2 µm High Power Short Pulse Laser Based on Monolithic Semiconductor Saturable Absorber, POLMOSSA

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ABSTRACT

POLMOSSA project targeted new frontiers in developing ultrafast fibre lasers operating at 2 µm wavelength range. It aimed at achieving mode-locking operation with simultaneously high output power and broad tunability. These key advances were enabled by the development of monolithic, lattice matched, GaSb-based semiconductor saturable absorber mirrors (SESAMs). Several SESAM designs were fabricated and tested demonstrating mode-locking of Tm-doped fibre lasers with a 90 nm tuning range at around 1.9 µm and almost an order of magnitude power increase as compared to the current state-of-the-art. The tuning range could be further extended with simple modifications to the cavity or by shifting the stop band of the SESAM.

Keywords: Saturable absorber mirror, SESAM, fibre laser, mode-locking

1. INTRODUCTION

Ultrafast fibre lasers are becoming ubiquitous to many scientific, medical, and industrial applications at the same time triggering new advances for improved functionality. To this end, scaling the wavelength range to 2-µm and above has been an intensive field of research for the past recent years, yet such lack well behind the developments at 1 µm window, which have benefited from the availability of mature fibre and semiconductor technologies. In addition, improved functionality in terms of tuning range, output power, stability and fabrication approach, are instrumental for ensuring a wider application base.

The breakthrough character of this work is related to the demonstration of state-of-the-art ultrafast laser performance at 2 µm window and the method to achieve such operation performance, enable reproducible manufacturing for volume applications. Broad wavelength tunability and high-output power are achieved in a 2 µm mode-locked (ML) fibre laser. This result is enabled by the development and deployment of a monolithic, lattice matched semiconductor saturable absorber mirror (SESAM). First of all, utilizing a SESAM instead of the alternative carbon nanotube (CNT) or graphene based saturable absorbers allows laser operation at higher powers due to low nonsaturable losses and high damage threshold of the SESAM. Moreover, the moderately strained GaInSb/GaSb quantum-wells (QWs) enable tailoring of the absorption from value as low as 0.3% to well beyond 50% by simply changing the amount of QWs, and hence the absorption.

In terms of laser performance, maximum output power of 73 mW was achieved while the wavelength tuning span of the laser was 90 nm with an average output power exceeding 40 mW. The estimated pulse duration in in the range of 2 ps. Clear pathways to extend the bandwidth and the average output power are described. Overall, the project demonstrated the potential of GaSb-based SESAM technology for mode-locking fibre lasers beyond 1.9 µm wavelength range.

2. STATE OF THE ART

In the last few years, several 2 µm wavelength-tunable ML fibre lasers have been developed [1-7]. Among different techniques used to generate ML, Saturable Absorber (SA)-based ML lasers provide the most robust approach against environmental conditions and in terms of complexity. In order to achieve wide range of tunability around 2 µm, graphene and CNT SAs have been favoured over SESAMs [3-5,7], main motivation being their ease of fabrication. However, they are typically operated in transmission mode. This increases the nonsaturable losses, which attains values in the range of tens of per cents [3,5,7]. Moreover, the ability to tailor their nonlinear properties is limited by the intrinsic properties of typically single-layer materials, the nonlinear contrast attaining rather low values of a few % only. These factors limit either the average output power of these lasers to few mW, or the operation wavelength is affected by the selection of SA, as seen in Table 1. On the other hand, SESAM-based ML has shown broad tunability but the output power has been limited by the SESAMs damage threshold [6]. Thus, the main challenge here is to achieve a wide tuning range with high average output power. Therefore, the development of a lattice matched SESAM with broad operation bandwidth and high damage threshold is an utmost need.

Tab. 1. Performance of state of the art of SA-based wavelength tunable 2 µm ML fibre lasers. *Wavelength change only by switching the SA.

