Tellurite glasses and fibres for the development of coherent Mid-IR supercontinuum source

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Mid-IR (MIR) coherent SC source would benefit high impact applications in fields such as metrology, chemical sensing and biomedical science that lie in the MIR region,

Over the last decade MIR SC generation has been demonstrated using optical fibres made of glass, which possess high transparency in the MIR such as fluoride, tellurite and chalcogenide glasses. For engineering fiber dispersion adequately, most of these research efforts have focused on the development of complex holey microstructured optical fibres (MOFs). However, the inherent properties of soft glasses bring a series of technical drawbacks. In particular, the manufacture of precise microstructure features over extended length is more difficult to achieve than with silica glass, holey with standard optical fiber components is technically challenging.

Coherent MIR SC generation in step index fibre is achievable but indeed requires high numerical (NA) fibre to tailor the Zero Dispersion Wavelength (ZDW) of the fibre and its overall dispersion profile in order to extend the spectrum towards longer wavelengths. For this purpose we have developed a tellurite core and clad glass pair that offer both high NA and compatible thermo-mechanical properties for fibre drawing. The main physical properties of the core and clad glass pair are reporte in table 1. These compositions were designed for enhanced thermomechanical properties with respect to standard tellurite glass compositions.

Glass label	T_g (°C) ± 3 °C	T_x (°C) ± 3 °C	$\Delta T = T_x - T_g$ ± 6 °C	n@2 μm ± 0.001
TBG_1 (core)	353	575	200	1.975
TBG_2 (clad)	380	625	245	1.833

Table 1 – Glass labels, characteristic temperatures measured by DTA analysis and refractive index measured at 2 µm wavelength.

As a first fibre development step, we have produced a multimode fibre with a core diameter of 48±1 um, see Figure 1. Attenuation losses were measured to be 0.26 dB/m at 1.55 μm wavelength. The high quality level of this tellurite fibre in terms of glass homogeneity was also confirmed through near field observations of the fundamental mode propagation along several metres of fibre. Subsequently we have produced a single-mode fibre with a core of 2.75 μm in diameter whose dispersion profile is suitable for the generation of a coherent SC spectrum extending above 3 μm wavelength.

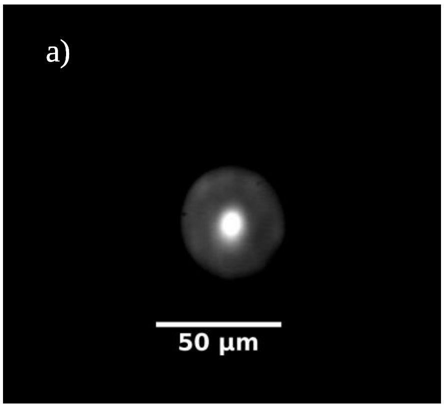

Fig. 1 *– Near fields imaging of the output of a 4.6 m long tellurite glass fibre when exciting fundamental*

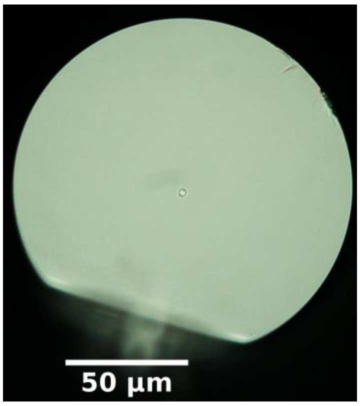

Fig. *2 – Optical Micrograph of 2.75 µm TeO_2 core fibre*

SC generation experiments are ongoing and will be presented and discussed.

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A tunable nanocavity fiber laser based on hybrid halide perovskite nanocrystals

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Downscaling photonic cavity sizes to the optical diffraction limit or even breaking this limit with the use of spaser-based plasmonic cavities is a topic of intense research interest due to the suitability of the respective lasers for a range nanophotonic applications [1, 2]. In the context of device miniaturization, optical micro-/nano-fibers represent a versatile host platform as they combine advantageous features such as strong confinement, large evanescent fields, and tailorable dispersion with robustness and flexibility [3]. Currently, colloidal, hybrid, semiconductor nanocrystals based on the ammonium lead halide perovskites ($CH_3NH_3PbX_3$, X = Cl, Br, I) are among the most studied quantum emitters for integrated light sources due to their high gain coefficients, remarkable photostability, optical nonlinearity, slow Auger recombination and broad tunability [4].

Here, we report on a single-mode, tunable, nanocavity laser realized by focused ion beam milling of silica fiber tapers (Fig. 1*a*). The gain medium, $CH_3NH_3PbBr_3$ nanocrystals, whose emission and absorption bands are shown in (Fig. 1*b*) was introduced in the cavity by the fountain pen nanolithography method [2], in a set-up that capitalized on electrically-driven deposition with atomic force feedback and the use of glass cantilevers as nanofountain pens.

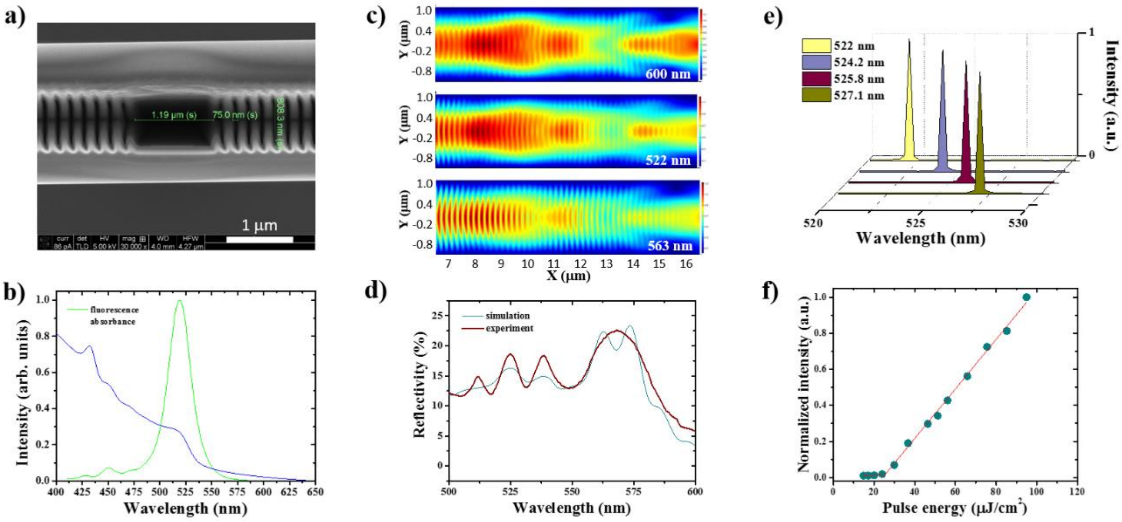

Fig. 1 (a) SEM image of the nanocavity and silica/air distributed Bragg reflectors (DBR) encoded in a tapered silica fiber. **(b)** Absorption and emission characteristics of the $CH_3NH_3PbBr_3$ nanocrystals. **(c)** Simulations of the electric field along a nanocavity with 20 silica/air DBRs for 3 different wavelengths, propagating from left to right. **(d)** Simulated and measured reflectivity spectra of the nanocavity filled with the gain medium. **(e)** Emission spectra from the nanocavity laser obtained by thermal tuning. **(f)** Input-output characteristics of the nanocavity laser for the two different gain media.

Simulations of the electric field along the fiber axis indicate energy confinement in the nanocavity for its resonance wavelength of 522 nm (Fig. 1*c*), whereas at 563 nm and 600 nm, corresponding to the maximum and minimum reflectivity, almost all the light is reflected and transmitted through the waveguide, respectively. The measured and simulated reflection responses of the nanocavity filled with the gain medium over the spectral area from 500 to 600 nm (Fig. 1*d*) are in very good agreement, showing reflectivities above 20%. The emission from the nanocavity source was thermally tuned over a range of 5 nm, as a result of the combined effects of changes in the bandgap and refractive index of the nanocrystals as well as of the period of the Bragg gratings (Fig. 1*e*). The input-output characteristics (Fig. 1*f*), obtained by pumping at 400 nm with 100-fs pulses though one of the fiber ends, indicate a laser threshold of 23 $\mu J \cdot cm^{-2}$. Such devices can be used as laser sensors, particularly in array settings using different gain media for multiple parallel detection. Ongoing work also relates to combating non-radiative Auger recombination by using both two-dimensional perovskite nanocrystals (quantum wells), and heat management methods so as to achieve lasing by pumping with pulses of long duration or continuous-wave sources.

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Mode Analysis of Fiber Beams Using Digital Holograms - Concept and Applications

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Mode-division multiplexing is mooted as an emerging technology to address bandwidth limitations in optical fiber communication systems, and as the name implies, requires encoding and de-encoding of the information stored in the spatial modes of fibers. Additionally, multimode fibers exhibiting extreme large effective areas and, hence, guiding an enormous number of spatial modes, may represent the route towards higher output powers of fiber lasers and amplifiers. While the excitation of higher-order modes in the aforementioned example is by design, degradation of the beam quality from fiber lasers can also be attributed to excitation of higher-order modes [1]. The amelioration of the latter also requires de-encoding of the modal content of the fiber output. In general, there is a need for "modal tools" to study the transmission properties of a waveguide in a modally resolved manner, and this requires techniques for the excitation of spatial modes and their superpositions, and the subsequent modal decomposition of such beams.

Here we present a holistic fiber characterization technique that makes use of digital holography for mode multiplexing as well as for demultiplexing. In contrast to the existing approaches, we excite pure modes and controlled phase-dependent superpositions of modes in the fiber under test. By using a Spatial Light Modulator's ability to rapidly refresh its transmission function, real-time excitation processes and continuous phase variations of induced mode interferences become possible. In addition to the arbitrary multiplexing of modes at the input of the fiber, we achieve a full modal decomposition of the output field from the fiber. We extend existing modal decomposition techniques to perform a complete modal decomposition (including modal amplitudes, phases and polarization states) by a corresponding digital hologram. This yields the full information on the response to the fiber by the excited field. Such control over the input and simultaneous measurement at the output represents a comprehensive all-digital "modal tool" for studying spatial mode propagation in fibers, e.g. modal power loss, intermodal coupling, mode selective delay and should be invaluable for the testing of new fibers for, e.g., encoding information into spatial modes or high-power laser applications.

The concept is applied to a rod-type amplifier as final stage of a MOPA system under development [4], and will help to understand the mechanism of undesired **H**igher **O**rder **M**ode excitation and – based on this – to suppress it.

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Nanoparticles containing glasses prepared using direct doping method

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The fabrication of new rare-earth (RE) doped fibers has attracted lots of research interests, the improvement in the performances of the fibers remaining the prime objective of the studies.

Silica glass, as a host material for fiber, has proven to be very attractive because it has a number of very favorable properties such as wide wavelength range with good optical transparency, zero dispersion at around 1.3 μm wavelength, high mechanical strength against pulling and even bending as well as chemically very stable. However, some potential applications of these fibers suffer from limitations in terms of spectroscopic properties resulting from RE clustering or inappropriate RE local environment when doped into silica. Phosphate glasses have been extensively studied in the field of optical glasses due to their ability to incorporate high amount of dopant (as opposed to silicate glasses). Because the local environment around the RE is of paramount importance for determining the optical properties, there is a constant interest in investigating new RE doped glasses with improved spectroscopic properties.

Another route of interest to improve the spectroscopic properties of the RE doped glass consists of controlling the RE optical response independent of the core glass composition. Different techniques have been developed. One technique consists of synthesizing RE doped nanoparticles directly *in-situ* in the glass. In this method, the glass containing precursor ions is heated above the glass transition temperature to facilitate diffusion of ions inside the glass to form crystal seeds that grow into *in-situ* RE doped nanoparticles. An alternative technique consists of adding RE doped nanoparticles, formed by solution chemistry, in the glass batch prior to or after the melting.

In this presentation, we will review our latest development of novel particles containing glasses using direct doping method. We will show that it is possible to prepare glasses which possess the spectroscopic properties of the nanoparticles.

This work is also in collaboration with Dr. Lastusaari from Turku University (Finland) and Dr. Benoit Glorieux from Bordeaux University (France), dr. Nadia G. Boetti from Istituto Superiore Mario Boella (Italy) and Dr. Diego Pugliese at Politecnico di Torino (Italy).

