TALENTS Photonique Nouvelle-Aquitaine

BOOK OF ABSTRACTS

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Integrated Photonics for NV diamond based quantum sensing

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Abstract

Quantum sciences are currently transforming into technological devices that exploit the quantum properties of fundamental particles to advance socially impactful fields such as computing, communication, and sensing. Among the diverse quantum systems investigated for quantum technologies, Diamond Nitrogen-Vacancy (NV) centers play a prominent role. Due to a unique interplay between optical and spin degrees of freedom, NV centers have proven particularly relevant in quantum sensing, contributing to the development of sensitive magnetometers with unprecedented nano-metric spatial resolution[1]. The room temperature operation of NV-based quantum sensors, coupled with their solid-state packaging in diamonds, suggests further development for a broad range of sensing applications, from biomedical sciences to industrial nondestructive testing.

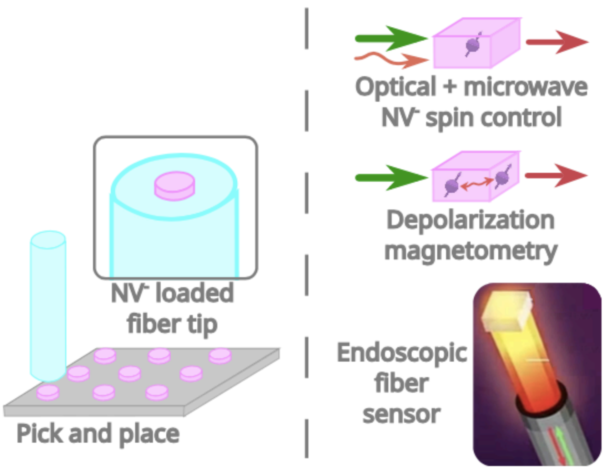

Figure 1 : Photonics integration and NV sensing tools aimed for Neuronal Field imager, non destructive testing and all optical magnetic field stabilisation at zero field.

To fully unlock the potential of NV-based quantum sensors and explore new applications, current challenges include decreasing sensor sensitivity to spin projection noise[2], miniaturising their size, and developing new sensing modalities such as endoscopic or network sensors(Figure 1). Photonic sciences, as an enabling technology, offer a clear path to address these challenges. This research direction, of my thesis focus on the integration of diamond materials onto photonic devices using state-of-the-art cleanroom technologies. The initial development will involve integrating diamond microdisks onto the tips of optical fibers to create endoscopic type sensors. Additionally, Diamond-on-Silica photonic guiding structures will be explored within the framework of quantum sensing. Alongside these technological advancements , we also plan to develop a fully automated interface for magnetometry using NV diamonds which will be capable of laser, RF pulse sequencing, detection and spin manipulations in the NV centers.

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High power UV nanosecond laser from MOPA IR amplification laser system based on aperiodic fibers

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I am a second year PhD student between the Xlim laboratory (Limoges, France) **[1]**, which research activities deal with high-power fiber designs and lasers/amplifiers set-ups, and the BLOOM lasers company (Pessac, France) **[2]** which develops and commercializes high power nanosecond ultraviolet (UV) lasers for industrial applications. My PhD overall objective is to develop a high-power nanosecond UV laser source for industrial applications from conversion of high infrared (IR) power obtained by MOPA (Master Oscillator Power Amplification) amplification system based on innovative amplification fibers. The objectives are mainly focused on amplifying the infrared power to obtain high peak power pulses while keeping a narrow spectrum linewidth and single mode laser emission, which gives the best conditions for an efficient UV conversion. The objectives defined in my PhD on lasers are:

- Development of an agile laser source to achieve >20W of average power at 0.5-20ns with a rate of 200 to 5000 kHz, with optimal modal quality and stability. This source will serve as a seeder for the second objective.
- Exploration of the performance of rod-type FA-LPF fibers (Xlim) **[3]** for production of high-power amplifiers, targeting 300 W of average power with a peak power of about 1 MW and a transverse single-mode emission.

During my first year for the first objective, I experimented with multiple commercially available LMA (Large Mode Area) fibers mostly targeting the nonlinear effect of Stimulated Brillouin Scattering (SBS) apparition at low repetition rate. To target higher peak power (2nd objective of my PhD), in the past years, Very Large Mode Area (VLMA) fibers have been successfully used to generate high average power, high peak power with single-mode infrared output. However, increasing more and more the core size while keeping a singlemode behavior implies a drastic reduction of the core numerical aperture, which, in addition to representing a real challenge to fabricate, can potentially result in a weakly guided mode, thus highly sensitive to external perturbations. To circumvent this issue, designs such as Large Pitch Fibers **[4]** Leakage Channel Fibers (LCFs) **[5]**, Distributed Mode Filtering (DMF) fibers **[6]** and Fully-Aperiodic (FA) LPFs **[3]** have been proposed, this last one is the main part of my studies. Despite the relevance of such fiber designs, a new power scaling limitation arose, related to thermally induced effects and resulting in dynamic energy transfers between different transverse modes above a certain power threshold making the beam transversely and temporally unstable, thus strongly degrading the laser performances. This is the so-called Transverse Mode Instabilities (TMI) effect, limiting the progression of the VLMA technology in terms of average power **[7]**. The FA-LPF (we name it FA-LPF6) aperiodic fiber design on which I work on has been designed specially to obtain a high TMI threshold and a high-quality ($M^2<1.1$) single mode beam output, based on modal sieve concept and low index inclusions aperiodically arranged to ensure avoided crossings.

My major results for now are the characterization of TMI threshold, output power, polarization extinction ratio (PER), spectrum, and beam quality of the FA-LPF6 fibers drawn. There is still a lot of experiment to do to explore the subject thoroughly. A poster from my work on FA-LPF6 was accepted and presented at Photonic West 2024 **[8]**. I will present my results in April at Photonics Europe 2024 and currently writing an article on the FA-LPF6 laser results.

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Tunable four-wave mixing based light source for nonlinear imaging

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Abstract

Label-free nonlinear imaging based on stimulated Raman scattering (SRS) microscopy offers significant advantages, including non-invasive nature, high spatial resolution, and high chemical selectivity. Currently available SRS light sources allow for measurements in the CH-stretch regions by exploiting second harmonic generation in nonlinear crystals, which often have a free-space part in their design [1]. Recently, alternative tunable light source has been developed based on an all-fiber configuration, covering the whole fingerprint and CH-stretch regions. It uses four-wave mixing (FWM) nonlinear effects generated in photonic crystal fiber (PCF) placed in a resonant cavity that has been pumped by a wavelength-tunable oscillator mode-locked by a semiconductor saturable absorber mirror (SESAM) [2]. In our work, we developed a tunable all-fiber optical parametric oscillator system (FOPO) based on the FWM effect. However, to pump the resonant cavity, we used an oscillator mode-locked by a nonlinear optical loop mirror (NOLM) [3], ensuring an environmentally stable and long-term reliable operation. Our FOPO system provides spectral tunability of the FWM signal wavelength from 730 nm to 830 nm with an average output power of 12 mW and spectral resolution of around 2 nm. When considering the second beam at around 1030 nm, this range enables measurements in the C-H stretch region from 2340 cm^{-1} to 3990 cm^{-1}. Our system may find potential application in biomedicine, in particular, when implementing in SRS microscope while advancing label-free nonlinear imaging technologies.

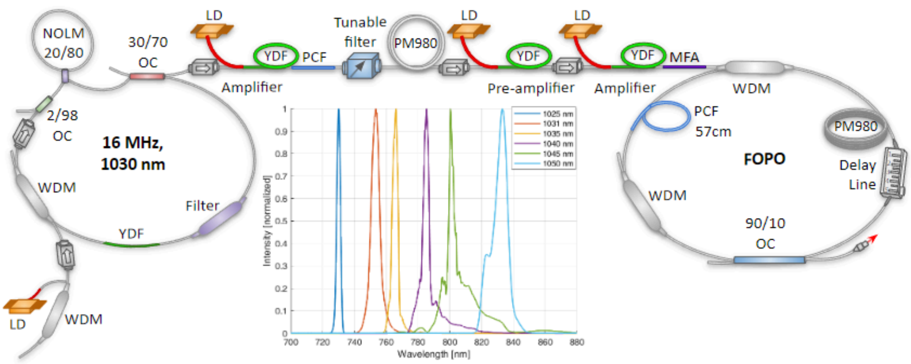

Figure 1. Experimental setup of the FWM light source in FOPO configuration. And, the spectra of the FWM signal generated by tuning the pump wavelength.

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All-fiber high repetition rate Mamyshev Oscillator

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Abstract

The Mamyshev oscillator is a mode-locked laser sources based on cascaded spectral broadening and offset spectral filtering. Up to now, no investigation has been carried out to optimize the fundamental repetition rate and the highest value published is 24 MHz in a ring cavity, and 52 MHz in a linear cavity incorporating chirped fiber Bragg gratings [1,2]. We present here, to our knowledge, the Mamyshev ring oscillator with the highest repetition rate in the fundamental regime.

In the experimental setup shown in Figure 1(a), all components are 6 µm core polarization maintaining (PM) fiber. Both amplifiers are based on a 0,5 m long Ytterbium doped fiber (YDF) with 1200 dB/m absorption at 975 nm. These fibers are forward core pumped by two single mode laser diodes (LD1 and LD2) using a wavelength-division-multiplexer (WDM). Two isolators (ISO) are placed before each WDM to ensure unidirectional propagation of the signal. A 6 nm FWHM spectral filter with supergaussian transmission profile centered at 1034 nm (F1) and a low-pass filter (F2) are placed in the cavity to ensure the MO mechanism. Their transmission spectra are shown Figure 1(b). Finally, a 90/10 fiber coupler is used to extract laser energy and to start our cavity with a homemade laser source.

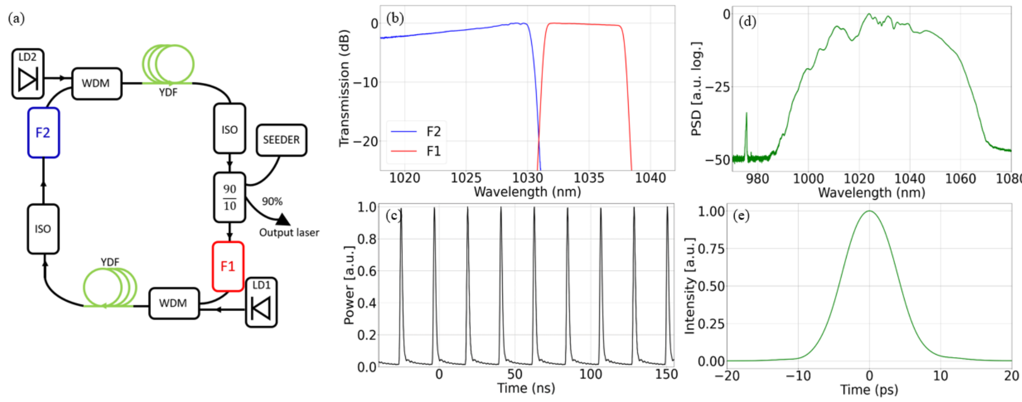

Figure 1(a) Experimental setup. (b) Transmission spectra of spectral filters F1 and F2. (c) 45 MHz recorded pulse train. (d),(e) Spectral and temporal characteristics of output pulses

The output pulse train of the oscillator is shown Figure 1(c) and demonstrate the 45 MHz repetition rate obtained, who correspond to the fundamental regime of the oscillator considering the cavity length. The Figure 1(d),(e) present spectral and temporal characteristics of generated pulses. We can achieve a 330 mW signal at the output oscillator, corresponding to 7 nJ pulses.

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A miniature atomic magnetometer prototype

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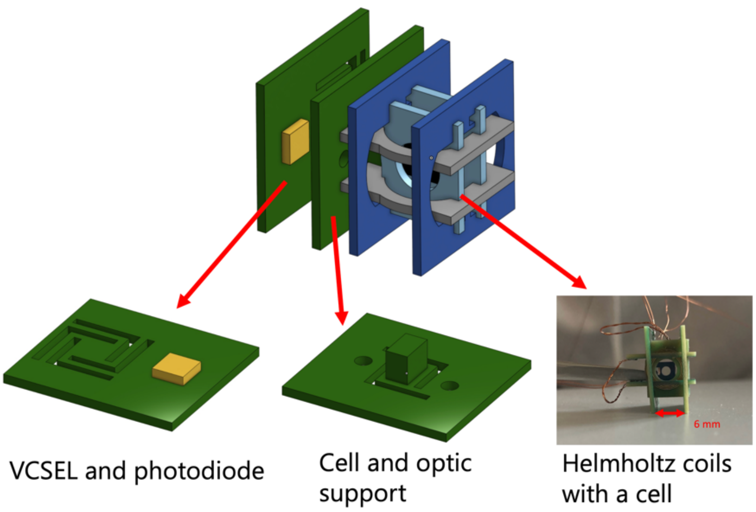
Abstract

We report on the ongoing development of a miniature atomic magnetometer at IEMN. Such sensors benefit from chip-integrated lasers such as VCSELs (vertical-cavity surface-emitting lasers) to probe atoms in physical packages with a high degree of integration [1]. While bare VCSEL chips are commercially available, turn-key and standalone laser sources meeting the requirements for atomic devices are still lacking.

