Frequency beating between monolithically integrated semiconductor ring lasers

Hongjun Cao, Chiyu Liu, Hai Ling, Hui Deng, Marcita Benavidez, Vladimir A. Smagley, and Robert B. Caldwell
Center for High Technology Materials, University of New Mexico, 1313 Goddard SE, Albuquerque, New Mexico 87106-4343

Gregory M. Peake
Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185

Gennady A. Smolyakov, Petr G. Eliseev, and Marek Osiński
Center for High Technology Materials, University of New Mexico, 1313 Goddard SE, Albuquerque, New Mexico 87106-4343

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Optoelectronic integrated circuits incorporating a pair of optically independent large-cavity semiconductor ring lasers (SRLs), directional couplers, waveguides, Y-junction mixer, and photodetectors are demonstrated. Counterclockwise and clockwise output beams from the two SRLs are collected separately and mixed prior to detection. Frequency beating between modes of two SRLs is measured. The beat frequency is fine-tuned by an integrated Joule heater, designed for thermal control of the lasing wavelength. No signs of frequency lock-in in the vicinity of zero detuning are observed, which makes this structure a promising candidate for applications in ring laser gyros and optical rotation sensors. © 2005 American Institute of Physics.

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Semiconductor ring lasers (SRLs) are attractive for monolithic integration in optoelectronic integrated circuits (OEICs) because neither cleaved facets nor gratings are required for optical feedback. Since their first demonstration,1 monolithic SRLs have been studied in many aspects, such as continuous-wave operation,2 single-frequency3 and unidirectional operation,4 mode-locking,5 and unidirectional bistability.6,7 SRLs are of particular interest for applications in optical inertial rotation sensors, in which the beat frequency shifts between two counterpropagating lasing beams is directly proportional to the applied angular velocity corresponding to the Sagnac effect.8,9 The scheme of a compact and low-cost monolithic gyro or rotation sensor is very attractive, but due to the lock-in phenomenon,9,10 which locks the frequency of counterpropagating beams within a single cavity, the Sagnac effect has never been observed in a monolithic SRL. In this letter, we report an OEIC design that circumvents the lock-in problem and has a potential to become a monolithic rotation sensor. Mode beating and tuning of the beat frequency between two optically isolated SRLs are reported.

A diagram of the OEIC with integrated rings, waveguides, and photodetectors (PDs) is shown in Fig. 1(a). The OEIC contains a pair of ring lasers R1 and R2 with single-lateral-mode ridge waveguides of 3 μm width. The racetrack-shaped rings have a 1 mm radius of curvature and 2-mm-long straight sections. The total cavity length is 10.28 mm. As shown in Fig. 1(a), the ring lasers are coupled to absorbing spiral elements located inside the ring for R1 and outside the ring for R2. The spirals provide asymmetric losses and favor counterclockwise (CCW) lasing for R1 and clockwise (CW) lasing for R2. The straight sections of ring lasers form parts of directional couplers with 3-μm-wide external waveguides that deliver the laser light to monitoring PDs and to a mixer section. The edge-to-edge distance between the waveguides in the coupler is 3 μm, which results in ~1% evanescent outcoupling of the lasing light. The distance between the two waveguides before they are combined into a Y-junction mixer is 0.6 mm. The mixer combines the CCW wave from R1 and CW wave from R2 for frequency beating. In order to minimize reflections at the waveguide-detector junctions, the integrated PDs are cut at a Brewster angle at the tapered ends of each outcoupling waveguide. A branched-off waveguide conducts portion of the mixed light to the chip edge at a tilted angle for direct optical output.

The devices are fabricated using metalorganic-chemical-vapor-deposition-grown wafers with InGaAs/GaAs/AlGaAs double-quantum-well graded-index separate-confinement heterostructure emitting light at ~1.02 μm. Ring laser ridges, waveguides, and PDs are defined in a single photolithography step and dry-etched to a depth of 0.85 μm, which is about 0.3 μm above the active region. In a second etching step, isolation trenches are formed along boundaries between ring lasers, waveguides, and PDs. These trenches penetrate about 1.5 μm below the active region in order to reduce possible electrical crosstalk. The OEIC is planarized using benzocyclobutene (BCB). P-side contacts (Ti/Pt/Au) and thicker bonding metallization (Ti/Au) are then deposited. Integrated Ti/Pt/Au 20-μm-wide stripe Joule heaters with the resistance of ~20 Ω, located at the inner sides of ring ridges and residing on top of BCB, are added for thermal fine tuning of lasing wavelength. Figure 1(b) shows a micrograph of a finished device near a ring-waveguide coupler, including a segment of the Joule heater.

