MINIMODS

MINIaturised diagnostics and frequency-conversion MODuleS for ultrafast lasers

Final Publishable Summary Report

November 2015

The research leading to these results has received funding from the European Union Seventh Framework Program (*FP7/2007-2013*) under grant agreement no. 606141

1 EXECUTIVE SUMMARY

The state-of-the-art in modern laser sources are characterised by a high degree of performance coupled with a highly functional electronics control and software user interfacing. The next logical step in laser source development is the use of this platform to include additional functionality, which can be integrated into the source, giving increased diagnostic facilities or output conversion capabilities. These next generation innovations will provide a higher level of user control and awareness, adding value to the technology and the wide range of processes in which they are deployed.

The concept for the MINIMODS project was to create a range of miniature and cost-effective modules for advanced laser diagnostics and control. The targeted developments were: an autocorrelator unit, a beam propagation factor detector, a spectrometer, a frequency tripler and a pulse compressor. The main objectives we aimed to solve in developing this technology were to create highly compact, rugged, cost-effective, wavelength flexible and broadband modules.

The research necessary to realise such objectives was undertaken in a wide collaboration between two research partners and four small and medium-sized enterprises, specialising in system, source, subsystem and component manufacturing. Robust industrial and scientific laser sources such as those produced by the SME supply chain grouping brought together in this project will have a broad impact on the targeted application areas, which include: semiconductor metrology, multiphoton microscopy, defence and security and high-speed optical telecommunications. The benefits experienced by end users in these areas provide compelling product differentiation and add significant value to the supply chain.

MINIMODS is a €1.99M project (EU contribution just under €1.5M) coordinated by M Squared Lasers Limited, with a project consortium consisting of six of Europe's leading photonics research groups and small to medium sized companies from five different countries. The project has produced a variety of results which will be able to be exploited across a range of sectors, illustrating a compelling use of resource and research funds.

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2 Project Context and Objectives

There is a strong pull for practical ultrafast laser sources from a magnitude of applications and associated markets. These applications often demand systems with high reliability and maintenance-/alignment-free operation while at the same time, be highly adaptable to cater the numerous requirements imposed by the specific application. One of the key issues that prevent state-of-the-art ultrafast lasers offering such capabilities is their intrinsic complexity which often causes the requirement of intervention from highly skilled engineers and makes implementation of ultrafast technology into demanding applications outside research laboratories almost impossible.

MINIMODS aims to address these short comings by developing miniaturised laser diagnostic tools and frequency conversion modules that are small enough to be integrated directly into the optical heads of ultrafast lasers and synchronously-pumped optical parametric oscillators. These modules will not only add direct readouts of key performance (e.g. pulse duration, spectrum, beam quality) and functionality but will also offer the ability to use adaptive control loops to control the laser performance parameters to unprecedented accuracy. This will negate the need for any user intervention when operating these systems, thereby making them suitable for a wide range of real world applications.

While there are various ultrafast diagnostic tools on the market already, these are generally very expensive and bulky apparatus that don’t lend themselves for integration into fully engineered systems. MINIMODS will overcome this by exploiting a series of new technological concepts developed by the consortium to realise autocorrelators, beam quality detectors, spectrometers, compressors and third harmonic generators. In this context, cost effectiveness and a highly compact form are paramount factors to ensure that these systems can be utilized as a mainstream component in future generations of ultrafast oscillators.

2.1 Context

Femto- and picosecond pulsed lasers have become the most rapidly growing area of the global laser market and the technology largely owes its success to several key applications areas including: advanced semiconductor metrology systems, multiphoton imaging/microscopy, micromachining and defence/security applications. While ultrafast lasers have been around for a number of decades now and are well established on the market, they are still very complex and demanding systems that often require regular user

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intervention to maintain alignment contrasting with the applications requirements for ruggedised, maintenance-free systems.

The primary reason for this complexity is the relation between the pulse duration and spectral bandwidth (expressed through the bandwidth-duration product). The consequence of this relationship is that careful balancing of the group velocity dispersion (GVD) of the resonator is required to maximise/optimise the spectral bandwidth, and hence, the pulse duration of the laser. This fine balancing act requires additional intracavity components such as negative dispersive mirrors or prisms that need careful alignment and significantly increase the system complexity. This impact further increases when a degree of wavelength tunability is incorporated into these ultrashort pulse laser systems - as the dispersion and alignment are dependent on the central oscillation wavelength maintaining an optimal pulse duration over the entire tuning range becomes a considerably complex issue.

The majority of state-of-the-art ultrashort pulse lasers are based on near-infrared systems such as titanium-doped sapphire and ytterbium-doped tungstate lasers. When ultrashort pulses are required in other spectral regions such as the ultraviolet (UV) or mid-/far-infrared, as is often the case, the system complexity and aforementioned issues increase dramatically.

In the mid-infrared (λ=3-12μm), direct generation of ultrashort pulses has proved very challenging. Ultrashort pulse laser systems operating in the mid-IR are typically based on frequency conversion of near-IR lasers using nonlinear processes in optical parametric oscillators (OPO). Such systems utilise the technique of synchronously pumping to maintain a precise temporal overlap of the converted pulses within the OPO with the pumping pulse. This interferometric cavity length matching necessitates sophisticated control loops to maintain optimum alignment, stability and performance of the ultrashort pulse OPO.

To extend ultrashort pulse technology into the UV and visible spectral regions frequency upconversion techniques such as second-harmonic generation or frequency tripling are often used. Here, external enhancement cavities can be exploited to optimise the conversion efficiency – at the cost, again, of the additional system complexity. While the second harmonic can be generated from a single conversion, third-harmonic generation requires a two-step process where part of the light is first doubled and then mixed with the fundamental radiation. As all the conversion stages need to be synchronised to the master oscillator to ensure temporal overlap of the pulses, yet again, the system complexity is increased.

Advances in the fields of adaptive optics and adaptive control loops have already had a significant impact on the development of hands- and alignment-free laser systems. In the ultrafast segment, however, these developments have been hampered by the availability of

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practical sensors that measure key parameters of the systems directly. In this context, the pulse duration, its phase (in the temporal or spectral domain), spectrum, and beam quality are the most important optimisation parameters. To date, technical solutions to monitor these parameters have been large, expensive and cumbersome and therefore do not offer themselves for the direct implementation into laser systems. We therefore proposed here to develop novel ultra-compact diagnostic modules that will fundamentally change the way ultrafast laser systems are designed, controlled and used. The origin of this project was the supply of a simple and compact autocorrelation sub-system from the University of Warsaw (Ultrafast PhenomenaLab) to M Squared Lasers (the coordinator of this project). It was quickly realised that the following key aspects make the technology highly relevant to the core businesses of the SME partners.

