Towards Monolithic Integration of Non-linear Optical Frequency Conversion

Usman Younis, Barry M. Holmes, David C. Hutchings
Dept. of Electronics & Electrical Engineering
University of Glasgow
Glasgow, United Kingdom, G12 8QQ
younis@elec.gla.ac.uk

John S. Roberts
EPSRC National Centre for III-V Technologies
University of Sheffield
Sheffield, United Kingdom, S1 3JD

***Abstract*—The monolithic integration of an all optical frequency converter is developed. The wavelength routing is demonstrated with a di-chroic MMI coupler, which has a minimum cross talk of -12 dB. The stimulated emission at 801 nm has been achieved in a half ring superlattice laser.**

Keywords-Nonlinear optics; di-chroic MMI coupler; semiconductor superlattice laser

I. INTRODUCTION

Compound semiconductors are an attractive choice for non-linear optical frequency conversion applications. They benefit from mature fabrication technologies – and, with the inclusion of an on-chip pump source, it is possible to achieve a fully integrated all optical frequency converter. GaAs/AlGaAs superlattices can be used to obtain a substantive modulation in the non-linear optical properties through post-growth quantum-well intermixing (QWI) techniques. We have engineered the $\chi^{(2)}$ modulation in our domain-disordered quasi-phase matching (DD-QPM) GaAs/AlGaAs superlattices using ion-implantation induced QWI, and have demonstrated the second order non-linear processes of continuous wave (CW) second harmonic generation (SHG) [1] in type-I polarization configuration, pulsed type-II SHG [2], and, more recently, we have achieved difference frequency generation (DFG) [3]. In this paper, we demonstrate the components required in a monolithically integrated optical frequency converter, which include: (1) a di-chroic multimode interference (MMI) coupler for wavelength routing, and (2) superlattice laser, which in a ring configuration, would serve as an on-chip pump.

II. DI-CHROIC MMI COUPLER

The simultaneous conversion of different wavelengths requires the routing components in our designed integrated optical frequency converter for 1.5 µm telecommunication band, shown in Fig. 1. The material structure, which has been previously presented in [2], has a band gap near 775 nm. The pump wavelength (band gap excitation) couples into the DD-QPM waveguide, and then couples back into the ring laser cavity. However, due to the di-chroic nature of couplers, signal and idler wavelengths (near the half band gap excitation) do not enter the ring.

The designed MMI coupler cavity is 220 µm long and 6.5 µm wide – the design has been optimized with beam-propagation-based simulations using a commercial package[1]. The access waveguides to the coupler are 3 µm wide. Considering these parameters, MMI couplers with a range of cavity lengths were fabricated. The fabrication process involved electron beam (E-beam) patterning and subsequent definition with $SiCl_4$ reactive ion etching (RIE). RIE was assisted with an *in-situ* laser reflectometry to achieve an etch depth of 1.35 µm.

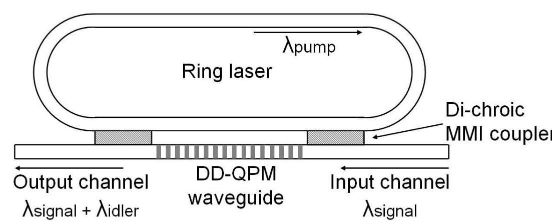

Figure 1. The designed integrated optical frequency converter

The couplers were characterized with a CW Ti:sapphire laser and a CW C-band laser, for the measurements near the band gap and the half band gap wavelengths, respectively. The coupled light was detected using both Silicon and Germanium photo-detectors. The cross talk, which in this case is the ratio between the unwanted signal and the wanted signal, is given in Fig. 2 (a) for the measurements near the band gap, and in Fig. 2 (b) for the measurements near the half band gap. The peak coupling in both cases occurred for ~220 µm MMI cavity length, which is consistent with the initial design. The minimum cross talk of -12 dB is satisfactory under the given design constraints – and the high performance is achievable in the integrated chip with reduced out coupling of the ring laser mode.

III. SUPERLATTICE LASER

The laser action has been achieved using a thinner superlattice core material structure, to demonstrate an on-chip pump source. The *p-i-n* laser diode has a 600 nm thick intrinsic core, which includes a 100 nm 14:14 monolayer

1 BeamPROP from Research Software (Rsoft) Inc.

$GaAs/Al_{0.85}Ga_{0.15}As$ superlattice active medium, with 250 nm $Al_{0.45}Ga_{0.55}As$ buffers on either side. The claddings are similar to the previous material structure, but are doped with C and Si to make them p-type and n-type, respectively. The wafer was grown using metalorganic vapor phase epitaxy (MOVPE), and has an intense measured electroluminescence (EL) of 772 nm.

Low pressure MOVPE growth was undertaken using a robot loading 6x2 Aixtron showerhead reactor. A high quality superlattice was deposited using the precursors trimethylgallium, trimethylaluminium and arsine in combination with an *in-situ* oxygen gettering. The precise control of the superlattice period was achieved using an array of purged four-way vent/run valves and the growth process was monitored using a Laytec EpiTT reflectivity/pyrometer system.

