Wavelength conversion and All-Optical Switching in Quantum Cascade Lasers.

Charalambos Zervos, Mark D. Frogley, Dmytro O. Kundys, Luke. R. Wilson, John.W.Cockburn , Mark Hopkinson , Maurice S. Skolnick and Chris C. Phillips

Abstract—**We study a novel optical device, comprising a λ~9µm GaAs-based QCL whose active region is standard, but which is clad with wide bandgap AlGaAs, is grown on a Bragg Mirror, and is processed with a window in the top contact to allow optical access to bandgap radiation. The QCL output can be 100% modulated with a near-IR control beam, with a 15 nJ switching energy, and acts as a resettable photon flux integrator which would give it a retiming function if used as a component for free-space communications. A similar device, but with slightly lower Al concentrations in the waveguide, allows doubly resonant frequency mixing which generates coherent sidebands on a normally-incident near-IR carrier beam in a way which is insensitive to phase matching issues. The resulting two terminal electrically modulatable device offers a means of performing various routing , switching and detection operations of interest for all-optical telecommunications.**

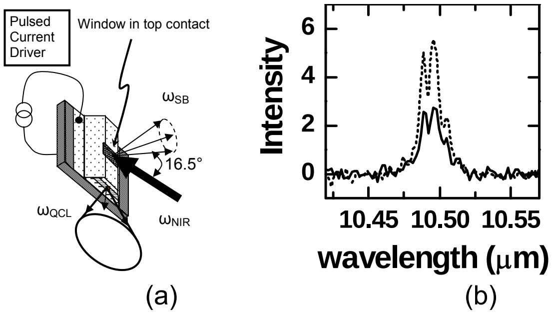
Index Terms— **Heterodyning, Optoelectronic devices, Optical switches, Optical modulation, Semiconductor lasers.**

I. INTRODUCTION

BANDSTRUCTURE engineering of the intersubband transitions in semiconductor quantum wells has produced quantum cascade lasers (QCLs) operating from the Mid-infrared (IR) to THz wavelengths [1], with outputs suited to medical and security imaging, environmental sensing or free-space communications. There are devices with ultrafast-pulsed and continuous wave outputs at room temperature[2], and the inherent non-linear optical susceptibility of the constituent semiconductors has been used to produce optical frequency shifters[3,4].

In this letter we demonstrate switching of the mid-IR output of standard QCLs by near infrared (NIR) laser light, in a way which is capable of data-transparent regeneration with simultaneous wavelength conversion. The nature of the switching mechanism means that driving the QCL with a local oscillator would allow for the re-timing of an optical pulse train which has been subjected to random timing jitter during propagation, as well as re-shaping and re-amplifying it, i.e. so-called "3R" regeneration. We also demonstrate intracavity frequency mixing in a new geometry which, is insensitive to phase matching issues, and workable over a large wavelength range.

II. DEVICE DETAILS.



(a) (b)

Figure 1. (a) Optical switching geometry for the quantum Cascade laser with optical window. 1(b) QCL mid-Ir output spectra with (dashed) and without (solid) ~70 mw of λ_{NIR} = 750nm control beam entering the window.

The QCL (Fig.1) has a 10µm x 50µm central window created in the metal of the top Ti:Au contact and is unusual in its high Al-content transparent waveguiding layers, which allow NIR optical access to the active region (AR). All devices had nominally the same QCL active AR, designed to lase at λ~10 µm and consisting of 36 periods of graded-injector heterostructure, each with GaAs wells and **AlAs** barriers of thicknesses (Si doping densities) 4.8(0)/**0.8**(0)/4.6(0)/**0.8**(0) /4.3(5 x 10^{17} cm^{-3})/**1.0**(0)/4.2(5 x 10 ^{17} cm^{-3})/**1.0**(0)/4.0(0) /**1.7**(0)/3.0(0) /**0.6**(0)/6.8(0)/**0.6**(0)/6.0(0)/**1.1**(0) nm .

We work in reflection, (at wavelengths were the substrate is opaque) with the device grown on top of an 8-period multilayer distributed Bragg reflector (DBR) mirror, which reflects >80% of near-IR over a spectral region ~80 nm wide, centred at the λ~780nm AR effective band gap. The DBR has a negligible effect on the I-V characteristic and doubles as the lower waveguide cladding, giving a QCL mode profile similar to that of a conventional $Al_{0.9}$ $Ga_{0.1}$ As clad. Devices were driven, at T=15K with 100 nsec current pulses at a 5 kHz repetition rate, and the near-IR power entering the device was ~10mW .

