1 Publishable Executive summary

1.1 Objectives

The project ANSWER aims to address the growing needs for compact solid state laser sources in the λ~3-5µm wavelength band. This wavelength region is under exploited due to a dearth of compact, power solid state lasers sources that can emit in this region. However, there are a number of important applications in this region. The spectroscopic absorption lines of many important molecules (CO, NO etc) fall in this wavelength band. Therefore compact, sensitive (ppb), and rapid (real time) detection systems can be foreseen with the appropriate laser sources. The application of these systems for the detection of hazardous substances and explosives in homeland security in airports, metro systems and points of mass transit and gathering is of particular relevance in today's world.

An overview of laser technology in the 3-5µm band is given in Table I. The emergence of the quantum cascade lasers (QCL) has opened up a new possibility to bridge the 3-5µm wavelength gap. QCLs have the advantage of being small compact and robust with continuous spectral coverage. Other technologies are powerful but bulky and are limited to naturally occurring emission lines in the laser material.

Technology	Spectral coverage	Power	Size	Comments
QCL	3.4-100µm	0.5W	mm x µm	Compact, robust, powerful with large spectral coverage
OPO	3-5µm	5W	~1m3	Large and bulky
Laser diode	<2.3µm	1W	mm x µm	Compact can't attain 3-5µm
CO laser	Discrete lines 4-5µm	W+	>1m length	Large and fragile with limited spectral coverage

Table I: Overview of laser technology in λ~3-5µm range

The QCL uses inter-sub-band transitions between bound states in the conduction band of a quantum well for light generation. This is in marked contrast conventional semiconductor optoelectronic devices which exploit the natural bandgap of the semiconductor material platform. The advantage of inter-sub-band transitions is that the wavelength is no longer limited by the energy of the bandgap. Instead the separation between the bound energy states in the quantum well are a function of the well dimensions. Modern epitaxial techniques readily allow the growth of semiconductor layers to atomic monolayer precision. Therefore control of the well widths on a nano-meter scale allows the emission wavelength to be varied over a wide range using the same host material platform. The spectral coverage of current QCL technology is from λ~3.4-100µm.

However, there is a fundamental short wavelength limit for the devices based on inter-sub-band transitions. This occurs when the energy separation between bound states becomes important relative to the depth of the quantum well. In this situation, electrons in the upper levels are weakly confined by the quantum well and may readily escape as the operating temperature is increased. This thermally activated leakage quenches the gain of the QCL and in the principle barrier to room temperature operation in the 3-5µm band.

To overcome this problem deeper quantum wells are needed for strong electronic confinement at short wavelengths and room temperature. At present the highest performance from QCLs has been achieved with the lattice matched heterostructures based on the InGaAs/AlInAs/InP material system. The performance of these devices falls rapidly for wavelengths shorter than 5µm. The maximum operating temperature of QCLs found in the literature are presented in fig. 1. The conduction band offset for this material is 520meV.

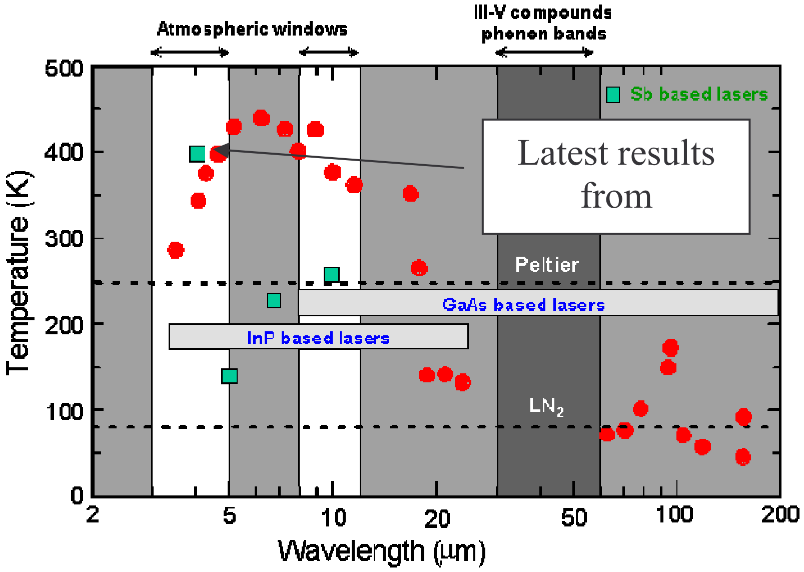

***Figure 1:** the maximum pulsed mode operating temperature of various QCLs is reporting as a function of wavelength. The sharp reduction (red circles) in operating temperature in the 3-5µm range is associated with carrier leakage out of the quantum well. The green squares shows the current results for Sb based QCLs. The latest data from the ANSWER project highlights the potential of Sb based materials for emission in the 3-5µm band.*

