

**Final Report : GR/S59994/01:**  
**1.3 $\mu$ m GaInNAs Vertical-Cavity Semiconductor Optical Amplifiers**  
**(VCISOAs) and applications**

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**Summary:** This report summarises the outputs of a 30-month programme (6/2/2004 to 6/8/2006 including a 6-month extension) whose original goals were to investigate both optically- and electrically-pumped 1300nm GaInNAs-based Vertical-Cavity Semiconductor Optical Amplifiers (VCISOAs). However, the exceptional improvement of GaInNAs-based 1550nm materials which occurred during this project and the opportunity we recognised to make an impact there led us to devote more attention and resources to the development of 1550nm devices rather than electrically-driven devices. Particular highlights of this work include (i) the demonstration of 1300nm VCISOAs with performance comparable to InP-based devices and (ii) the first achievement of pulsed operation at 1550nm by a GaAs-based vertical-cavity laser. Studies of wavelength-tunable operation, dynamics of VCISOAs as well as investigations of a novel potential application as delay lines have also formed part of this programme.

## **1. Background and context**

The work on VCISOAs dates back to 1991 when Koyama et al [1] demonstrated the first “active filter” based on an 885nm Vertical-Cavity Surface Emitting Laser (VCSEL). Further progress was made in the mid 1990’s at near infrared wavelength [2-3] before being transferred to the long-wavelength window (1.3-1.55 $\mu$ m) using InP-based active regions [4-8]. At the beginning of the project, the best performance long-wavelength devices were optically-pumped components made of an InGaAsP active region wafer bonded to two AlGaAs DBRs. On-chip gains of ~10dB at 1300nm without mesa formation [6][6] and of 24dB when the carriers were confined within a mesa [8] had been reported. Application of the latter devices as external modulators for bit rates up to 2.5Gb/s with 5.5dB contrast [7] had also been shown.

Despite these reports, a number of key challenges had been left unaddressed, including (i) the need to simplify growth and processing to improve manufacture, (ii) potential temperature sensitivity of the devices, (iii) the lack of an electrically-driven demonstration, and (vii) the lack of tuneability of these devices. To address these issues, we proposed to use GaInNAs, a novel III-V alloy material compatible with AlGaAs DBRs in monolithic growth and capable of producing emission up to 1350nm at the time, to form the active regions of our long-wavelength devices. A pilot study led to the demonstration of the first monolithically-grown 1290nm VCISOA with gain values of up to 17.7dB [9], showing great promise for this kind of device. This status constituted the background and motivation for the proposed work on optically- and electrically-pumped GaInNAs VCISOAs.

## **2. Project Plan Review**

The original plan to develop 1.3 $\mu$ m optically- and electrically-pumped GaInNAs VCISOAs was amended because of exceptional material progress on GaAs-based structures emitting at 1550nm. It is only in the last 18-months that sufficiently promising strategies to achieve operation in that spectral range have been devised. We thus decided to embrace this novel research avenue by dedicating effort to the spectroscopic characterisation of these newly developed materials (GaInNAsSb) and their use in optically-pumped vertical-cavity devices.

The revised aims and objectives are then:

- Design and fabricate 1300nm GaInNAs optically- and electrically-pumped VCISOAs.
- Characterise and optimise 1300nm VCISOAs in CW and dynamic regimes.
- Investigate tunability.
- Assess GaInNAs-based material emitting at 1550nm.
- Exploit 1550nm GaInNAs-based material into vertical-cavity devices.

The specific objectives were modified to be:

1. Design and fabrication of optically-pumped VCISOAs operating between 1270 and 1330nm.
2. Delivery of an optimised CW optically-pumped VCISOA (target gain 15dB/32GHz).
3. Study of the response of the VCISOA to pump and/or signal modulation.
4. Demonstration of a telecommunication-relevant application of VCISOAs.
5. Demonstrate electrically-pumped devices and compare their performance to optically-pumped components.
6. Demonstrate a tunable VCISOA with at least 10nm tuning.
7. Report the material properties of 1550nm dilute nitride compounds.
8. Demonstrate the use of 1550nm material into a vertical-cavity device.

### **3. Management, Collaboration and Staff**

This EPSRC grant funding was based around the employment of a junior PDRA for 24 months. This award was complemented by the Institute of Photonics commitment to the PI as a newly appointed member of staff, which included the provision of refurbished air-conditioned laboratory space and support funding for a PhD student. Nicolas Laurand, an experienced French physicist (formerly employed as a R&D test engineer by the fibre component manufacturer Dicon, Inc), was recruited for the latter position. He possessed all the necessary skills to lead the device characterisation activity. It was then decided to utilise the PDRA support on experienced PDRAs ( C.W. Liu & H.D. Sun) for a shorter period of time (10 months at 100% & 9 months at 60% respectively) to complete the team and tackle the spectroscopic characterisation which was deemed important given the fast progress on 1550nm material. The management of the programme was undertaken by the PI and involved day-to-day supervision of the PDRAs and student with regular meetings with the remaining of the Institute semiconductor team. In this programme, the PI benefited throughout from Prof. M.D. Dawson's advice and support.

