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Thermally Stable External Cavity Laser Based on Silicon Nitride Periodic Nanostructures

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ABSTRACT

In this paper we demonstrate a thermally stable silicon nitride external cavity (SiN EC) laser based on a 250 µm sized Reflective Semiconductor Optical Amplifier (RSOA) butt-coupled to a series of Si_3N_4 Bragg gratings acting as wavelength selective reflectors. The laser shows power outputs over 3 mW, a very low lasing threshold of 12 mA and with a typical Side-Mode Suppression Ratio of 45 dB. In this configuration a mode-hop free lasing regime over a range of 47 mA has been achieved (from 15 mA to 62 mA). Thermal stability of the lasing wavelength at temperatures up to 80 °C is demonstrated. Further on, experimental results on a passive chip based on new 1D photonic crystal cavities are shown to have higher Q-Factors. This paves the way to avoiding thermal wavelength drifts and unlocks the possibility for these devices to be integrated in Dense WDM and optical-interconnect technologies, where transceivers must operate over a wide temperature range without active cooling.

1. INTRODUCTION

To face the rapidly increasing need for on-chip and fibre-optics data transmission rates [1], the quest for compact, energy efficient and cost-effective laser sources with a narrow linewidth for applications in dense Wavelength Division Multiplexing (dWDM) technology is paramount.

Such interconnects have to be integrated in challenging environments that expose them to a broad range of temperatures, thus greatly affecting their wavelength of operation, hindering their employment in WDM applications, in which accurate wavelength control and stability are fundamental [2]. Furthermore, the only way to achieve cost-effective and efficient single chip integrations of photonics is through Complementary Metal-Oxide Semiconductor (CMOS) processing, that requires high yield and fabrication repeatability. The inefficient light emission in silicon limits greatly the promising Silicon-On-Insulator (SOI) platform for optical applications. On the other hand, direct III-V semiconductors integration as gain medium for WDM lasers is greatly affected by lattice mismatch challenges and CMOS compatibility issues.

The solution of our choice is the heterogeneous integration of the gain, that is unlocked by the wafer bonding processes [2], and consist in the deployment of hybrid external cavity laser [3], whose cavity is composed of a commercially available Reflective Semiconductor Optical Amplifier (RSOA) that is butt-coupled to a silicon nitride chip patterned with Bragg gratings acting as a narrowband reflector. In this configuration, fabrication of the gain and the passive chips are separate, allowing independent optimization and modulation of the external cavity of the laser.

Recently, most of datacenter WDM optical links at the telecoms wavelengths are constituted by DBR lasers and external modulators [4], that are actively cooled [5] to offset the output wavelength shifts with the temperature fluctuations, due to the high material Thermo-Optic Coefficient (TOC). This is very energy inefficient and leads to a huge power cost. Si_3N_4 on the other hand, has a very low TOC and free-carrier absorption compared to silicon, and it is completely CMOS compatible.

Here we demonstrate a single-mode hybrid EC laser based on SiN gratings, operating in a mode-hop free regime over a broad range of injected carriers, that exhibits low threshold and wavelength stability over a wide range of temperatures, from 20 °C to 80 °C, thus eliminating the need of active cooling of any kind. Further on, we show the experimental results of a passive chip based on a new side-coupled 1D photonic crystal cavity design, that exhibits up to 10 times narrower resonances compared to the gratings, that could further improve the laser stability.

2. DESIGN AND CONCEPT

In Fig. 1a schematics of the EC laser is shown. Figure 1b shows the RSOA and passive SiN chip in butt-coupled configuration. The 2 µm wide waveguides on the silicon nitride chip have been designed to have an optical mode area similar to that of the RSOA, providing a smooth mode area transition between the two sections and leading to low losses and efficient coupling. The Bragg gratings are part of the SiN waveguides, minimizing the reflector footprint, opening the possibility for high integration density and high channel count. The gratings have been designed to operate in the 2nd order photonic bandgap, to achieve a narrower reflection peak compared to the 1st order bandgap. The FWHM of the Bragg reflection peak has been measured to be approximately 0.9 nm. An layer of Anti-Reflective (AR) coating was evaporated on both facets of the SiN passive chip to reduce Fabry-Perot modulations related to facet-to-facet reflections on the waveguides.

