1 What is the question that this proposal addresses?

What is the potential of InP-based InAs quantum (Q)- dots devices for telecommunication applications?

Up to now, there has been no successful way to produce Q-dot based light emitting devices at 1.5μm even though this is a key strategic wavelength for optical telecommunication systems. The best attempts involved the growth of InAs Q-dots on GaAs. These dots were able to provide emission at 1.3μm [1]. More recently, in Korea and in France the fabrication of InAs Q-dots on InP has been developed [2],[3]. The laboratories report devices working at room temperature with a low threshold current and a moderate linewidth enhancement factor. There are many studies required to assess this new material and to determine if Q-dot devices for optical telecommunications applications live up the high expectations. For instance does an InAs Q-dot based semiconductor optical amplifier (SOA) have better a performance than a bulk SOA? And if so, why? By how much?

2 Why is this problem significant?

In theory, there are many of positive consequences motivating the implementation of Q-dots in semiconductor active devices. Due to the Dirac-like density of state (DOS) of the Q-dots, a higher carrier density per energy transition is achieved. This has several advantages: a higher DOS leads to a low current threshold, higher quantum efficiency and a higher differential gain. The latter contributes to a smaller linewidth enhancement factor, as a result of the symmetrical gain.**In theory the linewidth enhancement factor is nil, thus Q-dot based semiconductor optical amplifiers should not introduced any chirp to the signal amplified.**

The discrete feature of the DOS produces reduced temperature sensitivity. Therefore it is expected that for the threshold current and the emission wavelength will be virtually independent of the temperature. **In theory Q-dot based semiconductor optical amplifiers should not require a temperature control system and should provide the same amplification independently from the temperature conditions.**

For aforementioned reasons, it is clear that InAs-based InAs Q-dot SOAs promise many advantages over conventional SOAs, and the necessary studies must be undertaken to probe their potential. Our investigations will test whether or not these new active material devices will lead to a next generation of chirp-free components. Another issue that will be considered in this project is the sensitivity of device performances to the polarization of the signal injected. Most telecommunication networks are based on single mode fibres, in which the polarization of the optical signal is not controlled. This leads to problem such as polarization mode dispersion which is relevant for data transmission above 40 Gb/s. In term of signal processing the polarization of the signal to be processed could influence the SOA's performance. Hence it is relevant to study how the polarization of the injected signal will affect the response of the InAs Q-dot SOA.

3 How will the question be addressed?

The investigation on the 1.5μm Q-dot device will be carried out according to the Gantt chart, presented Fig. 1. The **Deliverables** or **Milestones** are listed in each work-packages and they are referenced in the Gant Chart.

The study is scheduled over three years, involving two Irish research institutes, Dublin City University and Trinity College Dublin. Two PhD students will be training during this project, one in each institute. Our industrial collaborator, the III-V Alcatel-Thales laboratory, France, has agreed to provide us with three devices (see letter of support).

During this project, we will achieve two goals:

- To characterize the performance of the InAs Q-dot SOA as an in-line optical amplifier and compare them with the bulk SOA and
- To develop a deeper understanding of physics behind the InAs- Q-dots. We will perform these measurements in work-packages 1, 2 and 3. The techniques employed will give us some insight on Q-dots and their light-matter interaction. We will study the performances of Q-dots SOA as a function of four dependences: device's size, bias current, wavelength and polarization. We will complement the experimental work with the development of theoretical model of the devices in work-package 4.

First we would like to briefly describe the devices under test. The Q-dot SOA are In As quantum–dot buried ridge stripe laser, with an emission peak at $1.5\mu m$. For more details on the material and fabrication, see [3]. Even though this paper deals with laser components, their active layers are identical. The both facets are anti-reflection coated, with a reflection coefficient of the order of 10^{-4} , the active layer is angled with respect to the facets by 12^o in order to suppress the standing waves in the device. This contributes the reduction of the reflection coefficient. Each facet is tapered. We are in possession of three devices from $800\mu m$ and $1.5mm$.

3.1 Work-package 1

Wk1 deals with characterization of the devices.in continuous wave (CW).