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Recent progress in development of mode-locked holmium fiber laser

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Mode-locked fiber lasers emitting in the wavelength range beyond 2 µm are promising for a number of applications including environmental sensing, material processing, medicine etc. Both thulium and holmium mode-locked fiber lasers can operate beyond 2 µm, but holmium tends to demonstrate longer emission wavelength (longest wavelength of 2138 nm have been shown recently [1]). Practical applications require the lasers to be compact and stable. To fulfill these requirements all-fiber configuration should be implemented, preferably combined with the diode pumping. Important source of instability arises from the nonlinear polarization rotation effect in the fiber laser cavity, and this effect is very sensitive to vibrations and temperature fluctuations. The solution is to use the polarization-maintaining fibers. All-PM fiber lasers have been demonstrated based on Yb, Er, and Tm–doped fibers. Here we demonstrate for the first time the diode-pumped all-fiber all-PM holmium mode-locked laser.

The laser cavity setup is shown in Fig.1(a). FBG-stabilized single-mode laser diode with output power of 0.3 W at 1150 nm was coupled into the fiber cavity by fused fiber WDM coupler made using PM fiber. Single-clad PM holmium-doped fiber with 8 µm core diameter and ~15 dB/m core absorption at 1150 nm was used as an active fiber. Stable self-starting mode-locking regime was initiated and supported by a butt-coupled GaSb-based SESAM with modulation depth about 5%. Sagnac fiber loop formed by splicing together two ports of the PM fused fiber WDM coupler acted as an output coupler. PM fiber isolators were implemented to protect both the laser and the pump diode from the possible back-reflections. No polarization controllers were used in the cavity.

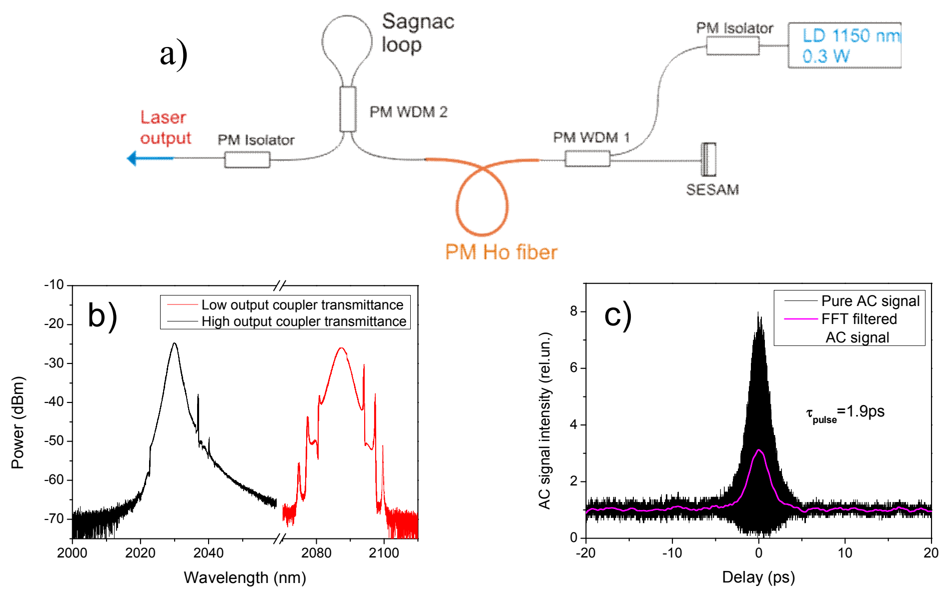

Fig. 1 The experimental setup of a holmium fiber laser (a); the optical spectrum (b) and autocorrelation trace (c) of a laser emission.

The laser operated at a pulse repetition rate of 17.5 MHz. Two output couplers were tested with transmittance of about 10% (low transmittance) and 90% (high transmittance) around 2090 nm. For the low transmittance output coupler the laser emitted around 2090 nm (3.7 nm spectral FWHM) with average output power of about 0.8 mW. Series of Kelly sidebands (Fig. 1b) indicate the fundamental soliton operation of the laser. The laser pulse energy was below the sensitivity limit of our autocorrelator. Implementation of the output coupler with high transmittance led to blue-shift of laser emission to 2030 nm and spectral narrowing (2.3 nm spectral FWHM). The average output power increased up to 8 mW (0.45 nJ pulse energy). Kelly sidebands were strongly suppressed by the high output coupling rate, but the increased pulse energy allowed measuring the autocorrelation trace (Fid. 1c). Pulse duration was estimated to be 1.9 ps, time-bandwidth product of 0.32 indicates nearly transform-limited pulses. The polarization extinction ratio of laser output was measured to be >15 dB. To the best of our knowledge, this is the first demonstration of all-PM all-fiber holmium fiber laser.

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Design of sensing elements for the mid-IR spectroscopy on the base of electromagnetic theory of optical fibers

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For creation of the fiber-optic spectroscopic tools in the mid-IR, broadband sources of coherent radiation and sensing elements based on optical fibers are to be designed as two counterparts of one problem of the mid-IR spectral range exploration. For analysis of the broadband radiation launching into a sensing element and the element functionality, this design is to be based on electromagnetic theory of optical fibers. However in theoretical consideration of the evanescent wave sensors base on multimode fibers, ray optics was previously used.

In [1], we have demonstrated that consideration of electromagnetic radiation propagating in a multimode fiber as a set of evanescent modes is efficient for revealing the peculiarities of the evanescent wave sensing in the mid-IR.

In this presentation, we focus on analysis of sensitivity and output characteristics of the sensing elements (made of multimode chalcogenide fibers) of various shapes and refractive index profiles, in theory and in spectroscopic measurements in the range of wavelengths of 3 – 10 microns. At first, properties of the evanescent modes of an optical fiber embedded into an absorbing medium will be briefly discussed. Next, peculiarities of the fiber-optic spectroscopic sensing in comparison with the traditional mid-IR spectroscopy will be highlighted. These peculiarities arise from the evanescent modes having different magnitudes of their attenuation coefficients, which depend on radial and azimuthal orders of the modes. Main attention will be paid to related tasks of various ways of filtering of the evanescent modes: at launching input radiation into a sensing element, at irregular parts of sensing elements.

In addition, the following problems related to fabrication of chalcogenide fibers will be briefly discussed: 1. fabrication of chalcogenide fibers with low optical losses in a given spectral window for sensing; 2. fabrication of chalcogenide fibers with low optical losses and group velocity dispersion for supercontinuum generation; 3. their junction and functionality.

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Independently tunable dual-wavelength fiber laser based on a discrete fiber Bragg grating array

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Abstract: We present a discrete tuning concept based on a theta ring cavity and an FBG array as spectral filter that enables an independently tunable dual-wavelength emission. Pulse synchronicity is analyzed based on a Time-Delay Spectrometer.

Tunable lasers show an increasing interest due to rising applications in the broad fields of e.g. spectroscopy, biophotonics and medical technology. Fiber lasers provide an excellent platform to develop novel tunable lasers. They not only combine an excellent beam quality and good efficiency with broad gain regions of rare-earth doped fibers, but particularly enable industry leading designs based on a fiber-integrated setup with robust and compact systems, user-friendly operation and low-maintenance requirements. Recently, a novel tuning concept has been introduced based on a fiber-integrated theta cavity fiber laser (TCFL) layout as shown in Fig. 1a and a discretely chirped fiber Bragg grating (FBG) array as versatile spectral filter using optical gating to control the emission wavelength λ_L [1]. This concept has been demonstrated with a discrete tuning range of 25nm utilizing 11 FBGs.

The TCFL layout enables for the first time FBG array tuned lasers with constant repetition rate over the full tuning range. This not only ensures stable pulse properties over the emission range, but also provides the possibility of a novel operation mode with 2 tunable emission wavelengths λ_{L1} & λ_{L2} oscillating at the same time [2]. Tunable dual-wavelength sources open new application fields like e.g. CARS spectroscopy or extending the spectral range of lasers to novel frequency regimes, e.g. MIR or THz [3] by exploiting nonlinear frequency conversion effects.

In this work, we present the unique operation mode of independently tunable dual-wavelength emission of a single fiber-integrated laser oscillator by simply adapting the electrical control signal of the TCFL. With an FBG array of 11 gratings, we demonstrate all $\binom{11}{2} = 55$ wavelength pairs covering 25nm tuning range around 1070nm as shown in Fig. 1b. Because prospective applications rely on a synchronized emission of both wavelengths, pulse synchronicity is studied based on a home-build Time-Delay Spectrometer (TDS). The investigation demonstrates synchronized emission wavelengths even down to a single-pulse analysis.

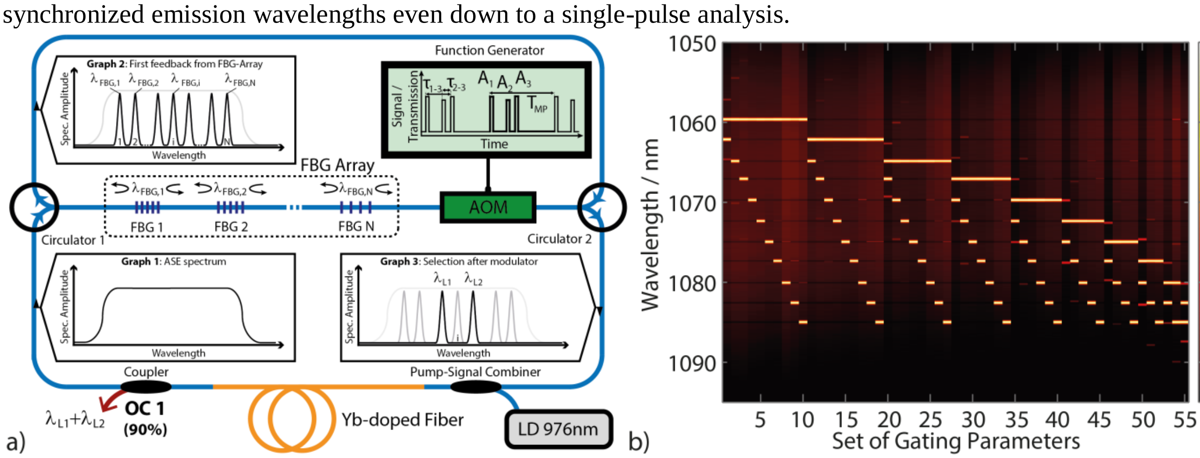

Fig. 1. Part a) shows a sketch of the experimental setup of the tunable TCFL using an FBG array as spectral filter. Pulse formation is sketched in the spectral domain along the first round trip by Graph 1 to Graph 3. The dual-wavelength mode is generated by optical gating of pulses applying three transmission windows at the acousto-optic modulator (AOM) with distinct timing (T_{MP}, $\tau_{2\text{-}3}$, $\tau_{1\text{-}3}$) and amplitudes (A_1, A_2, A_3). The intensity plot in part b) shows measured dual-wavelength spectra recorded with different settings of the gating parameter. With a tuning range of 25nm, all possible 55 wavelength pairs have been demonstrated successfully.

Funding by the Federal Ministry of Education and Research (BMBF, FKZ: 13N13865) is gratefully acknowledged.

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Interferometric Measurement of Chromatic Dispersion by Synchronized Control of Supercontinuum Pulse Overlapping

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ABSTRACT

Stable supercontinuum sources offer very significant advantages to characterize photonic devices: full VIS-NIR spectrum availability, high spectral power density and low-loss coupling, among others. Not only amplitude, but also phase properties can be measured comfortably. In this work we present an interferometric method to measure chromatic dispersion of photonic devices (e.g. photonic crystal fibers) using a pulsed FYLA SCT1000 supercontinuum source of fixed repetition rate. A synchronized control of the pulses overlapping allows an optimum visibility of fringes, resulting in very high resolution dispersion measurement.

