MINERVA project newsletter #8

Sep-2017

The MINERVA project has now finished, and has achieved significant successes in each of its many areas of research. The consortium believes that the project has given an important boost to mid-IR technology in Europe. It has developed ground-breaking photonic hardware, improved the understanding and underlying technology of mid-IR spectroscopy for clinical applications and integrated all these elements into the first supercontinuum-based mid-IR imaging microscope. This newsletter reports the headline achievements: more details are given in the final report which is available from the project website.

There is much more information available from the project website (www.minerva-project.eu). For any other questions, further contact info is given below.

Gooch & Housego
University of Exeter
LISA
Westfälische Wilhelms-Universität Münster
Vivid Components
NKT Photonics the power of light
DTU
The University of Nottingham United Kingdom · China · Malaysia
Gloucestershire Hospitals NHS Foundation Trust
Universidad Politecnica de Valencia
BBT
IRnova
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Fibre development

Over the course of MINERVA the University of Nottingham, UK, (NOTT) has successfully developed and publically reported for the first time, three major new types of mid-IR transmitting chalcogenide glass optical fibres

The University of Nottingham UNITED KINGDOM · CHINA · MALAYSIA

1) Lowest optical loss selenide chalcogenide glass optical fibre

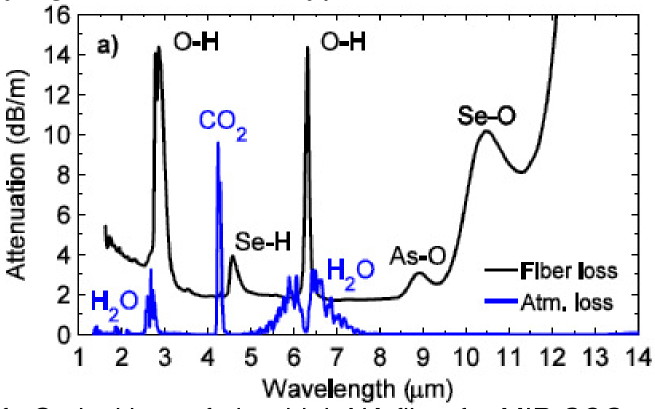
Ultra-low loss Ge-As-Se fibre was successfully achieved through chemical processing; the lowest loss recorded was 83 dB/km at 6.6 µm wavelength, with transmission through 52 m of fibre. This was the first ultra-low optical loss Ge-As-Se reported in the open literature. This breakthrough in low optical loss Ge-As-Se chalcogenide glass optical fibre served as the platform for much of the fibre development work at NOTT in MINERVA.

2) Longest excited state 10 ms lifetimes in small core rare earth chalcogenide glass fibre

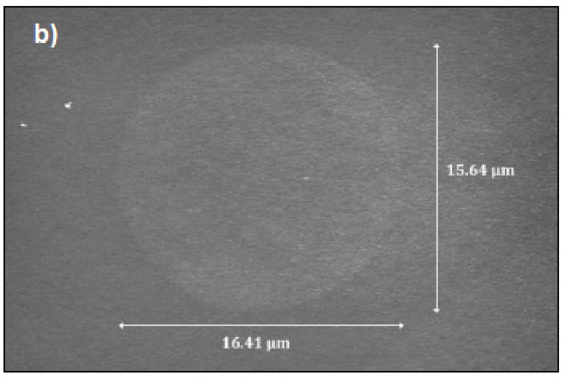
NOTT has considerable expertise regarding the problems of surface and bulk glass devitrification on incorporating rare earth ion dopants in selenide chalcogenide glasses. During MINERVA this prior knowledge was applied to fabricate rare earth ion doped selenide chalcogenide glass fibre of small core with long photo-luminescent (PL) lifetimes. This goal was successfully achieved and a new record was reported of long PL lifetimes (up to 10 ms) preserved in such fibres. The significance of this achievement is that it shows that neither glass devitrification nor rare earth ion clustering occurred during the intricate thermal processing to achieve fibre. These results show that NOTT leads this field on the world scene.

3) Widest span mid-IR supercontinuum generation in chalcogenide glass optical fibre

Prior to MINERVA NOTT had demonstrated that chalcogenide glasses with widely disparate refractive indices could be thermally co-processed, and Prof. Seddon had published the proposal that pumping chalcogenide glass step index fibre at longer wavelengths (4-5 µm) should provide a supercontinuum to span the molecular ‘fingerprint’ spectral region for identifying molecular cell types associated with cancer.



Left: Optical loss of ultra-high NA fibre for MIR-SCG using an intermediate-step fibre by standard cut-back.



Right: Scanning electron micrograph of core of ultra-high NA fibre for mid-IR SCG.

*[From: Nature Photonics **8** p. 830–834 (2014).]*

Through MINERVA, NOTT produced specially engineered ultra-high NA mid-IR optical fibre targeting specifications defined by DTU simulation work. Using this NOTT fibre with a pump source centred at 6.3 µm, the DTU team demonstrated supercontinuum generation beyond 13 µm: a great demonstration of simulation confirmed by experiment! (See pg 6).

For more information please contact Angela Seddon: Angela.Seddon@nottingham.ac.uk

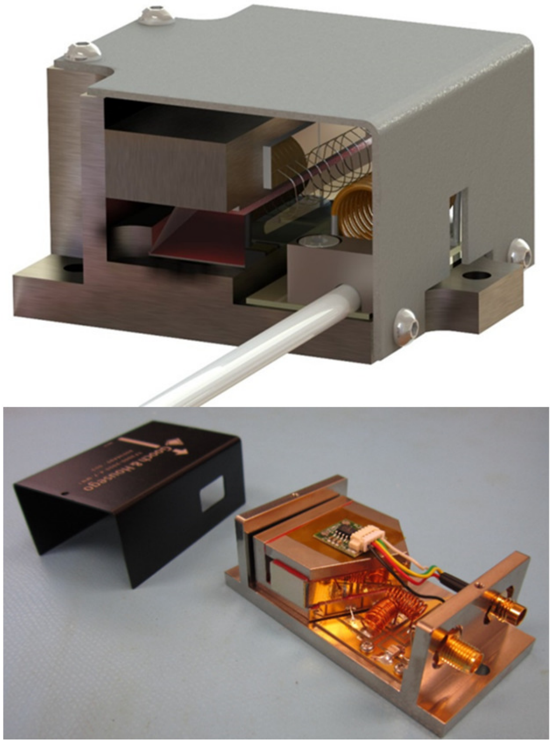
Mid-IR components

Acousto-optic devices

G&H (UK) played a key part in the project, acting as the Technical Coordinator and developing active optical components. In order to build the MINERVA imaging systems, specialised acousto-optic (AO) components were developed for operation in the 2-4 µm region.

