COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Action MP1401

Advanced fibre laser and coherent source as tools for society, manufacturing and life science

WG2 Technical Meeting
8 – 9 February 2018, Vienna, Austria

Technical Digest

The WG 2 “New laser, amplifier devices and coherent light sources” meeting will be held at the TU Vienna (Campus Gußhaus, Gusshausstrasse 25, EI 4 Reithoffer Hörsaal), Vienna, Austria.

Main Topics

- SG.2.1 Modelling and Design Tools
- SG.2.2 MIR coherent line sources and continuum sources
- SG.2.3 UV coherent line sources and continuum sources
- SG.2.4 Power scaling issues

Sessions at a glance

Thursday, February 8:

- 9.00-10.30 "Novel approaches and applications"
- 11:00-12:30 "Chalcogenide and LMA fibers"
- 14:00-15:30 "Ultrafast sources"
- 16:00-17:00 Lab tour, Photonics Institute.

Friday, February 9:

- 9.00-10.30 "Periodic structures"
- 11:00-12:30 WG2 meeting

WG2 Technical Meeting, 8 – 9 February 2018, Vienna, Austria
Scientific program

Thursday, February 8

9.00-10.30 "Chalcogenide and LMA fibers"

9:00 Opening remarks, organizational issues
S. Taccheo, E. Sorokin

9:05 Chalcogenide-Glass -based Mid -IR sources
V. Nazabal, J. Trolès, J.-L. Adam, J. Charrier, A. Braud

9:30 Efficient Very Large Mode Area Thulium Doped Fiber Laser for 2 μm operation
D. Darwich, R. Dauliat, M. Sabra, B.Leconte, R. Jamier, J.-L. Auguste, A. Schwuchow, K. Schuster, E. Lallier, P. Roy

9:50 Tunable Dual-Wavelength system based on a Polarization Maintaining Large Mode Area Thulium Doped Fiber Laser operated in the 2 μm region
M. Sabra, T. Tiess, R. Dauliat, B. Leconte, R. Jamier, M. Jager, G. Humbert, K. Schuster, P. Roy

10:10 Ytterbium doped phosphate fiber laser with nanostructured core
M. Franczyk, R. Stępień, A. Fliipkowski, D. Pysz, R. Buczyński

10:30 Coffee break

11:00-12:30 "Novel approaches and applications"

11:00 Using Fibre Lasers for Optical Wireless Communications, Optical Sensing and Detection Technologies for Increasing Reliability in Future Applications (including Autonomous Driving Scenarios)
E. Leitgeb, T. Plank, D. Kraus, P. Pezzei

11:30 Energy level of Ce^{3+} at energy higher than 2000 cm^{-1} in silica
M. R. Cicconi, W. Blanc, M. Benabdesselam, F. Mady, D. de Ligny, C. Armellini, M. Ferrari

11:50 Synchronous Interferometric Measurement of Dispersion Applied To Customization of Supercontinuum Sources
H. Muñoz-Marco, J. Abreu-Afonso, V. Otgon, R. Dauliat, R. Jamier, P. Roy, P. Pérez-Millán

12:10 Watt-level Tunable Narrow bandwidth Tm:YAP laser using a pair of Etalons
S. Noach, U. Sheintop, E. Perez, P. Komm, G. Marcus, N. Danzig

12:30 Lunch

WG2 Technical Meeting, 8 – 9 February 2018, Vienna, Austria
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Thursday, February 8

14:00-15:30 "Ultrafast sources"

14:00 Ultrafast Fiber-based mid-IR lasers
E. Sorokin, N. Tolstik,3, R. Richter, R. Chahal, I. T. Sorokina

14:20 Recent progress in broadband fiber-based mid-IR laser sources
K. M. Abramski, J. Sotor, G. Soboń

14:40 All-PM Diode-pumped Mode-locked Holmium Fiber MOPA
N. Tolstik, I. K. Bakke, E. Sorokin, I. T. Sorokina

15:00 High energy mid-IR ultrashort pulses: the parametric route
P. Malevich, I. Astrauskas, T. Kanai, S. S. Kangaparambil, H. Hoogland, R. Holzwarth, A. Pugzlys, A. Baltuska

15:30 Coffee break

16:00-17:00 Lab tour, Photonics Institute.

Friday, February 9

9.00-10.30 "Periodic structures"

9:00 Organizational issues
S. Taccheo, E. Sorokin

9:05 Conditions of single-mode light generation in DBR and DFB fiber lasers: wavelength-scale electromagnetic analysis by the method of single expression
H.V. Baghdasaryan, T.M. Knyazyan, T.T. Hovhannisyan, E. Leitgeb, M. Marciniak, S. Sujecki, S.Taccheo

9:30 Er^{3+} doped monolithic 1-D dielectric microcavity fabricated by rf-sputtering for coherent emission at 1.5 µm
A. Chiasera, F. Scotognella, B. Yann, G. Galzerano, A. Lukowiak, D.Ristic, G. Speranza, I. Vasilchenko, A. Vaccari, S. Valligatla, C. Meroni, S. Varas, L. Zur, M. Ivanda, G. C. Righini, S. Taccheo, R. Ramponi, M. Ferrari

9:50 Tailoring of geometries in Er^{3+} doped 1-D dielectric microcavity fabricated by RF-sputtering for the optimization of coherent emission at 1.5 µm
C. Meroni, A. Chiasera, F. Scotognella, Y.G. Boucher, A. Lukowiak, G. Speranza, S. Varas, L. Zur, S. Taccheo, M. Ferrari

10:10 Effects of gamma irradiation on phase-shifted grating based fiber laser
H. Qi, D. Sporea, A. Stancalie, D. Negu, W. Wang, J. Guo, Z. Song, C. Wang, G. Peng

10:30 Coffee break

11:00-12:30 WG2 Meeting

Chalcogenide-Glass-based Mid-IR sources

Virginie Nazabal[a], Johann Trolès[a], Jean-Luc Adam[a], Joël Charrier[b], Alain Braud[c]

[a]*Univ Rennes, CNRS, ISCR (Institut des Sciences Chimiques de Rennes) - UMR 6226, F-35000 Rennes, France*
[b]*Univ Rennes, CNRS, FOTON (Fonctions Optiques pour les Technologies de l'information) UMR 6082, F-22305 Lannion, France*
[c]*Centre de recherche sur les Ions, MAtériaux & Photonique (CIMAP), UMR 6252, Université de Caen-CNRS, France*

Abstract

Vitreous materials composed of chalcogen elements (S, Se, Te) show large transparency windows in the infrared. Indeed, chalcogenide glasses can be transparent from the visible up to 12-15 µm, depending on their compositions. This is due to the lower phonon energies of chalcogenides, which are also responsible for enhanced luminescence of rare-earth ions embedded in such matrices. Thus, sulfide glasses, for instance, allow light emission at wavelengths not accessible with silica. In addition, chalcogenide glasses contain large polarisable atoms and external lone electron pairs that induce exceptional non-linear properties. Consequently, the non-linear properties can be 100 or 1000 times as high as the non-linearity of silica.