The project can be divided into two concurrently running activities: a spectroscopic assessment of dilute nitride material and the design and characterisation of VCISOAs.

Material assessment was performed by the PDRAs. It involved both routine characterisation of the received device wafers and in-depth spectroscopic analysis of the quickly improving 1550nm GaInNAs(Sb) multi-quantum-well structures.

On the device side, the optimisation of the optically-pumped devices in CW mode at 1300nm was undertaken before studying their tunability. A collaboration with the University of Glasgow (Prof. A.C. Bryce) was established to process a wafer provided by Sheffield University into electrically-driven devices, but unfortunately these did not work. We subsequently worked with Dr A.E. Kelly (Glasgow University), formerly with Kamelian Ltd (industrial advisor of this project), to characterise the dynamics of the best performance 1300nm optically-pumped device. Pulsed characterisation of a 1550nm GaInNAsSb VCSEL and the study of slow-light effects in VCISOAs completed this workpackage.

Critical to the work was the supply of high-quality semiconductor wafers to our designs. Sheffield University National Centre (Dr M. Hopkinson) was the resourced wafer supplier for this project. Although they have been able to provide very good quality samples for spectroscopic investigations, unfortunately we encountered difficulties in the supply of working device structures. In the event, we were fortunate to be able to access device epilayer growth from

international collaborators. The components operating at 1300nm all came from the Tampere University of Technology (in Finland, Prof. Pessa's group) while most of the 1550nm spectroscopy and device wafers were provided by a new collaborator (Dr J. Gupta) of National Research Council, Canada. Also, early 1550nm material for spectroscopic assessment was supplied by one of our long-standing European partners, LETI (in France - Dr Millon's group). These interactions also enabled us to secure novel types of high quality Saturable Bragg Reflectors for both internal and collaborative (St Andrews – Prof. Sibbett's group) ultrafast laser research activity. The design and static characterisation of the latter components were performed as subsidiary activities of this programme.

#### 4. Key Advances and Supporting methodology

Until the early phase of this research programme, long-wavelength VCISOAs suffered from a complex fabrication requirement (three growths and two wafer fusions) [6-8]. This status changed with our demonstration of a monolithically-growth VCISOA operating at 1300nm and based on GaInNAs/AlGaAs technology [9]. The motivation was then to demonstrate that devices with as good performance could be obtained using GaInNAs as using this earlier method. We thus spent the early part of this programme investigating the optimisation of optically-pumped GaInNAs VCISOAs. The strategy was based upon getting VCSEL-type structures with a large number of QWs (6 and 15, respectively) and subsequently optimising the top-mirror reflectivity by a step-by-step etching/testing procedure. The epilayer structures were designed using a in-house multilayer simulation software with informed amplification predictions based on a rate-equation solver. Full results were reported in [P1-P2]. The best performing device had 6QW and a top mirror reflectivity of 97.7%. Maximum on-chip gain of 19 dB, 22 dB bandwidth and -1.5 dBm output saturation power for 10.5 dB gain were reached. These values are slightly short of the announced targeted values for the programme but are in on a par with InP-devices with no lateral confinement.

To enhance commercial interest, tunable operation was required so that the devices could track the wavelength shift observed in low-cost uncooled lasers that are expected to be used in metro and local access networks. We investigated two methods to tune the devices: temperature change and a mirror movable configuration. Using the device described above, the former technique led to tunable operation over 10nm with on-chip gain greater than 10dB as shown in [P2]. The mirror-movable demonstrator concept, illustrated in Figure 1, was based upon a half-VCSEL epilayer with 10QWs and a 99% mirror deposited on the tip of a cleaved fibre. Cavity tuning by piezo-electric displacement of the fibre was demonstrated with a tuning range of up to 24nm at laser threshold, corresponding to ~6dB of on-chip gain [P3-P4]. These results do not quite match those reported with InP-based active region and MEMs-tunable mirrors [10] but they were achieved from only two epitaxial growths and a careful optimisation of the active structure and top mirror reflectivity should enable similar characteristics to be reached.