3.1.1 Electrical Characterization

Firstly we will carry out an electrical characterization of the each component. The voltage across a device will be measured as a function of the injected current. We assess whether the V-I characteristic will fit the Shockley equation (**Deliverable 1**). The calculated $IdV/dI - I$ characteristic will give information on any spurious parallel resistance. From this will be able to determine various current paths taken by the injected current (**Deliverable 2**).

3.1.2 Optical characterizations

The optical performance will be studied by the $L - I$ characteristic of the device will also be carried out. For this measurement, the SOA is not under any light injection; the amplified spontaneous emission (ASE) is collected and measured as a function of the bias current. It is possible assess some of the SOA parameters from the ASE, such the gain bandwidth, the gain peak. Obviously, the longer device should produce the largest amount of ASE. By expressing the bias conditions in term of current density, we will be able to compare the ASE output as a function of the device's length (**Deliverable 3**). We should be able to determine the optimal length, i.e. the minimum device length for maximal output power (**Deliverable 4**). Below this length, the device is too short to produce a maximum output emission above this length, the active region close to the output facet acts as a transparent section. This rough explanation does not take into account the temperature dynamics.

Using the $L-I$ curves; we will be able to measure the external quantum efficiency, η_{ext} by taking the slop of the curve above the amplification threshold (**Deliverable 5**). From this measurement, for each device we will be able to determine the value of the internal quantum efficiency, η_{int} and the optical internal loss α_l using the following formula:

$$\frac{1}{\eta_{ext}} = \frac{1}{\eta_{int}} - L\left(\frac{\alpha_l}{\eta_{int}\log R}\right)$$

where L is the device length and R the reflection coefficient. We will be able to evaluate the optical recombination in the SOA and its efficiency. The calculation of the internal efficiency is **Deliverable 6**.

The ASE spectrum will be recorded as a function of the bias current. As the current increases, different energy level will be filled in. We will be able to localise first the ground state, then excited level and finally the wetting layer. We will compare at constant current density if the ASE spectrum for the longer device is the same as that of the shorter device. If the Q-dot active material behaves in the same manner than the bulk material, we should observe two effects: a reduction of the gain bandwidth and red-shift of the ASE peak with the device's length. These are due to a reduction of the free carrier density accentuated by the length of the devices. The regions closer to the output facets are saturated by the ASE and their gain spectrum get narrower and peaked at longer wavelength.

The gain will be measured for each device. A CW input power will be launched into the SOA under test. The polarisation of the injected signal will be matching the condition of maximal gain. The output signal will be collected and then measured by an optical spectrum analyser (OSA). Care will be taken to prevent from any reflection between the source, the SOA and the OSA. The ratio of the output signal over the input will determine the value of gain produced by the SOA. The gain depends on the wavelength of the injected signal. We will work according the bandwidth spectrum of the ASE measured previously. We will carry a measurement of the gain as a function of the output power. When the gain is reduced by 3 dB from its initial value the associated output power is the saturation output power. We will study the small-signal gain for the several devices' length. Based on the same experimental set-up we will measure the noise-figure of the devices. The noise figure (NF) is equal to the ratio on the signal to noise ratio of the input signal over the signal to noise ratio of the output signal.

The gain and the saturation output power and NF will be measured according to the current bias, the wavelength and the length of the devices. We expect the gain increases with the length, however as the ASE increases with length the gain can be penalised and the saturation output power would be set to a value depending more on the ASE rather than the length.

The NF should increase with the device's length. This is anticipated as the carrier density is lower in longer devices, resulting in a low inversion degree responsible to a higher NF.

The studies of the gain, the power saturation and the noise figure are **Deliverable 7**. These will be of interest in order to assess the trade-off between the short SOA, a wide and blue-shifted gain bandwidth with a low small signal gain and NF and the long SOA, a narrow and red-shifted gain bandwidth with a high small signal gain and NF. The CW measurement achieved here, will be of importance for the evaluation of the devices' performances for system application carried out in **Workpackage 4** and also the simulation of the Q-dots SOA.

As mentioned above, the ASE spectrum will be recorded as a function of bias current. These spectra will be polarization resolved with respect to the TE and the TM axis of the SOAs' waveguide, in order first to evaluate the birefringence in the Q-dot SOA, as demonstrated in bulk SOA by [4],[5]. The study of the birefringence in the Q-dot SOAs is **Deliverable 8**. This measurement will be useful in order to determine the limitation of the device in four-wave-mixing (FWM). Unfortunately The FWM cannot be treated within the time-frame of this project.