2.2 Project Objectives

The primary objectives of the project are to design and develop a number of pre-prototype systems that have been conceptualised by the companies and RTD performers:

- Autocorrelators for femtosecond as well as picosecond pulses
- Low-cost, spectrometer for the near- to mid-infrared
- Beam propagation parameter detector
- Monolithic third-harmonic generator
- Ultra-compact pulse compressor

The targeted modules will be designed to embody the following characteristics:

- Highly compact
- Rugged in design
- Very cost effective concept
- Wavelength flexible
- Broadly tunable

2.3 Project Team

A highly experience team of European academic and industrial organisations was assembled for the MINIMODS project. The project team is introduced below:

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M Squared Lasers Limited (M2) and manufactures next-generation compact lasers and related systems. The company expertise spans the entire laser performance spectrum, from ultra-narrow, highly stabilized continuous wave to broadband femtosecond sources, and from deep ultraviolet to terahertz wavelengths. M Squared has longstanding experience and demonstrated success in delivering innovative solid-state laser products, meeting customer application requirements, and delivering the highest levels of customer service and support.

In this project, M Squared sought to expand the capabilites of its core product lines with the object of increasing its customer base and sales revenue. In this context, M Squared was particularly interested in the development of integratable and modular systems that are compatible with several key product lines, along with opportunities for the commercialisation of stand-alone diagnostic modules.

The principle responsibilities of M Squared were the project management and demonstration activities of the work.

JDSU, formerly Time-Bandwidth Products (TBWP) is a leading manufacturer of ultrafast pico- and femtosecond laser systems for industrial and scientific applications, featuring a combination of excellent performance specifications with reliable, turn-key operation. TBWP pioneered the commercialization of semiconductor saturable absorber mirror (SESAM) mode-locking, originally developed at ETH Zurich (Swiss Federal Institute of Technology) and continues to develop reliable ultrafast lasers based on this technology for commercial applications in micromachining, semiconductor, life sciences, telecom, medical, and scientific markets. Their key expertise includes prototype development, testing, packaging and commercialization of high performance ultrafast solid-state lasers implementing SESAM technology, and technology road-mapping for novel lasers for biophotonics and other applications.

TBWP expects to benefit from RTD partners within this project the acquired IP, know-how in developing, and built and tested new “Femtosecond Blocks” tailored and optimized for TBWP’s lasers. Built-in compact autocorrelator as a critical diagnostics, as well as accessories such as THG (tripler) and compressor could bring a large competitive advantage to TBWP over other, mainly non-EU based manufacturers of femtosecond tunable lasers.

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Most of the TBWP customer base in industrial laser applications including material processing and biomedical imaging require a hands-off, user friendly laser with compact, easily added accessories. The integrated compact autocorrelator will bring the option of the key-laser parameter continuous monitoring on a screen, while in current lasers this is possible only with significant extra experimental efforts in alignment, space and an additional expensive instrument. The compact, low cost tripler will enable UV fs pulses and could open the whole range of new applications. The compact compressor will make the fs optics experiments with our lasers significantly simpler, as it will enable to keep the shortest pulse at the sample by compensating the dispersion caused pulse broadening along the optical path of the experiment.

The principal responsibilities of TBWP were the interaction and guidance for the RTD performers as well as demonstration activities at the end of the project.

LASEROPTIK GmbH (LO) was founded in 1984 and since the company lives and constantly grows based on its reputation and customer´s recommendations in the laser business. From the beginning, the primary goal of LASEROPTIK was to support customers to produce better lasers with improved optical components. This goal still remains as a business philosophy and was an important factor for the company to become a fully integrated producer of UV-, VIS- and NIR laser optics. As an owner-managed high-tech company we attach great importance to our social and environmental responsibility.

The principal responsibilities of LO were the supply of specialised optical components to the consortium.

Radiant Light SL (RAD) are specialist suppliers of advanced solid state instruments for laser tuning. They design, manufacture and market state of the art frequency conversion systems that expand the wavelength coverage of lasers and laser-based systems. They offer the latest technology in broadband laser tuning; their optical frequency conversion instruments include Optical Parametric Oscillators and Harmonic Generators which extend laser wavelengths from the UV to the IR, with high performance and ease of use.

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The principal responsibilities of RAD were the interaction and guidance for the RTD performers as well as the demonstration activities at the end of the project.

The University of Warsaw (UWAR), founded in 1816, is the largest university in Poland with some 56000 students and more than 3000 academic staff. The UW Faculty of Physics (FUW) is the leading Polish faculty of physics with almost 100 years of history and a very strong record in optics in particular.

The Division of Optics has a long tradition in laser physics and engineering and associated technologies, including the high precision spectroscopy instruments, excimer lasers (in the 80s), femtosecond lasers and amplifiers and ultrashort pulse diagnostics (from the 90s on). A lot of unique scientific equipment has been designed and built as the experiments rarely rely on the commercial solutions. This includes femtosecond NIR lasers, terawatt-class femtosecond amplifiers (laser and parametric - NOCPAs), frequency converters, femtosecond pulse diagnostic devices, fast high voltage electronics, customized optomechanical solutions. The two research groups involved in the project: Photonic Nanostructure Facility and Ultrafast Phenomena Lab, add up to a team of some 5 young researchers (aged between 25-40) with hand-on experience in experimental ultrafast optics: from CAD design, optical design (also with custom-written software), machining to optical testing and characterization. A number of the devices developed and built has been sold to or shared with the cooperating scientific partners (mainly at universities and research institutes). Each year several papers in the broadly understood experimental ultrafast optics is published in top peer-reviewed journals and presented in conferences around the world.

The principal responsibilities of UWAR in the MINIMODS project were:

- Development of miniaturised autocorrelator for distinct wavelengths
- Development of miniaturised autocorrelator for broadband near-IR operation
- Development of frequency tripler

Fraunhofer UK Research Limited (FCAP) The Fraunhofer Centre for Applied Photonics is the first Fraunhofer Centre to be established in the UK and is based at the University of Strathclyde incorporating what was

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previously the Institute of Photonics. Fraunhofer UK Research Limited is a Research and Technology Organisation (RTO) which is incorporated as a not-for-profit, limited by guarantee company which provides applied research and development services to industry. We are a reliable partner with 5 years' of core funding, around €13 million, to underpin our long term success.