The incident near-IR (~10mW) was generated in a tuneable Ti:sapphire laser and used for PL, PLE and photocurrent

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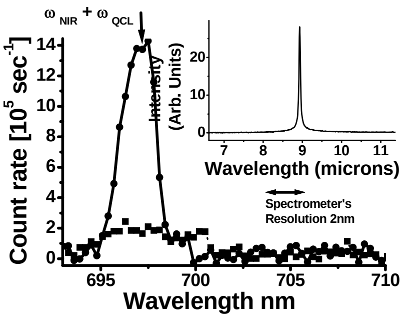

Fig. 2. Circles:- Difference between NIR re-emitted through the top window with and without QCL radiation present. The input wavelength, 756 nm is tuned to the h1-e2 resonance in the QCL active region, and Input and output beams have the same linear polarizations. Squares, the same quantity with input and output polarisers crossed. Inset, lasing spectrum.

spectroscopy. The NIR re-emitted the top window was dispersed, and detected with a gated photon counting system with a ~5nsec temporal resolution so as to isolate the NIR generated only when the QCL was lasing.

Figure 2 shows a sideband spectrum [5], at the double resonance condition, with the NIR tuned to the hh1 → e2 AR transition, and the sideband matching the hh1 → e3 transition. In reality the sideband peak is the Gaussian sum of the linewidths of the Ti:sapphire laser (~0.165 meV) and the multimode output of the QCL (~0.18 meV) , giving an estimated sideband linewidth of ~0.25 meV/ 0.1 nm.

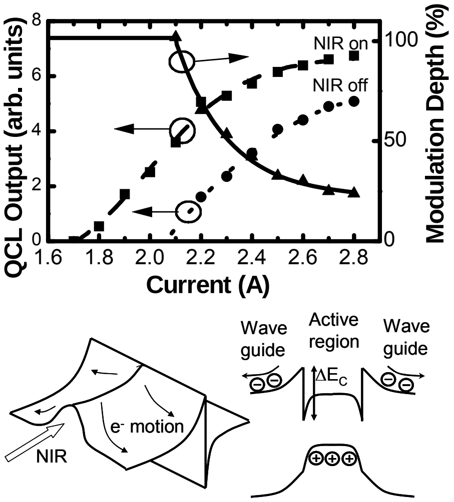

Figure 3. Upper:-L-I curves for a 20μm wide QCL device with (dashed curve) and without (dotted curve) ~70mW of CW λ_{NIR} = 750nm entering throughthe top window. The solid curve shows the depth to which the QCL output can be modulated with the NIR control beam. Lower, schematic of space charge fields separating photocarriers and driving them away from the illuminated window area.

The resonant $\chi^{(2)}$ mixing process involves 3 electronic states each of which are products of GaAs Bloch waves whose envelope function symmetries reflect the heterostructure potential. The latter, unlike any Bravais lattice, is isotropic in the growth plane and uniaxially inversion-asymmetric in the growth direction. In our experimental geometry [6] this gives a sideband polarisation, which whether linear or circular, matches the input NIR beam. The $\chi^{(2)}$ non-linearity operates over the full optical bandwidth, and the fast (~ 1 psec) ISBT s lifetime promises THz electrical QCL modulation rates. As the QCL wavelengths themselves head out into the THz region [7] these devices offer electronically modulatable wavelength shifters with operating speeds and channel separations suitable for a wide range of high bit-rate switching functions [8].

In devices with 25% Al waveguides the NIR beam was also found both to increase the above-threshold QCL efficiency, and decrease the threshold current density, by ~18% (from j^{dark}_{th} = 5.5 kAcm^{-2} to j^{light}_{th} = 4.5kAcm^{-2}). Biasing it just below threshold could produce a QCL output pulse sequence 100% modulated by the NIR control beam, at power levels up to 50% of the device maximum (Fig.3). The wavelength dependence of the switching amplitude showed the same spectral features as the PLE spectrum from the λ_{PL}= 785nm AR luminescence, implying that the switching was initiated by carriers created in the AR.

Pulsed experiments[9] ruled out the possibility of a thermal origin of the switching, and showed that its size depended only on the aggregated fluence of NIR photons arriving between QCL current pulses, with a switching energy of ~15 nJ at λ=785nm. The QCL's "memory" of how much NIR it had received was completely reset with each current pulse, and, surprisingly, exceeded 500msec for all temperatures at which it would lase.

Cladding layer Al concentrations of 0%, 10%, 20% and 25%, were tried but only the 25% ones showed the switching effect, and this, coupled with the long storage times, suggests a role for so-called DX centres, metastable electron traps[10] associated with donors in AlGaAs alloys with > 22% Al.

However, assuming literature values for the bandgap and a 60:40 band offset ratio, we find that the 25% samples alone have a ~140 meV high potential barrier at the AR/ waveguiding layer junction (fig. 3). This would separate electron hole pairs and generate space charge fields, and repel them from the window region via a "giant ambipolar diffusion" known in doping superlattices[11], keeping the photocharge density in the window area below ~5 x 10^{6} and stopping the potential barrier being screened out. Separating the contributions of these two mechanisms will need time-resolved experiments with QCL's which lase at higher temperatures than those presently available.

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