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Integrated Phase-locked Laser Diodes at 1.55µm

Lianping Hou*, Song Tang, John H. Marsh
School of Engineering, University of Glasgow, Glasgow, G12 8QQ, U.K.
(*Lianping.Hou@glasgow.ac.uk)

***Abstract*—Two types of integrated phased locked laser diodes operating at 1.55 µm were demonstrated, using either a distributed feedback laser seeding source or a self-locking multi-mode interference array. Both exhibited far field patterns that reflected mutual coherence between the light from the output waveguides.**

***Index Terms*—Lasers, distributed-feedback, integrated optics devices, coherence imaging.**

I. INTRODUCTION

There is an urgent demand for cost-effective high power, quasi-single-spatial-mode semiconductor lasers operating at wavelengths around 1.55 µm [1]. Recently techniques have been developed based on seeding arrays of semiconductor optical amplifiers (SOAs) from a single laser, to generate output beams that can be combined coherently [2].

Here we report two types of monolithically integrated phased-locked semiconductor laser arrays operating at 1.55 µm. The first comprises a 1.55 µm sidewall grating distributed feedback (DFB) laser feeding two stages of multi-mode interference couplers (MMIs) and SOAs to produce high power beams with a quasi-single-spatial-mode far field pattern (FFP). The second is a monolithically integrated approach, in which the light in individual amplifiers of a laser array is coupled through staggered passive 1×2 MMIs couplers. As the phase relationship between the input and output of a 1×2 MMI is fixed and each stage of SOAs is operated in a similar environment, the relative phase of the outputs remains nearly constant, which results in a spatially coherent FFP.

II. STRUCTURE AND FABRICATION OF THE ARRAYS

The design and processing for both types of devices are similar to those described in [3-6]. The dimensions and layout of the type-I array, alongside SEM pictures of the sidewall grating and MMI, are shown in Fig. 1. The device was described in detail in [3]. The array comprises a DFB laser, followed by two stages of optical amplification. The DFB laser is 470 µm long. First-order gratings with a 50% duty cycle are etched 0.6 µm into the sidewalls of the waveguide, as shown in Fig. 1(b). The grating period is 244 nm. The output SOAs have a pitch of 125 µm. The waveguides are tilted at the output facet by 10° to avoid back-reflections.

The dimensions and layout of the type-II array are shown in Fig. 2 [4]. The array comprises four ridge waveguide amplifiers, with a separation of 24 µm between two adjacent outputs, and a passive section with two staggered 1×2 MMIs. The MMIs are 16-µm-wide and 308-µm-long. The ridge waveguide width in the device is 2.5 µm.

III. DEVICE PERFORMANCE

For the type-I device, the total maximum output power was ~100 mW when I_{DFB} = 60 mA and all the SOA injection currents were set at 120 mA. The optical spectra from the SOA6 output facet as a function of I_{DFB} are shown in Fig. 3(a), with I_{SOA2} = 0 mA, I_{SOA5} = 120 mA, I_{SOA6} = 120 mA. The other sections were left floating. We found the operation of the DFB laser was very stable for I_{SOA5} varying between 0 and 120 mA, confirming that the design of the MMI is effective in suppressing back-reflections (Fig. 1(c)). The quasi-single spatial-mode FFP output is shown in Fig. 3(b) from the output of SOAs 3-6 for different drive conditions. In all cases, I_{DFB} = 60 mA and I_{SOA1} = I_{SOA2} = 120 mA. The black solid line shows the output for two pumped amplifiers, SOA5 and SOA6, the red dashed line for three amplifiers, SOA4-SOA6, and the green dotted line

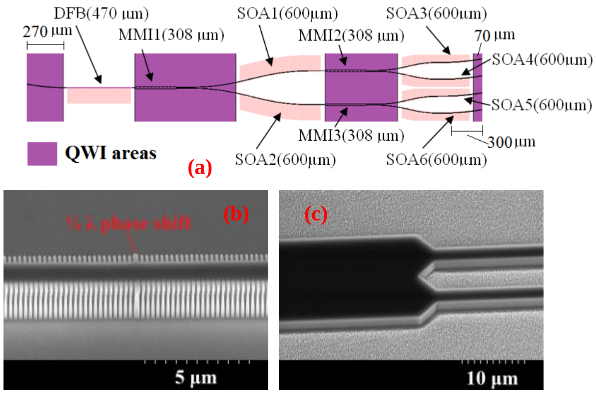

Fig. 1. (a) Layout of type-I device, (b) SEM micrograph of the first-order 50% duty cycle sidewall gratings with a 0.6 µm recess and λ/4 phase shift, (c) the output side from the MMI.

