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Compact Vertically-coupled Microring Laser Array Dual-Wavelength Source for Terahertz Mode Beating

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Abstract: *Continuous-wave operation of a fully tunable compact microring twin-laser array is demonstrated for the first time. The two active microrings, with radii of 70μm and 74μm, are vertically-coupled to a single passive waveguide. Tuning of the current facilitates a wavelength separation from 4.9nm to 6.3nm.*

Introduction

Microring lasers based on III-V semiconductor material are an attractive candidate as future ultra-compact light sources. They are expected to play a crucial role in the future large scale monolithic integration of photonic integrated circuits as they do not require cleaving to form edge mirrors.

However, while significant advances have been made using sophisticated passive microring topologies for dispersion compensation and filtering [1], the integration of multiple active components has been frustrated by the need for an integration technology which allows the close coupling of active devices with low loss bus waveguides.

One promising method for allowing effective integration has been the use of vertical-coupling, and several III-V microring devices involving active-passive integration have been studied for potential applications in telecommunications [1]. By implementing the active microring resonator and the passive bus waveguide on a different epilayer plane, one can achieve a greater flexibility in device design (allowing separate optimisation of ring and bus guides) and minimise the area of pumping in the device by using the minimum areas of active region waveguide. Closely spaced active and passive waveguides with controlled coupled coefficients may be realised by exploiting wafer-bonding technology [2]. A part-processed wafer may be inverted and wafer bonded to a transfer wafer, which provides mechanical support while the second face is etched back and processed. This enables the intergation of passive bus waveguides with active photonic components through 3-D interconnection. This approach has allowed active, vertically-coupled microdisk devices for switching and routing [3], demultiplexing [4] and microresonator arrays [5]. Vertically coupled active microrings have also been developed, where pulse-operated laser oscillation with a 13mA threshold current had recently been reported [6].

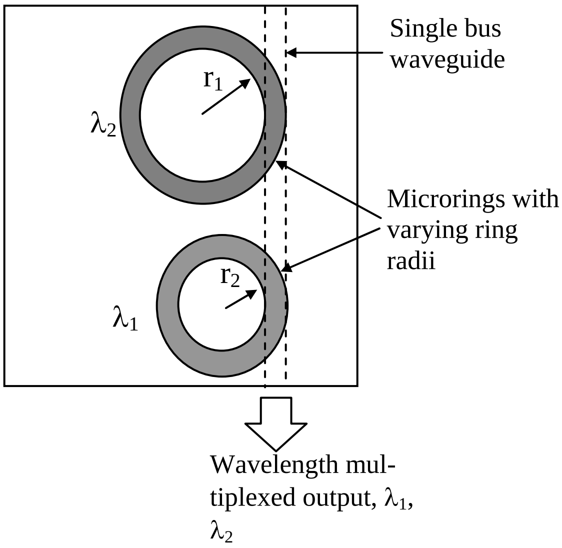

Fig. 1: Schematic of vertically-coupled microring laser array architecture.

In this paper, we demonstrate, for the first time to our knowledge, a CW-operated vertically-coupled microring dual-laser array. The twin lasers, as shown in the schematic in figure 1 above, are set to generate different wavelengths, this proving the feasibility of a compact and robust dual-wavelength light source for applications for example in terahertz generation.

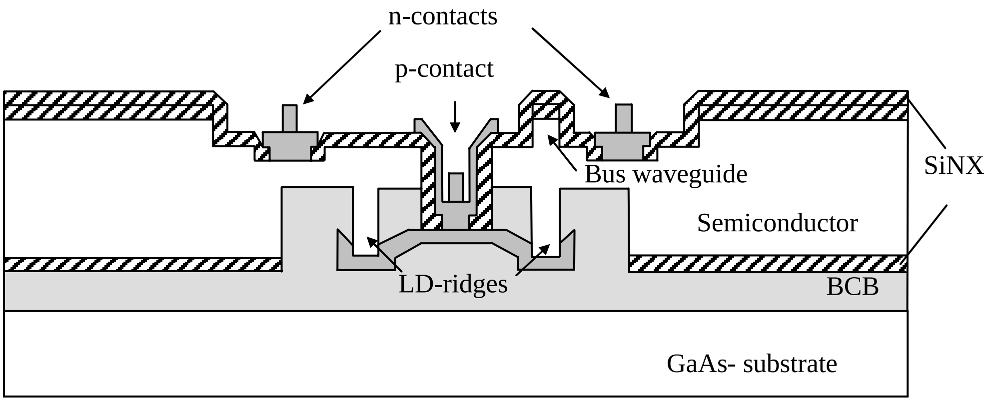

Fig. 2: Epitaxial layer structure of the microring laser.