CHROMATIC DISPERSION MEASUREMENT

Early in 2004/2005 SC sources are proposed and used to characterize 2D and 3D photonic crystals [1,2]. Now the use of commercial SC sources is very generalized in labs. Our FYLA SCT1000, for instance, offers a very broadband emission with SPD close to 1 mW/nm, consisting of a train of white pulses of few ps timewidth, trigger output for synchronized measurements and very stable emission, with full spectrum average power stability < 0.5% and peak to peak stability < 1% in VIS region and < 0.6% in NIR region. (Stabilities refer to standard deviation over mean value). Figure 6 illustrates an example of the measurement of dispersion of photonic crystal fibers. The sample to measure, which can be an optical fiber or any photonic device is placed in this interferometer. Interferences obtained with different displacements give values of dispersion at different wavelengths. The standard way is to use an SLED at each band. This makes the measurement long and tedious. These SLEDs can be replaced by a single FYLA SCT500 to obtain the dispersion curve in a fast and very robust way. Since the source is pulsed with a fixed rep rate, delay can be easily controlled to overlap properly light from arms of the interferometer. With a single source the complete dispersion curve is obtained with resolution below 1 nm.

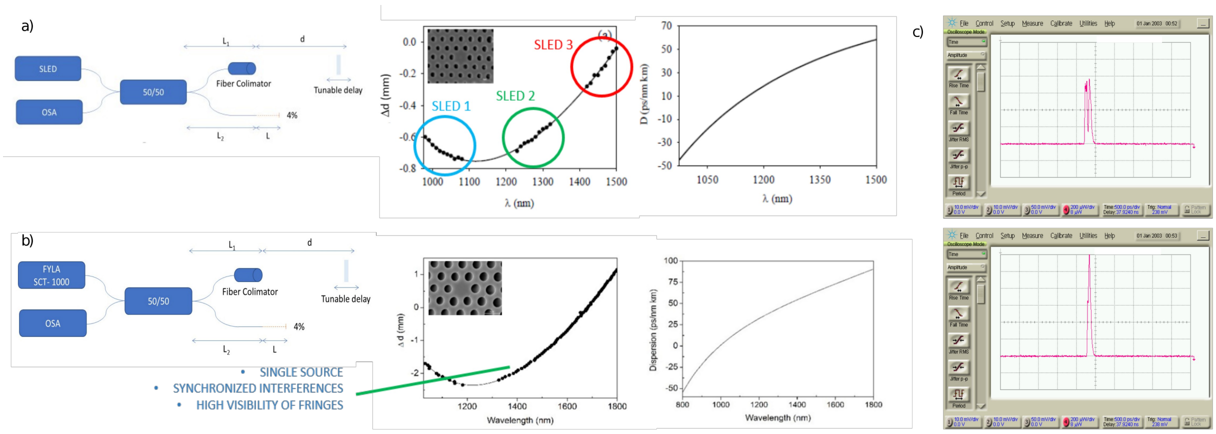

***Figure 1. a) Left**: Interferometric setup to obtain dispersion curve of a photonic device with SLEDs as illumination source **Right:** obtained dispersion curve of a photonic crystal fiber using 3 SLEDs of different wavelength band emission **b)** Equivalent setup and dispersion measurement obtained with a single supercontinuum source FYLA SCT100. **c)** Oscilloscope traces of the synchronized control of pulse overlapping. **Up:** Pulse travelling through arm 1 is delayed with regard to the pulse travelling through arm 2 **Down:** Time overlapped pulses, implying efficient interference with optimum visibility of fringes.*

CONCLUSIONS

An interferometric method to measure chromatic dispersion using a single picosecond pulsed SC source of fixed repetition rate is presented. Optimum visibility of fringes has been obtained by synchronized control of pulse overlapping within the full VIS-NIR range down to a resolution of less than 1nm. This method simplifies very significantly the long and tedious state-of-the-art interferometric methods based in several SLEDs as illumination sources.

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Event: Cost Meeting in Jena, September 18th – 19th 2017

Abstract title: Heraeus Quarzglas Fiber Laser Solutions

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Company: Heraeus Quarzglas GmbH & Co. KG, Quarzstr. 8, 63450 Hanau, Germany

Heraeus Quarzglas GmbH & Co. KG is part of the family owned Heraeus technology group and has a more than 100 years expertise in production, processing and refinement of natural quartz glass and high purity fused silica for semiconductor and photonic applications.

As a technology and market leader in Specialty Fiber Optics, Heraeus has a broad product portfolio of the specialty fiber products for high power laser applications. One of our core competences in Specialty Fiber Optics is the plasma outside deposition process (POD), which allows us to incorporate a unique high amount of Fluorine into the glass matrix to down-doped the refractive index of fused silica and produce the cladding glass for multi-mode step index fiber preforms. Depending on the desired wavelength range and the laser application, different types of high purity fused silica materials are available in house to form performs and tubes.

We have invented a process to manufacture rare earth doped fused silica several years ago, which can be utilizes as a core material for Yb-doped laser fibers. The unique material features an excellent axial and radial homogeneity in combination with a large batch size. Those features enable us to provide novel laser fiber designs with core diameters above 100 µm.

We use our core competencies such as POD, mechanical machining, hot forming, sleeving of core rods, and our expertise in un-doped and doped fused silica to provide a large bunch of products for laser and fiber laser applications. These products are for example Yb-doped silica rods, fiber laser preforms, custom tailored laser fibers, structured cladding tubes, which are used to form the pump cladding, un-doped and highly Fluorine doped tubes for photonic crystal fibers (PCF) and pump combiners as well as passive preforms for transmission fibers.

We continuously work together with partners, institutes and companies to improve our material properties and quality. We developed and strengthened our expertise in the field of fiber laser for more than 10 years in several public funded and bilateral customized fiber laser projects. We gratefully thank the German Ministry of Research and Education and the European Union for supporting our work.

Thulium doped germanate glasses and fibres for 2 µm lasers and amplifiers

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Abstract
New compositions of Tm^{3+}-doped germanate glasses were developed in the system GeO_2-PbO-ZnO-Na_2O-Nb_2O_3-SiO_2-Al_2O_3. The melting procedure was carried out at 1250˚C then the glass was cast into a brass mold preheated at Tg-10°C and annealed for 5 hours at this temperature.
Three glass compositions, namely Ge_01, Ge_02 and Ge_03, were prepared to be thermo-mechanically cross-compatible while offering a numerical aperture as large as possible when used as core/cladding glass pairs for fibre fabrication. The glass transition temperatures (Tg) were measured by differential thermal analysis technique using the PerkinElmer Diamond TG/DTA instrument, to be 497 °C, 503 °C and 506 °C for glasses Ge_01, Ge_02 and Ge_03, respectively. Such high transition temperatures (for this glass composition and as comparted to silicate glasses) make the fabricated glasses suitable for manufacturing glass lasing structures able to handle high average powers. Their refractive index was measured by ellipsometry using the MC05-Woolham-Ellipsometer. The minimum NA we achieved was 0.22, which is a good starting point to make a single mode fibre.
As a preliminary fibre drawing test, we have developed a passive fibre made of Ge_01 glass as core, and used a commercial SF6 glass from SCHOTT as cladding glass. An initial rod (120mm long and 11.5mm in diameter) of Ge_01 glass was drawn into a cane of 3.7 mm in diameter in a drawing tower. A commercial SF6 glass billet was extruded into a tube of 10.5mm of outer diameter and 4.2 mm of inner diameter. The Ge_01 glass rod and SF6 tube were drawn together into a fibre of 157 ± 1 µm at a speed of 5.4 m/min. The fabricated fibre was again pristine with no sign of crystallization. A cross-sectional view of the fibre is shown in Fig. 1. The fibre core was measured to be 60 ± 1 µm. The loss of the fibre were assessed by cut-back technique using a laser source operating at a wavelength of 1.55 µm. The measured loss of 1.2 dB/m confirmed the absence of crystallization (which would have otherwise produced significantly higher values), indicating that the glass is able to withstand the double thermal cycle necessary for fibre fabrication, without crystallising.

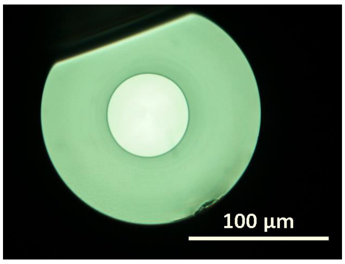

Fig.1. Transmission micrograph of fibre made from Ge_01 core glass and SF6 glass cladding

Photoluminescence and laser behavior of (Y,Gd)O2: Eu, Nd, Yb ceramics

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(Y,Gd)O2: Eu, Nd, Yb ceramics with different doping concentration were fabricated by the solid-state displacement reaction and low temperature calcination, and their fluorescence properties and laser behavior were investigated. Dependence of ceramic transparency on temperature and on size of nanoparticles is investigated. It is found that both the fluorescence intensity and lifetime depend deeply on both the doping concentration of Eu, Nd, Yb ions and the annealing treatment.

Oxyfluoride nano-glass-ceramics doped with rare-earth ions

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The growing field of photonics demands the design of new rare-earth (RE)-based optical materials for their use in optical telecommunications, solid-state lase and other applications. Oxyfluoride glass-ceramics [1,2], i.e. glasses that undergo a controlled crystallization, are promising RE-hosting candidates that combine the good thermal, chemical and mechanical stability of oxide-glass matrices with the excellent optical properties due to the low-phonon-energy fluoride nanocrystals. The optical properties improve significantly thanks to the controlled crystallization of certain crystalline phases such as LaF_3, $NaGdF_4$, $KLaF_4$, etc. [3]

Glass fibers doped with Nd3+ were prepared using both single crucible method and the rod-in-tube method. Glass fibers with diameters ranging 50÷500 µm were obtained using the single crucible method, from glass of composition $55SiO_2$-$20Al_2O_3$-$15Na_2O$-$10LaF_3$ (55Si-10La) doped with 0.1 and $2Nd^{3+}$ (in mol %) [6]. Glass fibers 30 cm in length were previously crystallized at 640 ºC-40 h and then covered with a silica cladding using sol-gel method. The coating was sintered at 450 ºC during 1h to obtain a dense SiO2 cladding. A crystallization delay was observed as compared to bulk samples but similar structure and optical properties were obtained. HRTEM and EDXS analysis showed the precipitation of LaF_3 nano-crystals in the glass matrix and Nd^{3+} enrichment inside them. Optical measurements reproduced optical properties of pure Nd^{3+} doped LaF_3 crystals [4].

By the rod-in-tube method $0.1Nd^{3+}$ doped $70SiO_2$-$7Al_2O_3$-$8Na_2O$-$8K_2O$-$7GdF_3$ (70Si-7Gd) optical fibers, in mol%, were prepared in Bialystok in a STSM MP1401 stage. Glass rods 5 cm in length were polished to guarantee a good contact between core and cladding during the whole drawing process. Good fiber quality was obtained and spectral losses of 16 dB/m in the infrared region around 1 µm were measured.

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ACTPHAST – A shining light for Photonics Innovation in Europe

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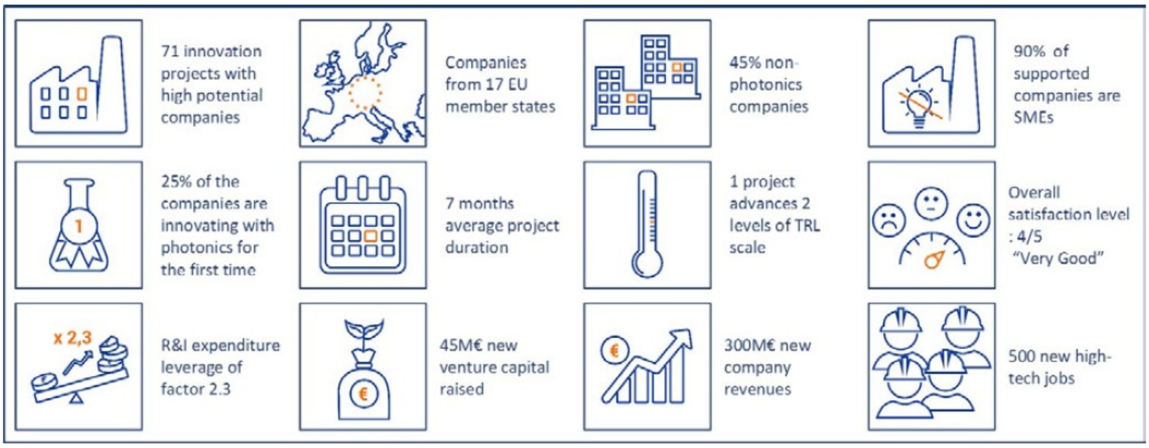
ACTPHAST comprises the state-of-the-art expertise and technologies of 23 of the top research institutes in photonics from across the different European networks (the ACTPHAST Partners), centrally coordinated by Brussels Photonics (B-PHOT) of the Vrije Universiteit Brussel, with the perspective to reach out to an ever more extensive network of European companies.