The 250 µm long RSOA makes use of AlInGaAs quaternary quantum wells, in which the Al^{+3} ions hinder carriers leakage typical at temperatures higher than 60 °C [6], improving the RSOA operation over all the temperature range considered, from 20 °C to 80 °C. The end facet of the gain chip was AR coated to achieve reflectivity approximately around 90%.

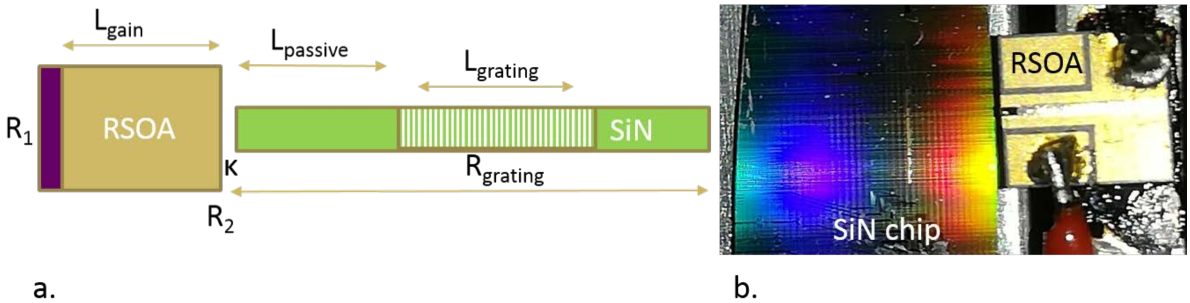

Figure 1: (a) Schematics of the hybrid EC laser; (b) Picture of the passive chip coupled to the RSOA form the laser.

During operation, carriers are injected in the RSOA and recombine inside its quantum wells, thus emitting photons. The light is then coupled to the SiN waveguide, propagating towards the reflector through guided by the waveguide. The off-resonance portion of the light is transmitted through the gratings and dropped at the end facet of the waveguide. The component of the light on-resonance is instead partially reflected back to the RSOA, generating the wavelength-selective feedback between the gratings and the reflective facet of the RSOA, the mirrors of the laser, whose characteristics can be predicted from the combination of the gain curve and the parameters of the cavity.

The longitudinal mode spacing of the composite cavity, $\Delta\lambda$, is defined as:

$$\Delta\lambda = \frac{\lambda^2}{2(l_{gain}n_{gain}+n_{passive}(l_{passive}+l_{grating}))} \quad (1)$$

where l_{gain}, $l_{passive}$ and $l_{grating}$ are the length of the gain, the passive chip and the gratings respectively. With n_{gain} and $n_{passive}$ being the group refractive index of the gain and the passive chip respectively. Lasing is achieved when the optical gain equals the total loss of light in one round trip of the cavity. Therefore, in a steady-state operation the threshold condition g can be defined as:

$$g = \alpha_i + \frac{1}{l_{gain}}\ln\left(\frac{1}{r_{RSOA}\kappa^2 r_{grating}}\right) \quad (2)$$

in which α_i is the optical loss coefficient, $r_{grating}$ and r_{RSOA} are the gratings and RSOA reflectivities and κ is the coupling coefficient between the RSOA and the waveguide of the SiN chip.

3. EXPERIMENTAL RESULTS

The hybrid EC laser thermal stability is intrinsically dependent on the thermo-optic coefficient of the SiN constituting the passive chip as its refractive index, $n_{passive}$, changes with temperature. In fact, the modes of the EC laser cavity are dependent on the effective optical length of the SiN chip, $n_{passive}(l_{passive}+l_{grating})$ (as shown in Eq. 1) and a temperature change on the material would lead to both a shift in wavelength of the Bragg reflection peak and a change of the effective length of the EC cavity, that directly affects mode spacing of the laser, the lasing wavelength and the its thermal shift. To assess the thermal stability of the silicon nitride chip, we calculated its TOC by experimentally measuring the Bragg reflection peak shift in wavelength with temperature. Transmission spectra of a SiN chip mounted on a thermo-controlled plate were acquired at each temperature step, from 20 °C to 80 °C, leading to a reflection peak shift of 12.4 pm/°C and a very low TOC of 1.62×10^{-5} RIU/°C (as shown in Fig. 2).