Design

Two microring laser cavities with an offset resonance, integrated onto a single bus waveguide, can lase independently while coupling their output to the same passive bus waveguides. The resonance condition in a microring cavity is given by:

$$m\lambda_{res} = 2\pi n_{eff} R, \qquad (1)$$

where m is an integer indicating the longitudinal mode number, λ_{res} is the resonance wavelength, n_{eff} is the effective index of the optical mode and R is the ring radius. By selecting two microrings with different ring radii, an offset can be introduced to the resonance wavelength of the two microring lasers. The effective index in a laser cavity is a function of the injection current, temperature distribution and cavity geometry. The effective indices in the two microring lasers exhibit different sensitivity against injection current, an effect which can be exploited in order to tune the separation in the resonance wavelength by simply varying the injection current to the two laser cavities.

Device Structure

Previous studies of vertically coupled microring lasers using a wafer-bonded transfer substrate [7] have defined the bus waveguide prior to inverting the wafer. The microring resonators are therefore processed on the bonded wafers. However this approach may become susceptible to tight alignment tolerances resulting from run-out in the mask alignment features or warping in the composite wafer. This becomes increasingly important for active laser structres where multiple photolithographic steps are performed. To avoid this possibility, the laser structures are defined on the first face, prior to wafer bonding. The complete epitaxial structure is grown, the laser waveguides are defined and the p-type metal is deposited prior to wafer bonding to the transfer wafer. The substrate is removed by etching prior to the formation of bus waveguides and the opening of via holes to the p-metal at the transfer wafer. This results in a buried active microring waveguide structure, with the additional advantage that the laser is well protected during wafer dicing process.

Furthermore, this enables a standard laser epitaxial growth processes prior to wafer bonding. Figure 2 shows the layer structure of the vertically-coupled microring laser. The buried microring structure is clad by low index benzo-cyclo-butene (BCB) material applied during the wafer-bonding process, where the high index difference ensures a good modal confinement within the waveguide.

The passive bus waveguides are formed on top of the active microring structure. Both p and n contacts are implemented on the top surface of the fabricated device. The width of both the passive bus waveguide and active microring are 1.8µm. The active region of the microring laser comprises of six InGaAs quantum wells, with a bandgap of $Q_{ring} = 1.55\mu m$, and is clad by a confinement layer with a thickness of 0.43µm. The InGaAsP bus waveguide has a bandgap of $Q_{bus} = 1.44\mu m$, and a thickness of 0.35µm. The serially cascaded microring lasers with ring radii of 70µm and 74µm are vertically-coupled to the same bus waveguide.

Experiment

Measurements are performed to assess the lasing performance of the fabricated devices in terms of light-current (LI) characteristics, wavelength spectrum and wavelength separation between lasing modes of the two cascaded lasers.

Figure 3 shows the LI characteristics for both clockwise and counter-clockwise oscillating modes for the two cascaded microring lasers.

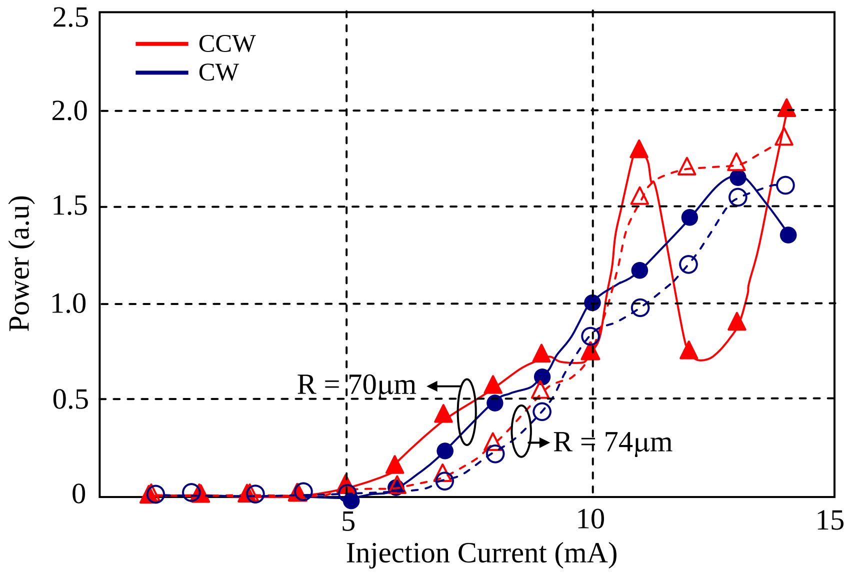

Fig. 3: Clockwise and counter-clockwise light-current characteristics of microring lasers.