An AO Q-Switch for operation at ~3 µm was built and incorporated by LISA Laser into an Er:ZBLAN fibre laser. With this system LISA demonstrated a pulse energy of 560 µJ and the peak power was 10.6 kW; this was world record-breaking performance (see later). This Q-switch design is now available as a commercial product.

In parallel, two designs of AO tunable filters (AOTFs) covering the spectral range 2-4·5 µm were developed to operate with NKT's new generation of md-IR supercontinuum source. A narrow resolution AOTF had a resolving power (R=λ/Δλ) of 500, whilst an ultra-narrow resolution AOTF had R=1000. Both of these represented excellent performance for an AOTF in this wavelength range. These AOTFs, or their derivatives are now available commercially.



Based on MINERVA work G&H now offers AO Q-switches for 3 µm operation (above) and ultra-narrow resolution AOTFs (below).

For more information please contact Jon Ward: jward@goochandhousego.com

Calomel crystals

Participation in the MINERVA project has been a significant step for BBT Materials Processing and its technological research and development activities. Through MINERVA, BBT has consolidated its position as the world leading producers of calomel, a material used for mid-IR components due to its excellent transmission at long wavelengths.

During the project, the first ever 35 mm diameter calomel single crystal of high optical quality was grown. The company now has the capability of routinely growing such crystal boules and is developing several products based on this new resource. A unique combination of IR-transparent, birefringent wedges made of calomel represents a brand new type of polarizer for the infrared optics market. Another spin-off covers the development of new type of spectrometer based on calomel prisms, and substrates for acousto-optic modulators.

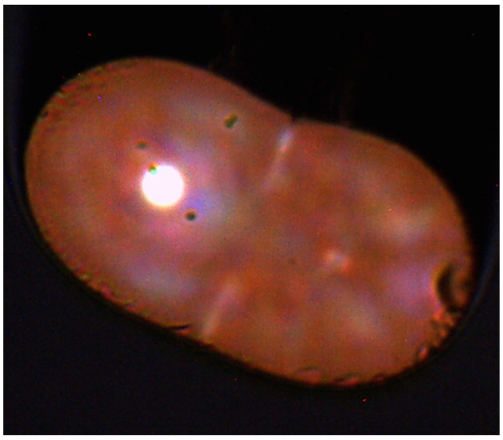
Optical quality calomel boule of diameter 35 mm

For more information please contact Cestmir Barta: bartabbt@atlas.cz

Mid-IR fibre component development

Development of fibre components for delivery of mid-IR radiation in MINERVA required all of G&H's technological expertise in fibre optics. Close collaboration with project partners, LISA and NOTT led to several significant technological advances in this field:

- End caps for preventing optical damage to fibre end facets
- SM fused chalcogenide fibre components
- First ever SM ZBLAN fused fibre coupler (Proc. SPIE **9730**, 973007; 2016)
- Process for connecting different fibre types (soft glass & silica) with low insertion loss.



End-view of the waist of a ZBLAN coupler made at G&H (Torquay)

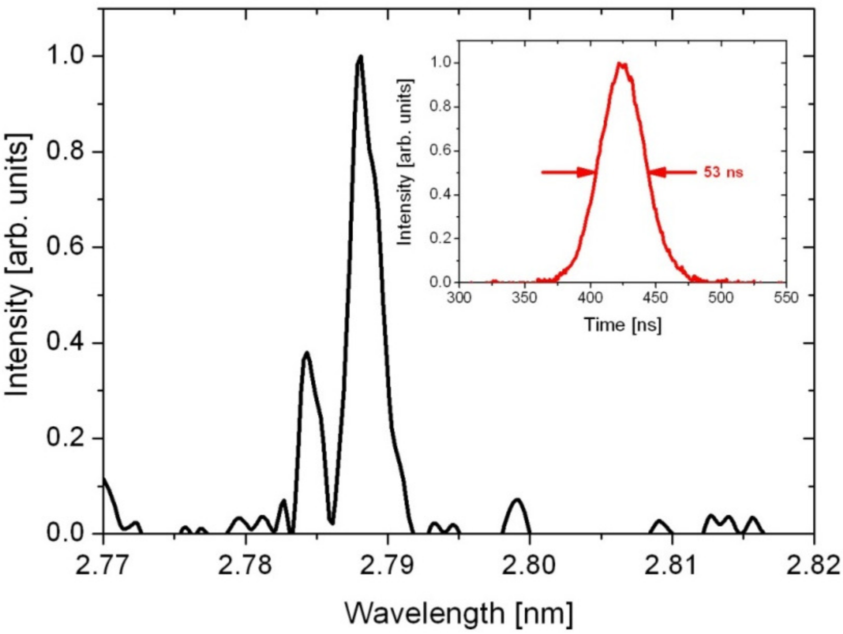
Soft-glass end caps from G&H were used for facet protection in the LISA Er:ZBLAN fibre which has shown the world-record breaking performance in both pulse energy and peak power (see below). This successful demonstration highlights the high quality of MINERVA fibre components and the effectiveness of this approach in ruggedisation of the ZBLAN fibres.

Current processes for manufacturing single-mode fused fibre couplers are based on mature silica technology. Soft glasses like ZBLAN present challenges due to the very different thermal and mechanical properties. Through MINERVA a step-change in material processing was achieved leading to the first demonstration of single-mode fused couplers in ZBLAN fibre.