A prototype of an electronic card for the control of a laser diode was designed, taking into account the different characteristics imposed by the VCSEL. The choice of each component and its justification are presented and thermal and electrical simulations were carried out. This board has three main parts: a current source, a heating source, and temperature control.

Besides the VCSEL, the miniature magnetometer must contain the optics (quarter-wave plate, lens and prisms), the alkali vapor cell and the coils. To reduce the volume, the photodiode and the VCSEL are placed on the same PCB. The cell needs to be heated and is placed on another PCB containing the thermistor and the heating resistor. The PCB also supports the optical elements. The cell is microfabricated, which supports large-scale production and miniaturization. The magnetometer must operate in a magnetic shield but the residual field must be compensated. Helmholtz coils are made on PCB for compensation and calibration.



Miniature magnetometer architecture and components

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Ultrafast Laser Processing: Restructuring the LHC Beam Screens In Situ

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Electron clouds driven by secondary electron emission hinder the operation of particle accelerators. At CERN's Large Hadron Collider (LHC), electron clouds are a consequence of a material with a high secondary electron yield (SEY) in proximity to the beam path. The SEY describes the number of emitted electrons from a surface when bombarded by incident electrons. Laser Engineered Surface Structuring (LESS) which modifies the surface topography has been demonstrated to reduce the SEY below unity, establishing its potential use to mitigate electron clouds [1]. To bring this solution to fruition, some technical challenges need to be addressed. Primarily the ability to structure out of focus, specifically 2.5mm either side of the focus, ensuring that no more than 30µm of copper is removed. Since the beam screen has a hippodrome geometry, internally coated with a 75µm thin layer of copper, illustrated in Fig. 1, left [2]. To facilitate uniform laser processing over a varied working distance, an investigation into diffractive optics for focal depth extension was conducted.

Here an EF-014-1030 axilens diffractive optical element (DOE) was used which alters the intensity profile of the gaussian beam, culminating in a Bessel beam leading to an extended focal depth, illustrated in Fig. 1, center. Clearly the intensity profile changes over the focal depth. Consequently, when structuring out of focus the generated features will vary [3]. Since the DOE modified beam reduces the power density, a higher power of 9.7W compared to the 6.5W without the DOE was required to yield 30µm trenches.

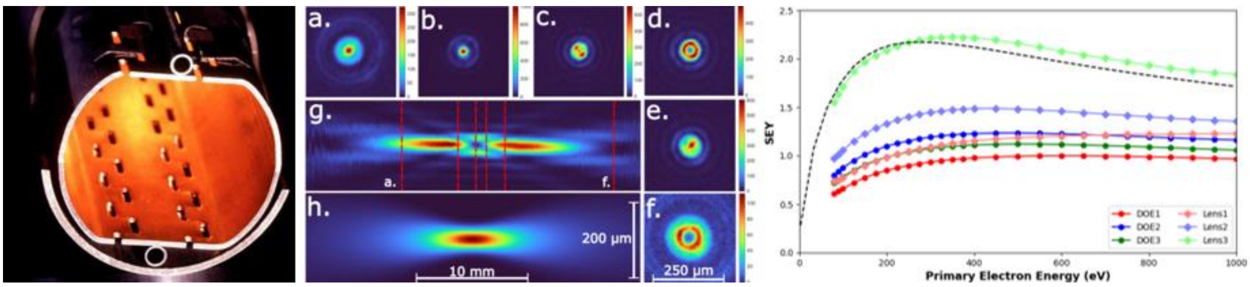

Fig. 1. Left indicates the beam screen design [2]. Centre illustrates the DOE modified beam over the focal depth including a comparison with a theoretical gaussian beam of a similar beam radii. Right plots the measured SEY.

To test this solution, 6 samples were produced with a solid-state laser operating at 1030nm, 800fs and 400kHz with a scanning speed set to 20mms^{-1}, divided into 2 sets. The first involves the DOE, processing in focus, 1.5mm and 2.5mm out of focus respectively. The second explores the standard solution excluding a DOE for a direct comparison.

Looking at the SEY measurements, plotted in Fig. 1, right, the DOE series effectively reduces the SEY consistently over the working distances of interest, whilst not exceeding the 30µm depth constraint. Remarkably the setup without the DOE marginally modifies the SEY at the maximum working distance. Simply because the gaussian beam spot size increases significantly out of focus, culminating in laser processing in the order of the damage threshold, thereby barely modifying the surface and therefore SEY.

In summary, we demonstrate the ability to structure out of focus using a DOE, thereby developing LESS for in situ treatment, revolutionising the LHC beam screens [3].

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Utilization of ns laser ablation process in conditioning of abrasive tools

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Abstract

To dress ultra-hard CBN and diamond grinding tools, mechanical dressing tools are typically used. However, the contact between the dressing tool and the abrasive tool generates high forces, causing the dresser to wear out relatively quickly. As a result, machining becomes increasingly inaccurate after prolonged use. With the advancement of laser technology, the application of laser ablation has constantly expanded in recent years so that it has become a fast and versatile tool, especially in the machining of hard and brittle materials such as CBN and diamond. Due to its high flexibility, the laser has other positive advantages such as targeted heat input and easy controllability. By using laser beams for dressing abrasive tools, the tool- and process-related disadvantages of mechanical dressing methods can be overcome. With selective laser ablation, abrasive tools can not only be conditioned reproducibly with high accuracy but also much more cost-effectively compared to conventional methods. In this study, the effect of ns laser parameters on the ablation rate of metal-bond abrasive tools is evaluated. The quality of ablation is also evaluated, and the required parameters for selective ablation are presented. It was shown that by using appropriate laser parameters, the required grain protrusion is achievable.

Keywords: ns laser ablation- selective ablation- metal-bond abrasive tools- protrusion

3D Beam Shaping for Ultrashort Laser Processing

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Abstract

One of the significant advantages of laser-based manufacturing methods is the ability to control the process by altering the deposition of the laser energy into the material[1]. Generally, this has been achieved through the dynamic positioning and temporal shaping of the laser pulse. However, there exists the unrealised capability of controlling the spatial energy density. The ability to modify the polarisation, phase and amplitude of a laser has become a popular approach in the previous decades due to the enhancements in beam-shaping methods such as spatial light modulators and deformable optical elements[2].

Most conventional focusing systems consist of a Gaussian input beam and standard lens arrangement resulting in a highly confined focal volume in three dimensions (Fig.1a). This is an optimal arrangement for some specific applications; however, others could benefit from the extended focal depth afforded by a Bessel-beam generated by an axicon lens (Fig.1b)[3]. Through the manipulation and redistribution of the incident light throughout the axicon system, it becomes possible to control the intensity distribution in all three dimensions. The application of this method is anticipated in aiding in the development of increasingly sophisticated processing techniques such as laser welding, waveguide inscription and laser surgery.

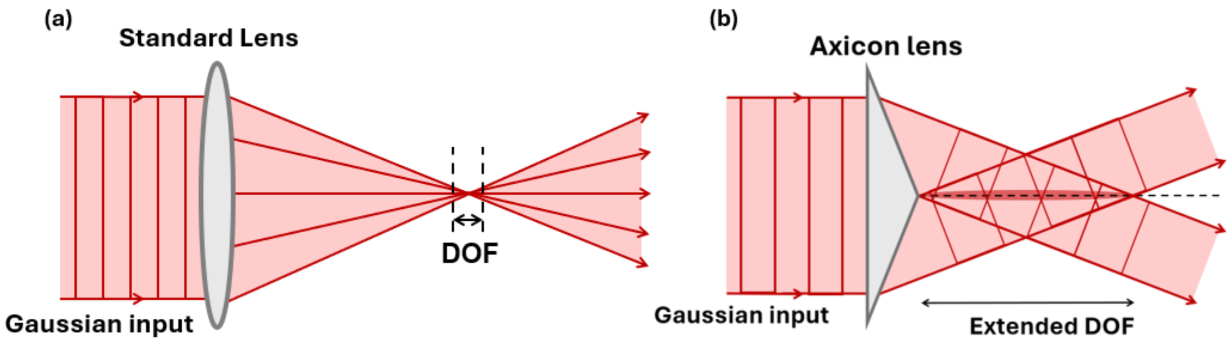

Figure 1 – Comparing the depth of focus (DOF) generated with a standard Gaussian optic 1(a), with that of a Bessel beam generated by an Axicon lens 1(b).

This research focuses on the non-linear light-matter interactions that occur during the ultrashort pulse laser irradiation of transparent materials. By combining in-situ diagnostics such as thermal measurements, high-speed imaging and holography, the internal modifications generated by different beam shapes will be quantified. The latter stages of the project will concentrate on the effects of modified Bessel beams with custom 3D intensity profiles.

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Stainless-Steel polishing with femtosecond GHz-burst mode laser

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Abstract

In this contribution, we report on the use of a femtosecond laser operating in GHz burst-mode for metal polishing, with and without ablation, in order to improve the micromachining quality.

Laser polishing has been widely investigated [1,2] as a contact-less and an efficient process compared to mechanical polishing. The principle is to melt the surface so that surface tension forces smooth the surface, therefore the energy deposition over time is a crucial point. It has been shown recently that GHz-bursts of femtosecond pulses can be used for this purpose [3] since the pulse-to-pulse delay is shorter than the mean heat relaxation time of the material. Moreover, the GHz-burst regime has also shown tremendous results in recent drilling and cutting studies [4,5].

For this experiment, we used a Tangor 100 from Amplitude allowing us to study several burst configurations in the GHz-burst regime. We led a comparative study between GHz bursts of 50, 100, 200, 400, 800 pulses at 1.2 GHz intra-burst repetition rate while keeping the same burst energy. The laser beam is focused onto the metal surface with a f-theta lens of 100 mm, resulting in a spot of 12 µm. The process is performed by scanning the flying spot over the metal surface. This study was realised on stainless steel and aluminium. The results are discussed in terms of surface roughness as a function of the pitch between two spots and lines, respectively, in the materials.

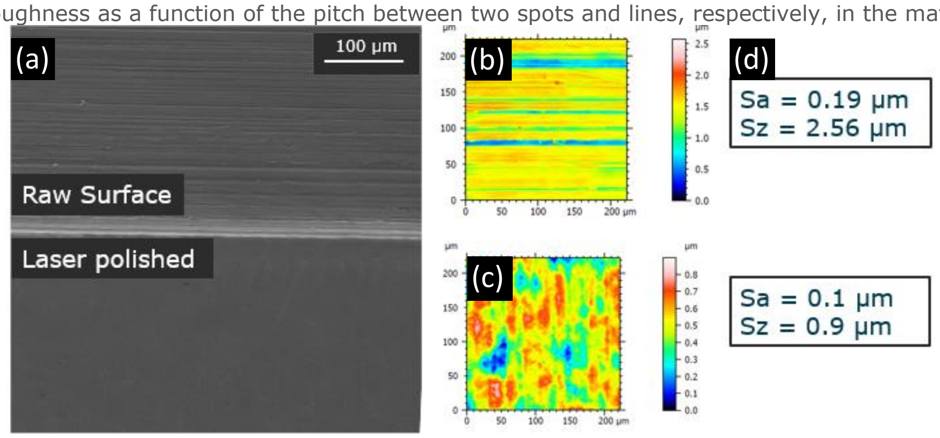

Figure 1: SEM image (a), topography measurements of unpolished (b) and laser-polished stainless steel (c) measured with a Zeiss Profilometer at 50x objective, λ_c=80 µm, (d) associated roughness measurements values.

Figure 1 (a) shows the SEM image of a stainless steel sample comparing the unpolished (raw surface) and laser-polished surface obtained for bursts of 131 µJ in the GHz-burst regime, with a spot-to-spot pitch of 8 µm and line-to-line pitch of 24 µm leading to an important overlap. Figures 1 (b) and (c) depict the associated topography measurement obtained with a confocal microscope. These measurements reveal a surface roughness (Sa) of 0.2 µm before and 0.1 µm after laser polishing, and a peak-to-valley (Sz) of 2.6 µm before and 0.9 µm after laser polishing (d).

During this study, we observed that for the same burst energy, longer bursts allow for a larger process window and a more versatile process.