The presentation deals with the latest results in the field of mid-infrared light emission from rare-earth-doped chalcogenide glasses and optical waveguides [1], and in the field of chalcogenide microstructured optical fibers, especially those with enhanced non-linearities for the generation of mid-IR supercontinuum [2, 3]

[1] Mid-infrared guided photoluminescence from integrated Pr^{3+}-doped selenide ridge waveguides, J. Charrier, L. Bodiou, F. Starecki, J. Lemaitre, V. Nazabal, J.-L. Doualan, E. Baudet, R. Chahal, A. Gutierrez, Y. Dumeige, I. Hardy, A. Braud, R. Soulard, P. Camy, P. Němec, G. Palma, F. Prudenzano, Opt. Mater. 75, 109-115 (2018)
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[3] C. Caillaud, C. Gilles, L. Provino, L. Brilland, T. Jouan, S. Ferre, M. Carras, M. Brun, D. Méchin, J.-L. Adam, and J. Trolès, "Highly birefringent chalcogenide optical fiber for polarization-maintaining in the 3-8.5 µm mid-IR window," Optics Exp. 24, 7977-7986 (2016).

COST TD 1402 – Main Author: Dia Darwich – Speaker: Romain Dauliat

Efficient Very Large Mode Area Thulium Doped Fiber Laser for 2 µm operation

Dia Darwich[1], Romain Dauliat[1], Mostafa Sabra[1], Baptiste Leconte[1], Raphael Jamier[1], Jean-Louis Auguste[1], Anka Schwuchow[2], Kay Schuster[2], Eric Lallier[3], Philippe Roy[1]

[1] *Univ. Limoges, CNRS, XLIM, UMR 7252, F-87000 Limoges, France*
[2] *Leibniz Institute of Photonic Technology, Albert-Einstein-Straβe 9, 07745 Jena, Germany*
[3] *Thales Optronique SA, Laser Solutions Unit, 2 avenue Gay-Lussac, 78995 Elancourt, France*
romain.dauliat@xlim.fr

For decades now, high power fiber laser have stand a remarkable progress in term of average power, peak power and energy, mainly at 1µm operating wavelength owing to the low quantum defect of ytterbium ions. This has been made possible thanks to the elaboration of singlemode very-large-mode area such as the Large-Pitch Fibers – LPF - [1] or the Distributed Mode Filtering fibers – DMF – [2] which fend off the appearance of non-linearities and allows for higher energy storage. Thus, transposing these performance to the 2µm operating range has drawn much interest since it will allow to work with even larger singlemode fiber core in an eye-safe region.

Till today, reports on efficient very-large mode-area fiber doped with thulium-doped ions are very seldom. However, there is one work from Jansen et al. deserving great attention [3]. In this contribution, a singlemode operation into an 81 µm core LPF – 60 µm in mode field diameter - was achieved with a M^2 value not exceeding 1.5 even at full extracted power: 52 W. However, the laser efficiency capped at 33% which remains moderate, especially since one is aware that through cross relaxation – a 2:1 photon process -, Tm-doped fiber laser can reach theoretically an efficiency of up to 82%. As a proof of it, when good care is paid on properly defining the fiber core composition, a laser efficiency of 70% can been achieved into step-index fiber [4].

Being aware of these achievements, our groups gathered their expertise to propose both an original fiber design known as Fully-Aperiodic Large-Pitch [5] for ensuring singlemodedness and an authentic synthesis technique refer to as Repusil [6] for maximizing the laser efficiency and stand high power operation. For a first realization, dopant concentrations have been set to be on a safe side regarding crystallization issues. Indeed, maximizing the cross-relaxation process requires to work with high concentration in both thulium and aluminum oxide but this makes the glass highly subjected to phase separation and crystallization which can prevent a proper laser operation. Therefore, the concentration used while synthesizing the core material were 0.3mol% of Tm_2O_3 and 3 mol% Al_2O_3. As first experimental results, we demonstrated out of a 48 µm core FA-LPF a singlemode operation around 1.95 µm while preserving a singlemode fashion since the M^2 do not overcome 1.45. The extracted power remains limited to about 30W using a pump diode of 100W at 792 nm, yielding in a laser efficiency 36.5%.

Further works will focus on pursuing the laser test for extracting higher even more power. Later, additional drawing of this FA-LPF will be perform after adjusting the core material composition to favor quantum defect limited efficiency.

The COST MP 1401 action has funded the STSM of Dia DARWICH to fabricate material enabling the conception of this fibre at IPHT in April 2016.

List of paper and conference:

1- D. Darwich et al. '' 140 µm single-polarization passive fully aperiodiclarge-pitch fibers operating near 2 µm'', Applied Optics 56 (33), 2017

2- D. Darwich et al. '' Relevance of the REPUSIL process for the production of LMA thulium-doped fibers'', Advanced Photonics Congress, 2016

[1] J. Limpert, "Large-pitch fibers: Pushing very large mode areas to highest powers," in *International Conference on Fibre Optics and Photonics*, p. T2A.1, 2012.

[2] M. Laurila, J. Saby, T. T. Alkeskjold, L. Scolari, B. Cocquelin, F. Salin, J. Broeng, and J. Lægsgaard, "Q-switching and efficient harmonic generation from a single-mode LMA photonic bandgap rod fiber laser," *Opt. Express*, vol. 19, no. 11, pp. 10824–33, May 2011.

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[5] D. Darwich et al. '' 140 µm single-polarization passive fully aperiodiclarge-pitch fibers operating near 2 µm'', Applied Optics 56 (33), 2017

[6] M. Leich, F. Just, A. Langner, M. Such, G. Schötz, T. Eschrich, and S. Grimm, "Highly efficient Yb-doped silica fibers prepared by powder sinter technology," *Opt. Lett.*, vol. 36, no. 9, pp. 1557–9, 2011.