For more information please contact Mark Farries: mfarries@goochandhousego.com

Pump lasers

Within MINERVA LISA's key task was the development of novel mid-IR lasers in close collaboration with the partners NOTT and G&H. After several initial fundamental tests LISA demonstrated a high energy Er:ZBLAN fibre laser with unprecedented performance using AO components from G&H (see earlier). The partners followed the approach of AO Q-switching an external cavity to exploit the full flexibility of the system. This effort led to world record values for both the pulse energy and peak power. The results were presented at CLEO Europe 2015 (Paper CJ-7.2).



Laser spectrum at 2.79 µm and pulse duration (inset) of the Q-switched Er:ZBLAN fibre laser at room-temperature.

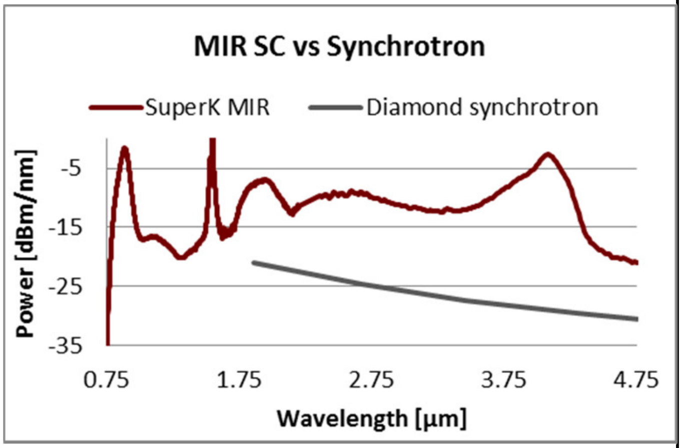
The main components are the 976 nm diode-pumped Er:ZBLAN multimode fibre and a novel TeO_2-based acousto-optic modulator (AOM) fabricated by G&H. The maximum pulse energy extracted from the laser oscillator was 560 µJ at a pulse repetition rate of 1 kHz. The corresponding minimum pulse duration was 53 ns corresponding to a maximum pulse peak power of 10.6 kW. The energy fluence at the output fibre end was calculated to be ~70 J/cm² at the maximum pulse energy level. These values exceed already published work by an order of magnitude and clearly demonstrate the potential for the practical use.

This laser exceeds the reported threshold for soft tissue cutting (*c.* 4.4 J/cm²) by a factor of almost twenty. Promising results were achieved by hand-guided cutting of soft tissue. These lasers show significantly reduced collateral damage and lower carbonisation effects compared with competitive technologies, *e.g.* 2 µm lasers. Work continues at LISA and products are expected in the near future.

For more information please contact Samir Lamrini: slamrini@lisalaser.de

Fluoride fibre-based supercontinuum sources

One of the goals of the MINERVA project was to develop a benchtop light source more than 1000× brighter than a “Globar” (the standard laboratory thermal source) to approach the performance of a synchrotron. At the beginning NKT Photonics had already demonstrated an initial prototype mid-IR supercontinuum source, but this proof-of-principle source relied on a rather unreliable and very expensive design.



Graph showing NKT SuperK MIR supercontinuum output power compared with the Diamond Light Source synchrotron (Didcot, UK).

Throughout MINERVA NKT has developed this prototype, reduced the noise level, improved the long-term stability, optimised the output spectrum shape and packaged the system in a robust housing. A maintenance-free lifetime of over two years of continuous 24-7 operation has been demonstrated, hugely exceeding the project targets.

For more information please contact
Peter Moselund: pmm@nktphotonics.com

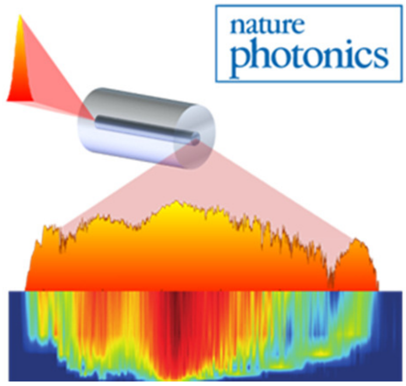
The SuperK MIR product launched at the end of the MINERVA project.

NKT has also far surpassed the original goals regarding the brightness of the source by developing sources more than a million times brighter than typical Globar thermal sources and even an order of magnitude brighter than a synchrotron! At the Laser World of Photonics trade show in Munich (Jun-2017) a new product (SuperK MIR) was released based on these MINEVA developments so that all research groups can get access to this new innovative light source which is also already catching the eye of potential OEM system manufacturers.

Chalcogenide fibre supercontinuum sources (3-12 µm)

Record supercontinuum spanning 1.4-13.3 µm

The ground-breaking theoretical basis for the project proposed by DTU was published (Optics Express **22**, p. 19169; Aug-2014) and highlighted the huge potential of the MINERVA approach. This theoretical basis was subsequently verified experimentally using MINERVA fibre and sources.

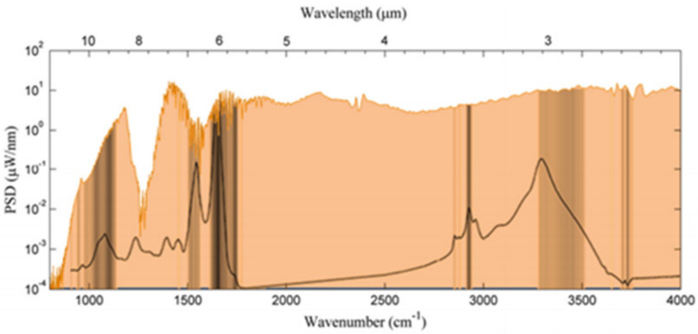


Schematic based on the Nature Photonics paper (Oct-2014) reporting SCG beyond 13 µm

The first experimental demonstration showing record long wavelength emission was a "hero experiment" using a fs pump source which was published in Nature Photonics (Vol. **8**, p. 830; Sep-2014). This served to demonstrate the capability of the chalcogenide fibres fabricated by Nottingham University to cover the MINERVA target wavelength range of *c.* 2-12 µm. It also served to validate the DTU simulations and numerical modelling that had led to the design of these fibres.

