Laser Action at High k-Space Values in Anti-Correlated Multi-Wavelength Quantum Cascade Lasers

Stefan Menzel[1,2], Kale J. Franz[2], Daniel Wasserman[2], Anthony J. Hoffman[2], John W. Cockburn[1] and Claire F. Gmachl[2]

[1]Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
E-mail: s.menzel@sheffield.ac.uk

[2]Department of Electrical Engineering and MIRTHE, Princeton University, Princeton, New Jersey, 08544, USA
E-mail: kfranz@princeton.edu

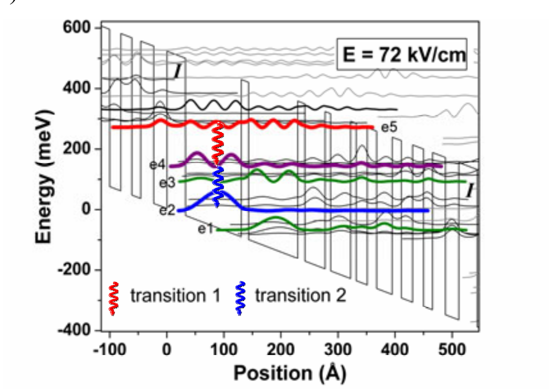
Abstract: A two-wavelength Quantum Cascade laser is reported in which one wavelength lases between subband states high in the k-space. Laser action at the two wavelengths is strongly anti-correlated in output power and threshold behaviour.

OCIS codes: 140.5965 Semiconductor lasers, quantum cascade

1. Introduction

Laser transitions in semiconductor lasers generally take place at the Γ-points of the band structure, because carriers relax quickly through ultra-fast intraband scattering to k = 0 in-plane momentum. This ultrafast relaxation does not allow for population inversion and lasing at high k-values. In this paper we report a two wavelength Quantum Cascade (QC) laser, where one of the two laser transitions is in fact occurring at high k-space values. This is made possible by the dynamics and interplay of radiative and non-radiative transitions of a cascaded transition in higher lying subbands. It is furthermore assisted by the subband non-parabolicity in quantum wells, which influences the intrasubband scattering, with longer scattering times at high k-values [1]. The Γ-point conduction band structure and a schematic of the energy dispersion E(k) of our devices are shown in Fig. 1. The two transitions share a common energy subband (e4), which acts as the lower laser level for the 9.5 μm transition (transition 1, red) and the upper laser level for the 8.1 μm transition (transition 2, blue). The population inversion of transition 2, which is placed high in k-space, depends on the intersubband scattering from e5 and e4/e2, either directly (e5 → e4(k)) or indirectly (e5 → e4 → e2(k)), and thus on the strength of transition 1, as confirmed by rate equation analysis [2]. This leads to an anti-correlation of both transitions, which is observed experimentally, as discussed in the following.

a)



b)

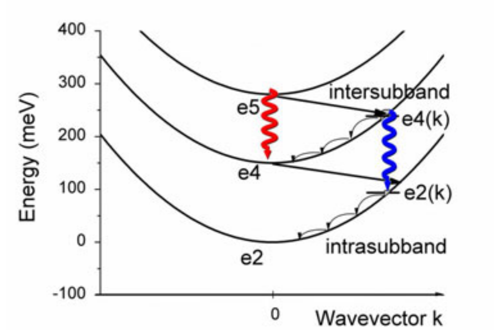


Fig. 1: (a) Γ-point, $k = 0$, conduction band structure of the dual-wavelength Quantum Cascade laser; and (b) the energy dispersion E(k) of the laser subbands e5, e4 and e2 illustrating the lasing at high k-values for transition 2, and the interaction of the two laser transitions.

978-1-55752-859-9/08/$25.00 ©2008 IEEE

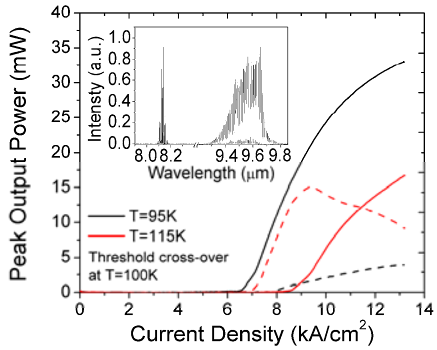


Fig. 2: Light output versus current curves for a 12 μm wide and 1.5 mm long QC laser. Solid lines belong to transition 1 (~ 9.5 μm) and dashed to transition 2 (~ 8.1 μm). The inset shows a representative spectrum taken at T=80K.