Tunable Dual-Wavelength system based on a Polarization Maintaining Large Mode Area Thulium Doped Fiber Laser operated in the 2 µm region

Mostafa Sabra[1], Tobias Tiess[2], Romain Dauliat[1], Baptiste Leconte[1], Raphael Jamier[1], Matthias Jager[2], Georges Humbert[1], Kay Schuster[2], Philippe Roy[1].

[1] *Univ. Limoges, CNRS, XLIM, UMR 7252, F-87000 Limoges, France*
[2] *Leibniz Institute of Photonic Technology, Albert-Einstein-Straβe 9, 07745 Jena, Germany*
mostafa.sabra@xlim.fr

In recent years, many studies have been conducted on the development of thulium-doped fiber laser sources which make possible the generation of high-power laser radiations in the 2 μm spectral range [1,2]. This domain has advantages for many applications: medicine, aeronautics, environment and defense [3,4]. Dual-frequency lasers (around 2 µm) are also attracting increasing interest in various industrial and scientific applications, such as materials processing, imaging systems, spectroscopy and terahertz wave generation [5,6].

In order to generate a Terahertz (THz) waves, we are working on different configurations – all-fibre MOPA or Free space setup – relying on the use of a thulium doped fiber lasers to obtain a tunable dual-wavelength pulsed laser, with high peak and average power. This pulsed laser will be used to generate THz waves by DFG (Difference frequency generation) using a nonlinear crystal.

In more details, we recently fabricated a singlemode hexagonal PM TDF with a 20 μm core diameter and 120 μm clad diameter. The raw materials that have been stacked and drawn together at xlim, have been synthetized at IPHT using the REPUSIL method. This fiber is a double clad fiber, the core of which is composed of a thulium-doped alumino-silicate with 0.3 mol% Tm2O3 and 6 mol% Al2O3, the first clad (pedestal) is composed of silica doped aluminum with 6.5 mol% of Al2O3 and the second clad is composed with silica. Tow boron rods are also implemented with 19 mol% to make the fiber maintain polarization. This fiber was used with 2 Volume Bragg Grating (VBG) to obtain a tunable and stable dual wavelength, in continuous wave regime to start, and then we will Q-switched this laser to operate in pulsed conditions. Using 90 cm of this fiber, we have obtained about 144 nm of tunability, and 7.1 W of signal power obtained for 30.09 W of launched pump power at 790 nm. The two wavelength were stable according to time, and they have the same contrast of 45 dB.

Next steps will be to Q-switch this laser by adding an AOM (Acousto Optic Modulator) in free space, and then to generate THz waves by DFG using a nonlinear crystal.

Authors would like to thanks the ANR and DFG that have funded the TERATUNE project. The COST MP 1401 action has funded the STSM of Dia DARWICH in order to fabricate the material at IPHT in April 2016.

List of paper and conference:
In progress: One journal paper in Applied optics and one summery in international conference Specialty Optical Fibers (SOF) in Zürich, July 2018.
Already presented at the conference and published in proceedings of JNOG 2017 (Limoges-France)
1- T. Tiess et al. '' LASER A FIBRE BI-FREQUENCES IMPULSIONNEL ET ACCORDABLE EN CONFIGURATION THETA''
2- M. Sabra et al '' LASER BI-FREQUENCES à FIBRE DOPEE THULIUM''

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[2] P. F. Moulton et al., IEEE J. Sel. Top. Quantum Electron., (2009)
[3] R.M. Kuntz et al., World Journal of Urology, (2007)
[4] G.J. Koch et al., Applied Optics, (2004)
[5] T. Kleine-Ostmann, et al., Electron. Lett. (2001)
[6] A. Saha, et al., Opt. Express (2006)

Ytterbium doped phosphate fiber laser with nanostructured core

Marcin Franczyk[1#], Ryszard Stępień[1], Adam Filipkowski[1], Dariusz Pysz[1], Ryszard Buczyński[1,2]

[1] Institute of Electronic Materials Technology, 133 Wólczyńska, 01-919 Warsaw, Poland
[2]Faculty of Physics, University of Warsaw, 7 Pasteura, 02-093 Warsaw, Poland

We report the novel ytterbium doped phosphate single-mode fiber laser with nanostructured core. We found out that nanostructurization could open new perspectives in design and development of fibers with precise control of refractive index distribution [1]. This approach is based on internal nanostructure composed of glasses with different refractive indices. The structure forms the effectively continuous refractive index with arbitrary designed profile. We create the nanostructure using standard stack-and-draw technology scaling down the single rods into subwavelength dimensions of less than 200nm [2].

The nanostructured core of presented active fiber was composed of two phosphate glasses undoped and doped with ytterbium, with uniform distribution. The proportions of glasses in the core were precisely designed to ensure single mode operation. The fiber core had the diameter of 19 µm and it consisted of over 11 thousands of subwavelength rods. The overall diameter of the double-clad fiber was 241 µm.

We achieved 63% of slope efficiency in relation of the launched power in the laser setup based on the fiber of 17 cm in length. The maximum generated power was 10.6 W in single-mode regime.

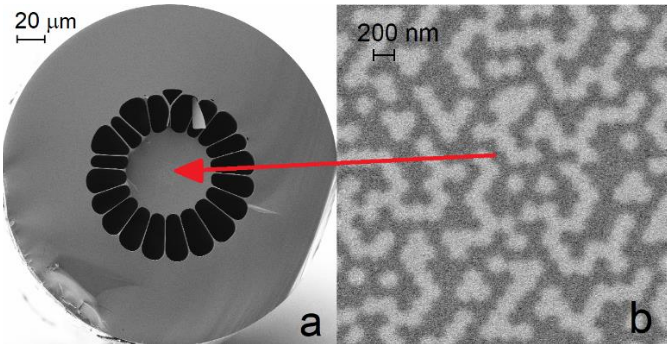

Fig. 1. Cross section of the fiber (a) with nanostructured core

This work was supported by the project TEAM TECH/2016-1/1 operated within the Foundation for Polish Science Team Programme co-financed by the European Regional Development Fund under Smart Growth Operational Programme (SG OP), Priority Axis IV.

