Compact InGaAsP/InP Flattened Ring Lasers with Etched Beam Splitters

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Abstract: We present results from novel compact InGaAsP/InP based flattened micro-ring resonators and lasers. Resonators with circumferences 30-300µm by using etched beam-splitters (EBS) are demonstrated. EBS coupler insertion loss is measured as low as 0.6dB.
OCIS codes: 230.5750 Resonators, 250.5300 Photonic integrated circuits

1. Introduction

Ring resonators are a critical building block in a variety of photonic components including: optical switches [1], serial and cascaded filters [2], tunable lasers [3], optical memory elements [4], tunable optical delay lines [5], and biosensors [6]. The multitude of uses for rings makes them extremely versatile in photonic integrated circuits (PICs) as a single dry etch can be used to define a variety of functional elements. Furthermore, low-cost photolithography can be used for the entire mask set, whereas the alternative for integrated cavities using gratings requires expensive electron-beam lithography or holography. Small active rings with a large free spectral range (FSR) are needed in channelizing filters for wavelength-division-multiplexing (WDM) and narrowband optical pre-filtering to reduce the data load before analog-to-digital conversion. In addition, smaller rings have a reduced cavity flight time allowing for faster optical switching and routing, and more rapid state changes in optical memory. As ring dimensions are reduced, smaller footprints for the functional elements and lower energy consumption makes compact rings an economically viable choice for the next generation of PICs.

The length of traditional ring resonators is limited by the size of the directional or multi-mode interference (MMI) coupler used. From recent ultra-compact coupler fabrication in InP (without the use of electron-beam lithography), a 55µm directional coupler [7] and a 20µm MMI coupler [8] were demonstrated. Traditional ring lengths are typically >4x larger than the coupler, that is >80µm.

Etched beam-splitter (EBS) couplers rely on evanescent wave coupling across a narrow lower index gap by the process of Frustrated Total Internal Reflection (FTIR). EBS couplers with straight connecting waveguides have been demonstrated in GaAs [9-10] and InP [11] for use as add-drop filters. The EBS couplers have a sub-micron footprint making them ideal for use in compact resonators. The flattened ring resonator uses a radius of curvature 3x larger than the traditional ring resonator or racetrack resonator; this is made possible because the flattened ring requires arcs to cover only 120^o of a full circle while each EBS coupler reflection adds an additional 120^o. As ring radius is reduced, the highly confined optical mode is pushed towards the outside of the waveguide and has a greater overlap with the sidewall roughness, which causes the scattering loss to increase exponentially. Allowing a larger radius of curvature thus translates to a significant improvement in roundtrip loss for micro-ring resonators. Previous work demonstrated flattened rings with greater than 800µm circumference [2]; here we present device results from ring with lengths 30, 60, 90, 150, and 300µm and lasing results from the largest three rings.

2. Design and fabrication

The device is fabricated on an InGaAsP/InP centered quantum well (CQW) platform with 10 compressively strained QWs centered in a 350nm waveguide layer. Passive waveguides are defined by an intermixing process of phosphorous implantation and rapid thermal annealing at 675^{o}C to shift the bandgap of the CQWs from 1545nm to 1410nm. A single blanket regrowth is used to cover the device with a 1.8µm p-InP cladding layer and p-InGaAs contact layer.

A bilayer Cr/SiO_2 (50/650nm) hardmask and a single lithography are used to define the waveguides and EBS couplers to avoid any misalignment between the coupler and the waveguide. The photoresist (PR) used is a 200nm thick THMR-M100 with a 300nm thick contrast enhancer CEM365iS. The thin PR was necessary to define 300nm gaps for the smallest EBS, and assured that all feature dimensions were conserved from the photolithography mask. The Cr was etched in a low power Cl_2 based inductively coupled plasma (ICP) etch, the PR removed, and 550nm of SiO_2 etched in a SF_6 based ICP etch. A PR lift-off and second Cr deposition was used to cover the waveguides away from the EBS in 40nm of additional Cr that served as a mask for a final 100nm SiO_2 etch in the EBS regions. The final mask provided a 100” etch delay for the waveguides, this accounted for the difference in etch speed in the narrow EBS gaps due to the RIE lag effect, which reduces the etch rate of high-aspect ratio features. The InGaAsP/InP was deeply etched in a Unaxis ICP RIE with $Cl_2/H_2/Ar$ chemistry and a 200°C heated chuck. The etch depth was 5µm for the waveguides and 7µm in the EBS regions. The processed devices are shown in fig. 1.

