Single-mode laser strategies for edge-coupled micro-transfer printed devices on silicon

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***Abstract*—We compare 3 strategies for single-mode lasing using transfer-printed edge-coupled gain sources to SOI waveguides, namely slotted laser, extended cavity with ring resonator and extended cavity with Bragg grating. Detailed spectral measurements are used to analyse the devices, which achieve over 40 dB SMSR.**

***Index Terms*—laser integration, silicon photonics, edge-coupling, micro-transfer printing, extended cavity laser**

I. Introduction

Silicon photonics (SiPh) has made many recent advancements in hybrid laser integration with III-V materials via transfer-printing [1]. One integration approach involves evanescent coupling of a III-V gain source to a cavity on Silicon on Insulator (SOI) waveguide to form a hybrid SiPh laser [2]. Another proven approach is edge-coupling to the SiPh waveguide by aligning the facet and waveguide of a reflective semiconductor optical amplifier (RSOA) to the SOI [3]. This approach can allow for on-chip testing of the devices before and after the printing stage. These edge-coupled devices on SOI have been limited to multi-mode lasing. Here, we demonstrate and discuss different approaches for single-mode lasing with edge-coupling on SOI, including a stand-alone slotted laser, self injection of an RSOA through a feedback micro-ring resonator (MMR) on the SOI and an extended cavity with a distributed Bragg reflector (DBR).

II. Design approaches and fabrication steps

The three different approaches are shown in Fig. 1. All designs are integrated on 220 nm SOI with fully-etched strip waveguides with width 500 nm. The gain elements emitting around 1550 nm are fabricated from the same III-V wafer and integrated using transfer printing. Approach (a) is a slotted laser device with a length of 300 μm butt-coupled to the silicon waveguide. The design for the slotted laser contains 30 etched slots, with deep etches into the ridge. Approach (b) includes a gain source 700 μm long with an 10° angled front facet, which couples to a 500 μm long silicon waveguide. A 1x2 MMI is then introduced with a MRR with radius of 25 μm and a gap of 150 nm between the bus and ring waveguides. Approach (c) is similar to (b) but instead has a DBR reflector after 1 mm long waveguide where the width of the Si is tapered up and alternated between 1 and 1.3 μm, with a period of 295 nm.

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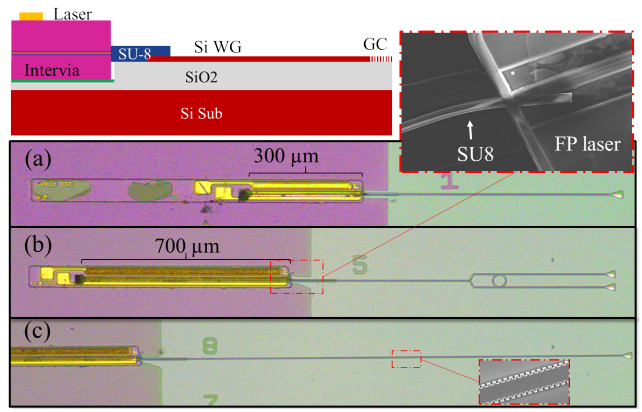

Fig. 1. A schematic of the laser design, and micrographs of the different approaches to single-mode lasers. (a) contains a slotted laser, (b) contains an angled facet RSOA with a micro-ring resonator, and (c) contains an angled RSOA coupled to a DBR. The detail of (b) is an image of the RSOA to SU-8 coupling interface, the inset for (c) shows the DBR.

This generates a 65 % reflection centred at 1588 nm, with 400 periods. All approaches use a square SU-8 waveguide that acts as a spot-size converter (SSC) from the RSOA to the silicon waveguide. A 100 μm long taper with a 100 nm wide tip on the silicon waveguide is used to adiabatically couple the light from the SU-8 to the silicon. The laser light is then measured through a single-etch grating coupler (GC) [4]. The GC has a transmission peak around 1560 nm with a loss of 6.8 dB, which increases to 20.8 dB at 1600 nm when measured at a 10° to normal incidence with a cleaved multimode fibre.

The SOI photonic integrated circuit was fabricated by electron-beam lithography using an SiO_2 hard-mask and Cl_2 etching. A trench was defined at the end of the silicon waveguides and etched 1.4 μm into the 2 μm BOx layer to align the edge emission from the gain block to the SU-8 waveguide. The gain elements were then printed into the trench, assisted by 100 nm thick InterVia^{TM} adhesive. Finally, SU-8 waveguides (3x3 μm) were lithographically defined. Information on the RSOA design and fabrication can be found in [5]. Figure 1 shows a schematic of the edge coupling scheme and optical images of the fabricated lasers.