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3+1D Printing of Core-Clad Waveguide by two-photon polymerization

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Abstract

The 3D fabrication of glass micro-optics using organic monomers was a major advance in the field of photonics. Nowadays, in order to meet the needs that follow the current evolution of 3D manufacturing of glass micro-optics and photonic architectures, we are working on 3D printing and optical characterization of photonic components. We are using several resins as a commercial ORMOCOMP® organic/inorganic polymer and some charged ones with different amount of silica. To solve the shrinkage problem inherent to the two-photon polymerization process, we are using such solvent-free polymers that show 4-6% shrinkage only and great thermal stability. Composed of monomers with a core of silicon atoms associated with silanized inorganic fillers, ORMOCOMP® combines properties of silicones, the hardness of polymers and the thermal stability of ceramics. We use Direct Laser Writing process (DLW) at 515 nm, with optimized parameters to reduce the printing time and to obtain micro-optics with optical quality surfaces designed for imaging applications. In this work, we are using 4D-printing by modulating the laser intensity on a transparent photopolymer ORMOCOMP® to create photonic components with optical characterization. Special attention is paid to studying the index variation induced by laser power variation and multi-pass laser, providing crucial insights for the design and optimization of waveguides. In this regard, we conduct in-depth analyses using Raman spectroscopic techniques to characterize the polymerization state of the material. This approach enables a detailed understanding of the molecular structure of the polymer material and its correlation with optical index properties.

As an example of application, we printed a core-cladding micro-waveguide with a 4.10^{-3} step index contrast between core and cladding and 3% shrinkage. However, we measured an optical transmission of 20% with infrared laser injection at 1 µm, which is currently being optimized.

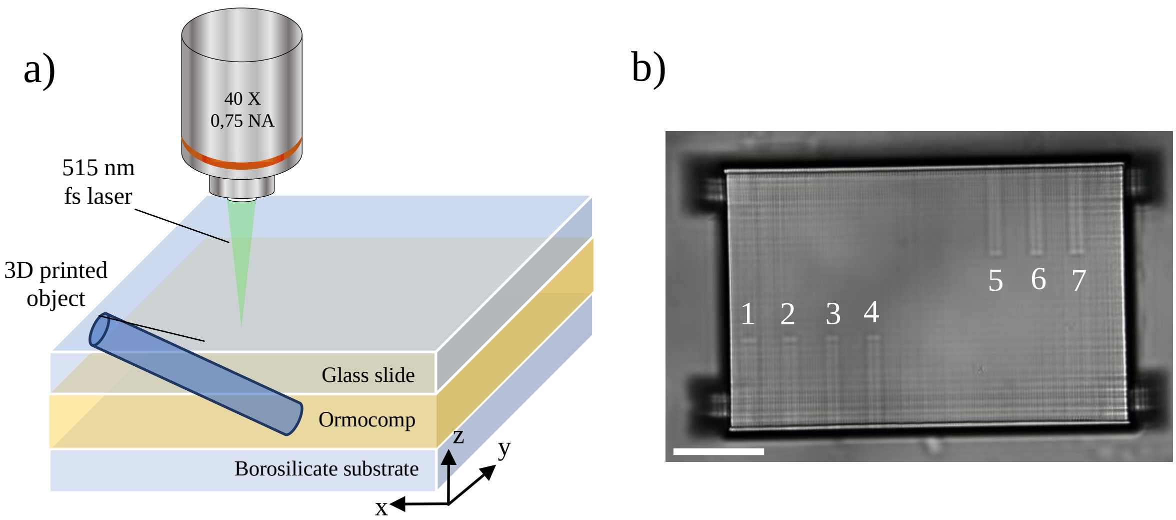

Fig. 1. Sketch of the direct-laser writing process using two-photon polymerization to fabricate the photonic devices. The stages under the substrate allow to make the additive fabrication. The refractive index is tuned by changing the laser power. (b) Bright field microscope (x20, 0.15 NA) image of a step index structure. The latter is a 300×200×50 µm block printed above 50 µm height pillars with multi laser-pass on structures 1 to 7 within the block. The white bar is 70 µm. The printing laser emits at 515 nm and delivers pulses of 350 fs duration and 19,79 to 39,58 J.mm^{-2} for structure number 1 to 7 with a 1mW average power increment. The repetition rate of 9.25 MHz and translation stages move at 0.75 mm.s^{-1} constant velocity.

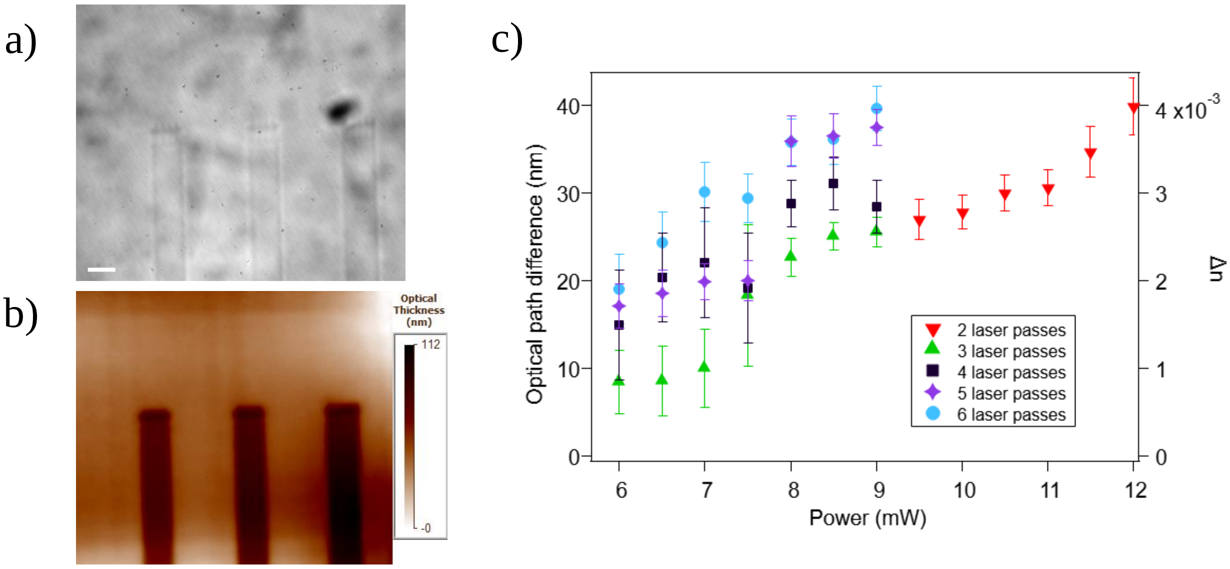

Fig. 2. (a) Bright field microscope image of 3 laser polymerized areas made within a 300×200 µm block with specific laser intensities. The block was made with a 19.79 J.mm^{-2} deposited energy and, respectively and from left to right, the step index areas were made with 26.33 J.mm^{-2}, 28.01 J.mm^{-2} and 29.53 J.mm^{-2} laser deposited energy. These structures were made with 6 laser-passes within the block. The white bar is 9 µm. The printing laser emits at 515 nm and delivers pulses of 350 fs duration with a repetition rate of 9.25 MHz. The translation stages move at constant velocity 0.75 mm.s^{-1}. (b) Corresponding optical phase difference image. (c) Optical path difference and refractive index evolution of several laser polymerized structures made with 2 to 6 laser passes and with several average laser power.

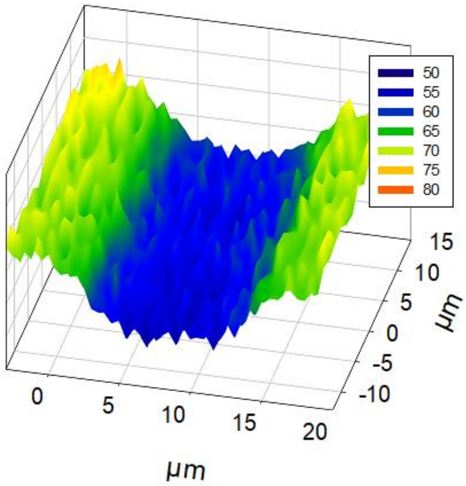

Fig. 3. Relative ratio under the curve of the Raman intensity peak of the C=C bond stretching vibration for a laser-polymerized area at 24.66 $J.mm^{-2}$ (blue) surrounded by a laser-polymerized area at 19.79 $J.mm^{-2}$ (green). This ratio is based on the peak intensity of the C=0 bond.

a) b)

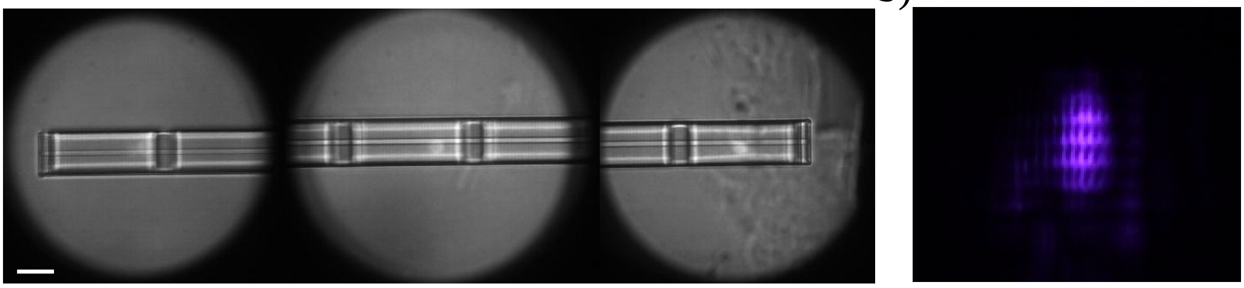

Fig. 4. (a) Wide-field imaging in red light through a camera of an 8,3 mm length printed waveguide injected at 1 µm laser wavelength with a 40X 0.75 NA objective. Clad section dimensions are 50×50 µm and core section is 7×6 µm. The white bar is 50 µm. (b) Camera image of the near field profile output after the propagation through the waveguide.

The Ultrafast Laser Welding of Crystalline and Amorphous Materials

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Abstract

Ultrafast laser welding has been the subject of much interest in the past decade, largely due to its ability to weld highly dissimilar materials with a minimised heat affected zone (HAZ) [1]. Welding of fused silica and BK7 glasses - aluminium and AlSi-YAG, among other combinations, have been demonstrated, Figure 1 [2, 3]. The highly compressed ultrashort pulses give access to nonlinear absorption, with multi-photon absorption dominating at higher photon density, or higher intensity. This is key – absorption can be triggered at a wavelength at which the material is usually transparent. This has led to the development of a welding process where at least one of the materials being welded is transparent to the laser used. This enables the welding of transparent-transparent materials or transparent-opaque (e.g., structural materials) without any intermediate layer. The transparent material is placed in contact with a weld target and the laser is focused through it to a point near the interface. As photons atoms are ionized, and provided subsequent pulses are delivered quickly enough inter-pulse thermal accumulation takes place. If the laser is focused at the correct position both materials can be ionized, and the mixed plasma, once resolidified, will create a bond.

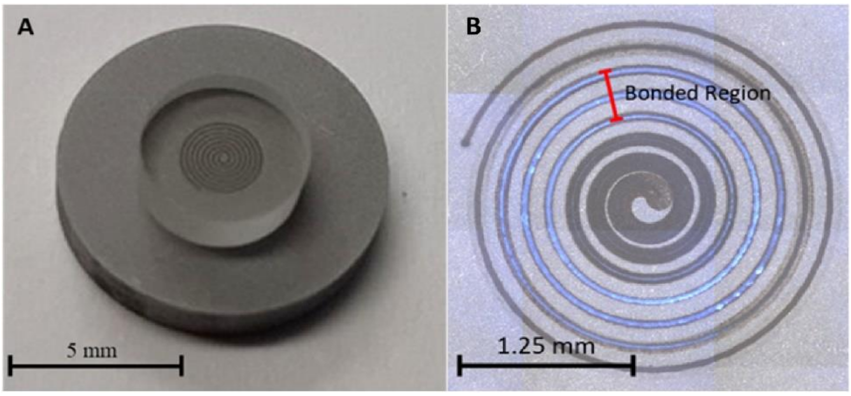

Figure 1: An image of a piece of YAG (top) welded to AlSi (bottom), and a brightfield microscope image of the weld spiral showing the region where the interafce is welded [3].

Small pieces of crystal are used in many devices and as such there is significant industry demand for a technique which can directly bond crystalline materials to each other, themselves and to structural materials with minimal impact to the workpieces. In my PhD I will investigate ultrafast laser welding of these crystalline materials, with a particular focus on trying to control the crystal microstructure after welding, and the welding of very thin workpieces. If the process can be optimized and scaled up, then it will improve on current techniques for fabricating electrical and optical devices and may enable entirely novel manufacturing techniques in other fields.