Typical dc light-current (L-I) curves are shown in Figs. 2(a) and 2(b) for ring lasers R1 and R2, respectively, with photocurrent response taken simultaneously from the inte-
grated PDs. Photocurrents of PD1 and PD2 correspond to the opposite directions, CW and CCW, of traveling waves in the rings. The lasing threshold is 310 mA/cm² for R1 and 340 mA for R2. Bidirectional operation is observed just above the lasing threshold. At higher currents, multiple directional switching occurs, indicating strong competition between counterpropagating waves. Similar switching behavior was reported in both small6,7 and large11 SRLs and was explained by mode competition via gain saturation. We believe that spontaneous emission plays also an important role in this process.

Figure 2 also indicates that CCW lasing of R1 and CW lasing of R2 are favored by the asymmetric spiral waveguides. Slope efficiency for these waves is over twice higher than for the counterpropagating waves. At high currents, the desirable lasing direction is dominant in both SRLs.

Tuning of lasing wavelength by the integrated Joule heater is shown in Fig. 3, with typical lasing spectra of R1 at pumping current of 400 mA and Joule heater current of 0 and 90 mA. The inset illustrates the spectral peak shift with Joule heater current varying from 0 to 90 mA, indicating linear tuning of the lasing wavelength at a rate of ~0.0011 nm/mA.

We report elsewhere the observation of frequency beating signal between modes of individual SRLs.11 The longitudinal mode spacing in the long ring cavity is ~0.026 nm, which is beyond the resolution capability of our monochromator (0.03 nm). Hence, the spectra in Fig. 3 do not resolve the individual cavity modes. However, measurements of the mode-beating spectra indicate that the SRLs usually operate in multiple longitudinal modes.

To observe a beating signal between the two SRLs, each of the ring lasers is preset to operate at a current such that the waves favored by the spiral waveguides predominate. As illustrated in Fig. 1(a), the output from both lasers is directed to the mixer section, and then split between an integrated PD and a branched waveguide for external collection. The waveguides and the mixer are biased above the transparency level (700 mA) for low-loss signal transmission. A beam splitter divides the external output into two parts. One part is sent to an optical spectrum analyzer (OSA). The other part is coupled to a high-speed photodetector; from which the signal is amplified and sent to an rf spectrum analyzer with bandwidth of 26 GHz. Typically, the frequency difference between the two beams from R1 and R2 is much bigger than 26 GHz. Their wavelength is therefore tuned roughly by the pump current. After careful tuning that caused the spectra from the two lasers to overlap with each other (as monitored by the OSA), a beating signal could be detected by the rf spectrum analyzer. Fine-tuning is then performed by using the integrated Joule heaters. Figure 4(a) shows typical beating spectra tuned by the Joule heater residing on R1. Results of fine-tuning measurements are summarized in Fig. 4(b). The averaged tuning rate is ~20 MHz/mA with some small
variations. This rate is much smaller than the tuning rate of individual laser spectra shown in Fig. 3. This is because the Joule heater on \( R_1 \) also shifts the wavelength of the adjacent SRL \( R_2 \) through thermal crosstalk. Only the difference between shifted mode wavelengths affects the tuning rate of beat frequency.

As shown in Fig. 4(b), the central beating frequency \( f_b \) passes zero at the heater current of \( \sim 14 \) mA. There are no signs of frequency lock-in in the vicinity of zero detuning, i.e., no strong deviation from linearity in \( f_b \) dependence on current and no spectral narrowing of \( f_b \) near zero. This demonstrates satisfactory optical isolation between SRLs. Moreover, the beating signal can be taken at arbitrary detuning, providing another way to avoid the frequency locking if it were to occur at zero detuning. The effective spectral linewidth is estimated to be 40–50 MHz for modes that produce the beating spectrum.

Important factors influencing the linewidth are multimode operation at high pumping levels and various instabilities associated with the current sources, temperature fluctuations, thermal convection in a nonhermetic package, etc. According to both theory\(^1\) and experiments on smaller SRLs,\(^7\) single-mode operation is preferable when the SRL operates unidirectionally. In our case, however, the rf spectra contain a strong beating signal at \( \sim 7.6 \) GHz, corresponding to 0.026 nm cavity mode spacing. This indicates multi-longitudinal-mode operation.

In conclusion, we have demonstrated a fully functional OEIC containing a pair of integrated unidirectional SRLs. Mode beating between two optically independent SRLs is reported. The beating signal can be followed over the rough tuning range of \( \sim 26 \) GHz by varying the pumping currents on SRLs. Fine tuning of the beat frequency by an integrated Joule heater is demonstrated in the range of 0–250 MHz. There are no signs of frequency lock-in between ring lasers when beating frequency passes zero.

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