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corresponding author: marcin.franczyk@itme.edu.pl

Using Fibre Lasers for Optical Wireless Communications, Optical Sensing and Detection Technologies for Increasing Reliability in Future Applications (including Autonomous Driving Scenarios)

Erich Leitgeb, Thomas Plank, Daniel Kraus, Pirmin Pezzei at Institute of Microwave and Photonic Engineering, Graz University of Technology Graz, Austria

Abstract: Among the different types of Lasers and light sources for Communications, fibre lasers (like investigated within MP1401) are becoming more and more important also for Optical Wireless and Optical Sensing applications. In this contribution Combinations of Optical- and RF-Wave Propagation are illustrated, considering new technologies of lasers and fibre lasers. The presentation includes Optical Wireless Communication (OWC, well known as Free Space Optics (FSO)) as hybrid transmission methods with telecommunication technologies (like WLAN, RF- and satellite communications, [1], [2]) and also Sensing Technologies (like LiDAR and radar combinations). The contribution deals with possible fields of application for optical wireless in conjunction with automated driving. The scope considers requirements (including infrastructural view and law), differences of Optical and RF-Wave Propagation and promising combinations of optical techniques with conventional wireless technologies. It should provide input to define new ideas and aspects for the future research focus within this area in Europe. This paper should serve as a basis for upcoming research tenders as well as for planning of future EU-funded project calls.

Optical wireless has a huge potential to cover the expected high data rate demands in relation to big data in all networks including automated driving. By using fibre lasers an additional light source with high power is available for future applications. A welcome side effect is the relief of the crowded RF bands respectively the support to fulfil the bandwidth demands with a combination of these technologies. It turned out that hybrid systems are currently the most promising approach as each technology has its own culprits and the combination provides the advantages without the disadvantages. In future it would not be possible to process and transmit the amount of data (as example Live/HD maps) in real-time even with the future 5G mobile networks, without using optical wave propagation. To ensure the accuracy of positioning data, supporting measures are required to transfer the data to the vehicle. Also the visible light communication (VLC) offers a sophisticated concept of optical communications, but research has to be done to reach a mature stage. As it is likely that the headlamps and taillights of vehicles will not disappear in the next time, they could also be used for communication purposes as well as serving exact position data in locations, where no satellite position system is in reach (e.g. tunnels, narrow house-canyons in cities). Also for VLC, fibre lasers could be used in new innovative applications, in road and railway-traffics and in home networks.

Additional, we also know LiDAR as an important technology for automated vehicles and fibre lasers can be a supplement of available light sources, well suited for such applications. Laser rays are used to draw a precise picture of the surroundings. The combination of LiDAR, Radar and cameras represents the current state-of-the-art system. To realise the broad use throughout industry, the costs need to be reduced. Optical solutions are not only designed to communicate outwards, they can also be implemented inside the vehicle. A reduction of vehicle weight and the complete lack of electromagnetic disturbances are interesting properties. It is also possible to increase the security of tramway systems and train controlling with LiDAR. The track is defined and other track or road users could be detected in an earlier stage. Fibre lasers will also help to improve the LiDAR-technology very fast in the future.

All those examples demonstrate optical wireless as an important part for networks (including home networks) and automated driving. Not all systems are suitable for mass markets yet, research and development has to be done to fulfil the requirements. Important steps have been taken in that direction and further ones will be taken in the next future to support the automated driving with optical technologies. As mentioned the applications could be extended to trains, ships, aeroplanes etc. Like presented so often in the past (see [1] and [2]), hybrid communication systems allow worldwide access to the Internet or other networks by combining satellite communications, FSO, Wireless LAN, Local Multipoint Distribution System (LMDS) and DVB-T (terrestrial digital video broadcast). Current and future applications of OWC and hybrid solutions also on deep space missions in combination with 5G networks will become more and more important and will be supplemented now for autonomous driving systems (for cars, ships and planes see [3]) by combining Optical- and RF-waves also for sensing and detecting targets, obstacles and neighbour-systems. Among the different types of Lasers, fibre lasers will also cover unusual wavelengths like 3 - 6 micron and beyond, to support mid-infrared applications and to enhance fibre performance to cover more efficiently visible and ultra-violet wavelength generation for Communications also. Within the COST Action MP1401 also glass materials and fibre designs are investigate to overcome the actual limitations for different applications.

Keywords: Fibre lasers, Light sources, Hybrid networks, Free Space Optics, Optical Wireless Communications, RF-links, Satellite Communications, Wireless LAN, Microwave link, weather conditions, reliability and availability, LMDS, DVB-T, Civil-Military-Cooperation (CIMIC), 5G networks, LiDAR, Sensing Technologies, Wave Propagation and Detection

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Energy level of Ce^{3+} at energy higher than 2000 cm^{-1} in silica

Maria Rita Cicconi[1§], Wilfried Blanc[2], Mourad Benabdesselam[2], Franck Mady[2], Dominique de Ligny[1], Cristina Armellini[3], Maurizio Ferrari[3,4]

1 – Department Werkstoffwissenschaften, Lehrstuhl für Glas und Keramik, Universität Erlangen-Nürnberg. Martensstrasse 5, D-91058 Erlangen, Germany

2 - Université Côte d'Azur, CNRS, Institut de Physique de Nice, UMR 7010, Parc Valrose, Nice, Cedex 2, France

3 - IFN-CNR CSMFO Lab. and FBK Photonics Unit, Via alla Cascata 56/C, 38123 Povo-Trento, Italy

4 - Enrico Fermi Center, Piazza del Viminale 1, 00184 Roma, Italy

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 emission band is due to the transition of an electron from the 5d energy levels to the 4f ones. As a consequence, the position of its emission wavelength depends strongly on the environment. It spans from UV in fluoride to red in nitride. Electrons on the two 4f levels ($^2F_{5/2}$ and $^2F_{7/2}$) are shielded from the external field by the $5s^2$ and $5p^6$ electrons. Then, the two 4f levels are usually known to be separated by ~2000 cm^{-1} whatever the change of the environment. However, it has been reported recently that a higher 4f energy level does exist in crystals, located at 3639 cm^{-1} in $Gd_3Ga_5O_{12}$ [1] and ~4000 cm^{-1} in $Lu_3Al_5O_{12}$ [2].

In cerium-doped silica glasses prepared by sol-gel, we have measured absorption spectra in the 4f energy levels domain. An absorption band at ~5300 cm^{-1} has been observed. During this presentation, we shall discuss on the origin of this absorption band, based on results obtained both in silica and silicates (silica containing aluminum or sodium) glasses prepared by sol-gel, melt-quenching and phase vapor (MCVD process).