Ref.	Saturable absorber	Tuning range, nm	Pulse duration, ps	Average output power, mW
[3]	Graphene	1880-1940 (60)	2	2
[4]	CNT	1866-1916 (50)	1	8
[5]	CNT	1733-2033 (300)	<6.5	1
[6]	SESAM	1862-1983 (121)	200	6.12
[7]	CNT	1926-1945* (19)	0.5	35

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The breakthrough achieved in this work arises from the pulsing method which was used to achieve the ML properties presented in the next section. A monolithically grown, lattice matched GaSb-based SESAM was utilized as the SA enabling broad tunability and high power of the 2 µm ML laser.

Capability to completely lattice match the AlAsSb/GaSb distributed Bragg reflector (DBR) allows growth of thick DBR layer without dislocations. Similarly, the active region can be grown using lattice matched spacers and moderately strained quantum wells (QWs), overall leading to a high material quality with increased damage threshold and reducing unnecessary nonsaturable losses outside the QWs. Simultaneously, the amount of QWs can be freely adjusted to tune the nonlinearity without comprising the material quality. Furthermore, the high refractive index contrast between AlAsSb and GaSb enables growth of DBR with a broad stopband, with 200 nm bandwidth.

As a key component to ML the laser, this SESAM gives a robust, repeatable and scalable option to broaden the tunability bandwidth while providing order of magnitude higher powers compared to previous SAs used to ML 2 µm lasers.

4. PROJECT RESULTS

Two generations of SESAMs were fabricated for ML assessment. The SESAMs were grown by solid-source molecular beam epitaxy on GaSb substrates. The lattice matched AlAsSb/GaSb DBR was followed by the active region consisting of GaInSb QWs embedded in GaSb barriers. The first generation SESAMs were used to assess the required nonlinearity to obtain reliable mode-locking. In Generation 2, a resonant and anti-resonant design were grown. The linear reflectivity spectra of the generation 2 SESAMs are shown in Fig. 1 showing the characteristic broad stop-band and the customizable absorption characteristics. The maximum nonlinearity of the resonant design exceeds 60%, whereas the non-resonant design offers 10% nonlinearity throughout the 200 nm broad stop-band.

In order to obtain an emission around 2 µm, a commercially available single-mode thulium-doped fibre was core-pumped using an erbium-doped fibre amplifier emitting at 1550 nm with an output power of 1 W (Fig. 2). The performance of the fabricated GaSb-SESAM in a linear laser cavity has been evaluated using two cavity architectures with two different output couplers. The first approach is used to investigate the effects of the fibre length, whereas the second approach focuses on the laser operation bandwidth.

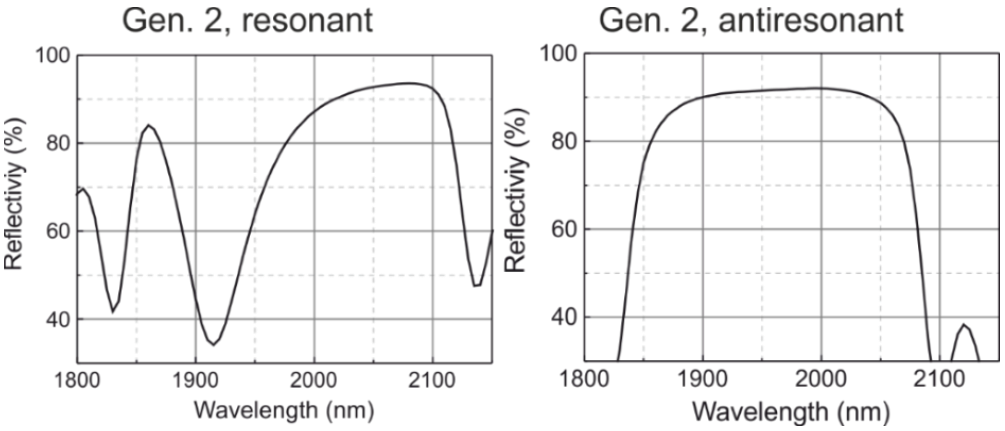

Fig. 1. The low intensity reflectivity curves of the resonant and antiresonant generation 2 SESAMs.