Fraunhofer Gesellschaft is Europe's largest organisation for applied research and the recently established Fraunhofer UK Research Ltd. (CAP) will be a hub for industry-driven laser research and technology for a variety of sectors including healthcare, security, energy and transport. The Fraunhofer Centre is based in the University’s world-class Technology and Innovation Centre, which is transforming the way universities, business and industry collaborate to find solutions to global challenges, create jobs and support the economy.

The principal responsibilities of FCAP were the development of a compact, low-cost spectrometer architecture that can be used in the NIR as an alternative to fixed grating array spectrometers. This format of spectrometer was then be adapted to the mid-IR at wavelengths above 2 µm to provide a real-time laser power spectrum diagnostic. The final part of this work was to maximise the bandwidth of the mid-IR spectrometer to make it applicable to the OPO products of the SME partners involved in MINIMODS. Secondly, working closely with M2, FCAP developed the miniature M Squared meter based on their recently protected IP and joint ideas for compact laser beam diagnostic with minimum complexity. These M Squared meters were explored at all wavelengths relevant to the SME partners of MINIMODS. The final work effort associated with the project was to take the autocorrelator work of UWAR in the NIR and explore the development of longer wavelength, mid-IR autocorrelation for the longer wave ultrafast lasers and OPO sources.

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3 Main Scientific and Technological Results

3.1 Project Overview

The MINIMODS work programme builds on a strong existing foundation of knowledge in the fields of ultrafast photonics, diagnostics, optics and optoelectronics. The project research activities are structured into three logical research related work packages, a diagram of which can be seen in Fig. 3.1 below.

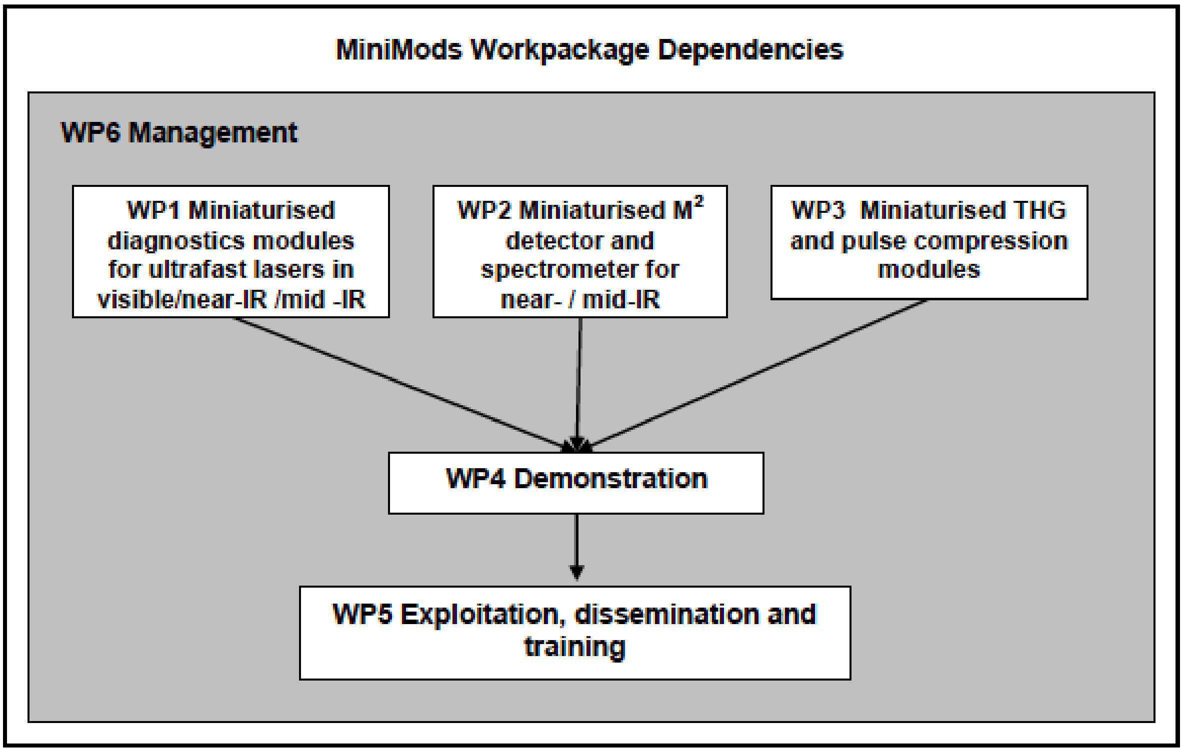

Fig. 3.1: Work package schematic for the project

The 3 research workpackages and their activities are described below:

Work Package 1: This work package is focussed on miniaturised diagnostic modules for ultrafast lasers in the visible/near infrared/mid infrared. In particular this work sought to establish designs for cost-effective autocorrelator units. The planned designs aimed to estsblish units capable of broadband operation at key near-infrared wavelengths as well as mid-infrared alternatives for synchronously-pumped optical parametric oscillators.

Work Package 2: This work package aimed to develop both a miniaturised M^2 meter and a compact spectrometer for near- and mid-infrared laser sources. The motivation was to create modules that could be operated in either stand-alone or integrated arrangements, that are capable of giving rapid and accurate read-outs of critical beam properties, namely the

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spatial quality and output wavelength, These outputs can then be used for monitoring or feedback in advanced systems.

Work Package 3: This work package targeted the creation of a series of highly-compact frequency tripler modules, designed for use with specific types of laser system ranging from narrow-band, fixed wavelength to widely tunable sources. A miniaturised pulse compressor based on novel dispersion-compensating optics was also designed.

3.2 WP1: Develop miniaturised and cost effective broadband diagnostics modules for ultrafast lasers

In this work package a refined design for a compact autocorrelator capable of measuring femtosecond laser pulses (in the duration range from approx. 100 fs to 1 ps, Fourier transform limited) for a broad range of wavelengths between 700-1030 nm for Ti:sapphire and Yb:crystal or Yb:fiber. The second-generation prototype was able to introduce several upgrades based on test and experiments with the first generation prototype design. The broadband capabilities of the new design have been measured with a commercial tunable femtosecond laser source. Test modules and training was provided to the relevant SME partners which describe in detail the procedure of setting up the hardware as well as the software distributed together with the device. The final device is shown in Fig. 3.2.