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Synchronous Interferometric Measurement of Dispersion Applied To Customization of Supercontinuum Sources

H. Muñoz-Marco (1), J. Abreu-Afonso (1), V. Otgon (1), R. Dauliat (2), R. Jamier (2), P. Roy (2), P. Pérez-Millán (1)

(1) FYLA LASER SL, Ronda Guglielmo Marconi 12, 46980 Paterna (Valencia), Spain

(2) XLIM, 123, avenue Albert Thomas, 87060 Limoges, France

Tel: +34 607 958 714, e-mail: hmunoz@fyla.com

ABSTRACT

Supercontinuum (SC) sources offer very significant advantages for imaging and characterization of materials: full VIS-NIR spectrum availability, high spectral power density, reduced temporal coherence, among others. Certain applications require a very accurately customized emission spectrum, which in turn requires reliable tools to measure the dispersion spectra of the microstructured optical fiber of the SC source with very high spectral resolution and very short acquisition time. This measurement to be done ideally on the fly, while manufacturing the fiber, in order to fine tune the drawing variables to match the aimed dispersion profile in real time. In this work we present an interferometric method to measure chromatic dispersion using a pulsed FYLA SCT1000 supercontinuum. Very high-resolution dispersion measurement is obtained by optimization of the visibility of interferometric fringes, which is achieved by a fast synchronization of pulses overlapping.

CHROMATIC DISPERSION MEASUREMENT

FYLA SCT1000 Supercontinuum 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 1. (Left - Up) illustrates the setup for 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 a lamp or a SLED at each band [1,2].

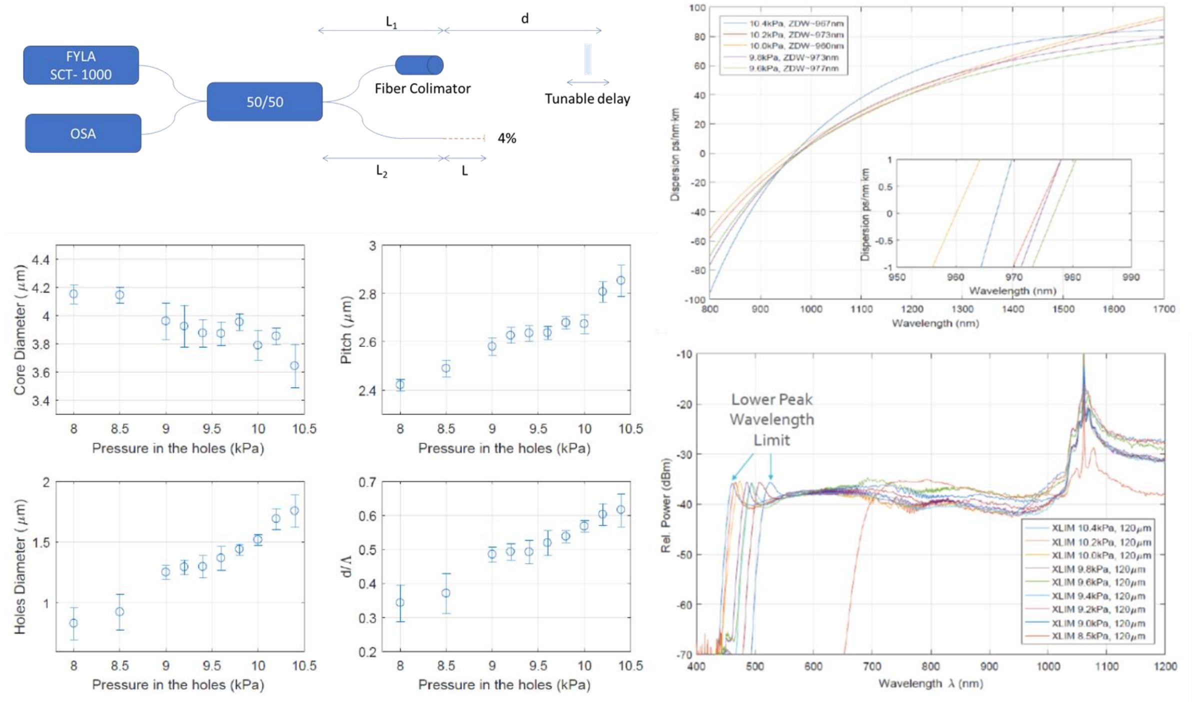

*Figure 1. **Left**. (Up): Interferometric setup to obtain dispersion curve of an optical fiber of length L. (Down) Geometric parameters of the structure of an air-silica photonic crystal fiber as a function of the pressure applied in the air holes in the drawing process. **Right**. (Up) Measured dispersion spectra of the photonic crystal fiber for different values of the pressure. (Down) Corresponding supercontinuum spectra obtained by excitation of the fiber with the same laser pumping conditions.*

This makes the measurement long and tedious. Lamps or SLEDs can be replaced by a single FYLA SCT1000 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. In this work this synchronous interferometric method to measure dispersion is proposed to optimize the design and manufacture of microstructured optical fibers through an iterative protocol implemented in the fiber drawing process.

CONCLUSIONS

An interferometric method to measure chromatic dispersion using a single picosecond pulsed SC source of fixed repetition rate applied to the design and fabrication of customized supercontinuum sources 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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Watt-level Tunable Narrow bandwidth Tm:YAP laser using a pair of Etalons

Salman Noach[1,#], Uziel Sheintop[1,2], Eytan Perez[1],Pavell Komm[2], Gilad Marcus[2], Nachum Danzig[1]

1. Department of Applied Physics, Electro-optics Engineering Faculty, Jerusalem College of Technology, Havaad Haleumi 21, Jerusalem, Israel
2. Department of Applied Physics, The Hebrew University of Jerusalem, Jerusalem, Israel

We demonstrated in this paper a watt-level tunable, narrow band, end-pumped Tm:YAP laser. Spectral tunability of $\mathbf{35}\boldsymbol{nm}$ ranging continuously between $\mathbf{1917-1951}\boldsymbol{nm}$ with a spectral linewidth of $\mathbf{0.15}\boldsymbol{nm}$ FWHM was achieved. The tuning and spectral band narrowing were obtained using a pair of YAG Etalons. Watt-level output power was measured along the laser tunable range, obtaining a maximal output power of $\mathbf{3.88}\boldsymbol{W}$ at $\mathbf{1934}\boldsymbol{nm}$. A slope efficiency of $\mathbf{44.8}\%$ is demonstrated for a maximal absorbed pump power of $\mathbf{12.1}\boldsymbol{W}$. The combination of the narrow bandwidth with tunability at those output power levels makes this laser a promising tool for bio-medical, sensing and material processing applications.