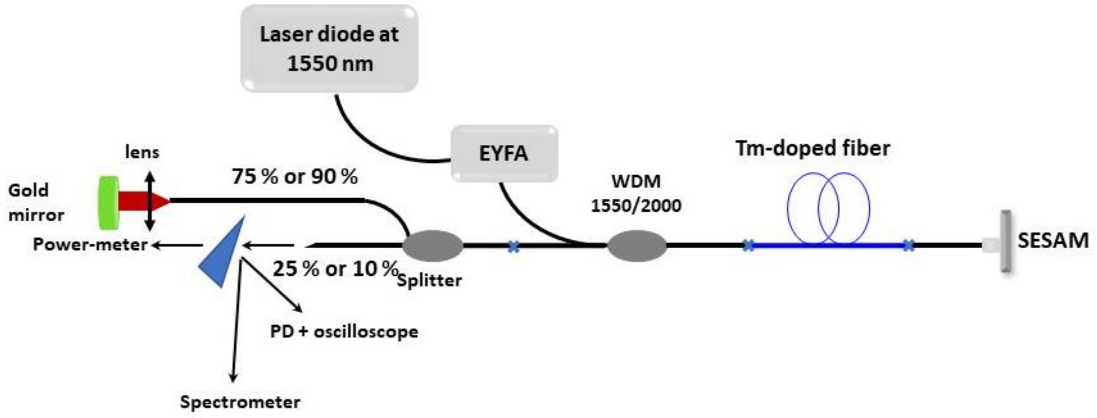

Fig. 2. Schematic illustration of the laser cavity.

The capability of the Generation 1 SESAM to operate at different wavelengths has been verified by changing the length of thulium-doped fibre, which changes the gain wavelength due to reabsorption process. A 30% output coupler and fibre length of 2.1 m and 7.1 m was used in this case. The laser cavity is formed by the SESAM and a gold mirror, without any supplementary wavelength selection component. Under these conditions, stable ML self-starts at pump power between 350 mW and 400 mW depending on the active fibre length. It is worth noting that no dispersion compensation component was added to the laser cavity, thus the ML occurs in the soliton regime. Fig. 2(a) shows the pulse train obtained using a 5.1 m of active fibre at maximum output power with no evidence for pulse splitting or multipulsing. The power scaling against pump power for different fibre lengths is illustrated in Fig. 3. An efficiency of 10% with an average output power as high as 73 mW is achieved.

Thereafter, the Generation 1 SESAM and the 30% output coupler were replaced by the Generation 2 SESAM and a 10% output coupler. A 4.1 m active fibre was used and a diffraction grating was inserted to the cavity for wavelength tuning. As seen in Fig. 5(a), maximum output power of 45 mW is achieved in this configuration using a pump power of 900 mW. This corresponds to efficiency of 6% with a ML threshold of 350 mW in terms of pump power.

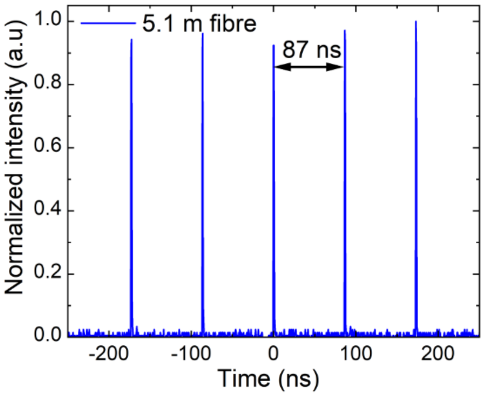

Fig. 3. Pulse train for the 5.1 m length active fibre, with 87 ns period.

Fig. 6 shows that stable ML is obtained for wavelengths between 1850 nm and 1940 nm. The 90 nm tuning range raises these primarily results comparable to the state of the art presented in Tab. 1, but with almost an order of magnitude higher output power, as output power exceeding 40 mW is obtained along the entire emission band. The bandwidth is limited on the long wavelength side by the fibre gain wavelength, which can be simply extended by using a longer fibre. On the short wavelength side, the limiting factor is the SESAM stop-band which extends from 1850 nm to 2050 nm. The minimum pulse duration is estimated to be 1.7 ps based on the spectrum full-width half maximum as a transform-limited sech2 pulse.