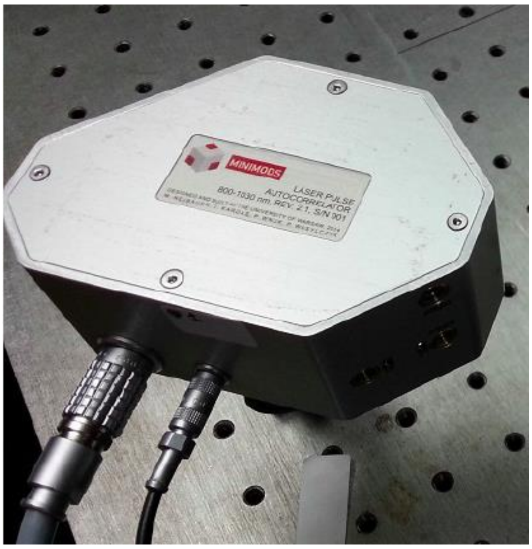

Fig. 3.2: MINIMODS prototype autocorrelator module created by UWAR

With an overall footprint of the order of 10x10 cm^2 and with the height limited to the extent that would ultimately fit into the femstosecond oscillator head enclosure, the unit represents

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a highly compact device. The potential outgassing of components was considered in case the end unit was to be used in a hermetically sealed laser enclosure.

The autocorrelators are designed to perform best with laser pulses having the width (FWHM) of the order of 200 fs. The lower limit is set by dispersion of the transmission optical elements and delay readout resolution, while the upperlimit is defined by the delay scanning range.

The SME partners requested that the autocorrelators can work in-line, i.e. a small fraction of the laser output power will be continuously supplied to the measuring device (as opposed to the flipper mirror concept where the entire beam is switched between the ACr and the laser output). This fraction was initially defined as “a few percent” of the total laser output power, which typically means a lower limit of some 5-10 mW of the average power at around 100 MHz repetition rate. For either manual or automatic feedback a decent refresh rate is required the lower limit is set at 10 Hz, i.e. at least 10 times every second a laser pulse autocorrelation width and/or the autocorrelator trace should be available at the autocorrelator output. It was also decided that the device would work with the commercially available electronics (e.g. A/D cards) at the first prototype stage, as the final version must have the electronics compatible with the laser controls and these will be easily integratable by the laser manufacturers.

The prototype is based around intensity autocorrelation measurements as, for the pulse shapes expected, there is little gain in the information available from interferometric autocorrelation while it inevitably poses several challenges in terms of long- and short-term stability of the autocorrelator.

Fig. 3.3: Construction of the autocorrelator prototypes at UWAR.

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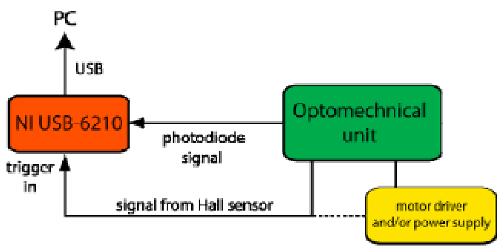

Fig. 3.4: Schematic of system electronics

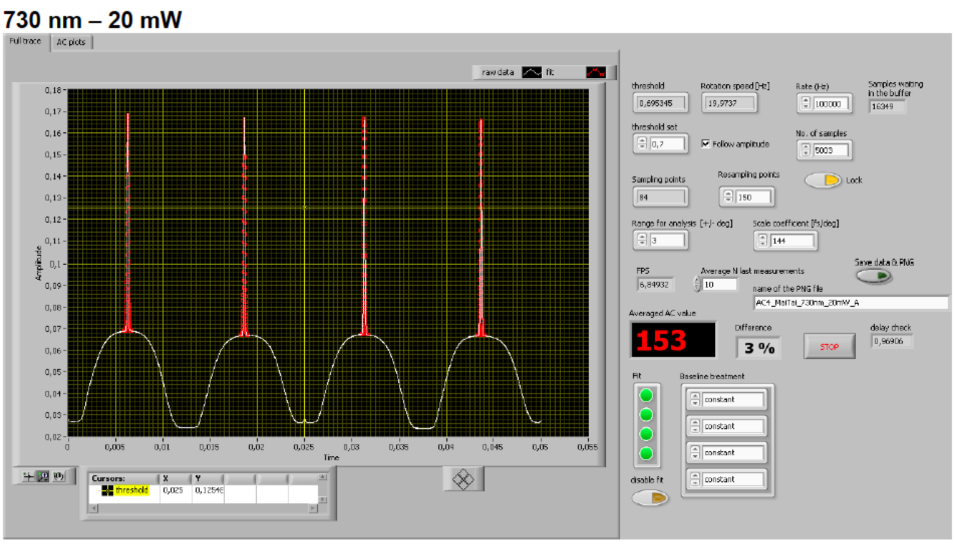

Fig. 3.5: Screenshot of autocorrelator user interface in LabVIEW

It was also decided that the device would work with the commercially available electronics (e.g. A/D cards) at the first prototype stage, as the final version must have the electronics compatible with the laser controls and these will be easily integratable by the laser manufacturers.

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In a separate developmemt FCAP researchers were tasked with creating an autocorrelator unit capable of operating in the mid-infrared, that would be suitable for use with synchronously-pumped optical parametric oscillators. A novel design was implemented by the FCAP team and subsequently tested by RAD. A screenshot of the resulting autocorrelation trace taken during a test with a modelocked 2μm

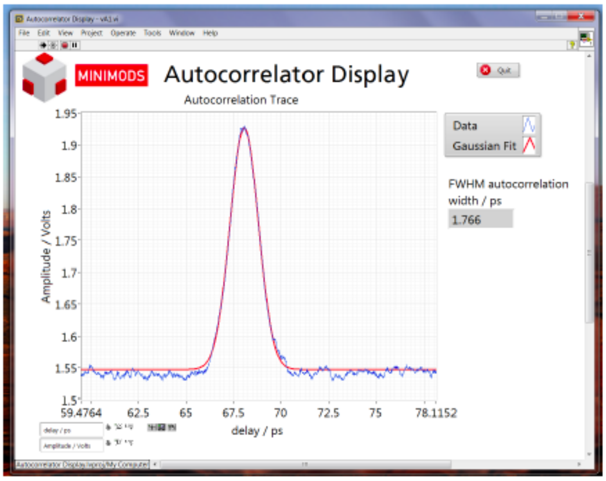

Fig. 3.6: Autocorrelation of pulses from a mode-locked 2μm laser at FCAP

3.3 WP2: Develop miniaturised M^2 meter and cost effective spectrometer for the mid-infrared

The laser beam quality is an important characteristic of a laser source and is critical for many applications. In lasers used in manufacturing, the laser spatial mode determines the minimum focused spot size and therefore sets, for example, the smallest feature size in a direct ablation or surface roughness in a milled work piece. The smaller the spot size the higher the irradiance that can be achieved at the focus and thus the lower the threshold laser power for the process to begin. This can lead to lower costs for the laser system or more rapid processing and greater throughput.