For more information please contact Christian Rosenberg Petersen: chru@fotonik.dtu.dk

Record average power from 1-11.5 µm

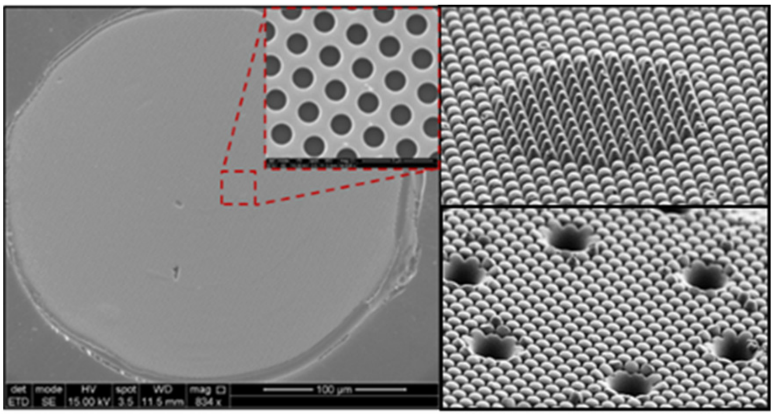


Schematic showing SCG from a tapered PCF with key absorption peaks of interest for MINERVA

In close collaboration with University of Rennes and French specialty fibre manufacturer SelenOptics, DTU demonstrated the highest average output power from a long wavelength mid-IR supercontinuum source with 35.4 mW from 1-11.5 µm and 57 mW from 1-8 µm (Optics Express **25**, p. 15336; 2017).

Fibre end-face nanoimprinting improves transmission

Because of the very high refractive index of many materials used to transmit the mid-IR, the reflection at fibre facets is very large, resulting in high loss from each interface. Coatings are very difficult with these materials and this severely reduces the output power of the sources.



Electron micrographs showing the "moth eye" nanoimprinting of soft glass fibre end facets performed at DTU in MINERVA.

In collaboration with DTU Nanotech, DTU Fotonik has demonstrated an increased transmission of 9% per end face in large core multimode chalcogenide fibres, and up to 13% in bulk glass discs.

In the most recent work the group has also demonstrated the feasibility of imprinting small core and photonic crystal fibres which is an exciting area which will continue to be pursued after the end of the MINERVA project.

Mid-IR imaging detectors

IRnova

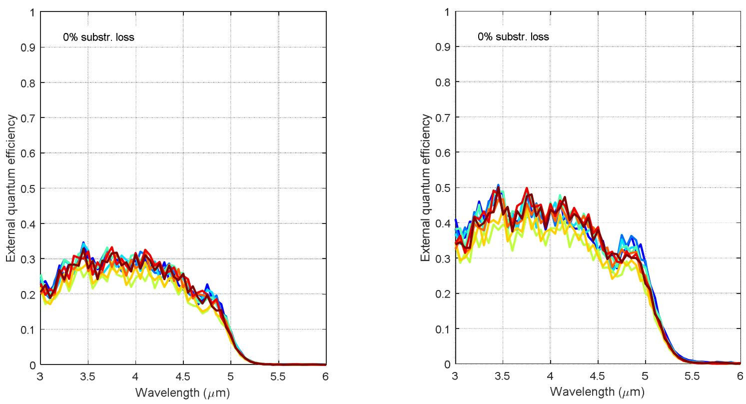
IRnova's task in MINERVA was to develop and manufacture an imaging detector to become a part of the demonstration instrument. This was carried out together with Xenics, whose first task was to provide a read-out integrated circuit (ROIC) and later to complement the integrated Dewar cooler assembly (IDCA), manufactured at IRnova, with a mechanical frame and case, optics and electronics to make it a camera.

A photo of the newly hybridised FPA. The photosensitive detector chip is bonded to the ROIC and the hybrid is mounted on specially designed ceramic carrier.

IRnova aimed to develop a focal plane array (FPA) based on novel Type-2 Superlattice (T2SL) technology with high resolution, small pitch and wide bandwidth. T2SL technology potentially combines the performance of currently used HgCdTe technology with the stability, image quality, robustness and manufacturability of III-V technology.

IRnova can now proudly report that MWIR arrays were successfully delivered. The innovation was to design a so-called "inverted structure" which greatly simplifies the semiconductor process and allows for ~100% fill factor, *i.e.* no light is lost because of pixelisation.

The hybridisation and integration processes derived through MINERVA have already been applied to two new IRnova products employing an array of 640×512 pixels on 15 μm pitch. IRnova640MW (based on T2SL) is sensitive in the 3-5 μm range, whilst IRnova640LW (based on QWIP) has good sensitivity in the 8-12 μm range.



External conversion efficiency of the MWIR sample array (cut-off λ 5.3 μm) without anti-reflective coating at 80 K (left) and 120 K (right). The sample is part of a fully processed detector chip hybridised with a specially designed fan-out chip. (No ROIC was involved in the measurements.)

Images taken with a demonstration camera using a new product from IRnova. The Irnova640LW is a detector with a resolution of 640×512 pixels on 15 μm pitch based on QWIP technology with good sensitivity in the 8-12 μm range. [Note the cool hair.]

For more information please contact Sergiy Smuk: Sergiy.Smuk@ir-nova.se

Mid-IR camera development

Working closely with IRnova, Xenics led the MINERVA work to improve mid-IR detection and develop high resolution cameras for this wavelength region based on T2SL. Megapixel arrays on 12 µm pitch (1280× 1024) with high yield and high QE were produced in an industrial environment for the MWIR domain.