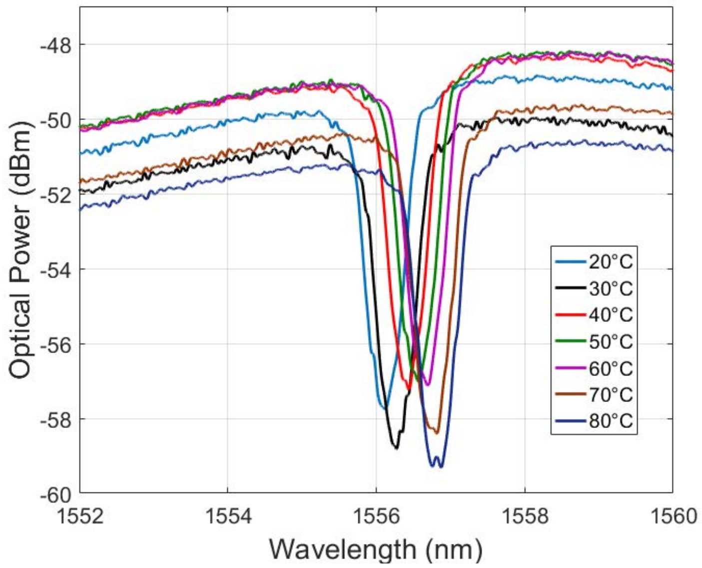

Figure 2. Optical transmission spectra of the gratings on the SiN chip acquired at different temperatures from 20ºC to 80ºC.

To demonstrate the hybrid EC laser operation and its thermal behaviour, the SiN chip and the RSOA, both on fixed in place on thermo-electric Al plates, were aligned in butt-coupled configuration through micrometric translational stages until lasing was achieved. Lasing spectra have been acquired over the range of driving currents from 10 mA to 100 mA, at 20 °C and without active cooling, at each current step of 1 mA.

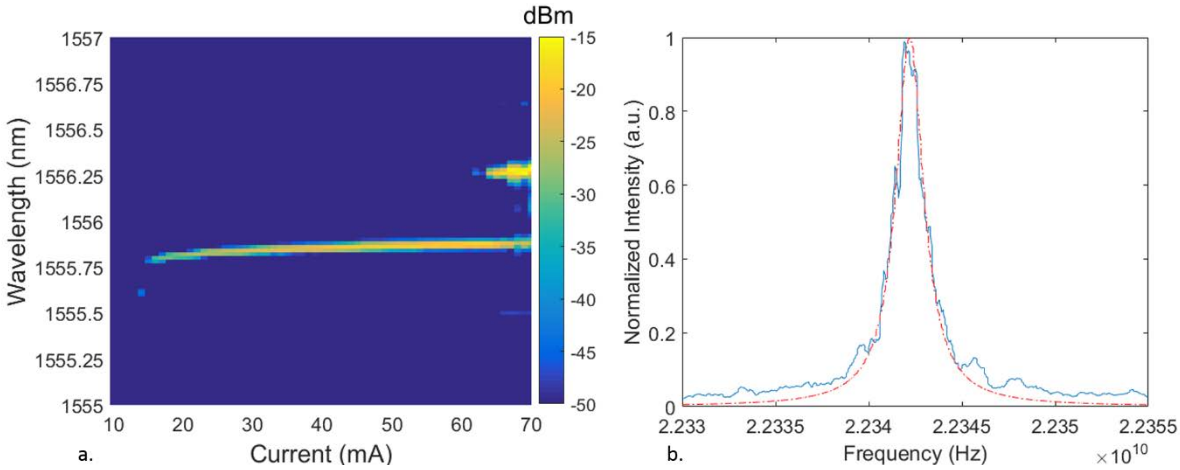

Figure 3. Laser characterisation: (a) False colour plot of the time-averaged optical spectrum of the EC laser against driving current; (b) Linewidth on the laser, experimental data (blue curve) and fitting (red curve).

In Fig. 3a is shown the EC laser time-averaged optical spectrum plotted in a false colour map with increasing drive current. By matching the longitudinal mode of the laser cavity with the gratings reflection peak, over the range 15 mA to 62 mA, a mode-hop free single mode lasing regime has been achieved. Here can also be noticed a lasing threshold as low as 12 mA. Figure 4b shows the linewidth of the SiN EC laser, measured with a tunable laser source though a delayed heterodyne technique, to be less than 3 MHz. The light output at the end facet of the SiN waveguide was collimated with a lens onto a power meter sensor, and the EC laser power was measured to be in the range of 3 mW (as shown in Fig. 4a).