In microscopy and laser imaging, the beam quality is a limiting factor in the performance of an imaging system, again limiting the spot size, resolution and optical through put of advanced microscopy systems, active imagers and remote sensing systems. Therefore, the measurement of this characteristic is of critical importance during the development, construction and operation of any advanced laser system.

The first main aim of WP2 is the development of a compact and cost-effective M^2 meter. The initial work in this task centred on a review of M^2 measurement, a comparison of commercially available systems and a study of the ISO documentation on the topic of laser beam measurement. A key finding of the initial design reviews was the conclusion that there

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was indeed a need for a lower cost, compact and rapid M^2 measurement system and that the M2 concept for achieving this was worth pursuing. Following discussions between FCAP and M2, the industrial beneficiary of this deliverables, the scope of work was agreed in terms of the extent of development and prototype capabilities. The planned outcome was an integratable or stand-alone unit providing a more rapid, compact and lower cost diagnostic for use in their laser development and production. The ability for it to be used across a wide range of laser wavelengths is also desirable. The requirement for operation across a wide wavelength range and with a variation of output beam spatial properties was the challenging aspect of this task and this greatly narrowed down the range of technologies that can be applied. The approach taken utilised a single-point detector, which lent itself to operation over a wide spectral range but also gave the option to simply replace the single low-cost detector component to access alternative spectral ranges.

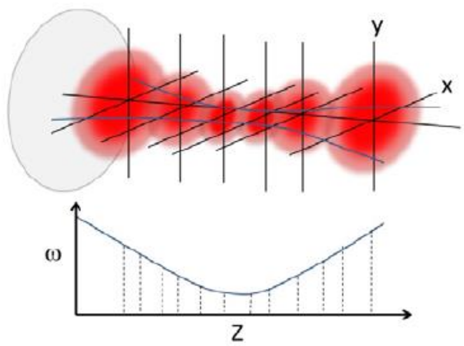

Fig. 3.7: A caustic of a focussed laser beam with multiple measurement planes, with beam waists, ω indicated. The fit to caustic built using multiple beam width measurements is used to retreive M^2.

The photodiode signals are recovered through a high-speed data acquisition unit and the signal processing is undertaken in real-time to provide a continuous output, with a refresh rate of 2 Hz. A screenshot of the output feed from the prototype's user interface is shown in Fig. 3.8 below.

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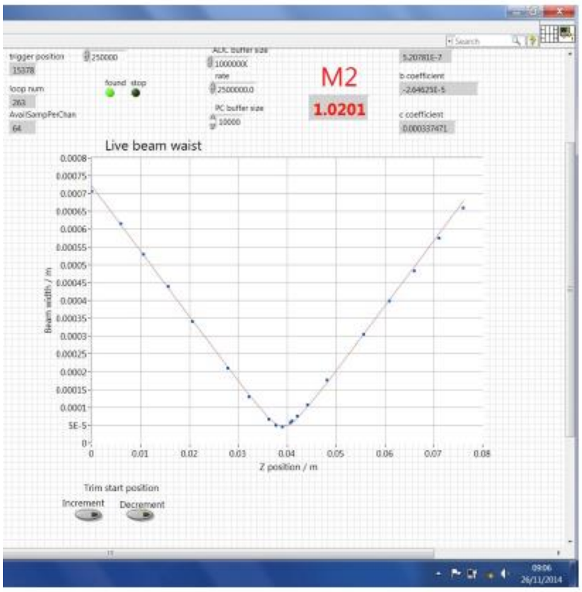

Fig. 3.8: Screenshot of the M^2 meter output, indicating real time beam waist data.

The second target outcome of WP2 was a compact, cost-effective spectrometer unit. The initial task was to establish the required performance parameters for the spectrometer were compiled to create a design specification. In order to measure the spectrum of lasers of interest a wide spectral bandwidth (0.7 µm to 4.0 µm) is required. To provide a useful level of detail in the spectral measurement, a Full Width Half Maximum (FWHM) resolution of 5 nm is required (but 1 nm would be better if possible). At the same time the spectrometer should have a small size (75 mm x 100 mm), and low production cost.

The basis for an instrument that can fulfil these capabilities was chosen to be a monochromator. A prototype spectrometer was built and characterised. It was measured to perform within the design specifications. The output from the spectrometer during a test with an optical parametric oscillator, is shown in Fig. 3.9, whilst the user interface of the module is shown in Fig. 3.10.

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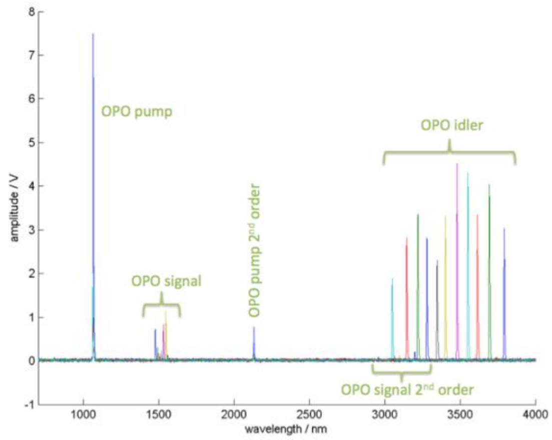

Fig. 3.9: Spectrometer output during test with OPO

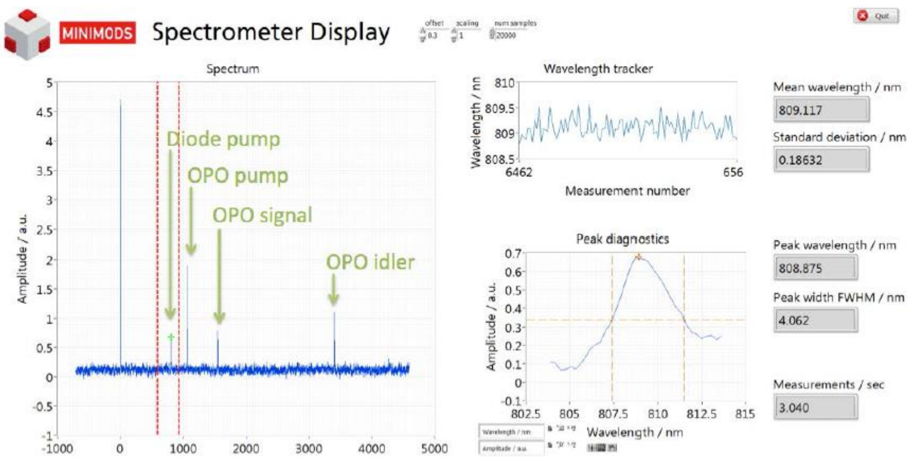

Fig. 3.10: Screenshot of the user interface of the spectrometer.