A vast number of companies across the EU, particularly SMEs, often encounter several constraints in their innovation efforts given the high administrative burden when accessing cutting-edge technologies as well as the lack of in-house expertise in photonics. This is why the ACTPHAST model comes in to provide a single entry point into a prototyping supply chain across a wide spectrum of photonics technology platforms ranging from fibre optics and micro optics, to highly integrated photonic platforms. Its 100% subsidized format available to any SME (50% for large-scale companies) can bring a substantial impact on the companies' business growth in terms of revenues and job creation.

In its first 3 years of programme evaluation, the ACTPHAST supported companies expect to generate almost 300M € in new revenues and 500 new EU jobs, as well as over 45M € in new venture capital. This could meet or even exceed the Key Performance Indicators (KPIs) targets, which assess the degree of compliance with the programme objectives. What is more, ACTPHAST receives a very positive feedback from participating companies in terms of customer satisfaction levels: an average score of 4 out of 5 (very good or excellent), according to the ACTPHAST assessment criteria.



Major achievements of ACTPHAST in relation to the KPI

The presentation explains how ACTPHAST operates, details the impact it has achieved so far and mentions company support projects pertaining to fibre laser technology.

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Action MP1401

For the special session for Early Career Investigator and Women researchers

Applications with fluorescent fibers

Summary:

1. SPR Based Hybrid Electro-Optic Biosensor for β-Lactam Antibiotics Determination in Water, using fluorescent fiber as emitter

The present work aims to provide a hybrid platform capable of complementary and sensitive detection of β-lactam antibiotics, ampicillin in particular. The use of an aptamer specific to ampicillin assures good selectivity and sensitivity for the detection of ampicillin from different matrice. This new approach is dedicated for a portable, remote sensing platform based on low-cost, small size and low-power consumption solution. The simple experimental hybrid platform integrates the results from the D-shape surface plasmon resonance plastic optical fiber (SPR-POF) and from the electrochemical (bio)sensor, for the analysis of ampicillin, delivering sensitive and reliable results. The SPR-POF already used in many previous applications is embedded in a new experimental setup with fluorescent fibers emitters, for broadband wavelength analysis, *low-power consumption and low-heating capabilities of the sensing platform.*

Keywords: electrochemical aptasensor, SPR aptasensor, β-lactams detection, plastic optical fiber, fluorescent fiber.

2. Low-cost Quasi-distributed Position Sensing Platform based on Blue Fluorescent Optical Fiber

Fluorescent optical fibers are used in a variety of sensing applications. In this work, we propose a novel position sensor implemented with a blue fluorescent optical fiber and a spectrometer. The novelty and advantage of the proposed solution is that it performs sensing at only one fiber end, in comparison to sensing at both fiber ends as formerly proposed in literature [1, 2]. Side-illumination of the fiber generates fluorescence with 3 spectral peaks. Fluorescence intensity varies with the distance between the spectrometer and the incidence point. Axial application of incident light via fiber bending changes the fluorescence spectrum. Accordingly, the position of the incident light source is determined by joint monitoring of the fluorescence wavelength and intensity.

Keywords: Fluorescent fiber, fiber bending, position sensor, optical sensor.

Motivation and Description of Work

1. SPR Based Hybrid Electro-Optic Biosensor for β-Lactam Antibiotics Determination in Water, using fluorescent fiber as emitter

The antibiotics have revolutionized the treatment of infectious diseases, being used not only in human, for prophylactic and treatment purposes, but also in animals and in agriculture. Nevertheless, their excessive and inappropriate use has resulted in the spread of allergy reactions related to antibiotics intake and in the development of antibiotic resistance, a serious threat to the public health, with over 25.000 people dying every year in the European Union alone from infections caused by antibiotic-resistant bacteria. If this trend continues, 300 million people worldwide are expected to die prematurely due to antibiotic resistance over the next 35 years. Antibiotic resistance has direct consequences on human and animal health and also heavily impacts for the economic costs, resulting in extra healthcare costs and loss in productivity in EU of at least €1.5 billion each year [1, 2]. Moreover, the environment becomes polluted with antibiotics from antibiotic waste discharged into local ground-waters and rivers from industrial

production and hospital use, from the runoff from farms and from our own sewers, increasing the antibiotic resistance. The World Health Organization (WHO) report from 2014 clearly states that resistance to common bacteria has reached alarming levels in many parts of the world indicating that many of the available treatment options for common infections are becoming ineffective. Thus, WHO strongly recommends an intensification of the prevention and control measures [2].

The 2015 report of the European Medicines Agency (EMA) about the consumption of antibiotics for veterinary use showed that the β-lactam antibiotics are among the most employed classes of antibiotics [3]. For this reason, our study is focused on the detection of ampicillin, a widely used antibiotic from this class. Ampicillin (Figure 1A) is semi-synthetic antibiotic from the class of aminopenicillins. Being active against both Gram-negative and Gram-positive bacteria, ampicillin is intensively used in human and veterinary medicine [4].

The most used methods to quantify pharmaceuticals in water are gas chromatography coupled with mass spectrometry (GC-MS) or tandem mass spectrometry (GC-MS/MS), and liquid chromatography with mass spectrometry (LC-MS) or tandem mass spectrometry (LC-MS/MS) [5-6].These analytical techniques are able to detect target compounds down to the nano-gram per liter level. However, these efficient methods display some drawbacks like expensive laboratory instruments, requiring skilled technicians, time-consuming methodologies, resulting in long analysis time, the use of pollutant solvents and the difficulty to perform rapid field analyses, making necessary the development of new sensors to overcome these limitations [7]. Electrochemical and optical (bio)sensors appear as an interesting and low-cost alternative for the antibiotics detection, since they present fast analytical response and they can be easily miniaturized to achieve portable sensors that can detect low levels of antibiotics with high selectivity.

Results

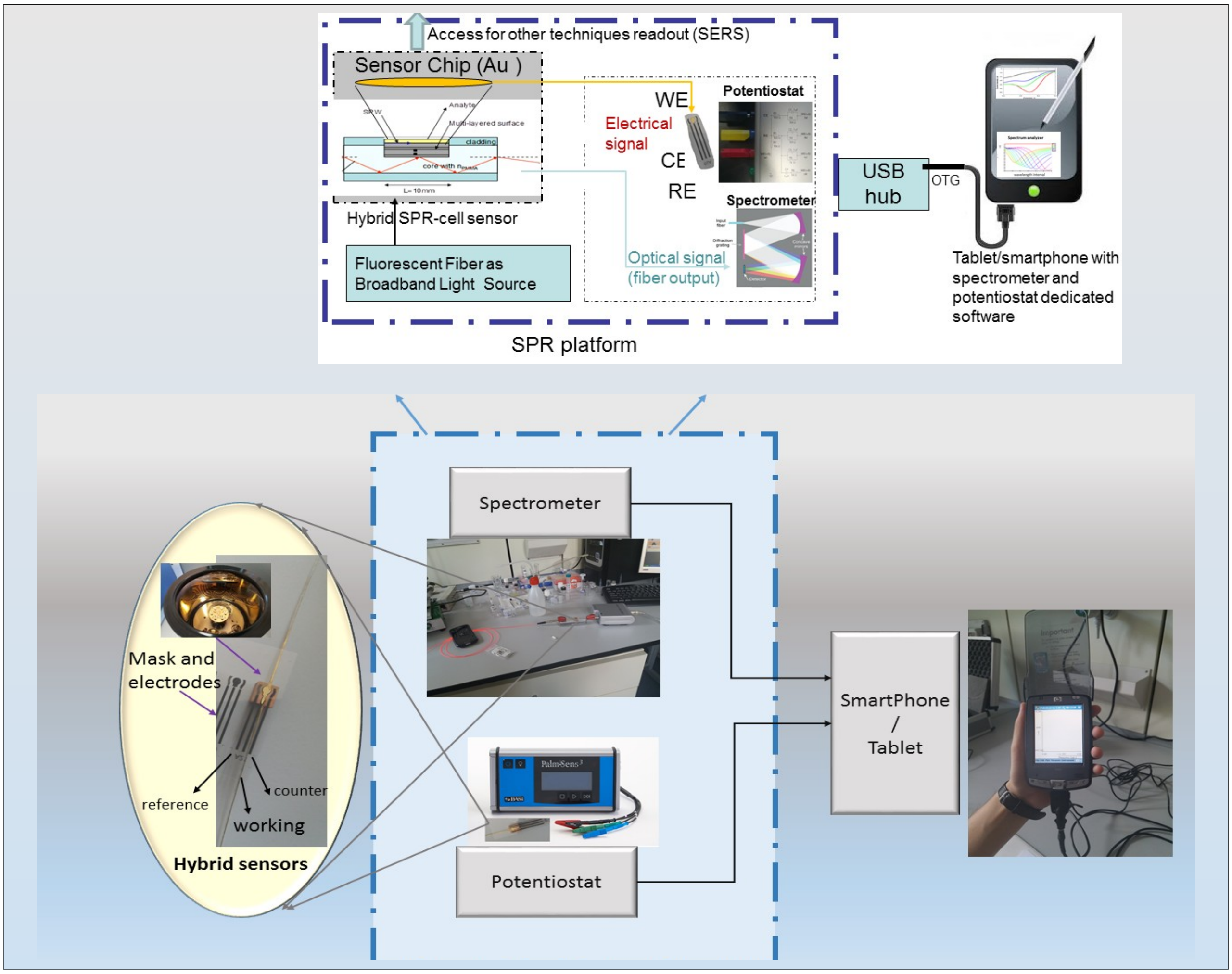

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Figure 1. Hybrid sensor platform

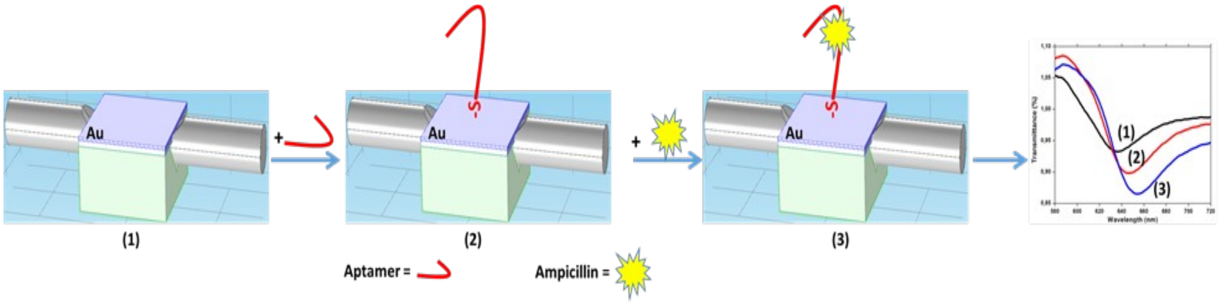

Figure 2. SPR sensor development

This mass-sensitive techniques depicts a relation between the concentrations of small molecules and SPR wavelength shift. The Au nanoparticles enhanced the SPR response for small molecules detection. The three curves in the graphic of Figure 2 corresponds to different time analysis in activation process of the chip surface. The resonance wavelength can occur due to adsorption of molecules on the Au chip surface. The kinetic parameters can be estimated from the optical response curves obtained. Preliminary results of hybrid sensor tests, confirm the feasibility of the proposed optical approach.

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2. Low-cost Quasi-distributed Position Sensing Platform based on Blue Fluorescent Optical Fiber

A fluorescent optical fiber is an optical fiber which generates fluorescence as a response to an incident phenomenon, usually an incident light. In this work, we propose a quasi-distributed position sensor, implemented with a blue fluorescent fiber and a spectrometer (figure 1). The spectrometer is used to determine the wavelength of the fiber fluorescence. A LED, deployed at distance *d* from the spectrometer end of the fiber, generates the incident light to create fluorescence. Additionally, bending points were deployed along the fiber.