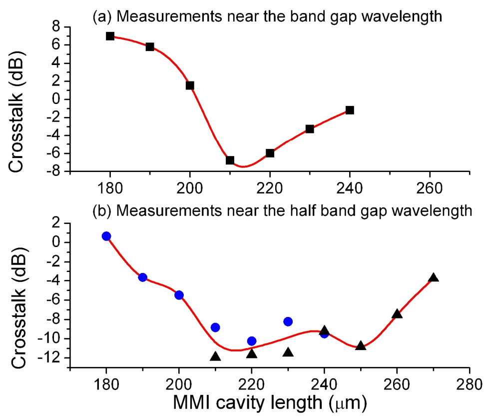

Figure 2. (a) Measured cross coupling near the band gap wavelength, (b) measured bar coupling near the half band gap wavelength. The solid lines are a smoothed fit to the data

The 3 μm wide ridge waveguide lasers were fabricated in half rings, with the ring radii of 450 μm and 475 μm. The laser patterns were designed such that the cleaved samples have 2200 μm long half ring cavities. The fabrication process included an initial rapid thermal annealing at 775 °C for 60 sec – which is mandatory as a post QWI treatment in fabrication of the final device. The waveguides were patterned in E-beam and defined by $SiCl_4$ RIE, again with an *in-situ* laser reflectometry to achieve 1.35 μm etch depth. The Ti-Pt-Au P-contacts and Au-Ge-Au-Ni-Au N-contacts were deposited by E-beam metal evaporation. The lasers were finally cleaved and mounted on the brass pads for testing.

The lasers were tested CW at the room temperature. The optical power was measured with a power meter. The lasing wavelength was obtained by coupling the light into a lens fiber and measuring it on an optical spectrum analyzer. The L-I curves for the half rings are given in Fig. 3. The higher lasing threshold of 450 μm half ring is caused by its higher bending losses, as compared to that of 475 μm half ring.

The inset in Fig. 3 shows the lasing wavelength of 801 nm, which was measured for a 500 μm long annealed Fabry-Perot (FP) ridge. A red shift of 29 nm is observed between the EL and the laser excitation, which can be attributed to a relatively high threshold current density of 3.5 kA/cm^2 for the device [4]. The loss factor for the annealed material is 3.21 cm^{-1} – calculated by plotting external quantum efficiency against FP cavity length. This shows an excellent structural quality and is confirmed by the X-ray measurements. Therefore, the growth defects – as a potential source of higher threshold – can be confidently ruled out; however, laser action was undetected for the devices fabricated using un-annealed material – and the turn-on voltage was reduced from ~4 V to ~2 V after annealing. Further investigations of the lasing characteristics are ongoing.

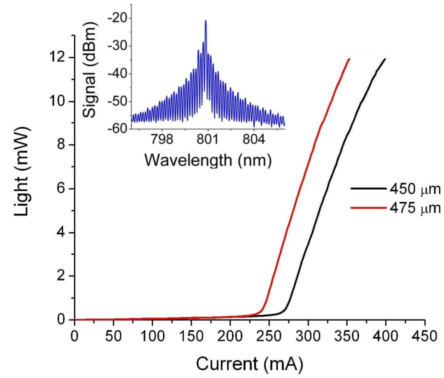

Figure 3. The L-I curves of the half rings - stimulated emission at 801 nm (the power meter saturated above 12 mW)

IV. CONCLUSIONS

Our recent demonstrations of various second order non-linear processes in a same material system [1-3], have reported higher conversion efficiencies; which is highly encouraging towards integrated all optical conversion devices. In this paper we have demonstrated the components that are required for the monolithic integration of our designed optical frequency converter. The wavelength routing has been demonstrated with a di-chroic MMI coupler, and the half ring superlattice laser has been demonstrated towards an on-chip pump source.

REFERENCES

[1] S. J. Wagner, B. M. Holmes, U. Younis, A. S. Helmy, J. S. Aitchison, and D. C. Hutchings, "Continuous wave second-harmonic generation using domain-disordered quasi-phase matching waveguides," Applied Physics Letters, vol. 94, pp. 151107-3, 2009.

[2] B. M. Holmes, U. Younis, D. C. Hutchings, S. J. Wagner, A. S. Helmy, and J. S. Aitchison, "Type-II quasi-phase-matched second-harmonic generation in domain-disordered semiconductor waveguides," in Conference on Lasers and Electro-Optics, and Conference on Quantum electronics and Laser Science Conference (CLEO/QELS 2009), Baltimore, USA, 31 May – 5 June 2009.

[3] S. J. Wagner, I. Sigal, A. S. Helmy, J. S. Aitchison, U. Younis, B. M. Holmes, *et al.*, "Difference Frequency Generation in Domain-Disordered Quasi-Phase Matching Semiconductor Waveguides," unpublished.

[4] R. D. Dupuis, P. D. Dapkus, J. Nick Holonyak, E. A. Rezek, and R. Chin, "Room-temperature laser operation of quantum-well $Ga_{(1-x)}Al_xAs$-GaAs laser diodes grown by metalorganic chemical vapor deposition," Applied Physics Letters, vol. 32, pp. 295-297, 1978.