3.4 WP3: Develop miniaturised third harmonic generation and pulse compression modules

The third harmonic generation (THG) process is required to obtain fs pulses in the UV region, since currently, there are no available solutions to generate fs pulses directly in the UV. Typical triplers (THG modules) use a beam splitting and recombination concept for tunable lasers, which is inherently costly, large in footprint, sensitive in alignment, and therefore does not provide adequate long-term stablility. Recently, triplers featuring an inline concept have been developed, which are more compact and less sensitive in alignment, however, they are not tunable and, as such, not suitable for broadband lasers. Within this project we target to push the state-of-the-art further and develop a broadly tunable tripler covering the 800-1300 nm and 700-950 nm spectral ranges based on the inline concept

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having a compact footprint, low cost, alignment insensitivity and long-term stability.

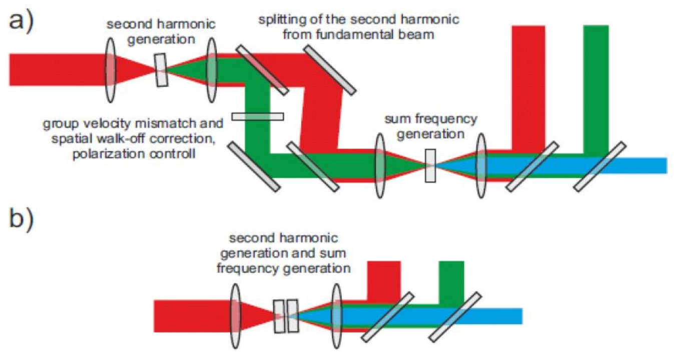

Fig. 3.11: Figure showing conventional (a) and compact (b) approaches to frequency triplers

The objective of the works described was to design, theoretically analyze, build and characterize experimentally a compact frequency tripler (third harmonic generator) module to be used for generating UV light from 1030 nm femtosecond pulses with high efficiency while maintaining short pulse duration at the output. The device can work as a stand-alone module, but it is also potentially attractive as a part built into the laser box.

The works started with the development of advanced simulation software capable of 3D modelling of laser pulse propagation in nonlinear and/or birefringent crystals. The simulation software was written and thoroughly tested with more and more complex arrangements up to the point where it was possible to reliably analyze the pulse propagation in the tripler and predict the third harmonic generation efficiency, the output pulse duration and energy and thus optimize the tripler configuration. Excellent agreement between the calculated and measured results in e.g. second harmonic generation efficiency in absolute numbers was achieved.

Once the tripler configuration was optimized, the prototyping phase followed in which a number of configurations was built and tested. Some were optimised for the highest efficiency, others for the short output pulse. Different focusing conditions were tested with a 3W fs 1030 nm YbIX oscillator from Lumentum as an IR pulsed source. The long-term stability of the tripler was also characterized.

In addition to the narrow-band tripler unit, some fundamental research was carried out in pursuit of realising a broadband version. Extensive simulation has shown the limitations of the trade-off between conversion efficiency and operating bandwidth.

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3.5 WP4: Demonstrators

This work package aimed to successfully demonstrate the miniaturised diagnostic and frequency tripler modules as a technically advanced, and highly competitive solution in three different application areas important to the SME partners and within their existing areas of market activity. The demonstration work is closely linked to the MINIMODS exploitation and dissemination activities to ensure relevant showcasing of the technology.

The SME partners and RTD performers worked together to undertake demonstration testing of the various modules. At M Squared Lasers, the compact autocorrelator was tested by the ultrafast laser team, as shown in Fig. 3.12 pictured with a Sprite-XT titanium sapphire laser. In addition the M^2 meter was tested with an optical parametric oscillator and its pump laser, whilst also being compared to a commercially available unit.

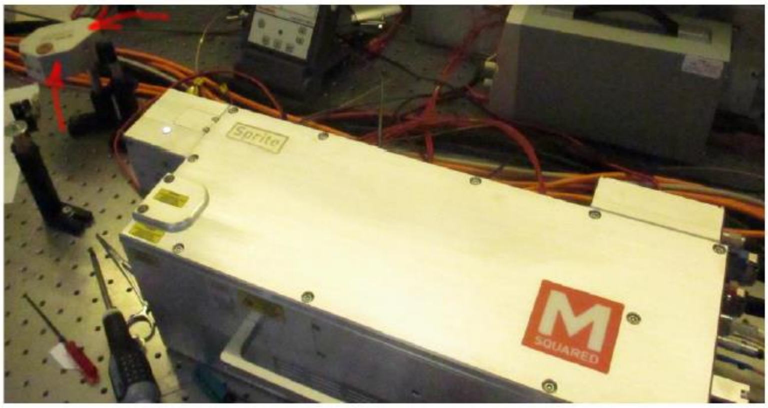

Fig. 3.12: M2 Sprite-XT laser with UWAR autocorrelator unit

At RAD an experiment to demonstrate the spectrometer unit was carried out using a Radiantis ORIA IR ultrafast optical parametric oscillator (OPO) synchronously-pumped by a Ti:sapphire laser (MAITAI, Spectra-Physics-Newport). This experiment was designed to make use of an ideal source to check the performance of the spectrometer from 1 microns up to 4 microns in the mid-IR. A set of steering mirrors, lenses and variable attenuator were employed to characterize both OPO signals and idlers, as well as pump spectra with the MINIMODS spectrometer. The ORIA IR is a femtosecond Optical Parametric Oscillator (OPO), pumped by a mode-locked femtosecond Ti:sapphire oscillator, which offers broad tunability in the near- and mid-IR. In more detail, the experimental setup consists of a ORIA IR OPO synchronously-pumped by a commercial MAITAI Ti:sapphire laser from Newport-Spectra Physics, delivering 90fs pulses at 80 MHz repetition rates, center wavelength at 800nm, and average powers about 2.8W. Independent tuning of the pump wavelength across 720-810 nm, and the signal wavelength across 1000-1580 nm, is provided through

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the two separate pump and signal output ports available in this OPO with more than 800mW average powers. Moreover, the idler port can provide wavelengths across 1600-4000 nm covering part of the mid-IR with more than 100mW average powers. The ORIA IR delivers unique conversion efficiency performance, resulting in high power levels across the wavelength range. Also, near-transform-limited pulses, excellent power stability and exceptional beam quality across the tuning range are provided. The outputs of the ORIA IR OPO were sent to the spectrometer using a set of steering mirrors, focusing lens for proper matching inside the spectrometer and a variable attenuator (only few mw average power is required). Furthermore, a commercial well-known spectrometer was used as a reference for some measurements only in the near-IR range. In Fig. 3.13 below a representative spectrum obtained from the Oria signal output is shown, demonstrating the efficacy of the spectrometer unit.