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Stable Free Electron Laser driven by a Bayesian-optimized laser-plasma accelerator

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Abstract

High-power laser systems are used in various fields, including material sciences, medicine, and astronomy. At Helmholtz-Zentrum Dresden-Rossendorf, we are developing a laser electron accelerator using the Amplitude high-power laser system DRACO. This accelerator can produce relativistic electrons for different applications in material science, particle physics, and medicine. These novel accelerators are capable of sustaining high energetic fields, which allows for the creation of high-charge multi-GeV beams within a few centimeters, resulting in compact facilities.[1]

One use of a laser electron accelerator is to drive a free electron laser (FEL) with an accelerated electron beam. This results in a compact, tunable, high-power X-ray source with excellent transverse coherence, as demonstrated in the COXINEL experiment.[2] [3] However, to achieve stable FEL radiation, the parameters of the accelerated electron beam must be tightly controlled. These parameters include stable electron energy, high charge, and low energy spread within the electron bunch.

Laser electron acceleration is a highly nonlinear process, which means that small fluctuations in laser and plasma parameters significantly impact the resulting electron parameters. This also raises the need for thorough characterization and control of the drive laser parameters, such as wavefront, laser energy, laser focus symmetry, and spatial and temporal phase. These parameters are ideally evaluated on an on-shot basis in a nondestructive way.
All of these laser parameters, as well as the plasma and electron parameters, are intertwined[4] and, therefore, cannot be independently optimized. To address this issue, we employ Bayesian Optimization to find a reliable and stable laser and plasma configuration tailored to each experiment.

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Generation of high-order harmonics in solids

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Abstract

High-order harmonic generation (HHG) is the foundation of attosecond science [1].

The Project aims at:

developing new theoretical, numerical, and experimental tools to study the time resolved HHG spectroscopy in extended systems, open the path to perform HHG pump and probe experiments and simulations, link the HHG properties to novel physical properties, produce new materials with technologically relevant HHG properties.

The envisaged results include:

reduced exciton binding energy and Mott transition in photoexcited TMD (MoS_2). Screening by photoexcited carriers reduces the exciton binding energy, thus changing the HHG spectrum [2]. Band structure of a TMD heterostructure reconstructed from MoS_2. TMD heterostructures provide efficient separation of photoexcited charges and show great promise for light-harvesting [3].

Optical control of the HHG emission from topological surface states (TSS) This step demonstrates the capability of the full optical control of the non-equilibrium electronic properties of topological matter. HHG emission from TSS only is switched on and off by tuning the wavelength of two optical pulses.

Plasmonic enhancement of the HHG emission from TSS. An additional degree of freedom is established to selectively enhance the HHG emission from TSS due to the plasmonic coupling of the 3D topological insulators surface with nano/meso-structures.

In conclusion, this project represents a significant step forward in attosecond science, focusing on HHG and its applications. Through the development of new tools and experimental techniques, it sheds light on the dynamics of HHG spectroscopy in extended systems, offering insights into exciton binding energy modulation, band structure reconstruction in TMDs, and optical control of HHG emission TSS. These achievements pave the way for advances in material engineering and the manipulation of electronic properties in topological matter, contributing to both fundamental understanding and technological innovation in ultrafast optics.

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DEVELOPMENT, CHARACTERIZATION AND IMPLEMENTATION OF SATURABLE ABSORBERS BASED ON MULTIMODE INTERFERENCE FOR MODE-LOCKED LASERS

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We report on the characterization of saturable absorbers (SA) based on the nonlinear multimode interference (NLMMI) in graded-index fiber and on their use in all-fiber mode-locked laser (MLL) operating at 1900 nm. Artificial SA based on the NLMMI, as schematically shown in Fig. Fig. 1a, was proposed initially by Nazemosadat and Mafi [1]. Fig. 1a shows the SA device based on a graded index fiber (GIF) sandwiched between two standard single-mode fibers (SMFs). We chose a GIF with core diameter D = 62.5 µm and relative index difference Δ of 0.0659. In the linear regime, it is well known that the spot size along the GIF varies as a result of the interference between the modes excited at the input. For given D and Δ, the spot size evolution depicted in Fig. 1a depends only on the size of the input beam (here provided by a standard SMF spliced to the GIF). The input spot is imaged periodically every self-imaging length $Z_{im} = D\pi/2\sqrt{2\Delta}$. In our experiments, Z_{im} = 541 µm. At the nodes of the periodical pattern, Kerr effect can be induced for sufficiently high peak power, leading to some slight decrease of the self-imaging length. If the length of the GIF sandwiched between the two SMF is slightly longer than a multiple integer of the self-imaging length, then the transmission of the whole device is expected to increase when the power is increased due to improved mode-matching between the GIF and the output SMF. This increase in transmission is expected to saturate when the spot size reaches its minimum. This behavior corresponds to some "saturable absorption" as schematically shown in Fig. 1a Since the seminal paper by Nazemosadat and Mafi [1], a large number of demonstrations of MLL based on such NLMMI-based SA were reported [2].

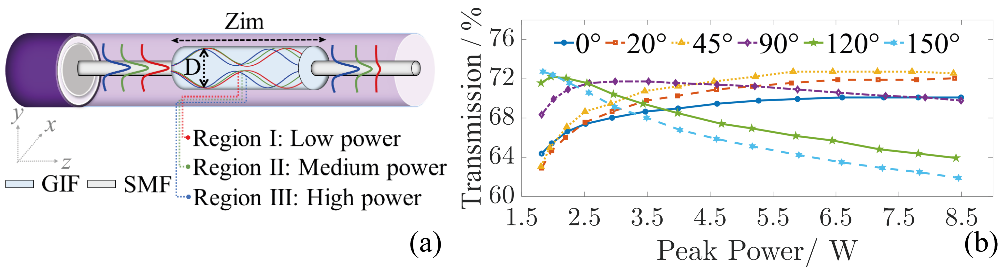

FIGURE 1 : (a) Schematic of the SA based multimode interference in GIF. (b) Transmission of the device measured as a function of the peak power for various configurations.

The result for a GIF length of 14 cm is shown in Fig. 1b. In the range of peak power studied, the transmission of the device increases from 64% to 70% . The saturation energy threshold of the transmission is observed for a peak power as low as 6.5 W, which indicates that this device might be used for initiating mode-locking in a laser cavity. To better understand the influence of torsion on the SA, the GIF was secured in a device that can be rotated by 150°. Here, a short 2-cm long piece of fiber was actually twisted in the device. The transmission behavior of the DUT was measured again for a range of twist angle. As shown in Fig. 1b, the modulation depth increases by 4% from the situation with no twist to the situation with 45° twist. The few % modulation depth is expected to be enough to initiate and stabilize mode-locking and indeed allowed to initiate a soliton pulse centered at 1900 nm, the 3-dB bandwidth of the spectrum was 3.8 nm corresponding to a Fourier-transform duration of 997 fs assuming a hyperbolic secant pulse. The output average power was 30 mW. Kelly sidebands were also observed on the spectrum. The mode-locked operation was stable for hours. This work presents a thorough characterization of an artificial saturable absorber devices based on nonlinear multimode interference in graded-index fiber. We have studied the influence of external forces applied to the device on its transmission properties and demonstrated that slightly twisting the fiber can indeed tune the properties, such as appearance threshold and modulation depth. Allowing to mode locked in an all-fibered Thulium cavity.

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Optimization of the power output in complex laser system

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Abstract

Thermal-stress-induced birefringence (TSIB) in high-power high-repetition rate laser systems is a severe problem limiting the beam quality and output power. TSIB causes a non-uniform polarization changes across the beams' cross-section. As a result, the efficiency of the polarization-sensitive processes such as harmonics generation and optical parametric amplification is severely decreased [2-5]. A significant advancement in the field of TSIB compensation in complex laser systems assisted by polarimetric measurement (see schematic in Fig.1) has been achieved by an optimization process demonstrated in [1]. However, the existing optimization process relies on a slow and limited four-parameter numerical approach. Recently, a fully analytical direct calculation alternative to the optimization process has been developed. A demonstration presented here employ previously published data from the pulsed laser system Bivoj/DiPOLE100 (with average power in a kilowatt-range). The new approach not only offers a deeper understanding of the polarimetric method for thermally-induced polarization changes driven power losses (TIPCL) suppression but also presents a more precise, reliable, and faster alternative to the numerical process.

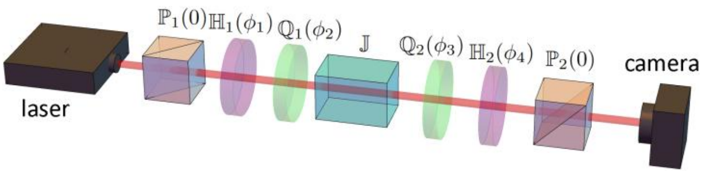

Fig.1 The Mueller matrix polarimeter: J—laser amplifier; P1,P2—polarizers; H1,H2—half-waveplates; Q1,Q2—quarter-waveplates. Angles Φ denotes the inclination of the waveplates fast axes from the vertical direction.

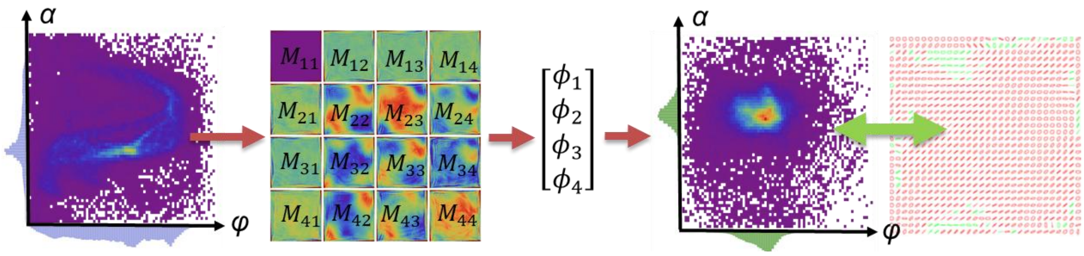

Fig.2 Schematic of the optimization process: calculated initial output beam emerging from the amplifier in polarization-state coordinates (α=azimuth, φ=phase delay); measured Mueller matrix of the amplifier chain; calculated optimal angles Φ1- Φ4 of the wave-plates which minimizes the power losses; calculated optimal output beam in coordinates (α, φ) and its' polarization ellipse-representation across the beams' cross section, sense of rotation is distinguished by red/green color.

The optimization process employing the proposed method is schematically depicted in Fig.2. As reported in [4], the Mueller-matrix polarimetry based method of TIPCL reduction can significantly decreases power losses, from 33% to to 3% in this case.

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Glass welding with femtosecond laser in different operating mode

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In this communication, we show transparent glass welding of sodalime using a femtosecond laser operating in different MHz regimes along with a galvanometric scanner. We demonstrate the possibility to perform large-area and crack-free welding with high scanning velocity without any surface preparation.

Although glass is widely used in a variety of industrial fields, joining glass remains a challenging issue. Laser-based transparent welding emerges as a promising solution for glass bonding due to its ability to provide rapid, high-precision, high-quality, and flexible bonding with minimal heat distortion. In fact, ultrashort laser pulses allow to locally weld transparent materials. Thanks to the ultrashort pulse duration and the well-localized non-linear absorption, melting appears in a very restricted volume nearby the focal region. By positioning the laser focus at the interface of two glass samples and scanning the laser spot, it is possible to produce a welding seam. The dimensions of the welding seam increase with high repetition rate (in the MHz range) owing to heat accumulation between successive repetitive pulses [1]. Moreover, we show that the use of bursts helps to reduce residual stress resulting in high breaking strength [2].

We used a Tangor 100 from Amplitude, allowing us to explore several burst configurations in the MHz regime. The laser beam was focused into the glass samples (sodalime) by a high numerical aperture (0.2) telecentric lens with a focal length of 30 mm resulting in a beam focus diameter of 5.3 µm. A galvanometric scanner allowed to move the spot according to a chosen trajectory to produce a welding seam. Preliminary tests have been conducted to identify the influence of the laser parameters on the interaction zone (energy, burst duration, frequency …) and on the mechanical resistance. We have identified several kinds of defects that can occur and deduced reasonable operating windows, where it becomes possible to produce uniform and transparent crack-free welding, as shown in Figure 1.