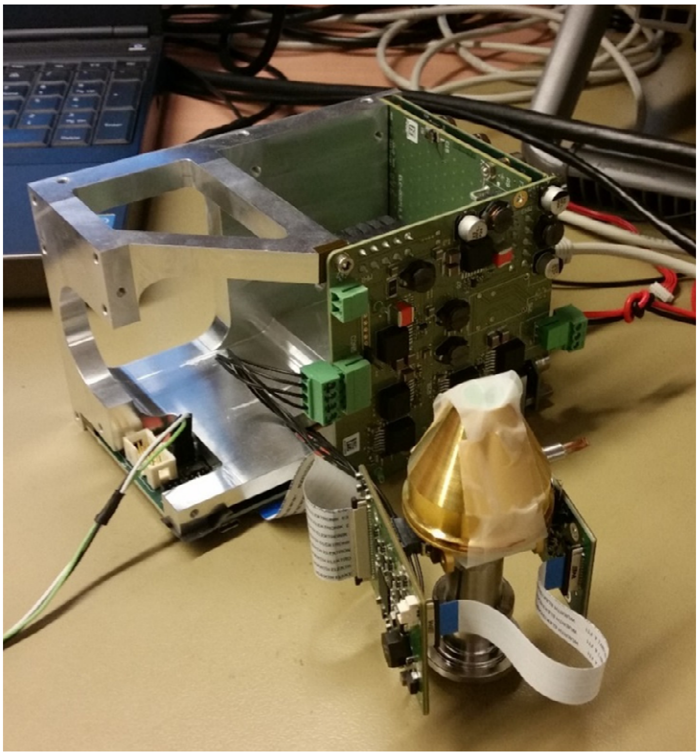


Photo of the XCO camera developed by Xenics, used to debug the proxy electronics with the mock-up IDCA without cooler.

Xenics' first task was to design and manufacture a ROIC suitable for integration with T2SL detectors and later to build a camera integrating the IDCA (manufactured by IRnova; see previous page) with mechanics, optics and custom electronics. The specification requirements were formulated extremely ambitiously. The challenge of the project was to develop a MWIR and LWIR FPA with the resolution of 1280×1024 on a 12 µm pitch. By the project start, Xenics had already experience with the design of a megapixel resolution ROIC, but this was on a larger pitch (17 µm) and chiefly for applications in the SWIR domain.

The design for the MINERVA ROIC turned out to be even more challenging than expected. Nevertheless, the measured yield at room temperature is very satisfactory for the first attempt.
•The pixel architecture is CMDI-based for high injection efficiency at low input photo current
•The ROIC presents two or four analogue outputs for frame rates up to 100 Hz
•The ROIC also supports on-chip bias generation, completely configured through SPI interface.

The second main task for Xenics was to design the camera to drive the IDCA provided by IRNova. The design of the camera includes both hardware and firmware:
•The hardware element consists of the proxy electronics needed to drive the ROIC and convert the signals emitted from it into a suitable format for further processing and presentation.
•The firmware consists of the digital platform governing the operation of the camera module. In this case the design was particularly complicated due to the high level of flexibility required to integrate different types of detectors in the same camera module. In due course this will allow development to a family of related products to be introduced on the market.

Although not used in the final MINERVA demonstrator, the camera developments within MINERVA projects allowed Xenics to launch a new family of MWIR camera modules (XCO-640) and high speed MWIR cameras (Tigris-640) integrating different detectors. In addition, the launch of Tigris-640 Thermography has been announced for Q1 2018.

For more info contact Rosa Maria Vinella: RosaMaria.Vinella@xenics.com

Screening pathology-process development

The first major MINERVA application is high volume pathology screening, led by Prof. Stone's team at the University of Exeter. By carefully analysing the mid-IR spectral information from microscope images of patient samples, it is hoped that healthy tissue may be distinguished from diseased material by an automatic process. This analysis is a specialism of GHNT, whose main task was to provide supporting evidence for the MINERVA instrument specifications.

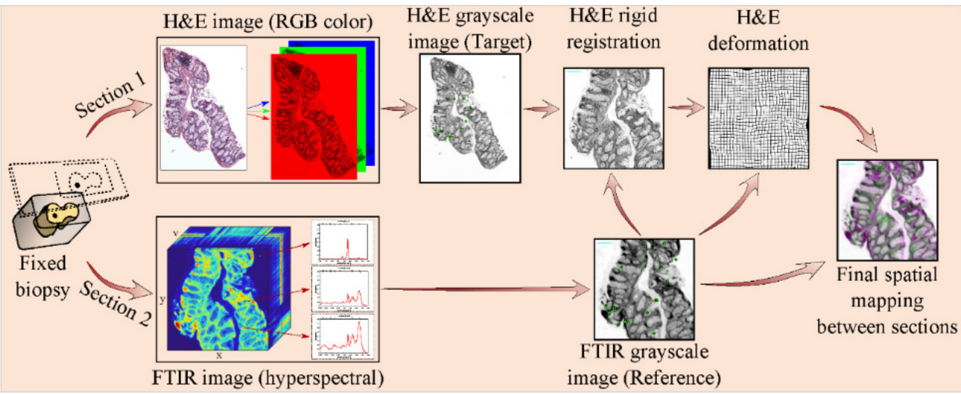
Gloucestershire Hospitals NHS Foundation Trust

Multivariate pattern recognition algorithms

GHNT analysed an existing dataset and applied pattern recognition techniques to discriminate between benign and cancerous samples from human colon tissue biopsies. Sensitivity and specificity of up 86-99% can be achieved with the existing dataset. Using this study as a baseline GHNT was able to assess the impact of various factors that will affect the quality and speed of the MINERVA instrument.

Reducing the number of data points per spectrum is one way to potentially speed up the system; measuring fewer wavenumbers means a faster total acquisition time. However, reducing acquisition time also increases the amount of noise. To determine what level of noise could be tolerated by the pattern recognition algorithms GHNT simulated the addition of noise to the baseline study until it was no longer able to discriminate between pathology groups. This allowed a minimum target SNR to be determined for the MINERVA instrument whilst maintaining an acceptable ability to discriminate between pathology types.