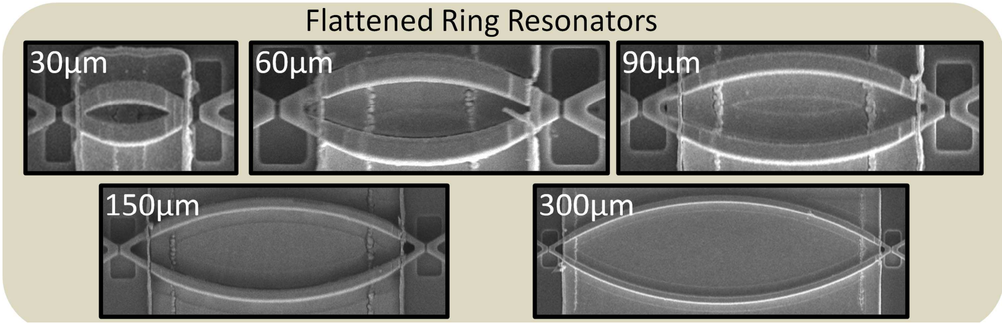


Fig. 1. Scanning electron microscope (SEM) images of flattened ring resonators with circumferences 30-300µm

The semiconductor optical amplifiers (SOAs) have a peak large signal gain of 50dB/mm at 1530nm for TE polarized light, and the internal losses, as calculated from 2µm width pulsed laser cleave-back measurements, were $\alpha_{i,passive} = 7.5cm^{-1}$ and $\alpha_{i,active} = 11.9cm^{-1}$.

3. Lasing in flattened rings

The flattened ring lasers were tested CW and the lasing curves for 90µm, 150µm, and 300µm circumference devices are shown in fig. 2. The extinction ratio on the non-lasing devices was measured to be 5.5dB and 4dB for the resonators with lengths 30µm and 60µm respectively. The net cavity losses (losses minus gain) per roundtrip (RT) for these resonators were calculated from their extinction ratios to be 3.97dB and 2.85dB respectively. Therefore, an additional 3-4dB of gain/RT is necessary to reach lasing in these cavities.

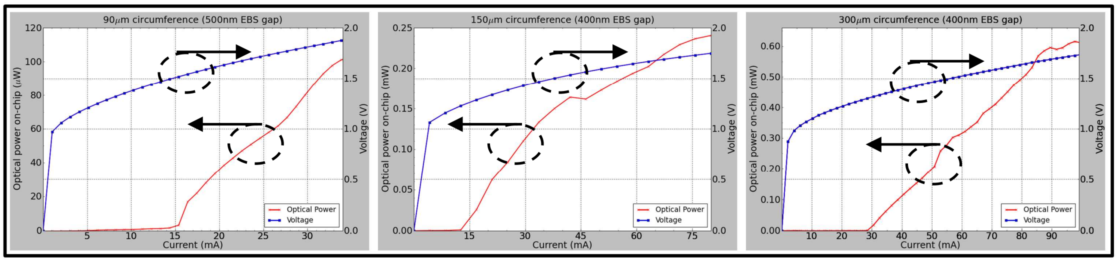


Fig. 2. LIV lasing curves for 90µm, 150µm, and 300µm circumference flattened rings.

The lasing spectra of the flattened rings are shown in fig. 3. The corresponding FSR and side-mode suppression ratio (SMSR) are listed in table 1. The lasing peak shifts to lower wavelengths as the ring dimensions are reduced. This is due to increased pumping of the partially intermixed material at the edges of the active region. The phosphorous implant used in intermixing diffuses during the RTA process causing the nearby active region to shift partially, resulting in a border region with a 1500nm bandgap. The design of the active regions was conservative to avoid large losses from unpumped active material. However since the partially intermixed region has a dominant effect in the smaller flattened rings, future designs may benefit from an offset quantum well platform so that quantum wells can be removed using a wet-etch. This approach would provide a more digital transition between the active and passive regions, while the trade-off would be reduced gain in the active region.