2. Experimental results

Fig. 2 shows characteristic light-current (LI) curves of a 12 μm wide and 15 mm long QC laser for two temperatures. Two cases are observed: (i) transtion 1 lases first at T=95K and (ii) transition 2 lases first at T=115K. If transition 2 lases first, we see a sharp roll-over in the output power of transition 2 when transition 1 sets in. This is the observed anti-correlation of the output power of the two lasers. The inset of Fig. 2 shows a spectrum taken from this laser ridge. Transition 1 lases at ~ 9.5 μm, and transition 2 at ~ 8.1 μm [3].

Fig. 3. shows the full, temperature dependent LI characteristics of both transitions. Transition 1 displays a behaviour which is typical for QC lasers, that is, lower output power and higher laser threshold at higher temperatures. This is due to the decrease of the gain at higher temperatures. Transition 2 on the other hand lases best at medium cryogenic temperatures and displays a strong non-monotonic performance over temperature. Such a behaviour is very unusual for QC lasers and is due to the temperature activated intersubband scattering from e5 to e4(k), as also shown in Fig. 1(b), and the vanishing of transition 1, respectively. The latter reduces the scattering from e4 to e2(k), again increasing the population inversion for transition 2; i.e. the presence or onset of transition 1 impede transition 2 via the strength of its photon field which, in turn, determines the in-plane population at high k-values for levels e4(k) and e2(k) and hence transition 2. The planar views in Fig. 3 show how the two lasers occupy different regions in the temperature-current density phase space.

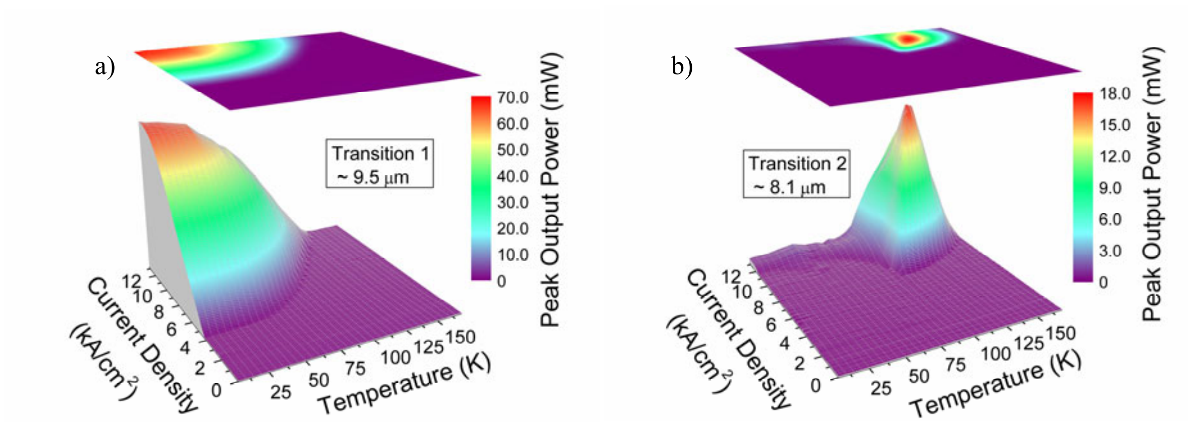


Fig. 3: Optical output power of (a) transition 1 (9.5μm) and (b) transition 2 (the 8.1μm) measured at different temperatures as a function of the injection current. The LI data were taken in temperature steps of 5K. One can easily see that the two transitions occupy different portions of the temperature-current phase-space.

3. Conclusion

We have reported to our knowledge the first semiconductor laser operating high in k-space of a continuous subband structure. The device operates on two different laser transitions, which are anti-correlated in power and threshold due to the k-space position of one transition.

This work was supported in part by MIRTHE (NSF-ERC) and the European Marie Curie research training network POISE.

References

[1] A. M. Alcalde and G. Weber, Phys. Rev. B **56**, 9619 (1997)
[2] S. Menzel *et. al.*, to be submitted
[3] K. J. Franz *et al*, Appl. Phys. Lett. 90, 091104 (2007)