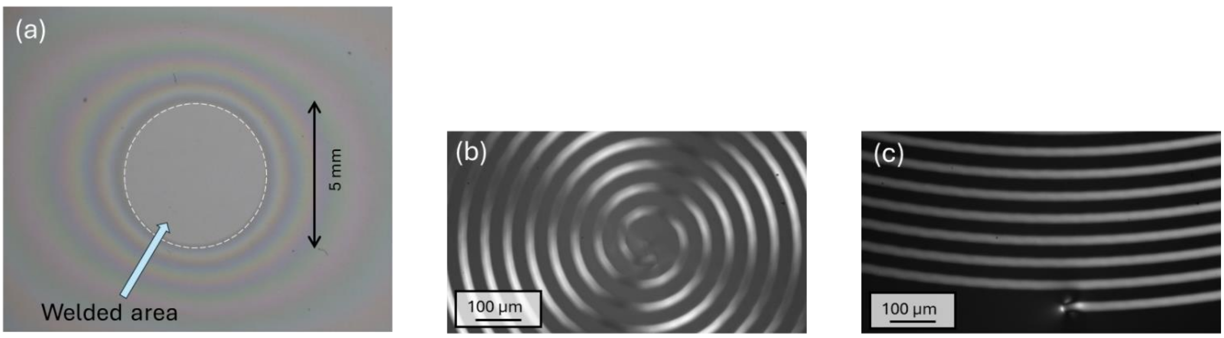

Figure 1: Microscope image of sodalime glass plates welded in single-pulse MHz regime with an energy of 13.7 µJ and a scanning speed of 50 mm/s (a), microscope images under crossed-polarization showing residual stress at the centre (b) and at the end of the spiral (c)

The process is repeatable and does not require any surface preparation. Additional characterizations of the welded samples were conducted, including mechanical tensile tests. These tests reveal that the pressure required to break the weld reaches up to 60 MPa.

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High-Peak-Power Optical Lasers at European XFEL's HED Instrument

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Keywords: Femtosecond Laser, High Intensity Laser, High Energy Laser, Diode-Pumped Laser

Abstract

The Helmholtz International Beamline for Extreme Fields (HiBEF) user consortium has successfully installed and commissioned two high-peak-power optical lasers at the HED instrument [1] at the European XFEL facility in Schenefeld, Germany. These installations represent a significant enhancement in the facility's research capabilities, enabling a broad range of experiments in conjunction with the European XFEL's high-intensity X-ray beam. The first laser, designated as the High Intensity (HI) Laser - Relativistic Laser at **X**FEL (ReLAX) [2], incorporates a 300 TW double-CPA Titanium Sapphire System from Amplitude Technologies, featuring a 25 fs pulse duration and 10 Hz operation. This optical compressor, beam transport, and diagnostics package were developed and provided by the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), showcasing advanced laser technology tailored for high-intensity applications. The second laser, the High Energy (HE) Laser DIPOLE D100-X, represents a 100 J class Ytterbium:YAG laser system, developed and manufactured by UKRI-STFC-RAL-CLF as contribution from the UK part of HiBEF. This system, powered entirely by diode pumping and capable of up to 10 Hz operation, features an adjustable energy output in the second harmonic (515 nm), accompanied by a versatile temporal pulse shaping capability ranging from 2 to 15 ns. It supports flat-top, ramp, and double-shock pulse configurations, providing a broad operational flexibility for diverse applications.

The HI Laser is designated for exploring a diverse array of phenomena, including the properties of highly-excited solids, high-energy density states of matter, quantum electrodynamics (QED) effects, ionization dynamics under intense light, and relativistic laser-plasma interactions. On the other hand, the HE Laser focuses in creating extreme density and pressure conditions through laser-driven shock and ramp compression techniques [3]. This capability is critical for experiments that simulate conditions akin to those found in the cores of Jupiter and Neptune, investigate equations of state, explore exotic phase transitions, and develop novel materials. When used in conjunction with the XFEL probe, the HE Laser facilitates unprecedented investigations into the dynamic properties of matter under extreme conditions. This contribution outlines the technical specifications, commissioning, and a selection of pioneering research applications facilitated by these state-of-the-art laser systems at the European XFEL, demonstrating their significant impact on the field of high-energy density science.

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Chaotic Dynamics of Near-Critical Density Plasmas for Laser-Ion Acceleration

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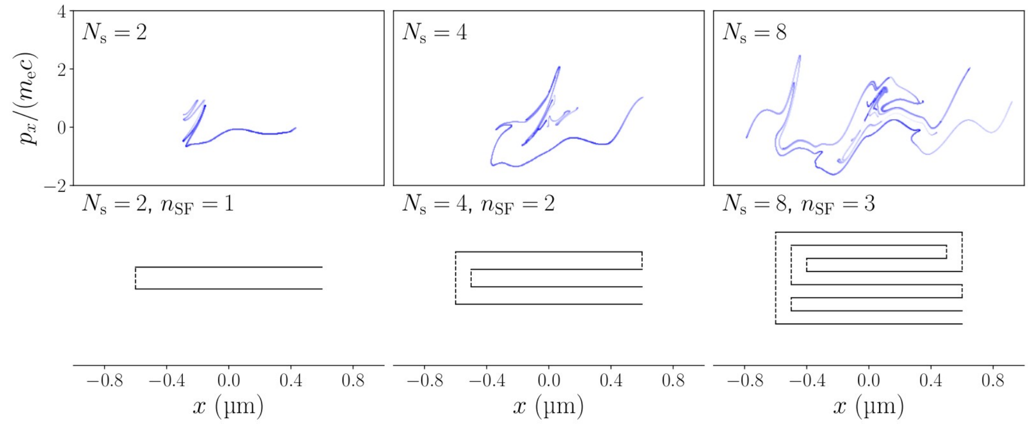
Abstract

We investigate the emergence and consequences of chaotic dynamics in the interaction of near-critical density plasmas with ultra-intense laser pulses in the context of laser-ion acceleration [1], leading to highly sensitive dependencies on initial conditions even for important macroscopic quantities such as the absorbed laser energy or the spectrum of ions accelerated in the process. The results of particle-in-cell simulations may vary strongly depending on the (macro)particle configuration, or, for the same configuration, due to accelerator-based computing using single precision. While in multidimensional geometries similar effects may be enabled by the emergence of plasma surface instabilities, in particular for optimized laser ion acceleration at the relativistic critical density surface [2], we find similar strong dependencies on initial conditions even in the idealized case of a one-dimensional geometry. For this case, the interplay of laser- and induced fields continuously accelerates electrons in both forward and backward directions, leading to the formation of electron phase spaces that exhibit varying degrees of mixedness.



Top: electron phase space for times t such that $N_s(t)=2$ (left), $N_s(t)=4$ (middle) and $N_s(t)=8$ (right), respectively. Bottom: Illustration of idealized stretching and folding dynamics. The total number of SF operations, n_{SF}, correspond to the number of streams $N_s=2$^n_{SF}.

We identify a stretching and folding process in the electron dynamics, which is a signature of deterministic chaos and also responsible for the creation of additional electron streams. Based on the results of particle-in-cell simulations with the PIC code Smilei [4], we present the intimate connection between the degree of mixing, particle correlations, electron temperature and chaotic dynamics, and we provide an approach to distinguish the effects between longitudinal and transversal nonlinear dynamics.

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Laser Functionalisation of Flexible Polymer-Carbon Composites for Medical Sensing

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Abstract

The project "Laser Functionalisation of Flexible Polymer-Carbon Composites for Medical Sensing" will use laser irradiation to pyrolyse polyimide into graphene, which can then act as a conductive circuit. Direct laser writing (DLW) will allow precise spatial confinement of conductive structures to be embedded within an insulating polymer. By controlling the carbon porosity and conductivity, composites can be functionalised to sense changes in pressure, temperature, moisture or pH level, which makes them ideal for use in the medical device industry. Using a focused laser beam and adaptive optics principles will allow the generation of sensors on the micron – and potentially nano – scale.

The novelty of the work lies in writing three-dimensional graphitic structures within the bulk of polymers, progressing from the highly investigated area of surface modification. The project aims to create conductive pathways under curved surfaces, which will allow the incorporation of sensors into the bulk material of catheters and stents, iterating the development of smart medical procedures and implants. Within this scope, we will explore the effect of light polarisation on the size and quality of sensing structures. A spatial light modulator (SLM) will be used to modify the phase, and hence polarisation of the beam. The SLM may also be used for aberration correction, to further confine the focal volume of the beam, resulting in smaller and sharper carbon features.

Prior work of this research group established polyimide as a new material for three-dimensional graphene conversion and successfully wired embedded electrical contacts. Results also indicated that pulses in the picosecond regime could generate DLW graphene structures. (Dorin et al., 2017, 2018). Subsequently, a strain sensor was written in polyimide using a femtosecond laser, however three-dimensionality was achieved with a kirigami design, rather than subsurface material modification (Biswas et al., 2023). The current work will focus on relating DLW parameters to structure size, porosity and conductivity, tuning the sensing response to specific external stimuli, and developing a process model for industrial scale-up of the operation. Further comparison between femto- and picosecond regimes in the context of thermal polymer reactions could establish low cost, low footprint picosecond lasers as a viable industrial option for 3D sensor inscription.

The work is being conducted using a customised ytterbium-doped fibre laser, with fixed repetition rate of 80 MHz and variable pulse length. Adjusting the separation of externally mounted gratings allows for the compression of pulse lengths from 2 ps to 70 fs. Working closely with our industrial partners Chromacity Ltd., we are investigating the range of capabilities of this custom-built laser system, mapping pulse length against grating separation, while studying the impact of dispersion effects. With the laser originally designed with multiphoton spectroscopy in mind, our bespoke system is being used for control of thermal reactions for the first time. The development of a stable, mode-locked laser source with adjustable parameters is therefore a key first step in the execution of our project deliverables.

This project intends to advance the state of smart technologies in the medical industry. Current graphene manufacturing methods involve bulk reactions in multistep processes. Hazardous chemicals are involved, necessitating the use of controlled environments. Furthermore, sensors are manufactured as a separate entity and later incorporated into the medical device, limiting size and increasing the risk rating of the finished product. The techniques being developed in the current work will allow for a streamlined, single step, digital manufacturing process. Due to the flexibility of the carbon-polymer composites, the manufacture can be scaled using continuous reel-to-reel throughput. Using digital control of laser parameters, sensor functionality could also be personalised for a patient's specific needs, for example in terms of sensitivity or location. With medical device manufacturers already bidding to incorporate industry 4.0 principles, the recent introduction of a new medical device regulation (MDR), has required manufacturers to re-certify their devices with enhanced safety and performance characteristics between 2026 – 2028. The flexible, agile and digital technology being developed in this project could be the solution businesses need to address the increased expectations of this directive, as sensor feedback will be required for physicians and manufacturers alike.

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Transportation of high power UV via hollow-core fiber for engraving/marking experiments

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Abstract

The purpose of this project is to achieve good quality material processing experiments (engraving and marking) by transporting high power UV with a hollow-core fiber. This is a French-Belgian collaboration involving three companies: Bloom Lasers, GLOphotonics and Orion Laser Tech.

Bloom Lasers provided a standard CAREX laser 30-343, a high power UV nanosecond laser source with a free-space output of ultra-high beam quality. GLOphotonics provided a specialty hollow-core fiber for delivering the UV from the laser to the processing machine. Orion Laser provided the instrumentation for the engraving/marking experiments based on galvo—scanner mirrors.

The focus of the first phase of this work was the development of the setup for the injection of the high power UV from free-space into the hollow-core fiber. 20 W of laser power at 343nm were obtained at fiber output with 94% transmission efficiency, as well as ultra-high beam quality at 15 W of fiber output power ($M^2 < 1.1$).
In the second phase of this work, the injection setup was re-installed in Belgium at the Orion Laser Tech facility. Processing experiments have been performed and good quality preliminary engravings/markings have been achieved on glass samples.

This proof of concept demonstration opens the way for a possible large-scale implementation of a similar setup for industrial processing applications.

Title of the abstract

Laser induced Plasma of titanium (Ti) as ion source for surface structural and mechanical modifications of Mg-alloy with vast range of Application in Material Engineering

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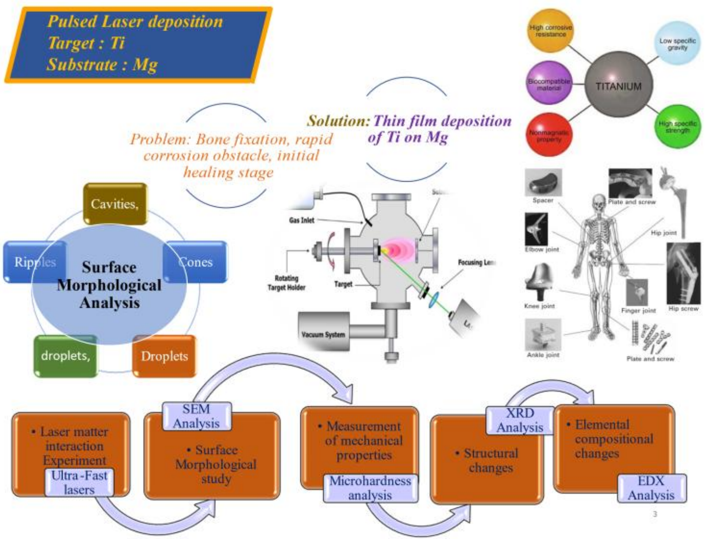
Abstracts

Laser induced plasma is a promising tool for generation of ions and has vast range of application in material processing, improving electrical, Optical and mechanical properties as well as oxidation resistance of many Materials [1]. The substantial quantity of work is reported on ion implantation of metals and their alloys by many researchers. Rafique et al [2] employed Thomson Parabola Scattering (TPS) technique to measure the energy of Coper ions from the Nd : YAG laser induced plasma. The objective of this study is to improve the behaviour of surgical magnesium alloy by titanium ion implantation. Magnesium alloys are widely used in biomedicine and industry and many physical properties like hardness, conductivity, corrosion resistance and bio compatibility can be improved after laser irradiation of Mg-alloy [3]. In my previous work, repoted that the micro-hardness of Mg-alloy significantly increase after laser ablation treatment.