III. Experimental results and discussion

The lasers were characterised through optical spectra and light power-current (LI) measurements. The optical spectra

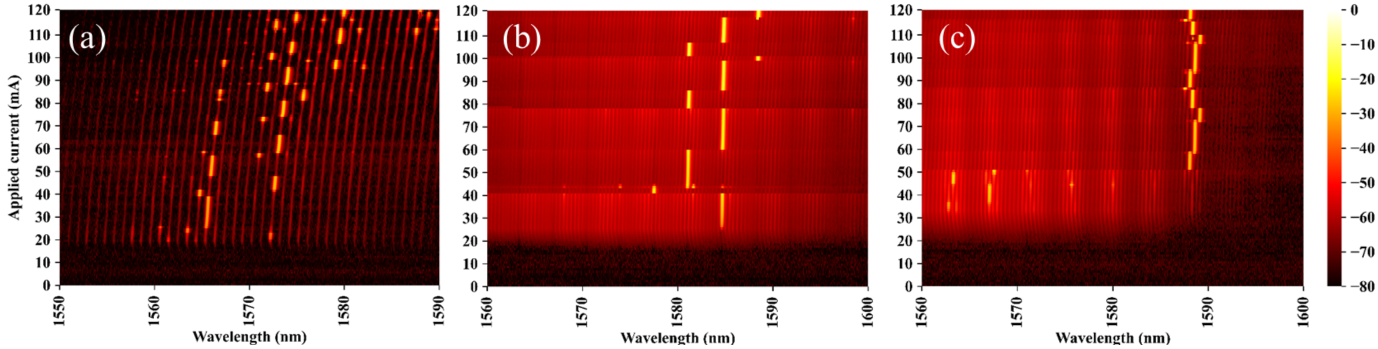

Fig. 2. 3D heat-map plot of spectra on a log scale versus applied current for (a) the slotted laser (b) the self injection MRR (c) the DBR design as measured through the grating coupler.

were recorded at an interval of 1 mA and the 3D heat-maps for each device with applied current are shown in Fig. 2. The corresponding LIs are shown in Fig. 3. The threshold current is 18 mA, 28 mA, and 36 mA for the slotted laser, MRR, and DBR designs, respectively. There is significant mode hopping as seen from the LI, evident by the sudden jumps in power with increasing applied current. The detailed spectra provide significant insight on the laser dynamics. For the slotted laser the mode hopping arises from the changes in the refractive index due to heating, in turn changing the wavelength peak for the slot distribution. This can be seen in Fig. 2 (a) as the resonant modes red shift with applied current, with a free spectral range (FSR) of 0.96 nm. Using $\frac{\Delta n}{\Delta T} = 0.0002/K$ the estimated temperature rise is 28°C at 120 mA. The MRR design has an FSR of 3.65 nm and each of these resonances is feeding back to the RSOA, seen from the periodic vertical dark lines in Fig. 2(b), while the spatial resonating modes FSR is 0.46 nm. The measured wavelength mode hops correspond to the the FSR of the MRR. It is noted that at each mode hop is a global shift in all the longitudinal modes suggesting a global phase shift. This hopping can be addressed by a phase control element or using coupled rings. Approach (c) maintains the modes as reflected by the DBR and sees smaller instability in wavelength hopping, this is due to the constant single high reflection point. The longitudinal mode separation (0.42 nm) is much smaller than the reflection bandwidth of the DBR ($\approx$ 5 nm). This causes a small periodic wavelength change as seen in Fig 2 (c), as the lasing wavelength and power depends on the overlap of these modes with the DBR reflection. There is no clear heating effect of the lasing modes for Fig 2.(b) and (c). There is over 300 μW measured from the grating coupler. This corresponds to at least 1 mW in the SOI waveguide at output, when subtracting the peak GC loss. There is also a measured 3.3 dB loss from the SU-8 SSC to the silicon waveguide due to a fabrication mismatch with the intended design.

The best side-mode suppression ratio (SMSR), over 40 dB, was measured with the MRR. The DBR provided 38 dB SMSR, which could be improved if the DBR reflection is more centred at the gain, and with more optimisation to induce a smaller bandwidth reflection. The slotted laser achieved a maximum SMSR of 30 dB.

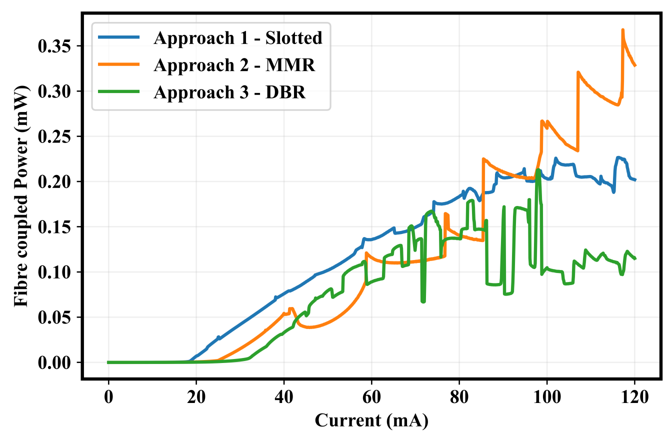

Fig. 3. LI for Approach (a) Slotted laser, (b) MRR, and (c) DBR measured from a cleaved multi-mode fibre

We have shown 3 different methods to obtain single-mode lasing with edge-coupled devices using transfer printing. This study provides alternative approaches to evanescent single-mode lasers. This work can be further developed with lower loss SSC waveguides, and phase tuning elements to accurately set the lasing wavelength.

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