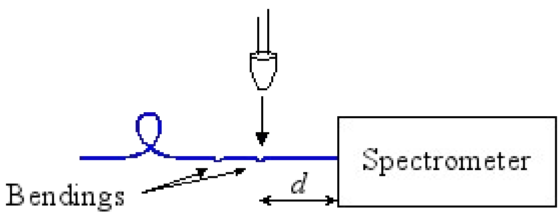

Fig. 1: Block diagram of the quasi-distributed position sensor.

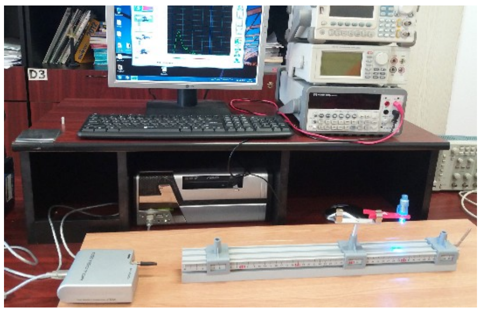

Fig. 2: Test setup of the quasi-distributed position sensor.

Operation of the proposed optical position sensor relies on two phenomena that take place within the fluorescence fiber. The fiber fluorescence intensity exhibits an exponential decrease with the distance *d* in-between the incidence point and the fiber end, as prescribed by the Beer-Lambert law [1 – 3]. Second, if the bending is larger than the fiber critical angle, the incident light enters axially into the fiber and changes the fluorescence spectral characteristics. Accordingly, position sensing is performed by monitoring the wavelength and the intensity of the fiber fluorescence.

Results

The fluorescence spectrum of the blue fiber exhibits 3 peaks (figure 3): blue, green and red. The blue fluorescent fiber was side-illuminated with 4 LED colors: blue, green, white and red, confirming the exponential attenuation of the fluorescence intensity (figure 4). Nevertheless, blue incident light generates the largest fluorescence.

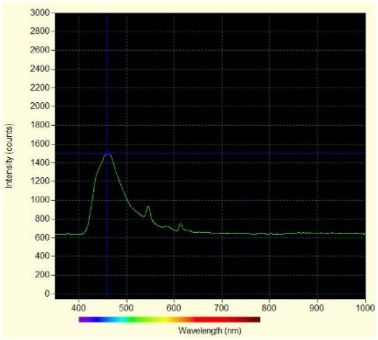

Fig. 3: Fluorescence spectrum of the blue fiber.

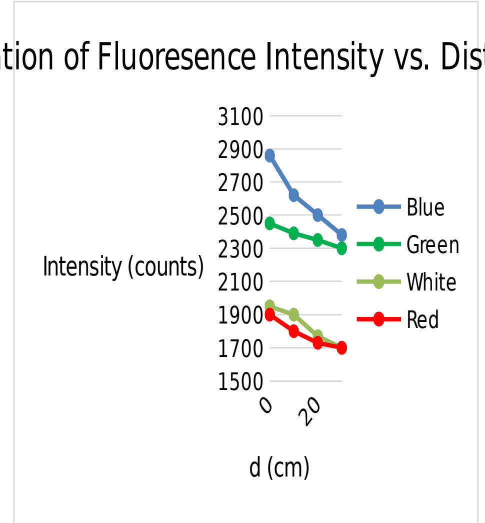

Fig. 4: Variation of the fluorescence intensity vs. distance, for various incident light colors.

At this stage of the development flow, two fiber bending points are considered at 40cm and 80cm from the spectrometer respectively. The test scenarios assumed the application to the bending points of green light (figure 5 and figure 6) and red light (figure 7 and figure 8). As illustrated, the position of the incident light is discriminated in both wavelength and intensity.

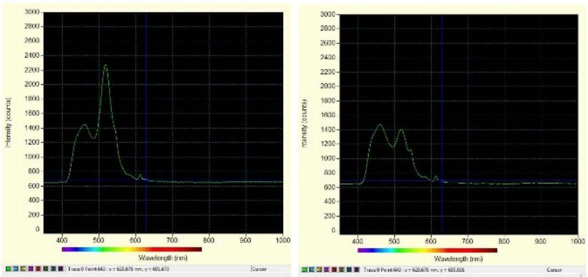

Fig. 5: Green light applied to the 40cm fiber bending.

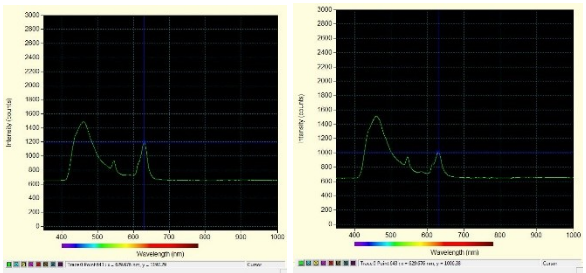

Fig. 6: Green light applied to the 80cm fiber bending.

Fig. 7: Red light applied to the 40cm fiber bending.

Fig. 8: Red light applied to the 80cm fiber bending.

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3. Optical data transmission with fluorescent fiber (idea: LIFI application)

The side photosensitivity along the fluorescent fiber is used for simple data transmission. A side fiber emitter Tx and in fiber data receiver Rx are used in a simple configuration like in figure 1.

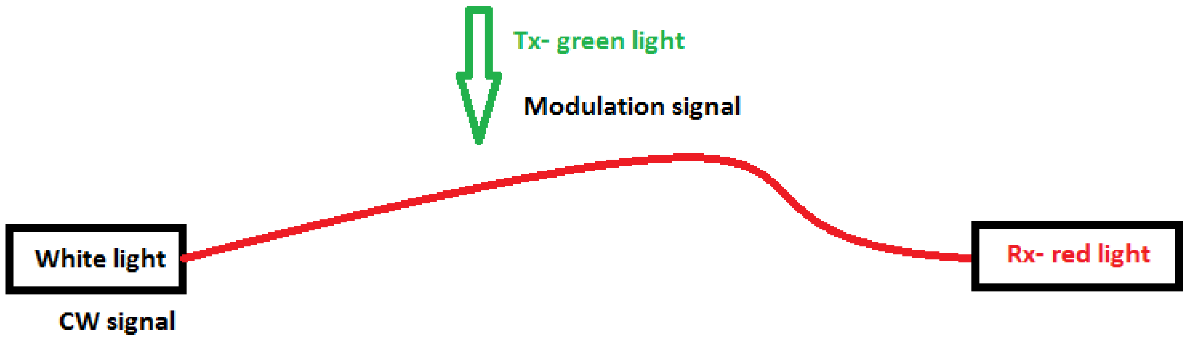

Figure 1. Side emitting Tx signal modulation (work in progress)!!!!!!!!!

Fabrication of high aspect-ratio microchannels on diamond surface by pulsed Bessel beams laser machining

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Abstract

Diamond substrates and films have been adapted for many uses because of the material's exceptional properties such as the highest thermal conductivity, high mechanical hardness, wide bandgap, very good optical properties, chemical resistance and biocompatibility. On the other hand, in the last few years, the femtosecond (fs) laser technology has seen a considerable growth in scientific and manufacturing communities for its precision and damage free capability [1] enabling the micromachining of different materials for photonics applications [2]. In the case of surface machining of diamond the use of the laser microfabrication technology has been mainly limited to investigating the periodical sub-micron ripples observed on the sample surface after laser irradiation [3], and to the generation of channel-like structures with an average depth of less than half micron [4].

Here we present a novel laser machining method based on the use of pulsed Bessel beams [5] to create, by single pass transverse writing, high aspect-ratio three-dimensional trench-like microstructures on a synthetic monocrystalline diamond substrate. By tuning the laser pulse energy and the writing speed, it is possible to control the features of the surface trenches obtained and to optimize the resulting high aspect-ratio and low roughness microstructures. In particular the presented results show the possibility to fabricate deep and precise microfluidic channels on biocompatible diamond substrates, offering a great potential for biomedical sensing applications.

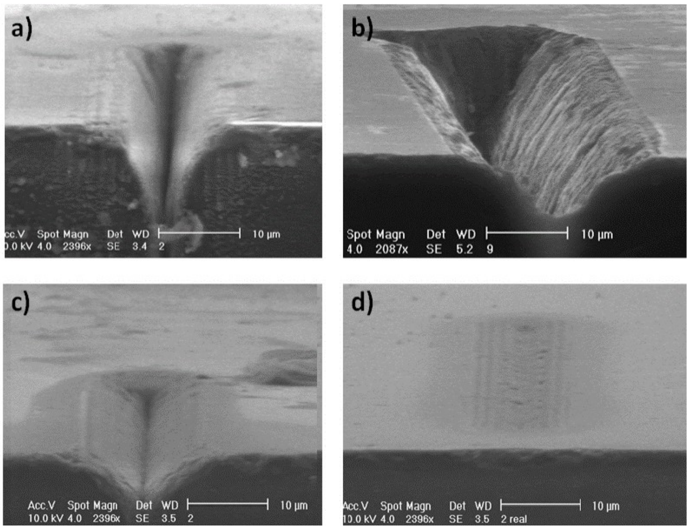

Fig 1: Example of microtracks (SEM images) machined in single pass on the diamond surface by means of a femtosecond pulsed Bessel beam with core size of about 0.7 µm (FHWM) in air, for different transverse writing speeds and pulse energies.

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Advances in bioresorbable optical fibers for light delivery and sensing

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Several biomedical applications require the use of optical fibers, since they are minimally invasive, highly flexible, immune to electromagnetic radiation and able to guide light both for therapeutic and sensing purposes. Traditional fibers include silica based materials thanks to its outstanding performance and biocompatibility. However, calcium phosphate glass (CPG) based optical fibers have been recently demonstrated to provide resorbability in biological media, thus allowing for deep tissue operation without the need of explant surgery to remove the fibers.

We report on the recent advances on the use of newly designed CPG optical fibers carried out within the framework of the current COST Action. The first consists in the successful fabrication of laser inscribed structures both on fiber and glass slabs using a scanning femtosecond laser source operating the visible wavelength region. Another activity concerns testing the CPG optical fibers as probe for pH sensing in physiological environment.

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Temperature Sensor based on a Suspended-web Microstructured Fiber

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In this work, a spatial filter based on a suspended-web microstructured fiber is proposed as a temperature sensor. The sensing head presents high sensitivity to temperature and quite low sensitivity to applied strain and variation of curvature radius. The proposed sensor configuration consists of a small section of a suspended-web fiber (~0.5 mm) spliced between two standard singlemode fibers (SMF28e), interrogated in transmission. The suspended-web fiber was designed and fabricated at IPHT facilities (ref. 574b1). In the fabrication process, it was used a stacked preform (Fig. 1a), consisting of two thin walled capillaries (outer diameter: OD 3.4 mm, inner diameter: ID 3.2 mm) placed in an overcladding tube (OD: 30mm, ID: 7 mm). The result is a microstructured fiber containing four central air holes and a suspended-core that forms a web shape (Fig. 1b). The fiber used in the proposed experiment has an outer diameter of 122.8 μm and a web diameter of 25.1 μm. The core has a rectangular shape and it is suspended by four bridges with a thickness of 0.35 μm each; the core dimensions are 23 μm and 0.35 μm in width and thickness, respectively. Due to the small thickness of the suspended-core (0.35 μm), light travels inside it as a multimode planar waveguide, obtaining at the output a filtering spectral behavior (Fig. 1c). To interrogate the proposed sensor in transmission, it was used a broadband source in the 1550 nm spectral range with a bandwidth of 100 nm, and an OSA as the interrogation unit. The sensing head exhibited a linear response to temperature variations, characterized by a high sensitivity of 31.2 pm/ºC. This result is determined by the temperature dependence of the effective refractive index and the thermal expansion of the microstructured fiber, and by the release of the thermal stress, which the fiber is undergone during fabrication process. When submitted to applied strain and variation of curvature radius, low sensitivities of 0.29 pm/με and 0.03 pm/m were obtained, respectively. The cross-sensitivity to strain is 9.3×10^{-3} ºC/με while for radius of curvature is 9.6×10^{-4} ºC/m.