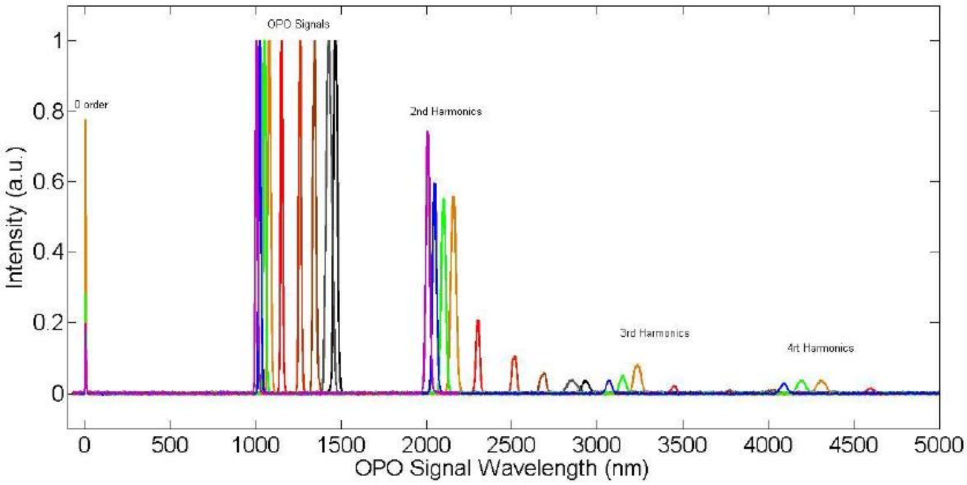

Fig. 3.13: Output signal from the spectrometer whilst measuring the Radiantis Oria signal field.

The frequency tripler unit was demonstrated using a JDSU femtosecond Ybix source. The source delivers 180fs pulses at a repetition rate of 83.9MHz and central wavelength of 1043nm. The pulse spectral width is 7.2nm (FWHM). From the 1043nm fundamental radiation, tripled output at 348nm was recovered with high efficiency, whilst the integrity of the propagating pulses was maintained.

3.6 MINIMODS Objectives Addressed

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The objectives of the programme have almost all been achieved with a number of clear highlights and excellent outcomes from the researchers at UWAR and FCAP.

The modules that have emerged include:

- Autocorrelators for a variety of ultrafast lasers
- Low-cost spectrometers for near- to mid-infrared sources
- A versatile beam propagation parameter detector
- A monolithic third-harmonic generator

The overall design philosophy of each of the modules was to create diagnostic and frequency conversion modules that were, where possible:

- Highly compact
- Rugged in design
- Cost effective
- Wavelength flexible
- Broadly tunable

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4 Potential Impact, Main Dissemination Activities and Exploitation of Results

4.1 Potential impact

The global market size for laser technologies related to MINIMODS was in excess of \$509million in 2011, and is forecast to grow tenfold to \$5billion by 2018. Based on predicted growth and routes to market, the following five main areas in which the SME beneficiaries are operating in which the MINIMODS outcomes will have an impact, are:

- Advanced semiconductor metrology systems
- Multiphoton imaging/microscopy and nanosurgery
- Defence and security applications
- Micromachining
- High-speed optical telecommunications

The MINIMODS project has created several prototype modules that have been brought to high technology readiness levels as a result of the work undertaken. The modules are ripe for commercialisation in a variety of formats. While a significant increase in revenues and competitive position can be expected through the direct sale of the MINIMODS diagnostic and frequency conversion modules, the key benefits for the SMEs is that MINIMODS will develop a series of highly compact systems that will be integrated into state of the art ultrafast lasers and mid-infrared optical parametric oscillators. Here, the MINIMODS technologies will be a significant market differentiator, thereby greatly strengthening the competitiveness of the SMEs. More specifically, implementation of MINIMODS modules into laser systems will allow real-time monitoring of key performance parameters, enabling highly advanced adaptive control loops that will extend the capabilities of state of the art ultrafast lasers and optical parametric oscillators (e.g. optimisation of pulse duration, beam quality, wavelength coverage, etc.). The modernisation of current laser systems by adding on-board diagnostics will furthermore be a key market differentiator for OEM customers that require autonomous and totally hands-free system operation without the need for user intervention. The MINIMODS technology will ensure that seamless integration and control of the laser systems with customer applications arrangements are possible.

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As a result of the variety of sectors that will benefit from the impact of the project will be widespread. Not only will the SME beneficiaries gain positive outcomes, their up- and down-stream supply chains will also see gains, whilst ultimately the targeted end-users will be able to make use of superior products. The position of pan-European firms and research organisations has been strengthened by the project and its outcomes.

The gains in functionality, provided by the next generation laser sources that will emerge during the exploitation of the MINIMODS project, will enable industrial, biomedical and scientific users to gain insight into the performance characterstics of the laser sources in real-time adding value to their own processes and understanding of the complex phenomena that these lasers are invariably used for.

The returns to the SMEs and the EU of investing in this project are expected to be several times higher than the co-financing provided; the business case behind this for the MINIMODS SME participants over the 5 years following the project is conservatively estimated and detailed below, producing additional profitability of more than €5M.

4.2 Main Dissemination Activities

Over the course of the project MINIMODS has been promoted at trade shows and also at the Polish Optics Conference (front page of presentation shown below).

A copy of the full presentation can be downloaded from the publications area of the project website – www.minimods.eu/publications

In addition, the MINIMODS partners have submitted results from the project to a number of journals, but to date no papers have been published.