Each of these spectra we will be used as well in a technique known as the Hakki-Pauli method [6], to determine the value of the line-width enhancement factor or α-factor. This technique is based on direct measurements of the refractive index change through detection of the frequency shift of residual longitudinal Fabry–Perot modes and the differential gain as the carrier density is varied by slightly changing the current of an SOA. This measurement relies on a high resolution optical spectrum analyser.

The linewidth enhancement factor achieved by this method will be compared to those based in the dynamic response of the devices, presented in **Work-package 2**.

We expect at low bias current that the line-width enhancement factor to be small, i.e. less than 1. As the current bias increases, the ground-state level will become saturated, the carrier in the excited state will rise and the optical spectrum will tend to more asymmetric as the current keeps increasing. The resulting effect will produce a larger value of the α-factor [7],[8] increasing with bias current. This effect has not yet been demonstrated with this type of Q-dot SOA. Further more, since the spectra are polarization resolved, we will be able to study the dependence of the α-factor with the polarization. This study will be carried out as a function of the device's sizes as well. The linewidth enhancement factor's results are compiled in **Deliverable 8**. We will compare some the performances of these Q-dot SOAs, with the bulk SOAs in our possession.

3.2 Work-package 2

WKk2 deals with characterizing the dynamics of the devices and gaining a deeper understanding of the gain recovery mechanisms in InP-based InAs quantum dot material. Two complementary experiments will be carried out in the time domain. The pulses are produced by an OPO with a pulsewidth varying from 11ps to 150fs, the pulse energy **from to**, the repetition rate is fixed at $82MHz$ and the lasing wavelength can be tuned **from to** . The experiments presented below will be carried with two pulse durations, at few picosecond to probe the carrier-heating dynamics and of few hundreds of femtosecond to look the SHB dynamics [9].

3.2.1 Frequency resolved optical gating

With frequency resolved optical gating we will analyse the time evolution of both the power and spectrum of the pulse passing through the Q-dots SOA under test. We will study the instantaneous variation of the optical spectrum introduced by the Q-dot SOAs and the consequences in term of propagation of pulse in fibre and application in a network. This measurement will be produced with the three length SOAs, hence we will be able to assess the influence of the length on the dynamics of the devices. This is **Deliverable 9**. The influence of the polarization on the response will also be analysed by varying the angle between the linear polarizations of the pulse signal with respect to the TE mode of the SOA waveguide [5]. We will look at the influence of the bias condition, (or in other words with or without saturation of the ground or excited energy levels) on the pulse-width and the chirp. Assuming that a Gaussian, a Lorentzian or a sech shape is injected in the device under study will be able to determine the α-factor based on the time-bandwidth product calculation. This approach is complementing the Hakki-Paoli method as the α-factor is measured for device in real working conditions, i.e. optical injection. The dependence of the linewidth enhancement factor as a function of the lunching condition is **Deliverable 10**. The dependence of the same factor with the bias condition is **Deliverable 11**.

3.2.2 Pump-probe

Two pump-probe set-ups are proposed: One co-propagation and the second one is in counter-propagation [10]. Both set-ups will be used to study the gain dynamics for the different SOA lengths. These set-ups are complementary of each other as in co-propagation, unless it is possible to build Borri's experiment [11], the pump and probe signals are cross polarized in order to select the probe signal from the pump signal. However in counter-propagation the probe signal exits from the input facet of the pump signal. Therefore this scheme allows any combination of pump and probe orientations. Using both of these schemes we will be able to study the gain mechanisms in Q-dot SOAs as a function of their length and also the orientation of the pump and probe signals. In the co-propagation set-up we will study the dynamics of the probe transmission with a pump signal in TE or in TM and the probe in TM or in TE. With the counter-propagation we will study these two cross-cases and we will compare the characteristic times achieved, but also we will look at the two other co-polarized cases, with both the pump and the probe in TE or in TM.