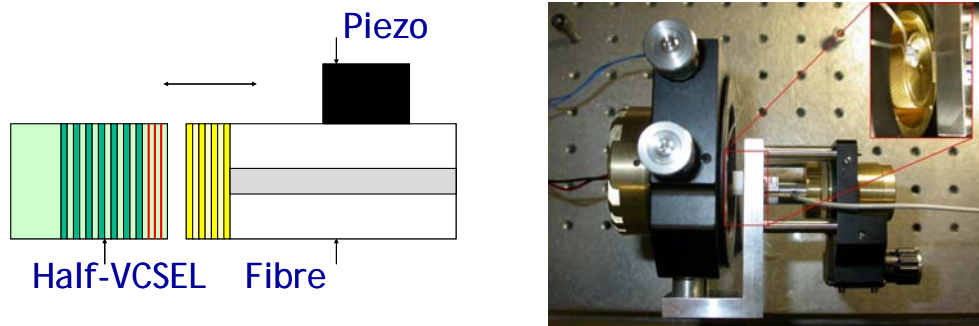


Figure 1: Mirror Tunable VCISOA.

Dynamic characterisation of the best performing optically-pumped VCSEA was undertaken using a pump-probe experiment at two operational points (anti-resonance and gain regime) showing gain and index recovery times of  $\sim 50$  ps. These results were presented in full in [P4].

Electrically-driven devices were one of the original prime targets of this research programme. Based on the success of the fibre-tunable configuration and to simplify growth, it was envisaged to build tunable electrically-driven devices. A short-cavity ( $3\lambda$ ) half-VCSEL structure comprising 9QWs (distributed over 3 antinodes) with intra-cavity p-doped contact was designed at the Institute, grown at the University of Sheffield and processed into small and large-mode area oxide-confined devices in collaboration with Glasgow University. Figure 2 shows pictures of the devices at different stages in their fabrication. Unfortunately, none of the devices worked successfully. This was attributed to an insufficient quality of the epilayer (very weak PL) but should certainly succeed with a further commitment of growth effort. This remains a very promising line of development.

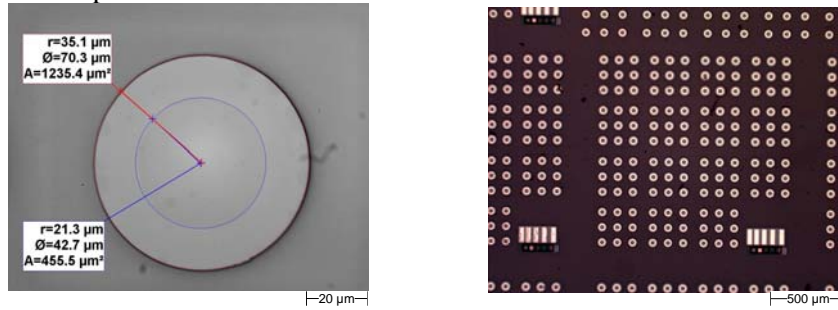


Figure 2: Right: oxidation front – Left: fully fabricated VCSEAs

We switched our attention to investigate experimentally and theoretically the use of VCSEAs as optical delay lines following upon the slow-light demonstration in a VCSEL [11]. We were successful in showing the first demonstration of slow-light in an optimised VCSEA and delays of up to 80ps were measured. We also revealed a delay-delay bandwidth trade-off and nonlinear limitations of this scheme [P6]. This work was very timely as P.C. Peng et al also presented the input power dependence of the group delay in a 1300nm quantum-dot based VCSEL [12].

In parallel to the 1300nm device activity, a significant part of our research efforts was dedicated to the evaluation of the progress of dilute nitride alloys towards emission at 1550nm. This assessment was conducted by performing photoluminescence and photoluminescence excitation (PLE) characterisation of multi-QW samples. Starting with a traditional approach of GaInNAs/GaAs QW which led to phase separated samples (provided by LETI) [P7], the subsequent strategic evolutions of barrier height reduction [P8] and addition of the surfactant Sb [P9-P10] showed significantly improved photoluminescence at 1550nm. The latter approach was fully exploited to allow us to demonstrate the first C-band operation of a GaAs-based VCSEL [P11]. The epilayer of the device included the active region and the bottom DBR while the top mirror was a dielectric DBR that had deposited commercially. This pulsed optically-pumped demonstration was again very timely as Stanford (Prof. J. Harris' group) managed to reach pulsed electrical operation using a fully monolithic growth a month after us [13]. Substantial work is still needed to achieve CW operation and this activity will form part of a proposed future research programme by the PI.