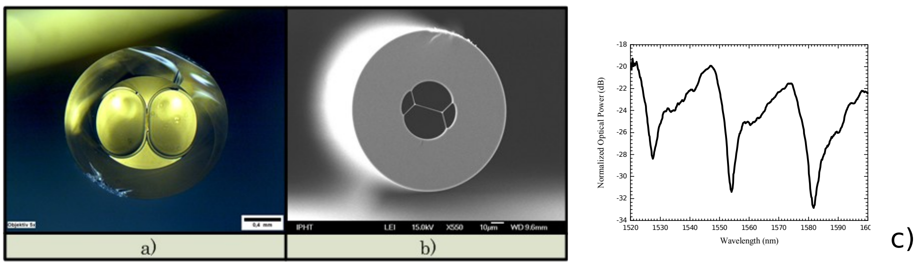

Fig. 1. a) Cross-section of the cane used for preparation of the suspended-web fiber; b) Cross-section of the suspended-web fiber achieved after fabrication; c) Optical spectrum of the proposed sensing head.

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Fabrication and Coating of Different Types of Optical Microcavities.

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Abstract.
Optical microresonators which are based on whispering gallery mode (WGM) are a powerful technique for investigating light interactions and they have many applications in nonlinear and quantum optics. Producing WGM spheres depends on the material from which it is made. Microspheres made of chalcogenide glasses due to their dangerous evaporation and much lower melting temperature have a different way of producing than silica microresonators and the technique of heating by inert gas has been used. Optical microcavities made of silica can acquire additional advantages by depositing a thin film on the surface of the sphere which gives them more usability. For the deposited material silicon has been used. For silicon coated silica spheres Q-factor up to $5*10^5$ was obtained.

High-power Acetylene Hollow Fiber Laser At 3 µm Wavelength

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Optically-pumped gas-filled hollow fiber lasers emerge recently as a novel type of laser source [1], based on the newly-developed technology of low-loss anti-resonant hollow-core fibers (AR-HCFs) [2]. Gas-filled hollow core fiber lasers combine advantages of both fiber lasers and gas lasers: flexibility, compactness, near-diffractive-limit beam quality, high power conversion efficiency, as well as a broad coverage of emission spectral lines owing to a rich selection of gaseous gain media. It is noted that the low optical nonlinearity and high optical damage threshold of AR-HCFs give hollow-core fiber lasers the potential to achieve much higher output power than their solid fiber counterparts.

We use acetylene molecules as gain medium for lasing emission at 3 µm mid-infrared wavelengths by optical pump in the 1.5 µm telecommunication band. AR-HCFs can provide low fiber losses down to tens of dB/km for both pump and laser wavelengths of acetylene gas. The newly developed optically-pumped acetylene gas fiber laser has been demonstrated to be capable of high slope efficiency and we are investigating scaling the output power up to the Watt level. By systematic characterization of pump absorption and laser power-scaling properties, we find that the dynamics of acetylene gas molecules inside the fiber play a decisive role in maintaining the efficiency of laser operation. A low molecular density is favorable for maximization of power conversion efficiency and laser power output, but is accompanied by reduced pump absorption and gain saturation under high-power pump. Our study shows that reduction of fiber attenuation is key to further develop optical-pumped acetylene fiber laser towards higher power laser generation in mid-infrared.

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Fabrication and characterization of step-index tellurite fibers with varying numerical aperture for near- and mid-infrared nonlinear optics

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Development of broadband supercontinuum (SC) laser sources in the mid-infrared (MIR) was widely studied during the last two decades for its high application potential in various fields such as spectroscopy, defense, medical science and others. TeO_2 based vitreous materials appear to be good candidates for the development of fiber-based SC sources emitting in the MIR thanks to their 1-6 µm transparency widow and relatively high nonlinear optical properties. However, at the moment, few studies report spectral broadening spreading further than 3 µm in tellurite fibers [1, 2, 3]. Most of those results were obtained using microstructured optical fibers (MOFs) in which an ageing process, inherent to the micrometric architecture and due to water contamination, has been identified for chalcogenide [4] and silica [5] glasses. MOFs allow the shifting of the zero-dispersion wavelength (ZDW) toward the near-infrared, where compact high-peak-power laser sources suitable for SC generation are commercially available. Nowadays, comparable pumping configurations are accessible around 2 µm with the development of thulium-based fiber lasers. In those conditions, less drastic dispersion tailoring is required, especially for tellurite materials, which exhibit ZDW located around 2 µm.

We report aging experiments performed on tellurite MOFs suggesting SC generation might also be limited by this kind of phenomenon. Consequently, all-solid step-index fiber profiles are considered for preventing water steam diffusion inside the waveguide in order to anticipate transmission degradation due to ageing. We then present results on the manufacturing of step-index tellurite, germanate and germanate-tellurite fibers including their linear and nonlinear characterizations. Three different step-index profiles with varying refractive index difference are explored. To this end suitable compositions are associated leading to step index fibers through a fabrication method combining built in casting and rod in tube processes. The potential of our fibers for nonlinear optics is next reported through SC generation experiments, by using a femtosecond fiber laser at 1.56 µm. SC spectra covering the 1.3-2.0 µm region were obtained for each fiber. Finally, we extend our study to the fabrication of step-index tellurite fiber made from purified glass. Nearly complete elimination of OH-related absorption bands of the vitreous materials is proven through attenuation measurements performed on several meter-long large-core multimode fiber. The beneficial impact of glass purification on SC generation towards the MIR is confirmed in a low-OH 3.5-µm-core tellurite step index fiber pumped above 2 µm resulting in SC spectra extending beyond 3µm.

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Photoluminescence of Antimony-Germanate Glass Nanocomposites

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In the field of materials engineering for photonics, a main effort is paid to develop novel materials with unique optical and structural properties. Up to day, a number of glasses, glass-ceramics and crystals doped with rare earth (RE) ions have been proposed as a promising material for light management in a wide spectral range. It includes a nanometric volume of molecules embedded in glassy material and called as nanocomposites [1]. The presence of some nanoparticles (NPs) of crystals, noble metals or even semiconductors simultaneously with RE ions allows to achieve new luminescent properties resulting from interaction of light and energy transfer between RE ions and embedded nanoparticles. Especially, in order to improve quantum efficiency of radiative transitions of RE ions and broadening of the spontaneous emission spectrum, low-phonon materials are required. Among oxide glasses the special attention should be paid to the antimony-germanate glasses - a matrix of different phonon energies formed as a combination of glass-forming elements. Antimony oxide glasses have attracted a considerable interest for their combination of chemical durability, low phonon energies (~600 cm^{-1}) and high transparency in a wide range. However, the low field strength (0.73) of Sb^{3+} makes it a poor glass former and it is unable to exist, particularly in the bulk monolithic form which is very much essential for practical applications. In our earlier investigations, we proposed the solution of this problem and synthesized a glass with a combination of different phonon energy of glass-forming elements [2, 3]. The presentation will show the influence of different high-phonon compounds like phosphorous (P_2O_5), boron (B_2O_3) and silica (SiO_2) on thermal and luminescent properties of RE ions doped antimony-germanate glass. Another part of presentation we will discuss the possibility of obtaining $EuPO_4$ nanocrystals. Optimisation of phosphate concentration (up to 5mol%) allows to create nanocrystals directly in melt-quenching process. In our experiment we confirmed that the specific glass composition and the controlled heat-treatment process give a new concept of creating nanocrystals in RE – doped optical fiber.

Special attention has been paid on photoluminescent properties of antimony-germanate glasses co-doped with RE ions and silver nanoparticles. In this part of our experiment we showed that Sb_2O_3 is a mild reducing agent of noble metal ions. This mild reduction property enables in-situ reduction of Ag^+ ($AgNO_3$) to Ag^0 in a single-step during the melting process, thereby providing a simple, low cost method for the preparation of bulk photonic materials. According to spectroscopic and structural properties of the antimony-germanate-silicate glass, the possibility of luminescence intensity enhancement of Eu^{3+} ions by surface plasmon resonance from Ag^0 nanoparticles was investigated. The perspectives of application antimony-germanate glass nanocomposites in special construction optical fiber for unconventional light sources were also discussed.

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Irradiation with alpha particles of Yb^{3+} and Er^{3+} co-doped phosphate glasses

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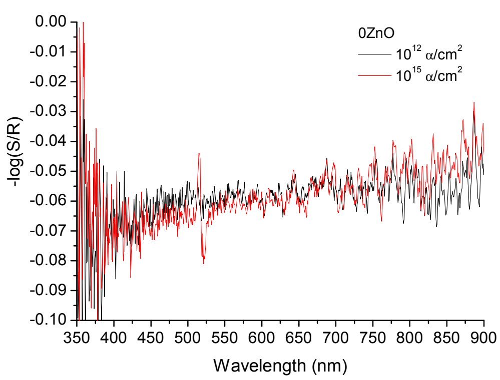
Phosphate glasses are of interest for the engineering of photonic devices, due to the following properties: easy processing, good thermal stability and excellent optical characteristics, such as high transparency in the UV, visible and near-IR region [1]. Besides, phosphate glasses allow high rare earth (RE) ions solubility. Due to these properties, phosphate glasses have recently become appealing for photonics [2].

In the last years, a special attention was paid on the ionizing radiation induced effects in doped glasses used for fiber amplifiers, targeting their use in space missions [3–8].

In this study, Yb^{3+} and Er^{3+} co-doped phosphate glasses with the composition (98.5_x) (0.5 P_2O5–0.4 SrO–0.1Na_2O)-xZnO-0.5Er_2O_3-1.5Yb_2O_3 (in mol%) were fabricated by melt-quenching technique with x=0, 1.25, 2.5 and 5. The changes in their thermal, structural and luminescence properties with the addition of ZnO were studied. Physical and thermal properties were investigated through density measurement and differential thermal analysis. Structural characterization was performed using the Raman and Infrared spectroscopy. We also report the impact of irradiation with alpha particles on the optical and THz transmittance, the surface profile and the luminescence of these glasses. Some examples of the obtained spectra are given in Figs. 1 and 2. For the optical absorption calculation the pristine sample was considered as reference.

The irradiation by alpha particles was performed at the 3 MeV U-120 Cyclotron accelerator, with a beam current of 3 nA, and for a flux of 10^{11} $\alpha/(cm^2s)$, in vacuum. The total fluence reached during this study was 10^{15} α/cm^2.



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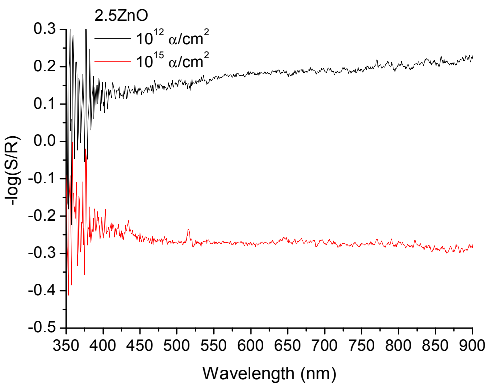

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Figure 1. Change of the absorption spectra in the optical spectral range, after alpha particles irradiation, for sample: a – 0ZnO; b – 2.5ZnO.

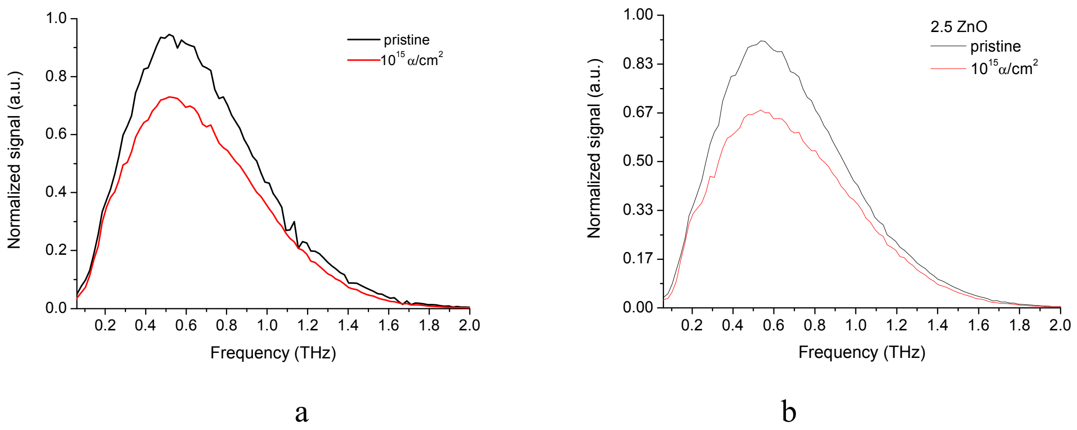

Figure 2. Change of the normalized spectral transmission in the THz spectral range, after alpha particles irradiation, for sample: a – 0ZnO; b – 2.5ZnO.