Conclusion

Mg-alloy being biodegradable are widely used in biomedicine and automobile industry due to high strength. Magnesium alloy is designed to be an absorbable bone implant. For bone implant applications, the bone healing duration is about one year or longer. Therefore, it is desired that the bone implant provides strong support during the first 3 months and then it gradually degrades in Volume and strength in the following healing process. So far, available magnesium and magnesium alloys as well as newly developed magnesium alloys all show a high degradation rate in a biological environment. As due to its bio compatibility used in bone *fixation but still have some obstacles such as rapid corrosion, initial healing stage.* The objective of next work is to improve the behaviour of surgical magnesium alloy by titanium ion implantation.



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Fiber optic probes exploiting localized surface plasmon resonance for chemical detection

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Optical sensors, especially optical fiber sensors, have become increasingly popular for use in biological and chemical sensing due to several key benefits. These include their compact size and light weight, high sensitivity and resolution, chemical resistance, and biocompatibility. A variety of transducer mechanisms and phenomena are currently utilized to develop refractive index (RI) sensors, including fiber Bragg gratings, long period gratings, interferometers, lossy mode resonance, and surface plasmon resonance (SPR) [1]. Regarding SPR techniques, they are distinguished for their rapid, label-free, and real-time sensitivity. In this process, there is an interaction and energy transfer between incident light photons and electrons on a metal surface, causing collective oscillation. When small metallic nanoparticles (typically on the order of tens of nanometers) are considered, they act as resonators and localized SPR occurs (LSPR). LSPR is employed in various fields, including biomedical imaging, photothermal therapy, and bio-chemical sensing [2]. In this work, we report regarding the fabrication and testing of a novel simple fiber optic probe levering on LSPR. The structure consists of a cladding removed multi-mode fiber (MMF) coated with gold nanoparticles (AuNPs). The performance of the device is thus evaluated for the detection of a harmful chemical compound, i.e. pesticide Thiram.

The optical fiber transducer described in this work is based on a simple configuration employing an uncladded silica MMF, working in a reflection or single-ended mode, as illustrated in Fig. 1(a). This setup involves removing the cladding of a MMF for few centimeters using hydrofluoric acid (HF). The aim is allowing the fiber core mode to interact with the surrounding environment through evanescent wave. A mirror integrated at the fiber's tip reflects the light, enabling detection in reflection mode [3]. Specifically, the MMF FG105LCA from Thorlabs was employed, featuring a 105 µm core and 125 µm cladding diameters. Etching of fiber down to a diameter of about 99 µm was obtained in a 24% HF solution for 25 minutes. Subsequently, the surface of the fiber was functionalized for the subsequent immobilization of AuNPs. This process began with an hour-long immersion in piranha solution (blending of H_2SO_4 and H_2O_2) to generate hydroxyl groups on the fiber's surface. The fiber tip was then cleaved and mirrored using Tollen's reaction to create a reflective surface. Then, the fiber was immersed into APTES (5% w/w) solution for 2 hours to silanize the surface, rinsed with acetone, and left to air-dry overnight. Finally, the so-prepared fiber was immersed in a 1 mM solution of AuNPs with average diameter of 43 nm, for 4 hours and allowed to air-dry. The optoelectronic setup for the measurement of sensor spectra is made of commercially available components, i.e. a white light source, a VIS spectrometer and a fiber coupler to collect the sensor reflected spectra. Fig. 1(b) illustrates the sensor's reflected spectrum following the deposition of gold nanoparticles when the device is exposed to air, which features two significant dips at 545 nm and 733 nm. Subsequently, the bulk refractive index sensitivity of the transducer was evaluated, obtaining a sensitivity of 433 nm/RIU and 581 nm/RIU for the first and second peak, respectively, within the range 1.33-1.36. To assess the performance of the fiber probe developed through the steps described earlier, we have measured changes in Thiram concentration within aqueous solutions ranging from 0.1 to 100 µM. Thiram pesticide contains functional groups such as amines and thiols, which have a strong affinity for binding AuNPs [4]. The response of the probe, specifically the shift in the resonance wavelength of the absorption peak, was monitored as the probe was sequentially immersed in solutions with increasing concentrations of Thiram. Fig. 1(c) displays the reflection spectra of the probe at various concentrations and a noticeable redshift in the attenuation band correlating with rising Thiram concentrations. Finally, the calibration curve for the sensor was obtained and reported in Fig. 1(d) using a semi-logarithmic scale, illustrating the shift in resonance wavelength of first peak relative to Thiram concentrations. The experimental data were also fitted using a sigmoidal function, depicted with dashed curve. Key performance metrics of the sensor are derived from the calibration curve, with the limit of detection (LOD) being a critical parameter and found to be equal to 5 nM.

Conclusions

In this contribution, we have developed a simple fiber optic probe starting from a cladding removed MMF which was subsequently coated with AuNPs. The reflection spectrum of this device is modulated by the absorption spectrum of AuNPs. After a refractometric characterization, the performance of the device was investigated for chemical sensing by using Thiram pesticide as a target. Notably, the simplicity and cost-effectiveness of this sensor provide a distinct advantage over more complex SERS-based methods and offering a lower LOD than UV-VIS-based methods.

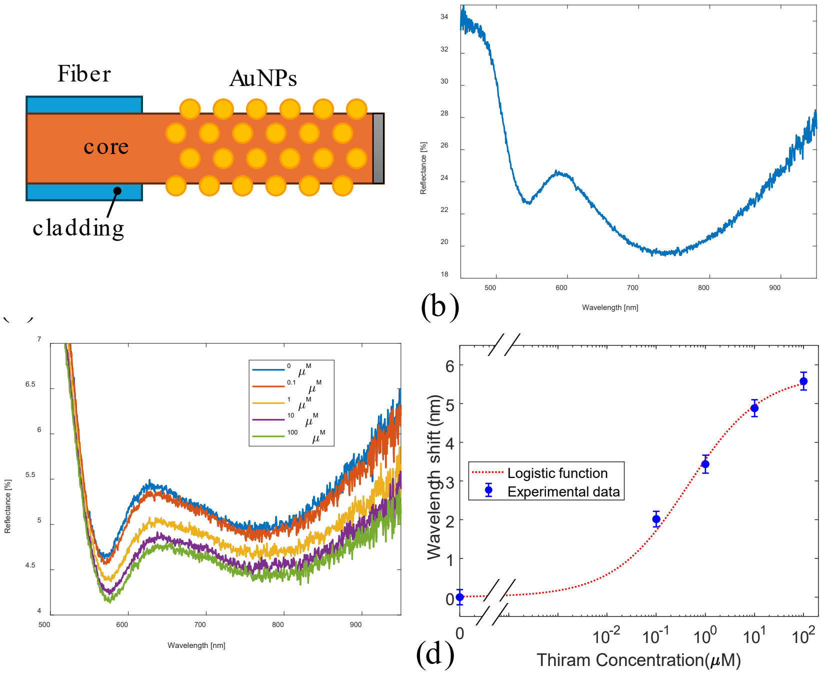

Fig. 1. LSPR fiber probe: (a) Schematic picture; (b) Reflectance spectrum in air; (c) Reflectance spectra at different Thiram concentration solutions; (d) Calibration curve for Thiram.

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Single pulse ablation of different types of stainless steel: A comparison of pulse duration and the use of different burst modes

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Abstract

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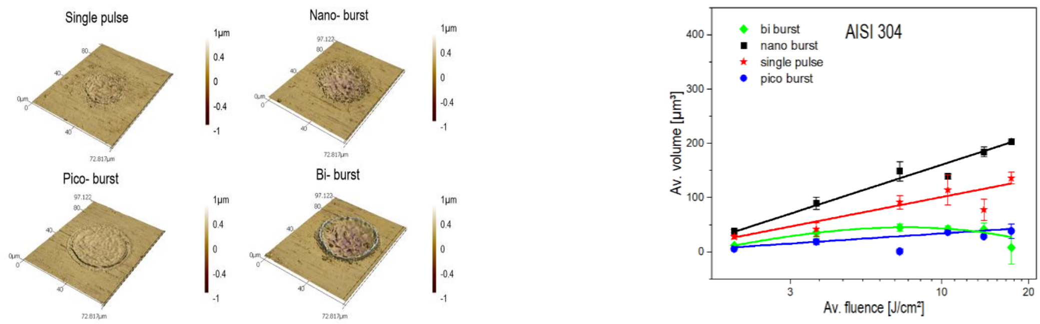
Stainless steel finds extensive use across diverse industrial sectors, including medical and food industries [1]. The surface characteristics of products made from these alloys play a crucial role in determining different properties such as corrosion resistance, heat transfer, biocompatibility, and bacteria adhesion. These functionalities can be modified for instance, using laser-based microstructuring methods with ultra-short pulsed lasers, as alternative to conventional surface modification technologies.
The samples of the three materials AISI 304, AISI 420 and AISI 316Ti were irradiated with single ultrashort pulses from different pulse widths, and burst modes in the MHz (nano burst) and GHz (pico burst) range. The goal is to investigate the differences in the ablation threshold, crater morphology and the ablation rate in order to achieve the best possible energy efficiency of the laser process.



(a) *(b)*

Figure 1 (a) Confocal images of craters produced on AISI 304 with 250 fs single pulse, nano-, pico-, and bi burst (b) Comparison of ablation rate on AISI 304 with 250 fs single pulse and different burst modes.

The results show that the surface morphology of the craters has significant differences. In Figure 1 (a)) confocal images of single laser pulses with 250 fs are depicted. When using a single pulse or nano burst, LIPSS structures can be observed. Whereas, by using pico burst Newton ring features surround the edge of the crater. When combining MHz and GHz burst (bi burst) the crater shows a layer of remolten material on top with neither LIPSS nor Newton rings.
Analysing the ablated volume of the pulse, the results indicate that shorter pulses lead to more efficient ablation. Furthermore, using burst mode in the GHz range significantly reduces the ablation rate (Figure 1 (b)). On the other hand, by using MHz burst, the ablation efficiency can be increased. In addition, using bi burst leads to a large material build up in the crater but only a very small amount of the material is ablated. Therefore, the ablation rate is very low compared to using single pulse or nano burst [2].

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Complex beam optimization of Bivoj laser system

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Abstract

The research focuses on enhancing the performance of the Bivoj laser system (Dolni Brezany, Czech Republic), a high-energy high-average-power laser generating 2-10 ns-long pulses with energy up to 150 J and a repetition rate of 10 Hz at 1030 nm [1]. It consists of 3 main parts: front-end, 10 J main amplifier, and 100 J main amplifier. Both main amplifiers employ cryogenically cooled Yb:YAG slabs pumped by laser diodes at 940 nm. The beam profile and its wavefront are being distorted at various stages of the laser during amplification, which significantly impact laser's performance, making optimization crucial for beam distribution and applications at our facility.

The first objective of my research is to improve the beam profile at the output of the front-end of the Bivoj laser system, where the intensity profile is distorted due to nonuniform gain distribution. Therefore, I developed a beam shaping system consisting of the spatial light modulator (SLM) and the near-field camera. It was implemented in the front-end of the laser and it improved the beam profile at its output (by pre-compensating for gain nonuniformity), resulting in improved beam homogeneity at the output of the 10 J main amplifier, especially at lower energies. Another possibility of having such a shaping system is to inject non-ordinary beam shapes into the amplifier chain, that I also successfully demonstrated. The beam shape change takes a few seconds, extending the output characteristics of the Bivoj laser system, and it was used in multiple experiments right after the shaping was available. The above-mentioned results were published in [2].

The second objective of my research is the wavefront optimization at all three stages of the laser, but the purpose is different at each section.