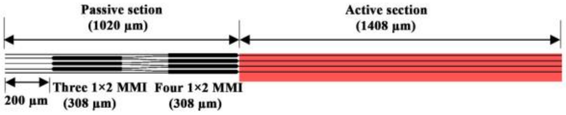

Fig. 2. Layout of the type-II phased locked laser diode array using a passive array of MMI couplers to couple the lasers.

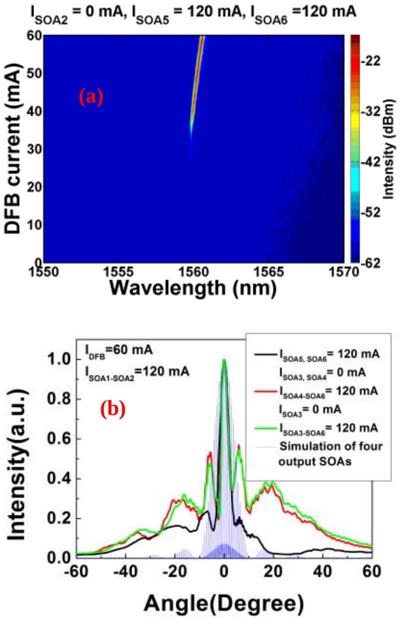

Fig. 3. Type I array: (a) 2-D optical spectra from SOA side as a function of I_{DFB} and (b) in-plane FFP measured on SOA side.

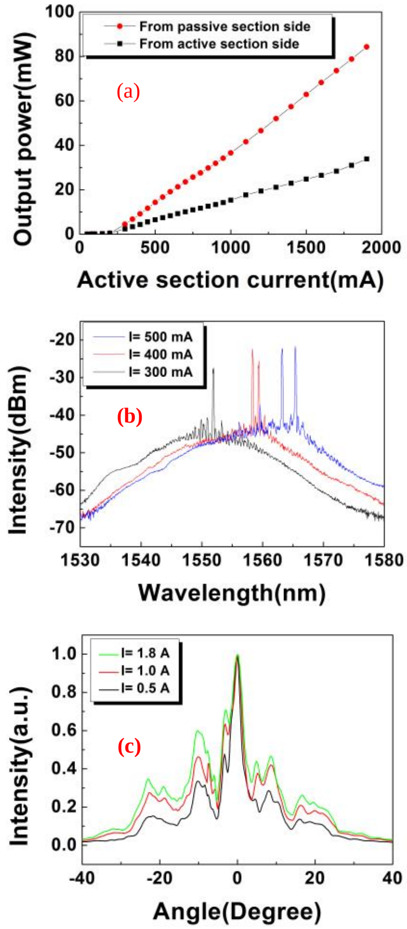

Fig. 4. Type II array: (a) output power from active and passive sections respectively; (b) optical spectrum from passive section side; (c) FFP from passive section side when I =0.5, 1.0, 1.8 A.

with all four amplifiers pumped, SOA3-SOA6. The injection current for each of the output SOAs was 120 mA. Moreover, for the case when all four output SOAs were driven, diffraction theory was used to simulate the FFP. The envelope (blue line) is similar to that to the measured results, with the narrowest measured FFP being 3.5° FWHM at the central in-plane peak.

The light-current curves from the active and passive sides of the type-II device are shown in Fig. 4(a). The threshold current is 200 mA and the maximum output power (84.3 mW) from the passive side is nearly 2.5 times that from the active side (33.9 mW) at I = 1.9 A. Optical spectra from the passive side are shown in Fig. 4(b) at I = 300, 400, 500 mA. As the drive current increases, heating results in a red shift in the peak wavelength. The quasi-single longitudinal mode operation seen in the optical spectra is consistent with phase-locking. Fig. 4(c) shows the measured FFP from the passive side when I = 0.5, 1.0, and 1.8 A. The FFP shows a coherent interference pattern with quasi-single-spatial-mode characteristics, albeit the side lobe intensities and/or angles changed when increasing the injection current. The smallest FWHM of FFP from passive side is 3.2°.

IV. CONCLUSION

We have demonstrated two approaches to scalable monolithically integrated phase locked laser diodes. The type-I device comprises a 1.56 μm laser feeding two stages of optical amplification. A single DFB laser was used as a seed and ~100 mW total output power from SOA side was achieved. The device delivers high power and a quasi-single spatial-mode FFP but requires electronic stabilization of the SOA drive currents to control the output FFP. Stable single-frequency operation with a side mode suppression ratio (SMSR) >40 dB and coherent FFP operation was maintained over a wide range of SOA drive currents. The type-II device was based on an array of lasers stabilized optically through a network of passive 1×2 MMI couplers. Coherent FFPs were observed from both the active and passive sides. Output powers for both designs are limited by thermal effects; the type-I design spreads heat across a wider area as well as supporting beam steering while the type-II device is self-stabilizing with a fixed FFP.

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