For more info contact Catherine Kendall: catherine.kendall1@nhs.net



*Schematic showing the multimodal registration method developed by UPV. Further details can be found in: Peñaranda et al., "Multimodal registration of optical microscopic and infrared spectroscopic images from different tissue sections: An application to colon cancer", Digital Signal Processing, **68**, p. 1-15 (2017).*

Segmentation and registration of images

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UPV had the task of segmentation and registration of different kinds of images: infrared spectral images (IR), white light, and the haematoxylin and eosin stained images (H&E). The latter is the current "gold standard" used to distinguish between a healthy or pathological patient sample.

Segmentation concerns the accurate extraction of the cell contours. This would reduce the huge amount of data to be analysed by looking for subtle biochemical changes ("cancer markers"). Once the contours have been identified, the regions must be classified as healthy or cancerous depending on subtle features including shape, texture and clustering. This is an extremely difficult task, but the use of the spectral information in the mid-IR should eventually aid clinicians to improve on the current gold standard.

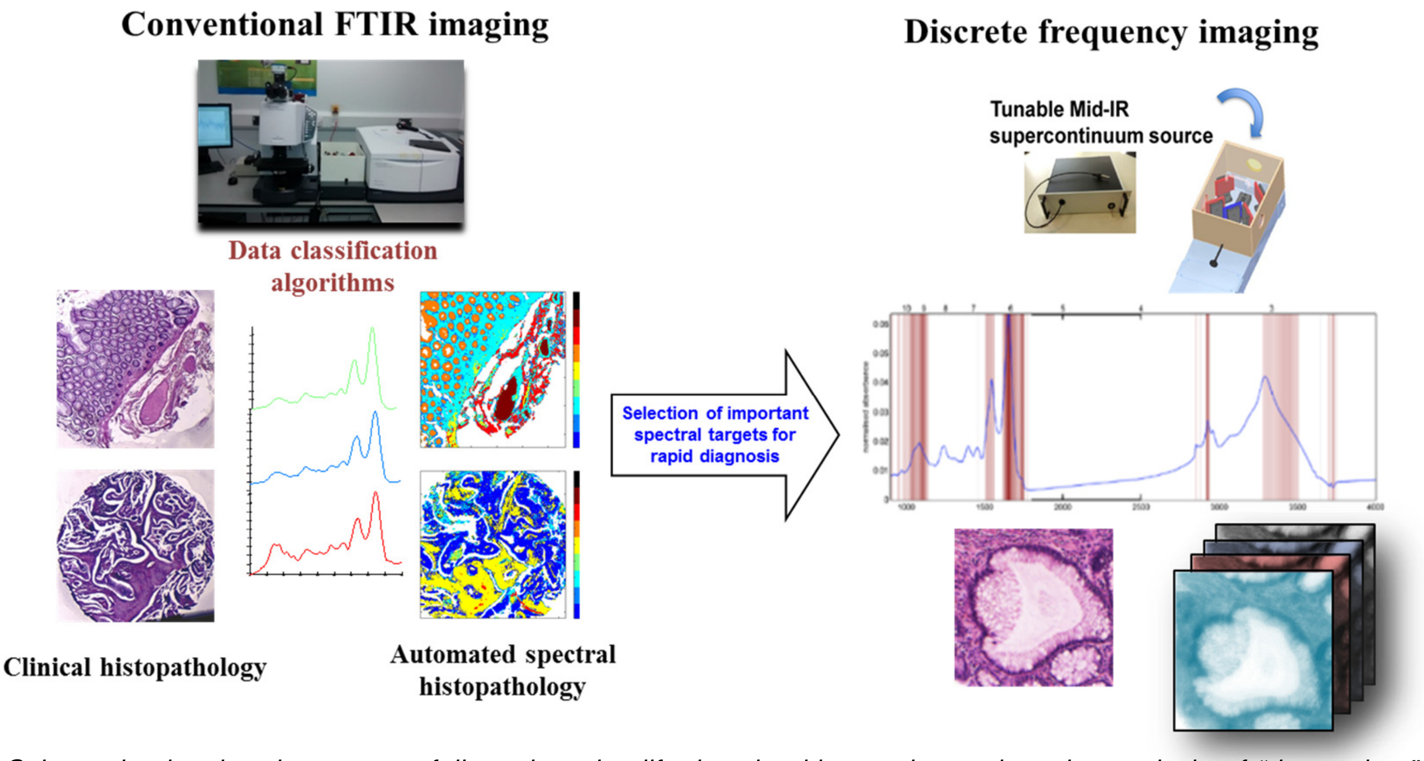
Registration allows the matching of elements that clinicians considered important in the H&E images with the spectral images. A successful registration allows users to learn, and later identify, the areas from which diseased and healthy samples and patients can be distinguished. This method, successfully applied to more than 100 different samples, allows the comparison of information obtained with the current gold standard in histopathology (H&E images) and with the promising analytical mid-IR micro-spectroscopy.

For more info contact: Francisco Peñaranda: frapeago@upv.es

Developing a working protocol for large scale pathology screening

A key Exeter task was to establish a working protocol for large scale pathology screening and diagnosis using mid-IR spectroscopy. Current technology assembled in a benchtop system, employs a “Globar” light source and a focal plane array (FPA) detector which record an entire mid-IR spectrum (2-12 µm) in each pixel of a hyperspectral image. In order to deliver a diagnosis, all the frequencies of this spectrum need to be subjected to rigorous data mining algorithms that can require huge amount of processing time and data storage facilities.

An improved diagnostic workflow was established for large scale pathology screening and diagnosis to be able to adapt the novel mid-IR imaging technology being developed in MINERVA. A total of 100 formalin fixed paraffin embedded samples from four pathology groups (normal, adenomatous, hyperplastic and cancerous) were imaged in standard (5.5×5.5 µm^2 pixel resolution) and high-resolution (1.1×1.1 µm^2 pixel resolution) modalities using a benchtop set-up. The FTIR images were segmented into their constituent pathology groups based on the molecular information using several approaches (independent K-means clustering, common K-means clustering, digital pathology based image segmentation and registration). Classification algorithms were trained and validated independently on each of this approach to discriminate different pathologies.