For several values of bias current, we will determine the saturation energy for each pulsewidth. We will set the energy of the pump below the saturation energy and the probe energy of the order of ten times smaller than that of the pump. As function of the time delay between the probe and the pump we will measure the transmission of the probe. The bias conditions will set in order to have the ground state more populated than the excited state.[9]. At 0 mA bias current, the pump will induce an electron-hole pair in dots, as no carrier is injected in the ground state from the current source. The probe signal will induce carrier recombination, or carrier escape to the excited level. Both effects are occurring on different timescale hundreds of ps for carrier recombination and less than ten ps for the carrier escape. With the proposed measurement we will be able to determine which branching mechanism is present in InP-based InAs quantum Q-dots. With moderate bias applied, the ground state is occupied and the pump signal is inducing stimulated recombination. The probe signal will measure the relaxation time of carrier from the excited carrier into the ground state. Fitting the transmission of the probe and we will be able to determine this relaxation time. According to [9], this measurement is clouded by the two-photon absorption (TPA) of both pump and probe signals. The co-applicant has a great expertise in TPA devices [12]. She has TPA microcavity detectors. We will be able to estimate the TPA intensity, by measuring in the same experimental conditions in term of pump and probe energy the photocurrent of TPA micro-cavity, which is a proportional the TPA intensity. It could be argued that the TPA micro-cavity detector and Q-dots SOA do not the same structure and active material, but this will give a good estimate of the TPA intensity.

Deliverable 12 is the polarization dependence of dynamic processes in the QD-SOA and **Deliverable 13** is the design dependence of dynamic processes in the QD-SOA.

3.3 Work-package 3

In Wk3, we will carry out a study of the SOA performance in term of system applications. As mentioned earlier, the Q-dots materials are given to have a faster gain recovery than that of the bulk or quantum well material and also a wide gain bandwidth. In term of system applications, the gain dynamics dictate the maximum bit rate or switching speed, the gain bandwidth limits the number of channels to be amplified or processed. In **work-package** 1 some of the fundamental features of the SOAs will have already been covered, such as the gain saturation, bandwidth and noise-figure. In **work-pacakge 2** we will have measured the chirp induced by the SOA or any distortion of the signal. In this work-package, we will investigate SOA's performance for in-line amplification in a fibre networks.

The CW signal from a tunable laser source, with a wavelength within the 3 dB gain bandwidth will be modulated by an electro-absorption modulator (EAM) driven by a pseudo-random bit sequence generator (PRBS) at a clock frequency of 10 GHz. The advantages of this method are: to be easy to implement, to generate low timing jitter, to work at high speed, to achieve a large extinction ratio of the generated signal with a low chirp and a low modulation distortion. It is also imperative that the optical spectrum of the pulses is as narrow as possible due to the penalty introduced by the chromatic dispersion of the fibre. The light pulses will pass through a given length of dispersion compensation fibre in order Fourrier limited data signal. The optical signals will be multiplexed by various lengths of fiber loops in order to reach 2 and/or 4 times the initial 10Gb/s. The optical signal is then injected into an SOA, and amplified. The output signal is converted with a photodiode into an electrical signal, and analyzed by a bit-error detector. The demuliplexed at 10Gb/s is done directly by the error detector getting the 10Ghz clock signal than the pattern generator. Using this scheme we will be able to assess the performance of the Q-dot SOAs as in-line amplifier function for 10, 20 and 40 Gbit/s transmission. We will measure the bit-error-rate, the penalty, the degradation of the optical signal to noise ratio and the timing jitter as a function of the bit-rate of the transmitted data, the power injected, the wavelength of the injected signal, the angle of a linear polarization injected into the signal, an the device length. This is summurized in **Delivarble 13.**

3.4 Work-package 4

In work-package 4, we will develop a theoretical understanding of the Q-dot SOAs by undertaking numerical simulations in parallel with the experimental work-packages. The model is based on a theoretical work carried out by [13],[14]. It deals with the time variation of the carrier population in the ground sate, the excited state and the wetting layer and the time variation of the signal interacting with the ground level and the time variation of the phase of the signal. This model provides solution for time varying signal injected, or modulated bias current, but it also provides solution in CW condition by setting all differential equations to zero. With this model we will be able to model the gain dynamics in our Q-dots SOAs. **Deliverable 14** is the completion of a model of pulse propagation in our QD-SOA. The CW computational results will be compared to the experimental data gathered in **work-package 1**. Then the model will be extended to time varying applications. The experimental results achieved **work-package 2** will be compared to that of the simulation. **Deliverable 15** is the completion of a model of pulse propagation in our Q dot-SOA. Once a good agreement is achieved between experiment and simulation, the simulation will be used to numerically probe the potential performance for systems applications. We will realize a model for pulse propagation in Q-dot SOA and then assess performance of the Q-dot SOA in a cross-gain modulation scheme for wavelength conversion. Furthermore through the simulations not only will be gain a deeper understanding of the Q-dot SOA device physics but we will be able to identify the ways in which the devices can be modified to achieve better performances.