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Cerium/aluminum correlation in aluminosilicate glasses and silica fiber preforms: implications on structural and optical properties.

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Among rare-earth ions, cerium is widely used in laser technology, fast scintillators and white emitting LEDs thanks to its ability to emit in the UV-visible. This element is also of interest to mitigate photodarkening in fiber lasers. In glasses, Ce is stable with two different oxidation states (3+ and 4+), and that has an impact on the applications. Indeed, Ce^{3+} species show efficient luminescence in the UV-Vis region, whereas Ce^{4+} species do not emit light; however, the latter is sought to mitigate photo-darkening. Thus, the understanding of the factors influencing Ce redox, and the detection of the different species, are crucial for applications, and it requires cross spectroscopic approach.

Within this study we enhance the understanding of the factors influencing Ce redox, and Ce structural/chemical role in amorphous materials in order to increase our knowledge for technical applications. Optical, structural properties and redox were studied for Ce-bearing silicate and aluminosilicate glasses and Ce-activated silica (SiO_2) fiber preforms, by X-ray Absorption, Raman and Photoluminescence Spectroscopy.

The results obtained show that Ce content, Na/Al ratio, and glass chemistry have a strong influence not only on the Ce^{3+}/Ce^{4+} ratio, but also on Ce^{3+} structural environment. Applications to Ce-doped SiO_2 optical fiber pre-forms will be discussed.

SiO_2-SnO_2:Er^{3+} glass ceramics for photonics: advances and perspectives

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Abstract

In previous meetings we have discussed fabrication procedures and photonic properties of SiO_2-SnO_2:Er^{3+} glass ceramics. Thin films, monoliths and planar waveguides were fabricated by sol-gel route. The Er^{3+} ions are embedded in tin dioxide nanocrystals dispersed in silica. The presence of tin dioxide nanocrystals led to the increase of both solubility and emission efficiency of Er^{3+} ions. The energy transfer from the nanocrystals to the Er^{3+} ions was proved by experiments. Density functional theory (DFT) simulation demonstrates that Er^{3+} ions substitute for Sn^{4+} ions in the nanocrystals.

Here we present some progresses:

i) a further step in the simulation of the electronic structure
ii) some approach to the design of the integrated optics structure on SiO_2-SnO_2 glass ceramics platform
iii) spectroscopic and optical properties of the SiO_2-SnO_2:Er^{3+} glass ceramics planar waveguides, single mode at 1542 nm
iv) fabrication procedure of SiO_2-SnO_2:Er^{3+} monoliths

After the confirmation of the local structure of SnO_2:Er^{3+}, we calculated the band-structure and the density of states of tin dioxide nanocrystal doped with 6 mol% of erbium. Er^{3+} substitution induces modification of the band-structure and the appearance of new defect band. This result has been experimentally proved by the observation of a broad emission band centered at 450 nm, which is equivalent to the band-gap of our calculation. With the idea of a compact laser structure we have designed Bragg reflectors based on photorefractivity and etching process. Concerning SiO_2-SnO_2:Er^{3+} glass ceramics planar waveguides the confinement at 1.5 µm is 82%, with a transmittance of about 90% between 300 nm – 3 µm. Finally, progresses in the fabrication of cylinders and monolithic squares of SiO_2-SnO_2:Er^{3+} glass ceramics will be presented.

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The Linewidth of MIR Intersubband Light Sources

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Intersubband lasers, such as Quantum Cascade Lasers (QCLs), are the prime sources for coherent radiation in the Mid-Infrared (MIR). Human breath is characterized by hundreds of gases and some of them have already been identified as disease biomarkers [1]. All gases and bio-materials of increasingly interest for both basic science and applications, such as breath analysis [1] have strong absorption signatures in the Mid Infrared or THz.

Detection of mixes of different gases with high sensitivity require a narrow laser linewidth, which can be strongly influenced by the linewidth enhancement (α-factor) due to fluctuations in the refractive index induced by carrier fluctuations. The α-factor of intersubband lasers was initially expected to be zero. However, values ranging from -0.5 to 3 have been found experimentally. This paper shows that counter rotating terms, usually ignored in simulations are the actual fundamental origin of nonzero α at peak gain. Nonparabolicity and manybody effects are needed to explain negative values and are included in the calculations presented here as a second step.

For laser without inversion conditions, significant as a potential out of the box solution for the elusive room temperature operation of terahertz lasers, α is found to be larger, but still at the same order of magnitude of conventional inverted medium lasers, thus ensuring their applicability to a huge number of spectroscopic applications which require sharp laser linewidths [2]

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Rare-earth doped chalcogenide glasses for mid-IR sensor applications

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ABSTRACT

Chalcogenide glasses were synthetized and studied based on their physico-chemical properties (chemical composition, density, thermal analysis, Raman spectroscopy, optical transmission …). Accordingly, the synthesis process to obtain homogeneous rare earth doped chalcogenide glasses has been optimized. Luminescence properties of rare earth doped chalcogenides glasses have also been studied. Spectrometric parameters estimated from Judd-Ofelt (J-O) method were compared to the experimental values. Fibers have been successfully drawn from the glass preforms and have been characterized. Bulk chalcogenide glass and fibers present a mid-IR luminescence from 3 to 6 µm depending on the choice of rare earth and chalcogenide glass matrix and they can be used in an environmental monitoring sensor.

Keywords: Chalcogenide glass, rare-earth, optical fiber, gas optical sensor

Mode instability induced Bragg gratings in fiber lasers: Numerical modelling of their reflectivity

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We report on reflectivity of transient Bragg gratings created in the active medium of a fiber laser with longitudinal mode instability. Despite long history of laser physics, reflectivity of such gratings were theoretically estimated and experimentally measured only recently. Based on coupled mode theory we derive theoretical model of the superimposed Bragg gratings for the special case of mode instability called spontaneous laser line sweeping (SLLS). The SLLS fiber lasers exhibit periodic wavelength drift over an interval of several nanometers, followed by quick bounce backward, narrow-band, mostly single-frequency operation, and pulsed output with pulse length of the order of microseconds. More details about the SLLS can be found for example in review [1]. The refractive index modulation inside the active fiber is given by the Kramers-Kronig relations, and for ytterbium the refractive index change in the 1060 nm wavelength band is directly proportional to the metastable level population with a factor of 2.1×10^{-31} m^{-3}. Taken into account realistic values of temporal damping of the gratings, significant reflectivity of the order of units to tens of percent is estimated. The reflectivity can be controlled by setting the SLLS laser parameters. Effect of the resonator length is shown as an example. Analogies of SLLS type of longitudinal mode instability with transverse mode instabilities and mode locking are reviewed to point out unique properties of self-sweeping. This work was supported by the Czech Science Foundation, project No. 16-13306S and by the European Action COST MP1401 “Advanced Fiber Laser and Coherent Source as tools for Society, Manufacturing and Lifescience”.

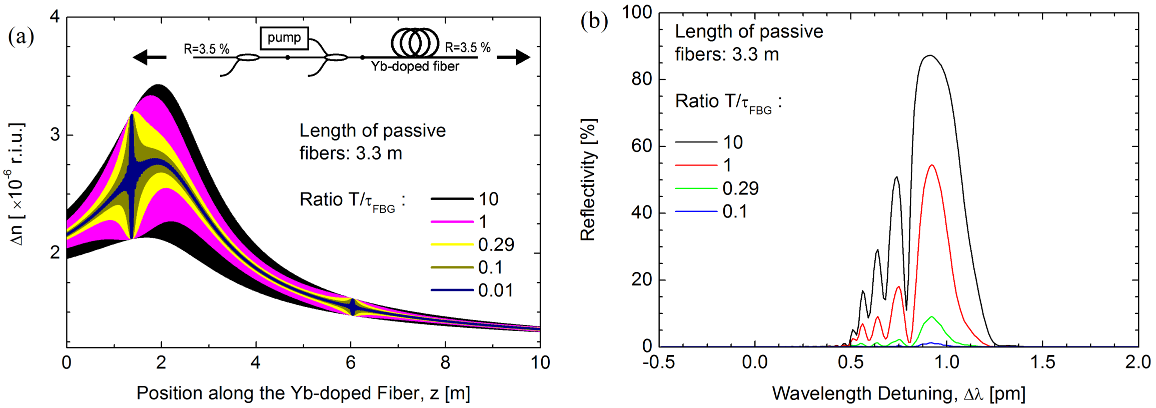

Fig. 3. (a) Refractive index modulation along the active fiber for various values of temporal damping of the Bragg grating T/τ_{FBG}, where T is the SLLS output pulse train period (29 µs) and τ_{FBG} is the lifetime of the Bragg grating that is not known but it is expected to comparable to the saturation time of the inversion population build-up t_{sat} = cca 100 µs for given pump and signal powers. Note that the grating pitch is 0.36 µm, i. e., 7 orders of magnitude shorter than the fiber length, therefore only refractive modulation envelope can be seen in the graph. The value T/τ_{FBG}=10 corresponds to practically only one grating (the gratings are not superimposed on each other). The value T/τ_{FBG}= 0.29 corresponds to the case of $\tau_{FBG} = t_{sat}$. The scheme of the self-swept fiber laser of the numerical model is in the inset, the Yb fiber was 10 m long and the passive part of the resonator was 3.3 m long. (b) Reflectivity of transient fiber Bragg gratings created by the standing waves of the consequential hopping longitudinal modes for various values of T/τ_{FBG}.

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Numerical modelling of pump absorption in double-clad active fibers: Overview of recent progress

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Ever extending applications of fiber lasers require energy efficient, high-power, small footprint and reliable fiber lasers and laser wavelength versatility [1]. To meet these demands, next generation of active fibers for high-power fiber lasers is coming out that will eventually offer tailored spectroscopic properties [2], high robustness and reduced cooling requirements [3] and improved efficiency through tailored pump absorption [4-6].

We report on our recent progress in investigation of the efficiency of the pump absorption in double clad active fibers. The propagation of the multimode pump radiation along the double-clad fiber is simulated using fast-Fourier transformation (or using FEM, alternatively) and beam-propagation methods. Conformal transformation of the refractive index profile is applied in order to account for the simultaneous coiling and twisting of the fiber. Firstly, we will review the modal field approach that allows study of absorption of the respective modes along the fiber [6]. Secondly, we will show preliminary results of investigation of the effect of different radii of the spool on which the fiber is coiled and different fiber twisting rates. Due to squeezing of the pump field by fiber bending, the overlap of the pump with the core changes and correspondingly the overall absorption is varying. We have found that by asymmetric position of the rare-earth-doped core we can significantly improve the pump absorption.

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Fluorescence Lifetime Imaging (FLIM) and Micro Spectroscopy of Yb-doped materials

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Imaging the dopants in fibers and preforms is an important task. This information allows you to monitor the preform fabricate and drawn fibers and investigate their quality. It has been show that using micro spectroscopy and fluorescence lifetime images can be used to detect erbium ions in silica samples[1]. The gathered lifetimes and spectra are not only used for monitoring the dopants profile, but also to gather data like emission cross-sections for simulations and so predict the fibers behavior for running a laser.
In this contribution, we set up a scanning confocal microscope, able to analyze light above 950nm in contrast to devices built for biological analysis in the visible. A laser diode at 910nm (up to 200mW) was used to excite ytterbium ions in order to also evaluate the 976nm fluorescence. The emitted light is evaluated with a spectrum analyzer for micro spectroscopy and an avalanche photodiode for lifetime imaging.
A validation of measured lifetimes was done with a 3 at% doped Yb:CaF_2 sample (1.9ms,[2]) and 1 at% doped Yb:YAG sample(1ms,[2]). So, gathering data is not restricted to the host material. The resolution was tested at the edge of doped volume of Yb:YAG. For fibers this led to a resolution of 5µm (10% to 90% criterion) and for preforms, which are placed at different position, 25µm.
We are showing an ytterbium doped preform example with different doping areas. Typical spectra of ytterbium doped aluminum- and phosphosilica are reported in [3]. Here, the main characteristic changing is the peak wavelength of the 1010nm-1035nm ytterbium emission and the intensity. Fig.1 shows normalized spectra and a FLIM like picture of an ytterbium doped preform with 3 doped areas and 1 non-doped sacrificial layer. The center is doped with 0.2 mol% Al_2O_3 and 0.05 mol%Yb_2O_3. The two doped rings are doped with 0.1mol% Yb_2O_3, 1mol% Al_2O_3 and 1mol%P_2O_5. The color defines the peak wavelength of the second broad peak at around 1030 nm. The brightness shows the normalized intensity.