Schematic showing the process followed to simplify the algorithm and speed up the analysis of “data cubes”. Conventional high resolution images were analysed to deduce the most important peaks for diagnosis. The rapidly tunable MINERVA source could then avoid many unnecessary wavelengths.

In order to establish a diagnostic work flow for the novel MINERVA technologies, key spectral signatures were identified, sufficient for delivering a diagnosis. In future, this discrete frequency imaging work flow can be incorporated into the novel MINERVA technology using supercontinuum light source and megapixel detectors providing improved signal to noise, faster imaging capabilities, lesser data storage capacities for an overall rapid screening and diagnosis.

For more info contact: Krupakar Nallala: J.Nallala@exeter.ac.uk

Skin cancer identification-process development

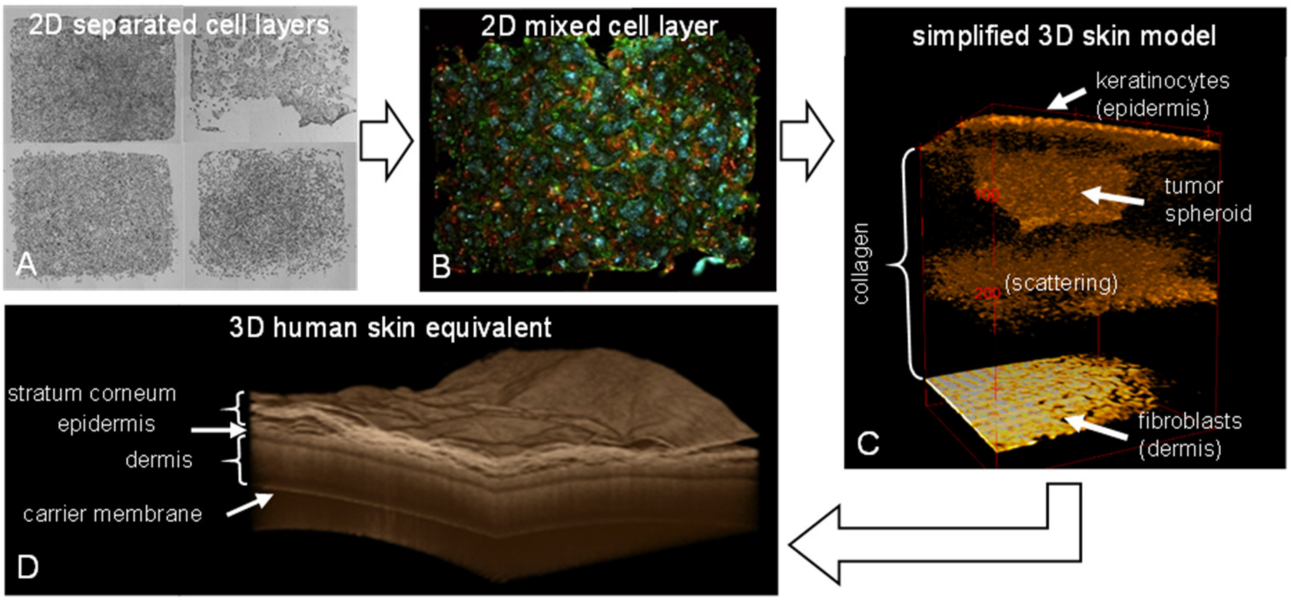
The second major MINERVA application was to develop a process which will allow clinicians to non-invasively assess skin lesions for signs of cancer. This work is led by Prof. Schnekenburger at WWU Münster with UPV providing specialist input on image processing. Prof. Naranjo leads the image and signal processing group at UPV.

WWU developed standardised human skin equivalents (HSEs) which can be used to study skin lesions in a systematic way. At UPV algorithms for identification and differentiation of tumour cells from normal skin cells were developed and characterized. Single cell standards for extended systematic investigations of skin cancer cell identification by mid-IR spectroscopy were designed, prepared and documented.

Westfälische Wilhelms-Universität Münster

Human skin equivalents

Part of the WWU work focused on the establishment of standardized samples with spectral information of representative skin constituents as well as normal and tumorous skin cells. The complexity of the established samples increased as the technology progressed: from rather simple single-layered 2D samples with separated cell types, via 2D samples with mixed cells, to three-dimensional, collagen-embedded, separated cell layers, and finally to complex 3D human skin equivalents.



A) Bright-field image of a single-layered test standard. B) Fluorescence image of a mixture of fluorescence labelled cells. C) OCT 3D image of a tumour spheroid embedded in collagen with dermal fibroblasts below and epidermal keratinocytes above. D) OCT image of human skin equivalents with different layers

Along with the design of the mid-IR test standards, procedures for sample preparation on mid-IR compatible substrates were developed and fluorescent markers were established to enable distinction of cells in mixed samples. The storage capabilities of the samples for long-term preservation of spectral properties was verified.

In order to identify suitable marker spectra of human skin, samples were analysed with mid-IR spectroscopy in collaboration with the GHNT and Exeter. The received spectral data were used as reference for technology performance testing and for the evaluation of novel algorithms for skin cancer cell recognition and classification developed by the MINERVA partner UPV.

For more info contact: Jürgen Schnekenburger: schneke@uni-muenster.de

Differentiation algorithms

UPV, with the help and supervision of Exeter and GHFT, was responsible for analysing hyperspectral FTIR images acquired from cell cultures of different types of skin cells including melanoma, which were prepared by WWU. This task required the application of different complex techniques, not only from the image processing field, but also from other analytical fields, such as multivariate analysis, machine learning and chemometrics. Special efforts were made to reduce unwanted variations in cell spectra not related with the cellular biochemistry that mislead the discrimination of malignant from benign skin cells. In particular, spectral pre-processing techniques based on the most advanced knowledge of the physicochemical phenomena involved in FTIR micro-spectroscopy were applied, which try to remove severe artefacts masked inside FTIR absorbance spectra, *e.g.* classical and resonant Mie scattering.