Deliverable 16 is a report on the potential of our devices for wavelength conversion in cross gain modulation scheme.

3.5 Work-package 5

Work-package 5 is devoted to the project management. Both collaborators will meet on regular bases to discuss the progress of the project. They will inform SFI on the development of their study at mid-term. This is **Milestone 1**. At the end of the project, they will report on the work completed during the project. This is **Milestone 2**. We will be also able to compare the performance of the Q-Dot SOAs with a conventional bulk SOA. We will be able as well to list improvements on the structure which could be performed. This is **Milestone 3**.

4 What is your recent record of accomplishment in research that would suggest you can achieve success in addressing this problem?

Dr. Pascal Landais is from the Radio & Optical Communications laboratory, RINCE, DCU. He is the author of 3 patents on the design of novel lasers and SOA structures. One of these devices are currently in production and commercially available from Eblana Photonics Ltd. He has also published many peer reviewed papers on physics, design and characterization of semiconductor devices, with the most relevant listed in the CV attached. He has studied widely the dynamic in bulk or quantum well semiconductor strucutures. He is currently supervising one post-graduate student and one post-doctoral researcher. He is involved in semiconductor measurement activities of COST 288. He will be collaborating with Dr. Louise Bradley a lecturer and PI in the Semiconductor Photonics Group in Trinity College Dublin. Her research interests include physics and control of quantum dot emission and dynamic studies in semiconductor optical amplifiers. She has over 50 publications, filed 2 patents and currently supervises a group of 4 post-graduate students and 2 post-doctoral researchers.

5 What is the value of this research to the people of Ireland?

This project will represent a giant leap forward in the study of 1.5μm InP-based InAs Q-dot devices. New semiconductor material and device physics will be uncovered, with consequences for Q-dot lasers and amplifiers in optical telecommunications domain. Skills in the arenas of characterization and simulation of nano strucutures will be developed in an Irish institutes which will yield benefit to this and future research. Two Ph.D. students will be trained during the duration of this project. Strong collaborations with a world-wide leading optical component and network facilities will continue to be developed. Designs and innovations for novel Q-dot based lasers and amplifiers can result form these studies. The PI and collaborator have an excellent track record in generating intellectual property.

6 Budget

Cost items	Year 1	Year 2	Year 3	Total
Staff (DCU)	21,500	22,500	23,000	67,000
Staff (TCD)	21,500	22,500	23,000	67,000
Equipment	0	0	0	0
Materials(DCU)	2,000	2,000	2,000	6,000
Materials(TCD)	2,000	2,000	2,000	6,000
Travel(DCU)	1,500	1,500	3,000	6,000
Travel(TCD)	1,500	1,500	3,000	6,000
Total, €	50,000	52,000	56,000	158,000

There will be two students hired to perform the work proposed in the project, one in Dublin City University and one in Trinity College Dublin. Their annual cost starts at €21,500 this includes stipend of €16,000 (the current IRCSET rate) and fees. It allows for projected increases in fees. There is no purchase of equipment foreseen for the study proposed. The devices are given at no cost by the 3-5 Laboratory, Alcatel-Thales (see Letter of Commitment), hence the equipment cost is nill. Each institute will get a €2,000 consumable budget per year for the purchase of optical components for the respective experimental benches (lenses, mounts, polarizers, fibres, filters, mirrors etc). For the travel budget we propose the following: In Years 1 and 2 participation in European conferences, (for example Conference on Laser and Electro-Optics (CLEO) Europe, SPIE Photonics Europe and European Conference on Optical Communication, (ECOC)). In Year 3, both teams will participate in European and American conferences such as SPIE Photonics West and CLEO US.

7 Letter of Commitment

See attached document from III-V laboratory.

8 Curriculum Vitae

See attached CVs from dr. Pascal Landais and Dr. Louise Bradley.

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