On-Chip InAs QD Ring-Resonator Multi-Mode Interference Reflector Lasers for PICs

Fwoziah T. Albeladi[1, 2], Sara-Jayne Gillgrass[1], Pawan Mishra[1], Noor Albittar[1], Susanna Power[1], Samuel Shutts[1], and Peter M. Smowton[1]

1. School of Physics and Astronomy, Cardiff University, The Parade, Cardiff. CF24 3AA. UK.
2. Physics Department, Faculty of Science, University of Jeddah, Jeddah 21589, Saudi Arabia
AlbeladiFT@cardiff.ac.uk, SmowtonPM@cardiff.ac.uk

***Abstract*—a compact on-chip laser that integrates a high-reflectivity MMIR and a ring-resonator on an InAs-QD platform is demonstrated. Such lasers offer significant benefits, including wavelength selectivity, fabrication tolerance, and simplified device fabrication through a single-step deep-etch waveguide process. The laser offers enhanced functionality for PICs.**

Keywords—on-chip laser, Ring resonator, MMIR, QD

I. INTRODUCTION

Photonic integrated circuits (PICs) can be fabricated across various platforms, yet a direct bandgap semiconductor is essential for effective on-chip light emission. Chip-scale single longitudinal mode laser sources, characterized by narrow linewidth, minimal frequency chirp, and versatile wavelength tunability, are essential in communication and sensing applications. On-chip quantum dot (QD) lasers offer numerous advantages, including a broad gain bandwidth and a lower threshold current. This results in compactness and cost-effectiveness, enabling integration into more complex photonic chips for advanced functionalities.

Currently, most on-chip laser sources are integrated using reflective gratings like distributed Bragg gratings (DBR) and distributed feedback (DFB). However, there are several challenges associated with these integrated grating structures. These structures have small feature sizes and require high lithographic resolution and additional epitaxial growth, which can lead to fabrication inaccuracies. This can particularly impact applications that require high passband uniformity. Additionally, imperfections in grating realization may induce interference effects and cause group delay ripples, posing additional difficulties to overcome.

Here we focus on multi-mode-interference reflectors (MMIRs) [1-2] as wideband mirrors. These broadband reflectors work on the same principles as MMIs [3]. Instead of using a traditional grating mirror, this innovative approach utilizes MMIRs to define the optical resonator, requiring only a single deep etch fabrication step. We have demonstrated InAs-QD MMIR lasers (illustrated in Fig 1a) with higher reflectivity than Fabry-Perot (FP) ridge lasers, resulting in a much lower threshold current of 6 mA compared to 46 mA for the same cavity length [1-2]. The threshold current density of the 1 mm MMIR laser is equivalent to the FP laser with a 3 mm cavity length (see Fig. 2).

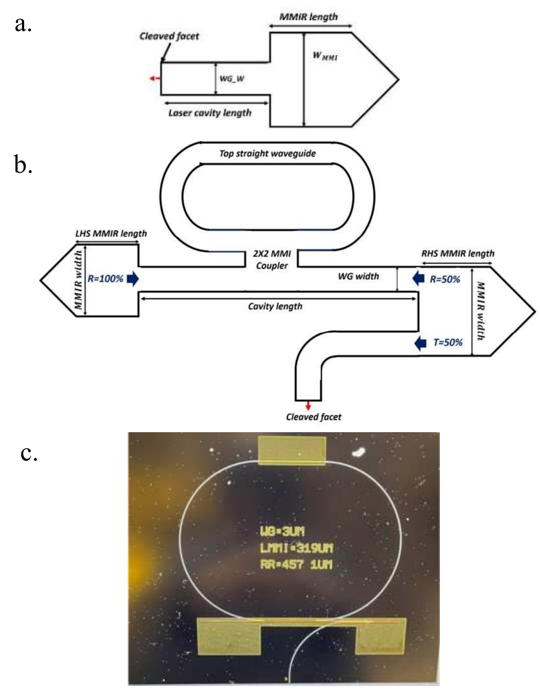

Fig. 1: Schema of the MMIR laser a.1xMMIR laser (one-port MMIR), b. is 2xMMIR laser devices integrated with all-pass ring resonator, MMIR-RR laser, and c. image of fabricated MMIR-RR laser

MMIRs have a significant advantage in terms of ease of fabrication. They are tolerant to device length and width variations and are made using the same process steps as the waveguide. As a result, MMIRs are an excellent option for on-chip waveguide mirrors used in laser cavities. MMIR lasers also have improved spectral properties and mode selectivity, which we describe later, and to gain still better control over the laser spectrum we have integrated an InAs-QD 2xMMIR laser with a racetrack ring resonator RR (see Fig. 1b).

In this work, we design, fabricate, and characterize the 2xMMIR laser devices integrated with passive all-pass Ring Resonator , MMIR-RR in Fig. 1 c . These devices include a 100% reflective one-port MMIR combined with a two-port MMIR with a 50:50% reflectivity ratio including an output waveguide. A 2x2 MMI coupler has been used in the coupling

Device fabrication was carried out in the cleanroom of the Institute for Compound Semiconductors (ICS) at Cardiff University. The EPSRC funded Future Compound Semiconductor Manufacturing Hub: reference EP/P006973/1 provided essential resources for this study.

region of the RR. In addition to relaxed fabrication requirements and being less sensitive to variations in wavelength or polarization, the RR-based MMI coupler maintains the single-step deep-etch waveguide fabrication for the whole laser device.