Corresponding Author: salman@jct.ac.il

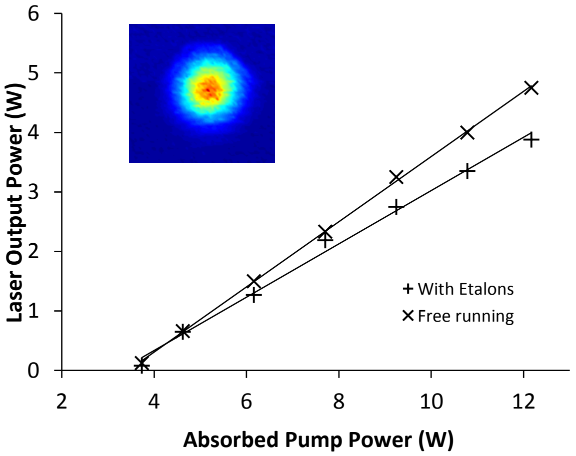

Fig 1. Laser performance and beam profile.

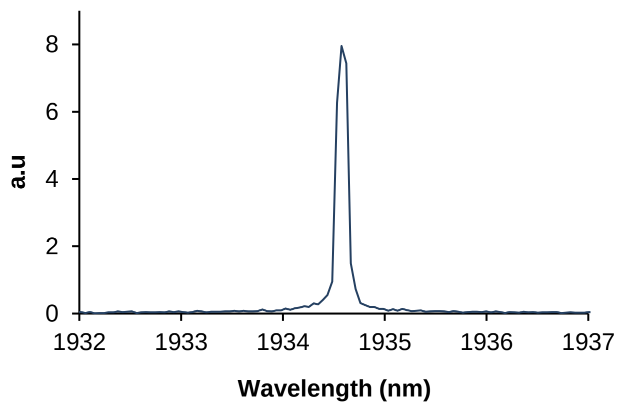

Fig. 2. Spectrum of the Tm:YAP laser using an Etalon pair.

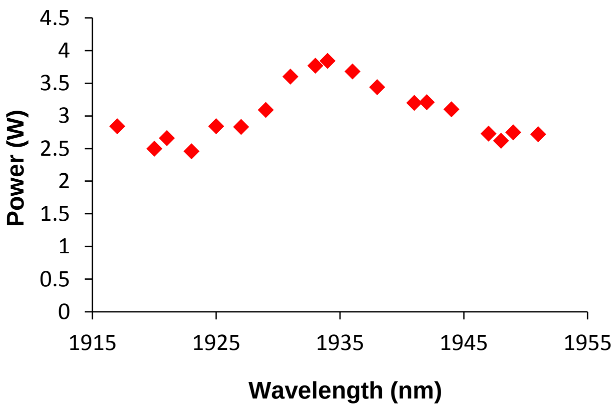

Fig. 3. Laser tunability performance

Ultrafast Fiber-based Mid-IR lasers

Evgeni Sorokin[1], Nikolai Tolstik[2,3], Roland Richter[2], Radwan Chahal[2], and Irina T. Sorokina[2,3]

[1] Institut für Photonik, TU Wien, Vienna, Austria
[2]Department of Physics, NTNU - Norwegian University of Science and Technology, Trondheim, Norway
[3]ATLA Lasers AS, Richard Birkelands vei 2B, 7034 Trondheim, Norway

The recent decade has witnessed a tremendous progress in femtosecond mode-locked sources operating beyond 2 µm, based on transitions in the rare-earth ions (Tm^{3+}, Er^{3+}, and Ho^{3+}) and vibronic transition in Cr^{2+} [1-3]. Interestingly, despite the difference in physical mechanisms, these successes were all made possible by extensive use of the fiber laser technology. For rare-earth ions, inhomogeneous broadening in fiber glasses is important for achieving the broad bandwidth, while the Cr-doped media critically depend on the continuous-wave Er- and Tm-fiber pump sources. Additionally, the fiber configuration is required for the tunable Raman self-frequency shift, and for environmental protection in the 2.8 µm wavelength region. This provides a whole new class of fiber based lasers, filling the gap between 2 and 3 µm to address demanding requirements set by the most advanced scientific and industrial applications.

The fiber-based femtosecond lasers have become available – even commercially – in the mid-IR wavelength range beyond 2 µm. In the region below 2.15 µm low-energy compact systems are based on Ho-fiber oscillators, while higher energy solution would use Tm-fiber based setups, with Raman solitons tunable up to 2.5 µm [3]. Further to the infrared one can make use of a fiber-laser pumped Cr:ZnS oscillator, covering the whole 2.1– 2.6 µm with few-cycle pulse durations and Watts of power [3,4]. Finally, Er- and Ho-based fiber lasers offer rapidly progressing femtosecond solutions at 2.8 µm with demonstrated capability of Raman soliton shift well beyond 3 µm [5,6].

Using the fiber technology is critical for a number of reasons: it is required for Raman solitons and environmental protection above 2.6 µm, as well as for reliability and ease of use. Among demonstrated applications are fast and sensitive frequency comb spectroscopy setups and subharmonic OPOs, which allow further extending the wavelength range to the mid-IR, with a spectral coverage up to 3–8 µm [7]. The laser systems do already find applications in industrial and scientific instrumentation – and the number of applications is gradually increasing as the technology develops.

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corresponding author: sorokin@tuwien.ac.at

Recent progress in broadband fiber-based mid-IR laser sources

Krzysztof M. Abramski, Jarosław Sotor, and Grzegorz Soboń

Laser & Fiber Electronics Group, Faculty of Electronics, Wrocław University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
E-mail: krzysztof.abramski@pwr.edu.pl

Broadband mid-infrared (mid-IR) sources, i.e. covering the wavelengths longer than 2 µm are unambiguously one of the most rapidly developed branches of laser technology. The development of laser sources in this spectral range is motivated by numerous applications, e.g. in spectroscopy, fundamental sciences, wireless communications or medical procedures. The Laser & Fiber Electronics Group carries out extensive research on novel fiber-based sources of broadband mid-IR radiation, based on femtosecond fiber lasers. Our recent demonstrations include: Holmium-doped all-fiber lasers based on graphene saturable absorbers [1]; coherent supercontinuum sources [2]; widely tunable femtosecond lasers based on Raman-induced soliton self-frequency shift (SSFS) [3], broadband sources based on difference frequency generation (DFG), operating at 3-4 µm [4] and 6-9 µm [5].