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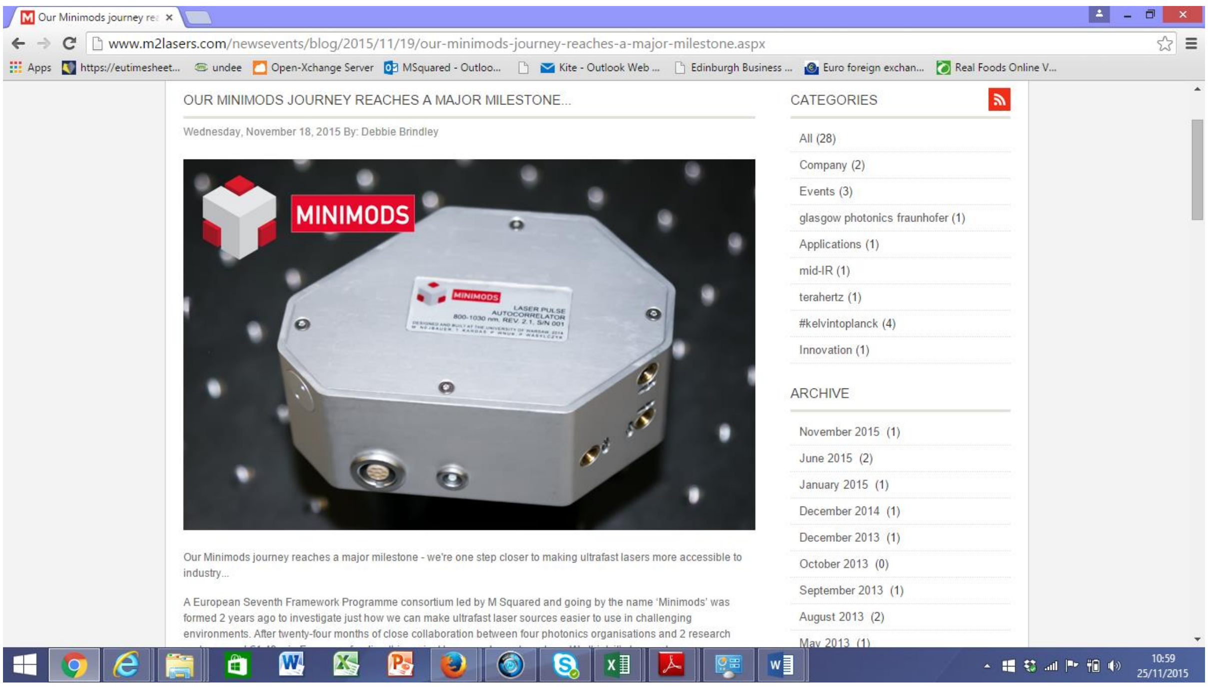
The project website, press releases, YouTube video and flyers have all been used to disseminate the project to a wider audience. All of these can be accessed via the publications area of the project website – www.minimods.eu/publications

An end of project blog post has been posted by M2 - http://www.m2lasers.com/newsevents/blog.aspx



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An end of project press release has also been published by UWAR. This can be viewed here: http://www.fuw.edu.pl/tl_files/press/docs/2015/FUW150923a%20-%20MINIMODS%20Project.pdf

4.3 Exploitation of Results

During the course of the project the project partners have been following the SQUADRON™ process for exploitation tracking, under the guidance of Kite Innovation (Europe) Ltd. The process assists the decision making processes during a project's life cycle and sets the foundation for the post-project market analysis and exploitation strategies.

The SQUADRON™ approach takes seven steps, considering initially the current position then desired final position and the route to get from one to the other. The first stage is to define the accessible market segments and product variations (Segmentation), before identifying and prioritizing the technical requirements to access these (QUality requirements). Analysis of the market sectors from the above allows consideration of the attractiveness of each, with appropriate market data (Attractiveness). A review of the project deliverables and their alignment with commercial opportunities enables us to check the on-going validity of our initial plans and provides a framework for adjustment to address newly identified opportunities (Deliverables). In order to identify the priorities for exploitation, each market segment can be defined and ranked based on their attractiveness and their dependence on the project deliverables (Ranking). In order for the preceding steps to have any impact on the project and its subsequent exploitation, these reviews should revisit the projects priorities and determine whether they still represent the best opportunities for the project. In the event of changes, there should be suitable updates to the form of the remaining project deliverables and every effort should be made to avoid project hysteresis, where initial targets that have been superseded are still pursued (Operationalising). The final stage is to evaluate the potential for new income streams that could result from the project activities (New income streams). These may include additional project lines, licensing revenues and emergent opportunities.

The MINIMODS project and successful commercialisation will allow the SMEs to expand their teams of world-class technologists and build on their strong competency in the implementation of next-generation laser sources and diagnostic/frequency conversion subsystems.

The key technical differentiation that this project has provided, along with the innovations that have emerged, have established clear technological advances for the SME's markets. Each of the SMEs has the opportunity to strengthen their competitive position and market

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share as a result of the advances that have been achieved during the project. These key advantages will confer significant commercial opportunity and will underpin the success of the supply chain and future growth of the companies involved.

Customers for the MINIMODS technology vary significantly in terms of their requirements depending on a number of variables such as position in the supply chain, industrial customer, academic customers, etc. The distinct needs of the most relevant target groups at various exploitation phases can be described as:

Early Adopters: It is expected that initial sales will be to early adopters and gurus in the respective fields. These customers will more easily adapt technology at a lower technology readiness level and are generally willing to accept higher costs. Their motivation is largely to be the first, either in terms of demonstrating a new technology or in achieving academic publications. While the first systems sold to these customers are often less demanding, later sales typically require significant improvements or upgrades to maintain the highest level of performance and novelty.

End-users: End-users of the technology that can directly be sold to are typically very demanding in terms of technology readiness level. For them, usability and practicality are amongst the most relevant parameters. In return, they might not require the highest performance specifications. Price sensitivity is expected to be medium given the competitive advantage of the technology

System Integrators: Original Equipment Manufacturer related customers are amongst the most demanding. The highest TRL levels, longevity test and very high performance are typically required. Furthermore, the price point is critical and a clear roadmap for downscaling of the price will be required.

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5 Project Details

Title	**MINIMODS: MINIaturised diagnostics and frequency-conversion MODuleS for ultrafast lasers** (GA no. 606141)
Coordinator	**M Squared Lasers Limited** United Kingdom
Consortium	**JDSU Ultrafast Lasers AG** Switzerland **Laseroptik GmbH** Germany **Radiant Light SL** Spain **University of Warsaw** Poland **Fraunhofer UK Research Limited** United Kingdom
Duration	1st October, 2013 – 30th September, 2015 (24 months)
Funding Scheme	SME-2013-1: Research for the benefit of SMEs
Budget	EU contribution: €1,489,000.00
Website	http://www.minimods.eu
For more information	minimods@m2lasers.com

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