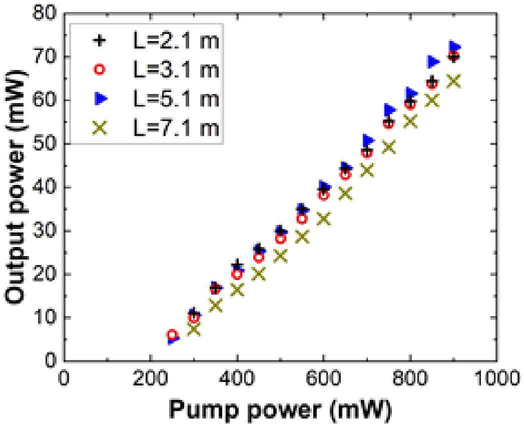

Fig. 4. Power scaling using SA (reference) with different active fibre lengths using a 30% output coupler**.**

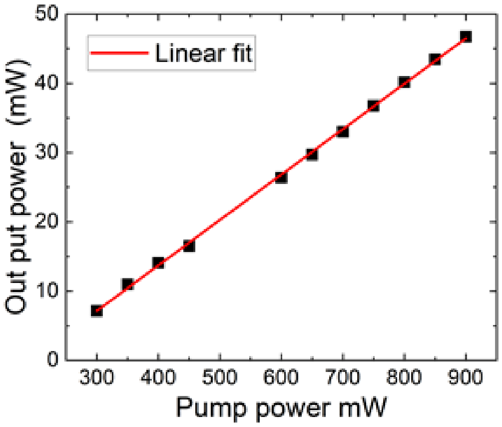

Fig. 5. Power scaling using the SA (reference: generation 2) and a 10% output coupler with diffraction grating.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The most crucial step to scale the technology is packaging of the laser. The first step is pig-tailing the SESAM to a commercial fibre connector or using precision optics and free-space coupling. Secondly, all the pump electronics should be packaged in a simple device with a computer-controlled user interface. The design shall be done according to the selected application together with the manufacturer of the device, where the laser is finally integrated, as described in the following.

5.2. Project Synergies and Outreach

Generating interest from potential future users/customers is crucial in order to establish a fit with the target application described in 5.3. and identify other potential applications. Potential partners in this group include medtech and advanced sensing instrument manufacturers.

Another important stakeholder group for outreach are collaborators who can help with further engineering towards TRL 9, industrialization and commercialization tasks. Docking on to an established laser manufacturer or at least a precision high-tech machine builder would bring a high value-add.

Dissemination efforts will focus on reaching the above-mentioned stakeholder groups and create awareness and excitement of key opinion leaders (KOLs) in the laser and laser application fields such as university professors, and key institute leaders. Outreach shall also include presentations via the networks of selected industry associations and innovation networks such as EPIC and Innovation Roundtable.

Contacts with other ATTRACT-funded projects, which may benefit from using the POLMOSSA laser in their applications have already been established.

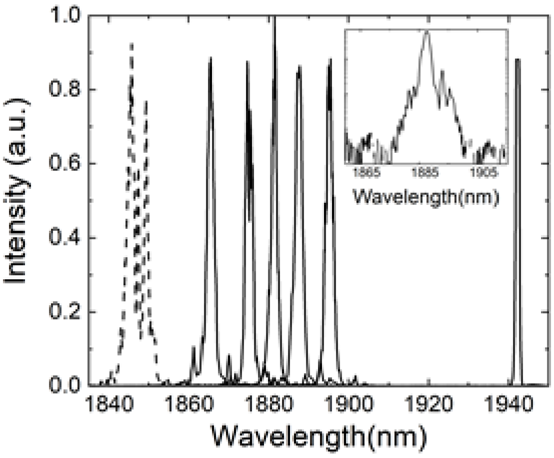

Fig. 6. Spectrum of the emitted wavelength with stable ML covering a range from 1850 nm to 1940 nm. The dotted curve, peak around 1845 nm, is marking the unstable behaviour. The inserted figure is a zoomed log scale plot for the peak around 1887 nm showing the Kelly side bands, which demonstrates that the laser is operating in soliton regime.