An example of a mid-IR DFG source developed recently in the Laser & Fiber Electronics Group is depicted in Fig. 1(a). The system is seeded by a graphene-based mode-locked Er-doped fiber laser (EDFL). The mid-infrared radiation is obtained via mixing of the output of the EDFL with frequency-shifted solitons at 1.9 µm generated in a highly nonlinear fiber using the same laser. Both beams interact in an orientation-patterned gallium phosphide (OP-GaP) crystal with different quasi-phase matching (QPM) periods.

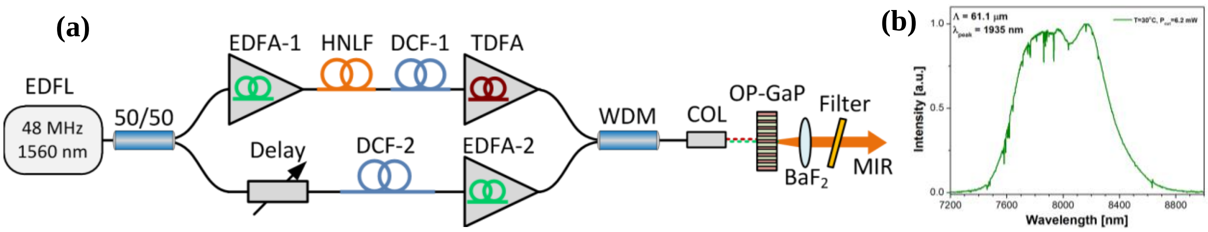

Fig. 1. Design of the mid-IR DFG system. EDFA: Er-doped fiber amplifier, TDFA: Tm-doped fiber amplifier, HNLF: highly nonlinear fiber, DCF: dispersion compensating fiber, WDM: wavelength division multiplexer, COL: collimator (a). Exemplary spectrum of the generated idler centered at 8000 nm (b).

As a result of the DFG process, we have obtained a mid-IR idler with average power of 7.4 mW at 7600 nm central wavelength, with >400 nm of bandwidth, at 48 MHz repetition frequency. By tuning of the signal wavelength and crystal QPM period, the DFG can easily cover the spectral range of 6000 – 9000 nm. An exemplary spectrum of the generated idler centered at 8000 nm is depicted in Fig. 1(b). The presented setup is the first truly all-fiber, all-polarization maintaining, alignment-free DFG source reported so far. Its unprecedented simplicity and compactness paves the way for applications in field-deployable optical frequency comb spectroscopy systems for gas sensing. The presentation will cover the recent achievements of our group in the area of broadband sources of mid-IR pulsed radiation.

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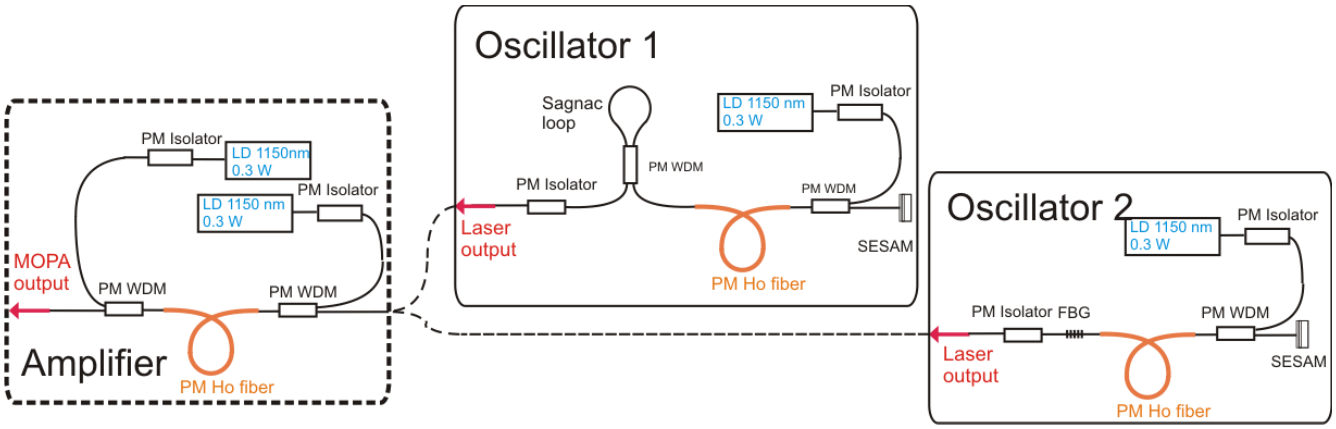
All-PM Diode-pumped Mode-locked Holmium Fiber MOPA

Nikolai Tolstik[1,3], Ingrid K. Bakke[1], Evgeni Sorokin[2], and Irina T. Sorokina[1,3]
[1] *Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway*
[2] *Institut für Photonik, TU Wien, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[3] *ATLA lasers AS, Richard Birkelands vei 2B, 7034 Trondheim Norway*

We report for the first time to our knowledge the diode-pumped all-fiber all-PM holmium mode-locked laser operating in fundamental soliton and dissipative soliton regimes. We also demonstrate the ultracompact diode-pumped all-PM holmium fiber amplifier.

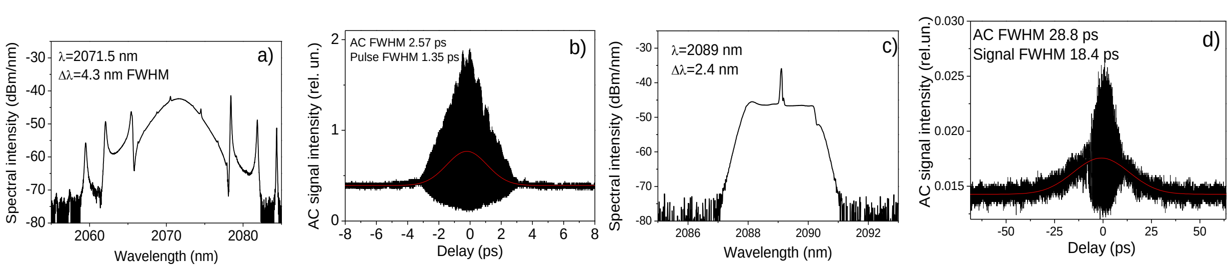
The experimental setup is shown in Fig.1. Two mode-locked fiber oscillators were assembled and used to seed diode-pumped fiber amplifier. Only PM fibers and fiber components were used in both oscillators and amplifier.