1. The spatial light modulator (in conjunction with the SID4 wavefront sensor) was successfully used also for aberration correction in the front-end of the system [2].
2. The adaptive optics (AO) system in the 10 J main amplifier can correct for thermal aberrations but sometimes, it leaves wavefront gradients at the very edges of the beam, causing intensity hot spots at various planes along the beam propagation that few times destroyed optical components at those planes. I identified this effect by computer-simulating the beam propagation in the laser. One of the future goals is to prevent the hot spots creation (most probably by utilizing both the SLM and the deformable mirror).
3. The AO system in the 100 J main amplifier is not able to converge to a flat wavefront resulting in the creation of hotspots outside of the image planes along beam propagation in the distribution system and, consequently, to optics damage. This prevents the laser operation at the full power. I identified this issue again by computer-simulating the beam propagation. The aim is first to determine why the AO loop is not able to converge to a flat wavefront and then correct the thermal aberrations arising in the amplifier head.

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Trade off-free microfabricated cells for atomic devices

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Abstract

Miniature atomic devices such as clocks and magnetometers rely on microfabricated alkali vapor cells [1]. Several techniques have been proposed to make such cells but they often entail specific advantages and drawbacks [2–4]. We recently demonstrated an alternative technique mimicking the approach found in the fabrication of standard glass-blown cells. It consists in wafer-integrated make-seal structures that can be closed locally with a CO2 laser [5, 6]. Here, we report on recent work to extend this concept further by connecting the wafer to a vacuum chamber filled with the desired chemical species before sealing the cells as shown in Fig. 1. This method benefits from microfabrication in terms of cost, reproducibility and mass fabrication.

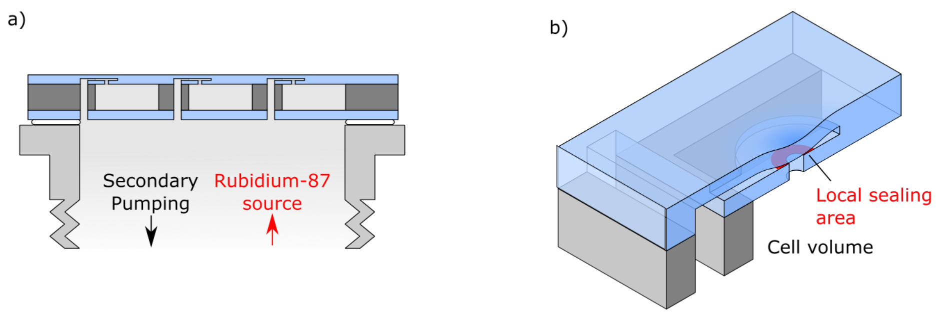

FIG. 1. a) A wafer of cells placed on a vacuum chamber to fill the cell with rubidium- 87 b) Local sealing using a CO_2 laser.

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Hybrid solid state quantum memory by femtosecond laser micromachining

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Abstract

Photonic quantum memories (QMs) are critical devices for the deployment of quantum networks out of the lab. Working as synchronization devices for more complex architectures, they are key components for many applications, from efficient and long-lived quantum repeater nodes to on-demand quantum state creation [1,2]. Solid state platforms such as rare-earth ion doped crystal matrices (REIDC) operated at cryogenic temperatures are a promising platform for the realization of scalable QMs that can be easily integrated with other photonic components [3]. The versatility of REIDC memories can be further pushed by realizing waveguide structures in the crystal matrix. The use of femtosecond laser micromachining (FLM) allows to inscribe arbitrarily complex 3D waveguide geometries directly inside the crystal substrate in a maskless procedure [4,5]. These waveguide memories show an increased interaction strength, while preserving the coherence properties of the rare earth ions [6]. Furthermore, on-demand operation [7] and direct fiber integration [8] have been shown on FLM-inscribed quantum memories in rare earth ion-doped YSO crystals.

In this work, we have performed preliminary assembly and testing of a hybrid glass-YSO interface in which a two identical waveguide QMs written inside a Praseodymium-doped YSO crystal are interfaced with two reconfigurable Mach-Zehnder interferometers (MZIs) realized in glass by FLM. The whole device is pigtailed to optical fibres. For this, we have optimized waveguide writing in YSO obtaining unprecedented low values of propagation losses and good coupling with glass-written waveguides, while ensuring that the coherence properties of the rare earth ions were not hindered by the waveguide writing. We have also developed low-power reconfigurable MZIs, suitable for cryostat operation. Such a composite device allows to perform on-chip state generation by path encoding photons with the first MZI, storage with the waveguide QMs, and state tomography using the second MZI. A complete assessment of the QM performances will be carried out according to the Atomic Frequency Comb protocol. This device constitutes the elementary node for more complex schemes which can be used as entanglement swapping nodes or deterministic single photon sources.

Furthering the integration capabilities of this platform, we also began to optimize metal photolithography on YSO. This will allow us to integrate active components directly on top of the crystal waveguides, to achieve direct electrical control of the QM devices.

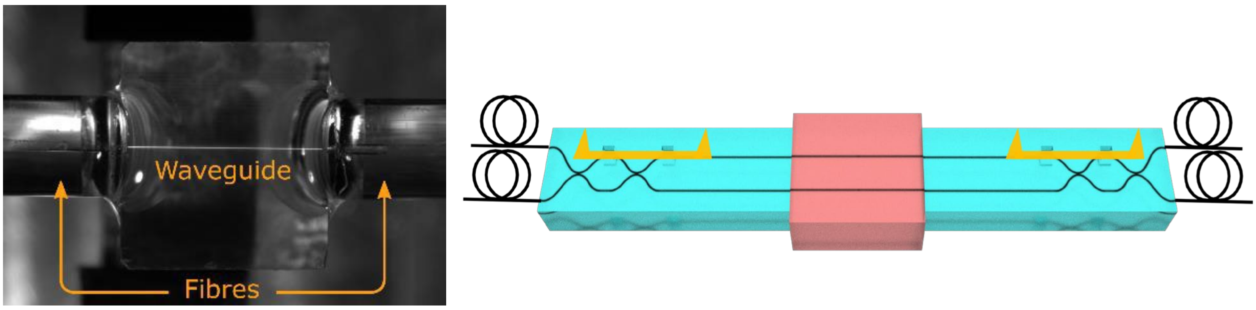

Figure 1 Left: fibre-integrated waveguide QM in a Praseodymium-doped YSO crystal (image from [8]). Right: conceptual scheme of a glass-crystal composite QM in which two reconfigurable glass circuits are used to address a pair of waveguide QMs.

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Molecularly Imprinted Polymer Sensor Empowered by Bound State in the Continuum for Selective Trace-Detection of TGF-beta

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Abstract

Optical biosensors represent innovative technology at the forefront of modern analytical chemistry and biotechnology. They have revolutionized the field by offering sensitive, rapid, and selective detection methods for a diverse array of biological molecules and analytes. Leveraging the principles of optics and molecular recognition, optical biosensors have found widespread applications in areas such as clinical diagnostics, environmental monitoring, food safety, and drug discovery. At their core, optical biosensors function by converting biochemical interactions into measurable optical signals. These sensors rely on the specific binding events between a target analyte and its corresponding recognition element, often an antibody, enzyme, aptamer, or nucleic acid sequence immobilized onto a transducer surface. The binding event induces changes in the optical properties of the sensor, which are then quantified to determine the concentration or presence of the analyte of interest [1].

We introduce here a novel sensor based on the bound state in the continuum (BIC) principle, enhanced by a molecularly imprinted polymer (MIP) cladding layer meticulously designed for specific binding to transforming growth factor-beta (TGF-β). [2] This cladding layer acts as a synthetic antibody matrix, facilitating BIC-field intensification of TGF-β binding to the imprinted sites. The synergy of enhanced detectivity and tailored selectivity is demonstrated also in case of interference from other analytes. The performance of our sensor is comprehensively evaluated through two differential readout analyses, incorporating spectral shift and optical lever analog. This validation demonstrates the sensor's capability to detect TGF-β in a complex matrix of spiked saliva, achieving a remarkable limit of detection of 10 fM and an impressive resolution of 0.5 pM at physiological concentrations in saliva. The sensor exhibits exponential sensitivity, highlighting its potential for high-precision quantification, surpassing existing state-of-the-art methods. This positions our system as a robust tool for biomarker detection, particularly in real-world diagnostic scenarios. More importantly, the architecture of the sensor streamlines the detection process by eliminating the need for complex sandwich immunoassays. This breakthrough paves the way for ultrasensitive biosensing in cancer diagnostics and various other medical applications.

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Impact of glass free volume on femtosecond laser-written nanograting formation in silica glass

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Abstract

Nanogratings created by femtosecond (fs) laser inscription in glasses are pivotal in advancing photonic technologies, with applications spanning from optical data storage [1] and thermal optical sensors [2] to microfluidics and the fabrication of optical elements like waveguides and polarization converters [3].

This study investigates the effects of densification through high pressure and temperature (up to 5GPa, 1000 °C) in the formation of fs-laser induced nanogratings in silica glass [4]. Utilizing polarized optical microscopy and scanning electron microscopy (Figure 1), it was demonstrated that the tendency for nanograting formation is related to the material's densification. Densified samples exhibited significantly lower retardance values and slopes, revealing a diminished efficiency in nanograting generation. This provides novel insights into the role of glass free volume as a crucial precursor for nanograting formation. Voids related free volume may serve as an ideal seed owing to its size and lower refractive index, thereby facilitating the formation of nanoplasma hotspots and subsequent nanogratings that consistently align perpendicular to light polarization. The suggested mechanism coherently explains why silica glass, which naturally possesses a high free volume, facilitates nanograting formation more efficiently than other types of glass [5]. The relationship between free volume and nanograting efficiency could guide the engineering of materials (e.g. nanoporous dedicated materials) with tailored optical properties, paving the way for improved applications in advanced photonic systems.

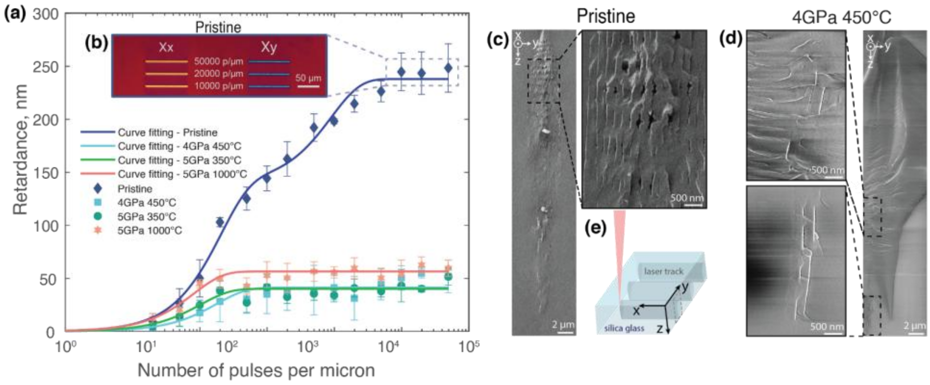

Figure 1. (a) Mean retardance of laser-written structures plotted against number of pulses per micron. (b) Optical microscope image of laser written structures using crossed polarizer and analyzer and a full retardation waveplate inserted at 45 indicating the orientation of the slow axis for pristine sample. (c) SEM images of a cross-section of the laser track (1000 pulses/µm, 1uJ, Xy writing configuration) in the pristine sample; (d) in the 4 GPa 450°C sample. (e) Scheme of the sample orientation for the SEM analyses.

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A new laser-plasma interaction system for applications in radiation sources: Status and perspectives with the upcoming I-LUCE facility at INFN-LNS

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Abstract

A new high-power laser system, will start operations at LNS-INFN's I-LUCE facility in 2026.

The main laser system is being built by combining versatile building blocks, starting from the primary oscillator to the compressor vacuum chamber. Each building block can be independently upgraded, allowing for fast scaling in total power and repetition rate for future performance upgrades.

The system is based on Ti:Sapphire technology and will have two outputs: the first one will be a 50 TW beam line (25 fs, 25-30 mJ, 10 Hz) while the main beam line will be a 350 TW laser (25 fs, 10 J, 2.5 Hz) and upgradable to 500 TW. In each case variable pulse widths from 25 fs to a few tens of picoseconds are possible by control mechanisms in the main stretcher.

I-LUCE will serve two distinct experimental areas known as E1 and E2.

E1 will offer a globally unique combination of laser-generated plasmas with accelerated heavy ion beams, generated by a Superconducting Cyclotron and a Tandem (already installed at LNS), thereby providing opportunities for novel experiments in the fields of plasma physics, nuclear physics, and atomic physics. For moderate laser beam intensities (up to 50 TW), the experimental room E1 will be dedicated to nuclear fusion and studying stopping power in plasma.