In addition to VCSEA work, we have recognised that the dilute nitride alloys could be exploited into a wider range of vertical-cavity devices than electrically-driven VCSEAs [P12]. In particular, as a first step to power-scale VCSEA and/or obtain operation at multiple wavelengths, we have demonstrated a “microchip Vertical External Cavity Surface Emitting Laser”. This device was constituted of a half VCSEL semiconductor wafer (same as for the tunable VCSEA)

bonded by liquid capillarity to a 250mm-thick mirror coated (99%) diamond platelet. The latter platelet acts both as a heatspreading material and as a way obtain a quasi-monolithic device with an artificially extended cavity length. It was optically-pumped and demonstrated single mode laser operation with more than 100mW of output power [P13]. Signal injection difficulties and increased cavity finesse prevented the accurate measurement of the device properties as an amplifier. Finally, it was also noticed that dilute nitride alloys could enhance the performance of passively modelocked lasers by improving long-wavelength Semiconductor Saturable Absorber Mirrors (SESAMs - which can be viewed as unpumped VCISOAs). This programme helped to secure appropriate structures at 1300nm and 1550nm. Static characterisation (reflectivity - PL) was done as part of this programme while laser assessment was performed by our collaborators at St Andrews University within the EPSRC project “Ultrafast Photonics Consortium” project [P14-P15].

## 5. Explanation of expenditure

The total budget for this 30-months programme was £115,863. This effectively supported 15.4-months of PDRA time, allocated as described above. Dr H.S. Sun and N. Laurand (now a PDRA) are still working at the Institute of Photonics while C.W. Liu is now at Bath University.

The equipment budget was used to buy a 1300nm tunable laser source from Agilent, a pump laser from LIMO GmbH, all which are essential testing equipments for the optically-pumped VCISOAs.

The consumable allocation was spent on fibres, fibre components (circulators, splitters, isolator), mirror depositions on fibre-tips for the mirror-movable devices, optical mounts, mechanical positioning mounts, wafers (Tampere University) and supply for the mechanical workshop.

The travel budget covered the attendance to the following international conferences: EMRS 2004 (Strasbourg), LEOS annual meeting 2005 (Puerto Rico), the COST 258 meeting (Athens), CLEO 2005 (Baltimore) and CLEO Europe 2005 (Munich) where our results were presented. Visits to Bristol University and Heriot-Watt University were also performed to enhance our collaboration on material modelling and fibre tunable VCSEL respectively.

## 6. Research Impact and benefits to society: Further Research

The number of research groups studying or using VCISOAs has been increasing over the past 30-month period as these devices gain recognition for their own merits. It is noteworthy that their applications are also slowly moving from telecommunications to biological sensing [14] or more fundamental physics [15], giving more breath to the field.

As far as our dissemination is concerned, this programme has led to the publication of 13 refereed journal papers and 13 peer-reviewed conference articles. We have also been invited to summarise our research into a chapter of book edited by Dr Erol Ayse entitled “*Dilute Nitrides: Physics and Applications*” to be published early 2007 by *Research Signpost*. A trade press article about the 1550nm VCSEL work was published in the March 2006 issue of *FibreSystems Europe* extending the visibility of this research to a wider community. Similarly, the *Virtual Journal of Ultrafast Science* (January 2006) established a link to our paper on the dynamics of the VCISOAs. We also kept Kamelian Ltd and its re-born venture Amphotonix, Ltd appraised of the developments in the field of VCISOAs through the collaborative work with Dr. A.E. Kelly, chief of R&D for the former company and co-founder of the latter organisation.

Furthermore, N. Laurand’s PhD work was entirely dedicated to the study of dilute nitride VCISOAs. His efforts and the project successes were rewarded by the attribution of a LEOS student travel grant to attend the CLEO 2005 conference and a prize for best student presentation at the 2006 Rank mini-symposium on “Dilute nitride semiconductor materials and devices”.

The pulsed 1550nm GaAs-based VCSEL demonstration is considered as one of the main achievements of this programme. The work is however likely to attract much more attention if continuous-wave operation can be obtained. Substantial progress is still needed to get to this position and evaluate whether this technology is a viable alternative for 1550nm devices. This forms part of a programme that the PI is currently preparing for EPSRC consideration.

The work on slow-light, a very active and fast developing research field, is also deemed of sufficient breadth to deserve a sustained effort. The initial study conducted within this programme should be viewed as a first step towards a much greater involvement into the field. Discussions about a joint project with St Andrews University on that subject are underway and should lead to another grant proposal.

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- [P2]: A.H. Clark et al., *IEEE Journal of Quantum Electronics*, **40** (7), (2004). Temp tuning 6QW
- [P3]: N. Laurand et al., *proceeding of the Indium Phosphide and Related Material (IPRM) conference*, or *Physics Status Solidi C*, **2** (11), 3895-3898 (2005) Mirror tuning
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\* indicates the major publications underpinned by this grant.