After characterising the laser at room temperature, its thermal behaviour was studied by changing the temperature of both the RSOA and SiN chips on the thermo-electric controlled plates. The lasing spectra were acquired with increasing driving current over the range from 20 °C to 80 °C, at each temperature step of 10 °C. Figure 4b shows the single mode lasing wavelength with increasing temperature, at a fixed driving current of 50 mA. A very low red-shift of the lasing wavelength of approximately 0.5 nm has been measured, as opposed to the 6 nm red-shift associated with the traditional InP DFB over the same temperature range (JDS CFQ935 [12]). The use of SiN, characterised by a low TOC, for the Bragg reflector provides a negligible thermal shift of the lasing wavelength of the EC laser, completely eliminating the need of active cooling normally employed in Si-based DFBs. Further on, the resonances of the new side-coupled nanobeam design (Fig. 4b) are shown to be up to a factor of 10 narrower than the ones related to the gratings, with measured lowest FWHM of 0.087 nm as opposed to 0.9 nm corresponding to the gratings.

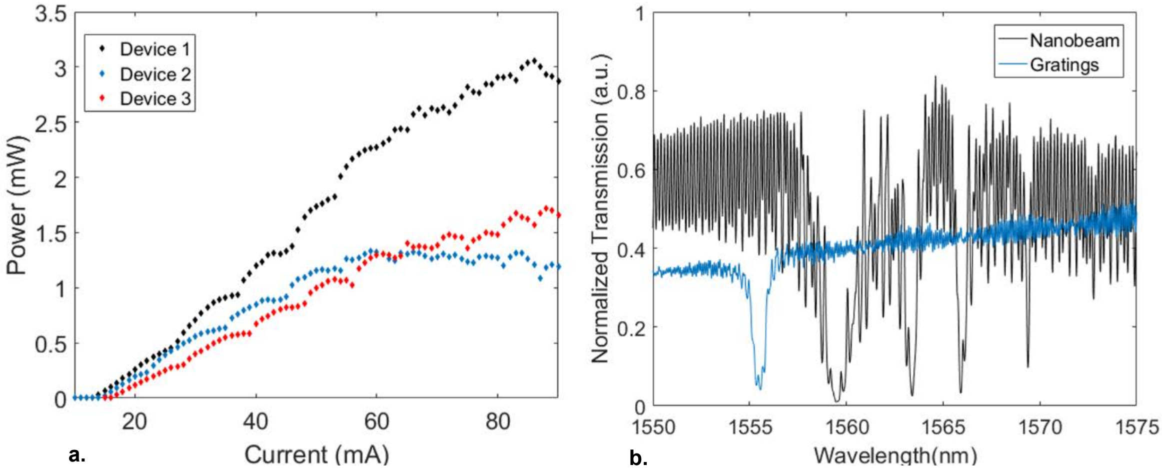

Figure 4: (a) L-I curves of the different hybrid EC laser devices; (b) Normalized transmission spectra of the gratings (blue curve) and the side-coupled 1D photonic crystal cavity (black curve) showing multiple resonances.

4. CONCLUSIONS

In conclusion, we demonstrated a hybrid single mode EC laser based on a SiN Bragg reflectors butt-coupled to a RSOA gain chip, characterised by threshold as low as 12 mA and high output power in the mW range, exhibiting a mode-hop free regime over the driving current range from 15 mA to 67 mA, that could be widened further with accurate optimization of the AR coatings of the SiN chip. A lasing wavelength thermal stability of 8.3 pm/ °C over the total temperature range of operation (20 °C to 80 °C), and the narrowing of the resonances on the passive chip by the new 1D photonic crystal design, paves the way for future employment of gratings or photonic crystal cavities based SiN chips, with different and densely spaced resonances, coupled to arrays of commercially available RSOAs, forming a network of compact transmitters with no need of any active cooling, thus minimizing their power consumption and cost and making these hybrid EC lasers an outstanding prospect for cost-effective dWDM technologies.

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