The objective is to produce high performance QCLs in the 3-5µm band. Specifically, we aim to produce a continuous wave (CW) i.e. DC operated QCL with modest Peltier cooling (T>240K) at a wavelength of λ<5µm. The strategy of this project is to develop different material platforms that have not previously been exploited for QCLs. These materials are characterised by strong electronic confinement to overcome the effects of carrier leakage. These materials are listed below:

1- Strain compensated InGaAs/AlInAs on <100> and <111> orientated InP substrates

Lattice matched InGaAs/AlInAs on <100> is the standard material platform for QCLs. However, its performance is limited to emission at λ>5µm due to its band offset of 520meV. One method to increase the band offset is to grow strain compensated InGaAs/AlInAs layers. Though strain balancing has been demonstrated in single quantum well devices, it becomes a considerable challenge in highly multi-layer structures such as QCLs (Nlayer>500). This major technological challenge is explored in this project. Alternatively, <111> orientated substrates. The change in crystallographic orientation allows further increases in band offset.

2- Lattice matched InGaAs/AlAsSb on <100> orientated InP substrates

The material system is similar to that in 1). Here the In the barrier material has been replaced by Sb. This change allows the band ΓΓ offset to be increased from 520meV to 1.8eV, significantly improving the electronic confinement. Although antimonide electronic devices have been demonstrated, this material has never previously been tried for QCLs.

3- Dilute Nitrides and Quantum dots (Advanced material concepts)

The addition of small quantities of nitrogen to III-V semiconductor heterostructures can have a strong effect on their band structure. Here we will explore, GaNInAs/AlGaAs on GaAs stubstrates and GaNInAs/AlNInAs on InP substrates. The modelling, growth and control of these materials are major scientific and technological challenges. Self-organised (Stransky-Krasternov) quantum dots offer exciting possibilities for advanced, high performance QCLs. The strong zero dimensional confinement in quantum dots presents all the advantages for short wavelength emission as large band-offset materials. Moreover, the reduced k-space allows the quenching of significant parasitic current channels (optical phonon emission) for higher performance lasers. Control of the coupling between inter-sub-band dot states is a significant scientific challenge.

1.2 Contractors

The consortium brings together the leading European actors in QCL development. They are:

III-V Lab (Co-ordinator) (France)

III-V Lab are a merger between Thales and Alcatel's French research centres. They have extensive facilities for the development of III-V semiconductor devices and are a world leader in the development of QCLs

University of Neuchatel (Switzerland)

A world leader in QCL development they have design, growth and characterisation expertise in all aspects of QCL development from the mid-infrared to the THz region. They are responsible for the development of strain balanced InGaAs/AlInAs materials.

Fraunhoffer Institute (Germany)

Has extensive world class facilities of the development of semiconductor devices. They have a rapidly growing reputation in the domain of QCL research. They are responsible for the development of antimonide based materials.

Technical University of Vienna (Austria)

A long term player in QCL research who have been at the forefront of many of the major technological developments over the years. They have the full capability for the development of QCL from design to final test. They will develop quantum dot QCLs.

University of Sheffield (UK)

Home to the UK's central growth facility, they University of Sheffield is an important international player on the QCL scene. They have pioneered new growth techniques for QCLs. They are responsible for the development of dilute Nitride QCLs.

University of Paris VII (France)

The University of Paris 7, is represented by the laboratory of "quantum physics and devices". They have strong links with III-V Lab and expertise in GaAs, In and GaSb based QCLs. Their role will be studying the gain and loss in the new QCL structures developed in this project.

University of Bari (Italy)

The optoelectronic research group of INFM at the University of Bari is led by one of the inventors of the superlattice quantum cascade laser. In the last five years the young researchers of the group have dedicated their activity to the experimental study of important issues for the development of both GaInAs/AlInAs/InP and GaAs/AlGaAs QCLs QCLs, such as i) the electronic distribution in the excited minibands ii) the local lattice temperatures iii) the non-equilibrium phonon generation associated with quantum transport iv) the assessment of the thermo-elastic effects in GaAs-based QCLs. The group has developed a state-of-art experimental approach for the on-line analysis of quantum cascade laser devices by micro-probe optical spectroscopy. More recently, the achievement of a complete clean-room facility has allowed the fabrication of GaAs-based QCLs. Their role will be to provide specialised characterisation of the QCLs developed in this project.

Alpes Laser SA (Switzerland)

A spin-off from the University of Neuchâtel and the first company to commercialise the QCL. They have developed numerous device processing techniques and pioneered QCL aging studies. They role will be to lend their considerable expertise in the development of high performance device, thermal mounting and facet treatments.