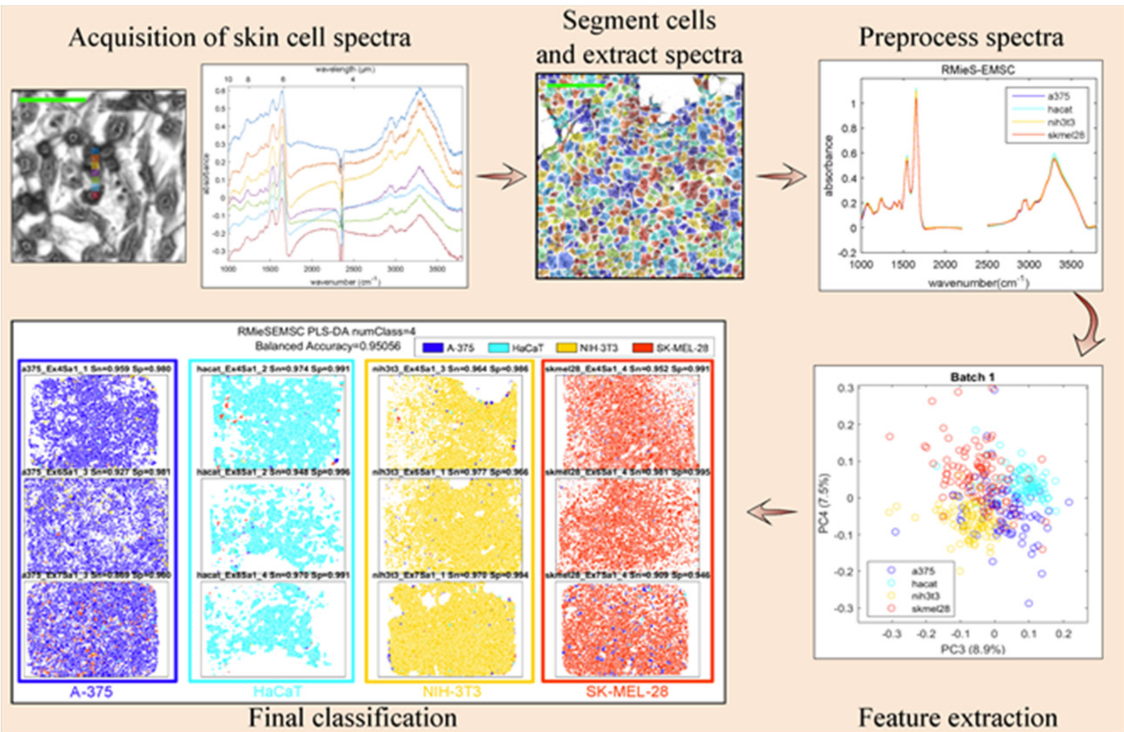


Illustration of the main tasks accomplished during the analysis of skin cell cultures. Further details can be found in: Peñaranda et al, "Multivariate classification of Fourier Transform Infrared hyperspectral images of skin cancer cells", EUSIPCO 2016, p. 1328-1332.

For more info contact: Valery Naranjo: vnaranjo@dcom.upv.es

Final demonstration

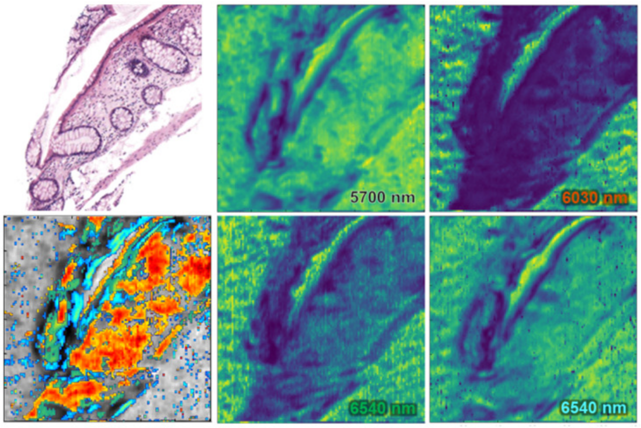
Fast hyper-spectral imaging

Typical measurements with state-of-the-art FTIR systems take several hours to build up spectral images with modest pixel counts. The aim in MINERVA was to reduce the time taken to collect data to a few seconds and at the same time to increase the spectral resolution and image pixel count.

The rapid cytological imaging system has been designed to operate over a wavelength range of 2-4.5 µm allowing for acquisition of 100 wavelength slices of 300k pixels each in only 2 s. While this wavelength region is of interest for diagnosing cancer and other medical conditions, far greater specificity can be obtained by extending the wavelength range into the fingerprint region (5.5-10 µm).

First demonstration of long-wavelength supercontinuum spectroscopic tissue imaging

Through the combined efforts of DTU, G&H, and University of Exeter, the MINERVA project achieved its objective of high resolution imaging using a supercontinuum-based system in the mid-IR. The team was able to demonstrate spectroscopic imaging of paraffinised colon tissue from 5.7-7.3 µm using the high-power mid-IR long wavelength supercontinuum source developed within MINERVA. In the MINERVA long-λ (4-7.5 µm) trials good images of cell samples were obtained. Cell nuclei could be well resolved and the image quality was comparable with those obtained by commercial FTIR instruments. These encouraging results highlight the viability of SCS-based imaging for mid-IR spectroscopic tissue differentiation.



Top left) H&E stained image of the sample. Middle and right) Sample images at different mid-IR wavelengths. Bottom left) False coloured composite image showing main absorption features

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MINERVA workshop

A final workshop was held on FRI 30-Jun-2017 at the Räter Park Hotel (Munich, Germany), and was a great success! The event was held on the day following the Laser World of Photonics exhibition to maximise the number and quality of attendees, and was fully booked (see images on the right). Slides are available from the project public website: http://minerva-project.eu/events/workshop-30-jun-2017

MINERVA at Photonics Europe 2018

MINERVA has an invited session at Photonics Europe 2018 (22-26 Apr-2018; Strasbourg, France). This will be part of the conference on “Fiber Lasers and Glass Photonics: Materials through Applications.