The threshold currents for the two devices are 6mA, which corresponds to a threshold current density of 720A/cm^2. Thermal roll-over in the LI characteristic occurs at an injection current of 14mA.
Figure 4 plots the output spectra for the clockwise propagating modes of the two lasers as well as the combined power against wavelength under a bias current of 8mA, 10mA and 12mA, respectively. The lasing wavelength of the cascaded microring laser is centred in the 1575nm window, where a current range of 4mA gives rise to a wavelength variation from 1573.9nm to 1580nm for the 70µm-radius device, and 1580.2nm to 1584.9nm for the 74µm-radius device. This corresponds to a wavelength-current sensitivity of 1.5nm/mA and 1.15nm/mA, respectively. Side-mode suppression-ratio is observed to be in excess of 20dB, demonstrating excellent single-mode operation.

In order to provide a graphical illustration of the fine-tuning mechanism of the wavelength separation Δλ between the two microring lasers, figure 5 plots the wavelength separation as a function of injection current. The wavelength difference is observed to vary from 6.3nm at an injection current of 8mA to 4.9nm at an injection current of 12mA, corresponding to an overall wavelength difference tuning characteristics of 0.35nm/mA.

The result presented here highlights the potential of cascaded microring laser as compact and robust tunable dual-wavelength light source suitable for applications in terahertz mode-beating.

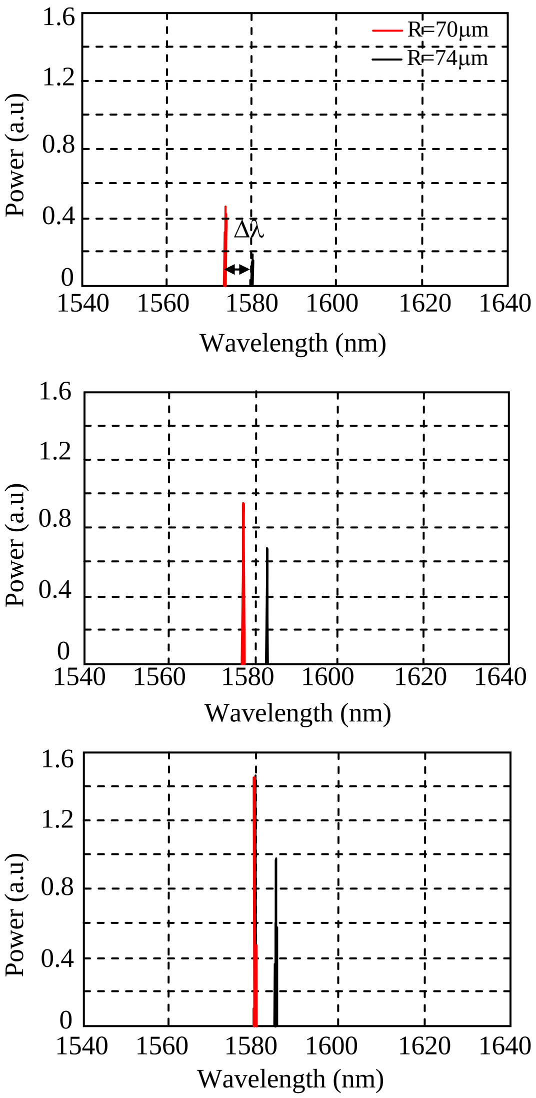

Fig. 4: Spectra of the dual-wavelength cascaded device at an injection current level of 8mA (top), 10mA (middle and 12mA (bottom).

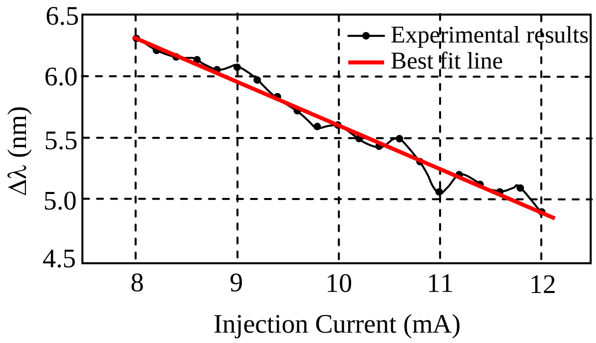

Fig. 5: Wavelength separation between the two lasing modes from the microring laser array.

Conclusions

A novel serially-cascaded vertically-coupled microring laser array, constructed using wafer-bonding technology, is demonstrated. CW operation of the lasers is demonstrated for the first time. The cascaded devices have threshold current of 6mA and oscillate with side mode suppression of greater than 20dB up to 12mA. The wavelength-current sensitivity of the two lasers is measured to be 1.5nm/mA and 1.15nm/mA. This corresponds to a tunable wavelength difference of 1.4nm across a current range of 4mA, highlighting its potential as compact and robust dual-wavelength light source suitable for broadband continuous tuning with a device footprint as small as 100×150μm².

Acknowledgments

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