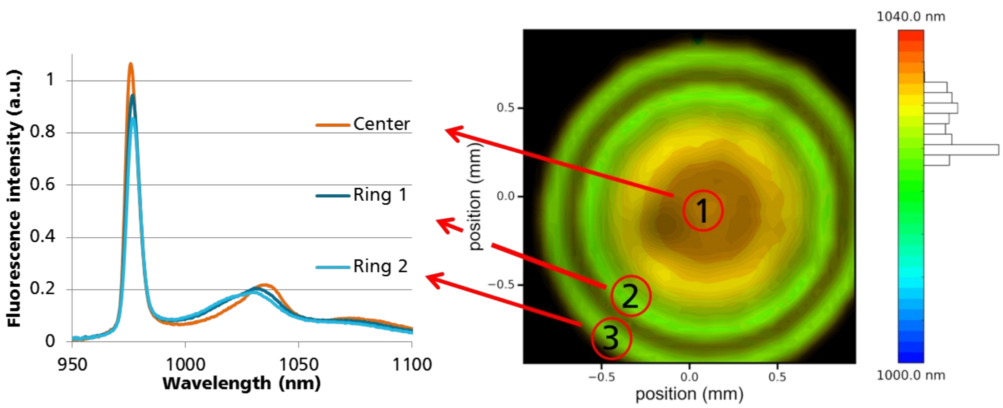

Fig. 1 Spectra of ytterbium ions in Aluminum environment while the Phosphorus content rises from 1 to 3

The rising content of Phosphorus shifts the peak from 1033 nm to 1026nm. The width of this peak is slightly increasing from 21nm to 23nm. Investigating the same preform slice in a FLIM Measurement gives us following lifetimes. Ring 1 and Ring 2 have a mean lifetime of 0.92ms while the center region has a lifetime of 0.85ms. The longer lifetime fits well with the observations made in [4], where a rising phosphorus concentration led to a rising lifetime. This shows that micro spectroscopy and fluorescence lifetime imaging is a valid technic to determine the qualitative ytterbium content in silica samples. The spectrum and lifetime allows to judge the environment of ytterbium. In order to predict the behavior of future samples, the creation of a data base is in progress. Samples with known concentration profiles will be taken into account and combined with fluorescence information.

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Modelling of MIR fibre sources

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Mid-infrared (MIR) light sources operating in the range of wavelengths spanning from 3 µm to 25 µm have many potential applications in the fields of medicine, pollution monitoring, biology, agriculture and security. This is because the resonant oscillation frequencies of many molecular bonds fall within MIR wavelength range. For instance, in medicine the application of MIR light would help to improve the effectiveness of cancer diagnostics.

The key enabling technology for exploiting the potential benefits of MIR light technology is an availability of low cost, robust light sources. There are several types of light sources currently available, which cover MIR wavelength range. An interesting type of recently developed MIR sources relies on using lanthanide doped low phonon energy glass fibres to obtain spontaneous MIR emission within a wide band. Such fibres can be conveniently pumped using relatively low cost continuous wave (CW) laser diodes, which are readily available. Modelling of such devices aids the design and optimisation process. We present a model of a MIR spontaneous emission fibre light source consisting of a set of ordinary differential equations describing the power distribution within the fibre couples with the rate equations, which allow for consistent calculation of energy level populations.

Figure 1 shows energy level diagram and pumping scheme, light source configuration and example power distribution within the fibre calculated for transitions $^3H_5$-$^3H_4$ and $^3H_6$-$^3H_5$, which correspond to MIR wavelengths. The fibre diameter was 0.2 mm, the pumping wavelength was 1480 nm whilst the chalcogenide-selenide fibre was doped with approximately 500 ppm of praseodymium ions.

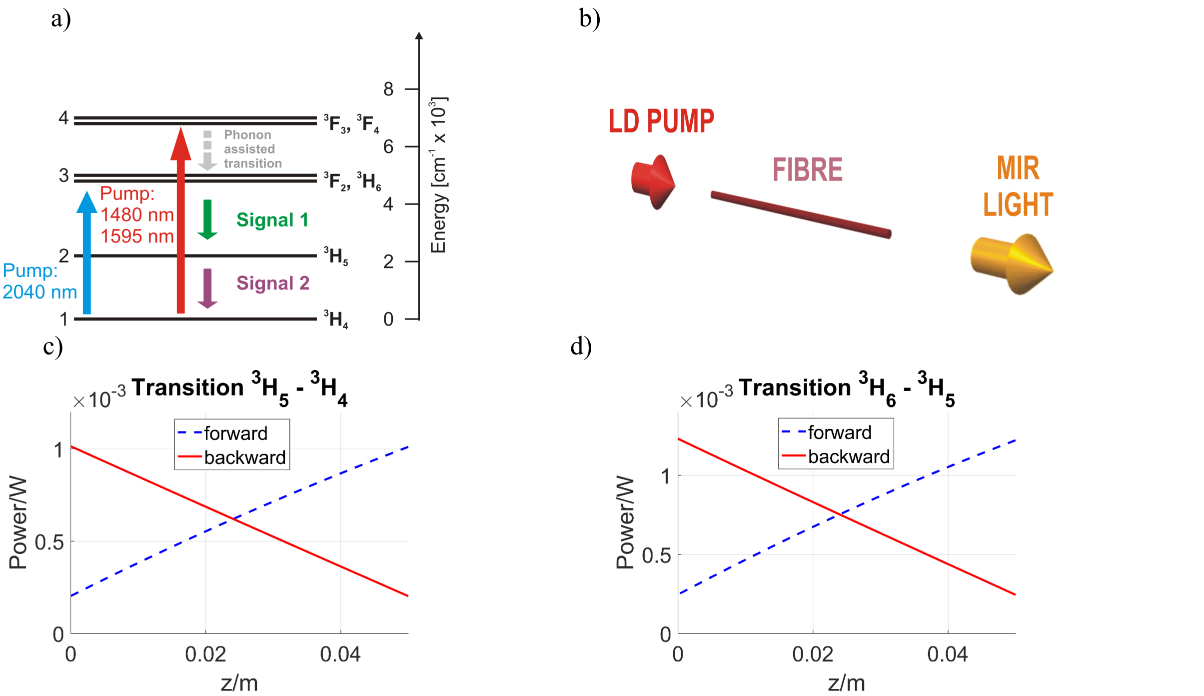

Fig.1 Energy level diagram a), light source configuration b), power distribution for $^3H_5$-$^3H_4$ transition c) and power distribution for $^3H_6$-$^3H_5$ transition d)

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Progress of Round Robin on fibre laser modelling

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Modelling and design is essential to the development of novel fibre lasers. Recently large research effort has been devoted to develop fibre lasers operating at wavelength exceeding 2000 nm. This effort has been accompanied by the development of the modelling and design tools. Therefore the first task within the modelling work package was to calculate numerically the output power of a dysprosium ion doped chalcogenide glass based fibre laser. We present the most recent results obtained by the participants of this action.

We also introduce a new action, which is the calculation of the output power and power distribution within a laser cavity of a ZBLAN fibre laser doped with erbium ions. The operating wavelength of the laser is 2800 nm whilst the pumping wavelength is 980 nm. The modelling parameters are provided in tables 1 and 2. Figure 1 shows the relevant energy level diagram. Table 3 presents the reference values of the output power calculated using shooting method together with the corresponding CPU times.

Table 1 Modelling parameters

parameter	Unit	value
b_1/b_2		0.1/0.16
W_{11}	m^3/s	$1x10^{-24}$
W_{22}	m^3/s	$0.3x10^{-24}$
λ_p	m	$976x10^{-9}$
λ_s	m	$2.8x10^{-6}$
σ_{GSA}	m^2	$2.1x10^{-25}$
σ_{SE}	m^2	$4.5x10^{-25}$
N_{Er}	$1/ m^3$	$9.6x10^{26}$
L	m	2.5
Γ_p		0.009
Γ_s		1.0
α_p	1/m	$23x10^{-3}$
α_s	1/m	$3.0x10^{-3}$
$R_p(z=0)$		0
$R_p(z=L)$		0.96
$R_s(z=0)$		0.04
$R_s(z=L)$		0.96

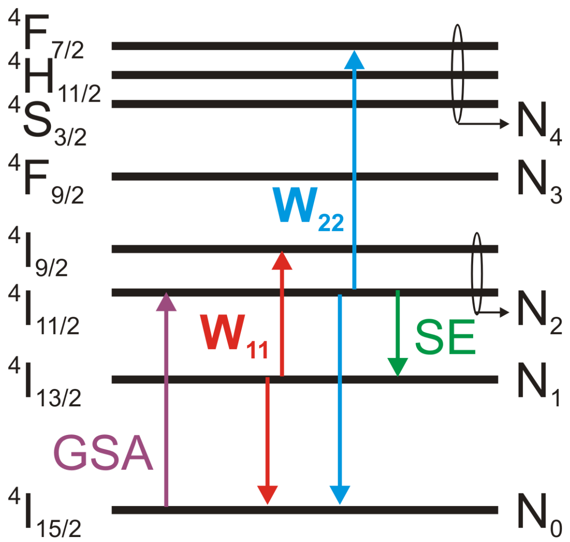
Table 2 Branching ratios and level lifetimes

parameter	Unit	value
τ_1	ms	9.0
τ_2	ms	6.9
τ_3	µs	10
τ_4	µs	120
β_{21}, β_{20}		0.37, 0.63
β_{32}, β_{31}, β_{30}		0.99, 0.0, 0.01
β_{43}, β_{42}, β_{41}, β_{40}		0.85, 0.006, 0.004, 0.14

Table 3 Calculated reference values of the output power and the corresponding CPU time

Pump power/W	Output power/W	CPU time/s
5	1.39527600015	78.76
10	3.11902141885	85.94
15	4.85305182935	86.19
20	6.55663433930	84.27

Fig.1. Energy level diagram used in the simulations



Fiber laser applications for free space optical links

Tibor Berceli

Abstract

The free space optical links are widely used for tele-metering and tele-control. One of its important applications is in healthcare when people with serious health problems have to be under continuous survey and control.

The free space optical links have a big advantage because they can be operated without licenses at any place. In these links there is a significant need for high power. However, the semiconductor lasers can provide usually not sufficient power for that purpose. Therefore fiber laser could be a proper candidate in this respect.

For information transmission purposes the optical signal has to be modulated by the information to be transmitted. However, the modulation capability of fiber lasers is very limited. Direct modulation can be done only with very small bit rates. The external modulation would be the other choice, but the well established Mach-Zehnder interferometer modulators can not tolerate the high power of fiber lasers.

In this paper a system is proposed which offers simultaneously high output power and high speed modulation capability utilizing fiber lasers. In that system the high speed modulation is carried out at low optical power levels by applying semiconductor lasers and optical phase shifters. Then the phase modulated optical beam is used to injection lock the fiber laser. This way we get a high power optical beam carrying information in the format of phase modulation. Therefore the power requirement of free space optical links is properly met. At the same time the frequency stability of the fiber laser is also significantly improved by the injection locking technique.

The free space optical links have many possible applications in data transmission and collection for healthcare, industry and banking beside telecommunications. For people with serious health problems the instantaneous message of their bad condition is the best method to notice sudden serious changes in their health and provide urgent help to them for avoiding dramatic situations. For that purpose the free space optics offer a proper solution in some cases in the form of ad hoc links.