Conversely, the E2 experimental room will be dedicated to both proton and electron acceleration. A specialized beamline designed to select, transport, and focus proton beams with energies between 5-60 MeV will be installed and optimized for radiobiological experiments. A corresponding beamline for selecting electron beams will also be implemented. Furthermore, stand-alone experiments involving intense laser beams will be conducted to explore various studies, including X-ray laser generation and neutron production.

Comparison of carrier-envelope offset stabilisation techniques for Cr:ZnS solid-state laser

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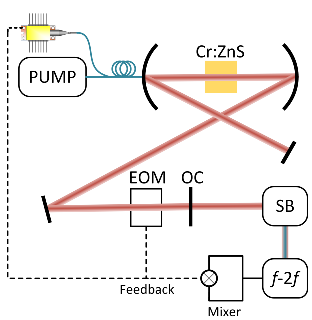
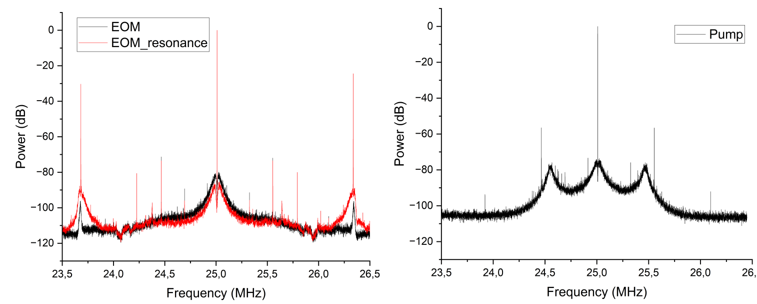
Stabilisation of carrier-envelope offset frequency (f_{CEO}) of a mode-locked laser has been a crucial aspect for seminal experiments awarded with two Nobel Prizes: in 2005 [1] and, very recently, in 2023 [2]. The former has been awarded for frequency combs, a technology requiring a locked f_{CEO}, while the latter relies on absolute carrier-envelope phase stabilisation (i.e. $f_{CEO} = 0$). Here, we present a comparison of two experimental techniques enabling absolute phase stabilisation in a Cr:ZnS mode-locked laser oscillator. First of them is one of the most commonly employed f_{CEO} control techniques based on a pump laser modulation [3]. Second one exploits linear electro-optic effect to directly control the carrier-envelope phase evolution [4].

The laser system used in our experiments (Fig.1a) is a Kerr-lens mode-locked solid-state laser based on a Cr:ZnS gain crystal, pumped by an erbium-doped fiber amplifier emitting at 1560 nm. An additional pump diode was implemented, to enable fast pump modulation. Produced pulses have a central wavelength at 2.4 µm, and duration of ~30 fs. The laser works with repetition rate f_{rep} of 25 MHz and average power amounting to 640 mW. To measure f_{CEO} in a f-2f interferometer, spectral bandwidth spanning over at least one optical octave is required. To achieve that pulses undergo spectral broadening (SB), by passing through a thin TiO_2 plate, causing SB by self-phase modulation [5]. Detected signal with f_{CEO} beat is then mixed with itself, resulting in an error signal - the basis of control system with PID controller, which is used to control the work of the electro-optic modulator (EOM) or the modulation diode. The EOM used in this setup is based on $3 \times 3 \times 3cm^3$ $LiNbO_3$ crystal. Electric field is generated in the crystal's Z-direction and the optical propagation- in the X-direction.



(a) Experimental setup (EOM- electro-optic modulator, SB- spectral broadening, OC- output coupler)



(b) RF spectra of the f_{CEO} beat-notes locked by the EOM with lower (black) and higher (red) locking loop gain. (c) RF spectrum of the f_{CEO} beat-notes locked by pump modulation.

Fig. 1. Experimental setup and initial results

Preliminary results of f_{CEO} stabilization are shown in (Fig. 1b,c). We have observed that the EOM-based locking is limited due to the piezoelectric effect occuring in the $LiNbO_3$ crystal. This is manifested by the appearance of strong resonance peaks at 1.3 MHz detuning from the locked beat-note at higher locking loop gain setting (Fig. 1b, red line). A limitation of the pump-modulation locking originates from a finite Cr:ZnS crystal fluorescent lifetime (~ 5µs), resulting in servo bumps located at ~400 kHz detuning (Fig. 1c.)

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THz pulse shaping with photo-conductive antennas excited by chirped optical pulses at 1 µm

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The terahertz (THz) domain, located between microwaves and infrared, is a frequency band offering multiple applications, particularly in non-destructive imaging [1] and telecommunications. However, the fabrication of sources in this domain is still complex and many efforts are made to develop and improve the processes. The method used here for THz generation is the excitation of photoconductive antennas [2], making it possible to convert ultra-fast pulses in the infrared to the THz frequencies. These antennas have the particularity of being able to be used both for the generation and detection of THz waves, and their good signal to noise ratio (≃ 60dB) makes them an attractive choice. The spectrum and temporal shape of the THz waves emitted by the antennas are imposed by the characteristics of the transmitter as well as by the duration and shape of the optical pulse (figure 1.a). Our objective is to provide control on THz generation by modifying the shape of the optical pulses, leading to a photo-mixing process [3]. This is done by chirping the optical pulse from 70fs to 110ps using a Volume Bragg Gratings (VBG) and then passing through a Michelson interferometer to obtain two delayed chirped pulses. The delay causes a beating frequency between the two pulses lying in the THz range. Thus, the antenna excitation is modulated at this beating frequency, converting in a generated long THz pulse with a selected narrow spectrum (figure 1.b). The tunability is achieved over the bandwidth from few GHz to 1.5 THz, similarly to the spectrum obtained with an ultra-short pulse excitation. The control provided by this process should allow simpler tunability of the THz spectrum by varying the relative delay.

Moreover, it is therefore possible to parameterize the optical pulses shape to control the properties of the THz radiation. Depending on the relative chirp of each pulse, it should be possible to target a certain shape of THz spectrum, while keeping the long duration of the pulse, allowing certain analysis techniques such as single-shot THz spectroscopy [4].

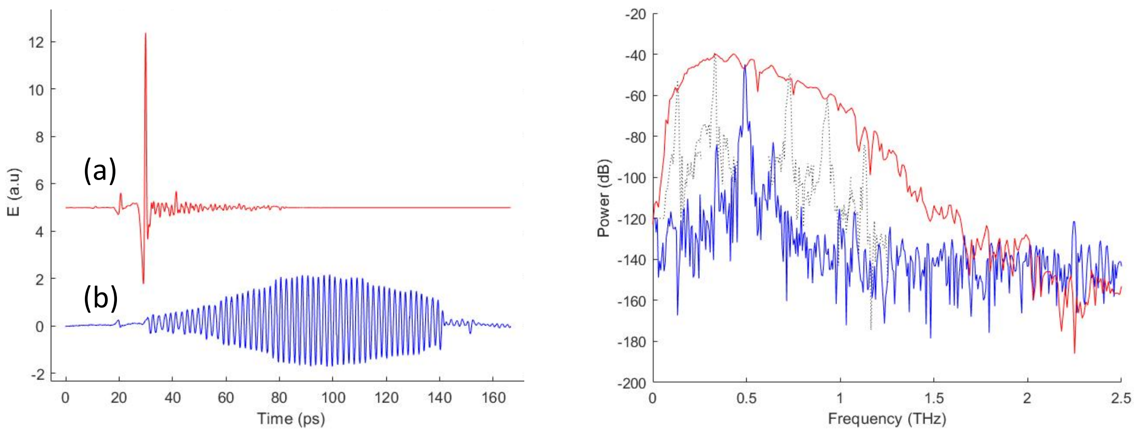

Figure 1: (left) THz pulse emitted and detected with GaAsBi antennas excited by: (a) a pulse of 70fs at 1030nm. (b) delayed chirped pulses of 110ps at 1030nm. The beating frequency is set at 0.5THz. (right) Corresponding spectra for an excitation with the ultra-short pulse (red line) and the delay chirped pulses (blue line). The grey dotted lines show the tunability when the delay between the two pulses is varied.

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Ultrashort lasers on Shape Memory Alloys

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Abstract

Shape Memory Alloys (SMAs) are a unique class of materials which can significantly alter their shape (to a pre-programmed, i.e. *memorized*, state). This change in state is triggered by crossing a transition temperature. There are a number of materials (both metal alloys and polymers) that have this shape memory property. The most well-known is nickel-titanium Ni-Ti alloy (often called nitinol), which has been exploited in a wide range of applications, including in medical devices such as stents due to its excellent biocompatibility. SMA materials can be used as the basis of high force, low volume actuators, where small changes in temperature (few degrees) generate the actuation. By combining SMA materials with other materials to provide mechanical constraint (springback mechanisms) it is possible to design and construct complex 2-way actuation. Such hybrid SMA devices can then be deployed in a wide range of applications, in which heating is used to actuate, and then cooling via heat dissipation (e.g. back to body temperature) results in the SMA becoming much more flexible and hence the mechanical constraint pulls the actuator back to its original position. The temperature at which the phase change occurs that drives the actuation can be tuned by adjusting the alloy composition or with thermomechanical treatment.

My PhD project is focused on the design and manufacture of in-vivo mechanical actuated devices. There are a range of potential applications including new types of surgical tools and implantable drug delivery devices that could be remotely actuated e.g. via induction heating from a suitable electromagnetic field.

Laser-based manufacturing processes including welding, cutting and micro-machining can be used to address manufacturing challenges associated with fabricating miniature hybrid SMA devices. It is important to choose suitable process parameters that will result in a minimal heat affected zone (in which the shape memory effect may be 'lost' due to the high temperature experienced). Pulsed lasers, both nanosecond and pico/femtosecond lasers can provide such processing when combined with suitable scanning approaches to drive an efficient process whilst minimizing heating. Such an approach is used for machining nitinol arterial stents, which are cooled whilst being inserted into the body and then expand on being allowed to rise to body temperature.

At Heriot-Watt University recent research has focused on the use of Laser-Induced Forward Transfer (LIFT) as a suitable 3D microfabrication technique for SMAs, that includes the possibility of locally tuning the SMA properties for particular devices. I plan to also exploit this process during my PhD.

Microcavities in optical fiber by direct laser micromachining

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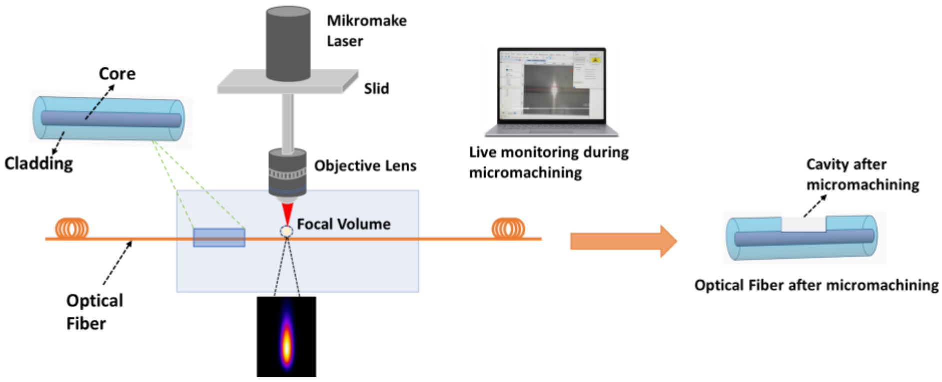
Abstract

Integrating micro cavities into optical fibres is a significant advancement in the photonics field, unlocking new opportunities for developing cutting-edge photonic devices with enhanced features and performance. These cavities help with resonating, enabling the containment and control of light on a small scale which leads to better interactions between light and matter, making it possible to achieve different photonic capabilities such as sensing, modulation, filtering, and lasing.

This study explores the process of creating micro cavities using laser micromachining technology, i.e. Mikromake from Bright System. This technology offers precise control over cavity dimensions and properties, enabling flexibility in design. Furthermore, the study investigates the influence of various factors such as cavity size, shape, and material properties on the performance of integrated micro cavities. Through comprehensive experimental studies, a deeper understanding of the fundamental physics governing cavity behaviour and performance is achieved. This allows for adjusting the cavity design to meet specific needs. Following a careful optimization of laser parameters and cavity design, a rectangular compact cavity measuring 200x50 μm was incorporated into a standard Single mode fiber (SMF) using a 90W laser power. The micromachining process was repeated several times until a precise micro cavity was achieved, eventually reaching the core of the fiber. Once the core of the optical fiber was touched, the micromachining process came to a halt. Once the cavity was integrated, it was tested through optical spectrum analyzer. In the end, the addition of micro cavities to optical fibers using Mikromake laser technology demonstrates significant promise in improving the capabilities of photonic devices. This approach enables accurate management of cavity properties and offers design flexibility, opening up new opportunities for enhancing upcoming photonic systems with better performance and functionality.



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