5.3. Technology application and demonstration cases

This Due to their excellent beam quality and compactness, 2 um pulsed fibre lasers are excellent candidates for several applications fields. These lasers can be used for LIDAR applications due to operation in the eye-safe spectral region. The capability to tune the emitted wavelength, makes realistic the detection of different molecules having absorption peaks around 2 µm (CO2, H2O, NH3 and N2O). In industry, these lasers can be used for plastic processing because of the high absorption of plastics at this wavelength. However, the main application of our laser source lies in the medical domain. The POLMOSSA laser is extremely interesting for ophthalmological surgeries. The water present in the cornea ensures high absorption around 2 µm. Thus, tuning the wavelength around 2 µm enables control over the penetration depth in the cornea without damaging the retina. Therefore, utilization of the POLMOSSA laser in eye surgeries will be our main demonstration case during the phase 2 of ATTRACT.

As another application path, the emission of the POLMOSSA laser can be amplified and used to generate a supercontinuum source in the mid-infrared region (2 µm – 12 µm). The absorption wavelengths of proteins and nucleic acids are located in this spectral band, which make these laser sources very interesting for medical imaging, especially cancer diagnostic. Moreover, several molecules (e.g. CH4, C2H4, C6H6, H2S, NH3, N2H4) present absorption in this spectral band. The detection of these toxic molecules will help EU countries to manage and reduce pollution, and the health risks linked to chemical exposure.

5.4. Technology commercialization

As stated in 5.2. above, efforts to engage with likely lead users of the future laser system are already starting. These efforts shall be expanded as the laser system reaches TRL 5+, when our project team will carry out and publish proof-of concept (PoC) work for prospective clients, and then further towards TRL 7+ when the project team fabricates prototype systems for targeted pilot customers. Furthermore, the SESAM as such has already reached TRL 7-8.

In the commercialization phase, the extended project team (start-up) will perform production of the core laser assembly, whereas integration into application-specific equipment for e.g. eye surgery, tissue analysis, etc.) would be performed by a larger, already established partner company. The start-up company would perform key R&D, system engineering, quality assurance, marketing and (technical) sales activities in-house, while relying on a network of supplier-partners (including notably project partner Reflekron Oy for the SESAM chips) for manufacturing and delivery of key components/subassemblies on a global network of distribution partners.

The initial stretch of the business incubation journey will be driven by the (evolved) POLMOSSA project team, for which financing from ATTRACT Phase II is required. Lebanon University will correspond of the scientific development of the laser, RefleKron produces the SESAMs, and as a new partner, Ephemer provides support in the commercialization work. For the final integration of the laser, it is essential to engage with the European venture capital, business angel and accelerator/incubator ecosystems with a focus on organisations funding photonics technologies and/or medical device businesses. Those investors would financially back and mentor the start-up.

5.5. Envisioned risks

The key risks of the Phase II are related to commercialization work. The medical device framework is tightly regulated and partnering the established businesses in the field may fail. The mitigation for this issue is found in the secondary application fields described in 5.3.

5.6. Liaison with Student Teams and Socio-Economic Study

The project was a real boost to the master’s degree “Laser optics and materials” at the Lebanese University. Masters internship was performed this year and for the next year with a new research axis related to fibre lasers is added. Engaging in Phase II would guarantee the continuation of this path. Thus, Prof. Zaraket from the Lebanese University will be in charge of the student team's integration during the Phase II.

The socio-economic study of Phase II will be supported by all project partners by sharing data on technology impact with the ATTRACT ecosystem as required.

6. ACKNOWLEDGEMENT

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