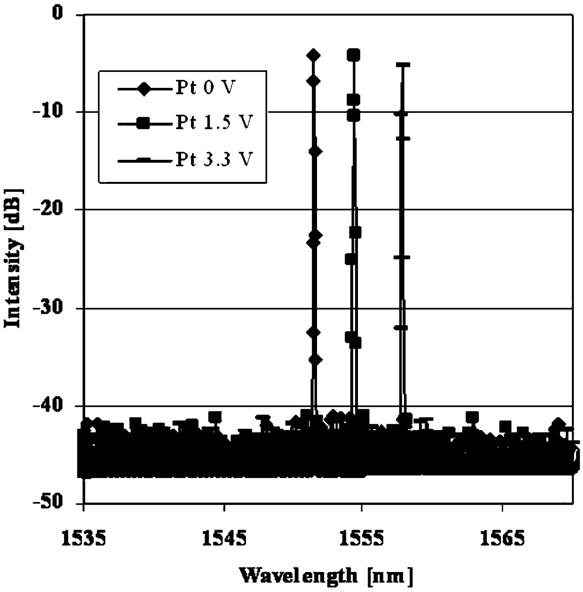

Fig. 5. Tuning of the DR-RCL using integrated platinum resistors.

The resonance wavelength of the rings can be tuned by the integrated platinum resistors [7] on top of the passive waveguides in the ring resonators.

The tunability (Fig. 5) is approximately 6 nm, which is due to the limiation given by the platinum resistors. The tuning of resistors, using this racetrack configuration and the current design of the resistors, in one ring enables only a tuning of 0.1 nm which is not the entire FSR of one ring of approximately 0.5 nm. If the tuning bandwidth of a single ring is multiplied by the tuning enhancement factor of 66 in our case, then this will lead to the obtained tuning bandwith of approximately 6.6 nm. The double-ring structure demonstrated tuning by discrete modes. Continuous fine tuning can be achieved by adding a separate phase section inside the laser cavity similar to multi section DBR lasers.

## IV. CONCLUSION

We have demonstrated for the first time a monolithic single-mode DR-RCL comprising two passive ring resonators, SOAs in the bus waveguides, and 3-dB codirectional couplers. An output power of 0.5 mW and a sidemode supression ratio of $>35$ dB were achieved. Further work will concentrate on improving the tunability and the output power.

## ACKNOWLEDGMENT

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