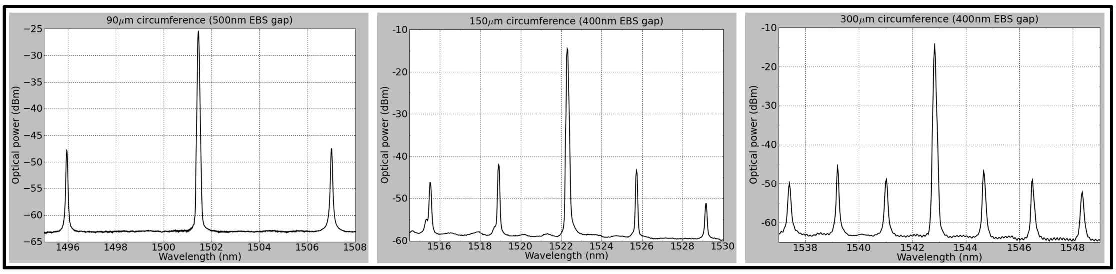


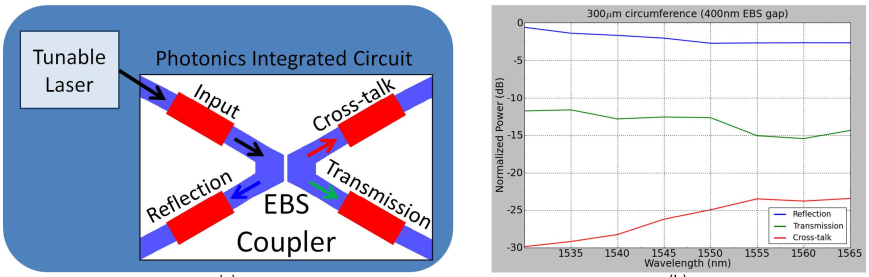
Fig. 3. Lasing spectrum of 90µm, 150µm, and 300µm circumference flattened rings.

Table 1: Flattened ring FSR and SMSR

Ring Length (µm)	30	60	90	150	300
FSR (nm)	13	7.2	5.5	3.4	1.8
SMSR (dB)	N/A	N/A	22	27	31

4. EBS coupler losses

The maximum SOA gain per RT in the 90µm ring is 3.5dB (L_{active}=70µm), therefore each 500nm EBS coupler must have losses <1.75dB assuming no other losses from waveguide scattering. The EBS couplers have an incident angle of 30^o, which is set far from the critical angle of 18^o in order to minimize loss on reflection. The high incident angle reduces the evanescent field coupling, and EBS gaps <600nm are necessary to have coupling >5%. For TE polarization, the wavelength dependence of the reflection, transmission, and cross-talk transmission of the EBS couplers was characterized by sweeping an external tunable laser and measuring on-chip reversed biased SOAs as illustrated in fig. 4a. The wavelength dependence of a 400nm gap EBS coupler on a 300µm circumference flattened ring is shown in fig. 4b. We calculate the power inside the 300µm cavity is around 11dB larger than detected outside the cavity, or 7mW at peak lasing. A minimum EBS loss of 0.6dB was measured at 1530nm, and <2.5dB variation in reflection over the C-band. There is 0.5dB of uncertainty due to the bias point for transparency current density, which results in gain variation between SOAs.



(a) (b)

Fig. 4.(a) EBS coupler test set-up, (b) Reflection, transmission, and cross-talk transmission of a 400nm EBS coupler.

5. Conclusion

Compact flattened ring resonators with circumferences 30-300µm have been fabricated and lasing spectra observed for the 90µm, 150µm and 300µm designs. The on-chiplasing power is greater than 0.6mW for the 300µm rings. The EBS coupler insertion loss was as low as 0.6dB with <2.5dB variation in reflection over the C-band. As the transmission is generally low through the EBS couplers, flattened rings are ideal for applications involving weakly coupled resonators such as coupled cavity tunable lasers, channelizing filters, and narrowband pre-filters.

Acknowledgements

This work was supported by the Office of Naval Research. A portion of the work was done in the UCSB nanofabrication facility, part of the NSF funded NNIN network.

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