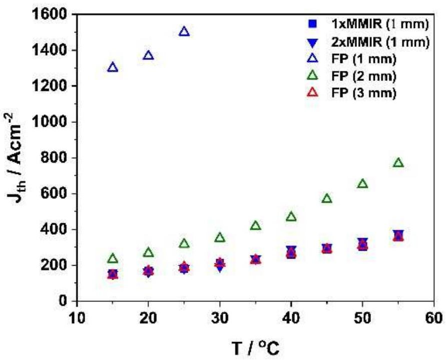

Fig 2: Threshold current density for MMIRs (solid symbols) and FP (open symbols) lasers as function of temperature.

II. Results

The simulation method of MMIR reflector elements are fully explained in [1], which also reports simulation and basic one-port MMIR device results. By optimizing the size of the MMI section, we achieved over 85% and 49:49% reflectivity for one and two-port MMIR (LHS and RHS MMIR in Fig. 1 b), respectively, at 1310 nm operating wavelength. This high reflectivity was maintained within a wavelength range from 1260 to 1380 nm.

One port MMIRs (as in Fig. 1a) can be designed and optimized to support the fundamental TE mode exclusively. On the other hand, a two-port MMIR laser supports both symmetric and asymmetric modes. Although, the sidewall loss is likely to be larger for higher-order modes. The laser spectra of Fig. 3 demonstrate the mode selectivity, b) and c), of MMIR one port and two port (without RR) structures respectively versus Fabry-Perot lasers of the same waveguide width, a).

The 2xMMIR laser combines both one- and two -port MMIR (see Fig 1 b), suppressing higher-order modes and amplifying the fundamental TE mode (see Fig. 3 d). The MMIR helps filter out asymmetric order modes from an input waveguide, allowing the single-mode ridge part of a laser to be slightly wider. This makes it more tolerant of fabrication uncertainty than a standalone ridge waveguide laser structure.

To enhance the mode filtering effect and allow greater control over mode spacing, a racetrack RR has been integrated into the cavity of 2xMMIR laser MMIR-RR (see Fig. 1 b and c). By combining the distinctive features of the RRs with the filtering capabilities of MMIRs, this laser can achieve significant improvements, including a high side mode suppression ratio, a narrow linewidth, reduced frequency chirp, and ultra-wide wavelength tuning.

Fig. 4 shows spectra of a MMIR-RR laser . By adjusting the bias to a contact on the ring resonator the spectra can be adjusted to where at, e.g. 1V forward bias, a clean free spectral range of just under 4nm is obtained. As would be expected forward and reverse bias on the RR contact provides a small amount of tuning of the whole spectrum.

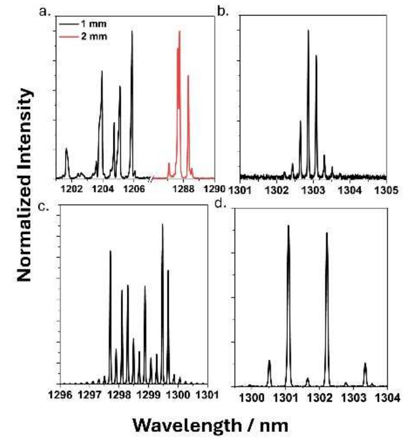

Fig 3: Emission spectra for a. FP laser with 1 and 2 mm cavity length, b.one-port MMIR, and c. two-port MMIR and d. 2xMMIR laser, with 1 mm cavity length.

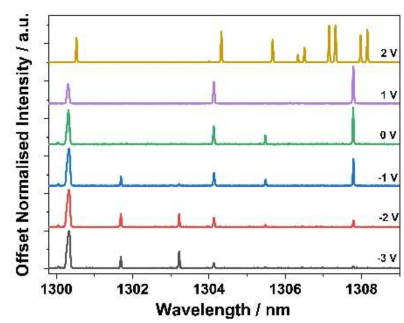

Fig 4: MMIR-RR lasing spectrum as a function of voltage applied to ring contact..

In summary, we will demonstrate an on-chip InAs-QD laser with high-reflectivity MMIRs and a RR. This laser is highly tolerant to fabrication and can be created through a single-step deep-etch waveguide fabrication process. With its compact size and laser mode selectivity provides enhanced spectral performance.

References

[1] F. T. Albeladi, S. Gillgrass, J. Nabialek, P. Mishra, R. Forrest, T. R. Albiladi, C. P. Allford, H. Deng, M. Tang, H. Y. Liu, S. Shutts, and P. M. Smowton, "Design and characterisation of multi-mode interference reflector lasers for integrated photonics," Journal of Physics D: Applied Physics, vol. 56, no. 38, p. 384001, 2023/06/19 2023, doi: 10.1088/1361-6463/acdb80.

[2] F. T. Albeladi, S. Gillgrass, J. Nabialek, P. Mishra, R. Forrest, T. R. Albiladi, C. P. Allford, S. Shutts, and P. M. Smowton, "Multi-Mode Interference Reflector for Integrated Photonics " presented at the IEEE Photonics Conference (IPC), Orlando, Florida,, November 2023.

[3] Soldano LB, Pennings ECM (1995) Optical multi-mode interference devices based on self-imaging: principles and applications. Journal of Lightwave Technology 13:615-627 doi: 10.1109/50.37247.