Single-mode laser diodes with 0.3 W output power at 1150 nm were used as pump sources for both oscillators and the amplifier. As an active fiber we used single-clad PM holmium-doped fiber with 8 μm core diameter. A butt-coupled commercial SESAM with modulation depth about 5% was used to obtain mode-locking. For the laser operating in the fundamental soliton regime Sagnac fiber loop was used as output coupler with transmission about 30%. For the laser operating in the dissipative soliton regime the chirped fiber Bragg grating (FBG) with 5.5 nm bandwidth and 32% reflectance, and around 2 ps^2 GVD was used as output coupler.

The fundamental soliton laser operated at a PRR of 18.2 MHz. Maximal output power of 1.7 mW (pulse energy slightly below 0.1 nJ) was limited by the soliton break-up. The laser emitted at 2071.5 nm and has an optical bandwidth of 4.3 nm. The transform limited pulse duration retrieved from the spectral width is around 1 ps. Amplifier boosts the average output power up to 70 mW (3.8 nJ pulse energy, 16 dB gain). For pulse energies higher than 1.8 nJ self-phase modulation distorts the pulse temporal and spectral profile. Autocorrelation of the amplified pulse at 1.81 nJ output power is shown in Fig. 2b.

In order to scale the pulse energy we switched the laser to dissipative soliton regime by implementing the chirped FBG as an output coupler. GDD of the FBG device is considerably higher than total roundtrip GDD induced by the cavity fibers. Increased transmittance of the output coupler gave higher average output power (12 mW resulting in 0.52 nJ energy at 23 MHz repetition rate). Pulses were strongly chirped with measured pulse duration around 18 ps. Amplification of chirped pulses resulted in 108 mW average output power (9.5 dB gain). Long pulse duration prevented spectral and temporal distortions during amplification, thus pulse energy of 4.7 nJ could be obtained with almost unchanged optical spectrum.



Finally we demonstrate the All-PM mode-locked holmium fiber MOPA laser system. Fundamental solitonic pulses with pulse energy up to 1.8 nJ were obtained at 2071 nm. Chirped pulse operation regime allowed scaling of the pulse energy up to 4.7 nJ with >100 mW average output power at 2089 nm, suitable for seeding of Ho:YAG regenerative amplifier

High energy mid-IR ultrashort pulses: the parametric route

Pavel Malevich[1], I. Astrauskas[1], T. Kanai[1], S. S. Kangaparambil[1], H. Hoogland[2,3], R. Holzwarth[2,4], A. Pugzlys[1,5], A. Baltuska[1,5]

[1] Photonics Institute, Vienna University of Technology, Gusshausstrasse 27-387, A-1040 Vienna, Austria
[2] Menlo Systems GmbH, Am Klopferspitz 19a, 82152 Martinsried, Germany
[3] Lehrstuhl für Laserphysik, Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 1, D-91058 Erlangen, Germany
[4] Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
[5] Center for Physical Sciences & Technology, Savanoriu Ave. 231 LT-02300 Vilnius, Lithuania

Many recent developments in the areas of medicine, spectroscopy, high field physics, etc. are associated with the implementation of intense mid-infrared (mid-IR) laser radiation. The majority of the above-listed applications also require an ultra- short pulse duration next to the specific wavelength and high energy. However, access to ultrashort mid-IR pulses is impeded not only by the lack of appropriate gain media, but on the top of it by difficulties of mode-locking in this wavelength range. Thus the most established method to access mid-IR is frequency conversion based on parametric nonlinear processes starting with near infrared lasers [1,2]. Generation of long mid-IR radiation requires special non-linear crystals, that typically have limited transparency range, which prevents using well-developed high-power 1 μm sources. Instead, longer wavelength sources can be used, such as Ho^{3+}- doped YAG or YLF laser crystals. Ho lasers operating in the vicinity of 2 μm are also of interest as stand-alone systems suitable for a range of medical, technological, and spectroscopic applications. To date, several (sub-)picosecond master oscillator/power amplifier (MOPA) systems operating in the vicinity of 2 μm have been reported [3-5].

The presented laser system is based on resonantly pumped Ho:YAG crystal, that operates at 2.1 μm. The ring cavity design is employed to avoid using of Faraday Rotators. For obtaining sub-ps pulse duration, gain narrowing in the CPA has been compensated by a spectral shaper and phase shift, accompanying amplification, has been corrected by Acousto-Optic Programmable Dispersive Filter. The laser system operates at room temperature and delivers 0.8-ps, 5.5-mJ pulses at a repetition rate of 1 kHz.

The laser is employed for driving a white-light-seeded cascaded mid-IR optical parametric amplifier (OPA) based on potassium titanyl arsenate (KTA) and ZGP nonlinear optical crystals. Matching of pump and seed duration is essential for the efficient conversion. Currently the system generates up to 80-μJ pulses, centered at 5.3 μm with bandwidth about 500 cm-1 tail-to-tail, supporting 4-optical cycles pulse duration.

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Conditions of single-mode light generation in DBR and DFB fiber lasers: wavelength-scale electromagnetic analysis by the method of single expression

H.V. Baghdasaryan[1#], T.M. Knyazyan[1], T.T. Hovhannisyan[1], Erich Leitgeb[2], M. Marciniak[3], Sławomir Sujecki[4], and Stefano Taccheo[5]

[1]National Polytechnic University of Armenia, 105 Terian str.Yerevan 0009, Armenia
[2]Institut fur Hochfrequenztechnik, Technische Universitat Graz, Inffeldgasse 12, 8010 Graz, Austria
[3]National Institute of Telecommunications, 1 Szachowa Street, 04-894 Warsaw, Poland
[4]The University of Nottingham, Nottingham, UK
[5] Swansea University, Singleton Park, SA2 8PP Swansea, United Kingdom

DBR (distributed Bragg reflector) and DFB (distributed feedback) fiber lasers are widely used in different area of science and technology [1]. Till now stable single-mode radiating fiber lasers operating in ultraviolet, visible and infrared bands are under strong demand [2]. Single-mode operation of fiber lasers is very advantageous for telecommunication, spectroscopy and sensors application. However, there is a lack of a strong wavelength-scale theoretical analysis of such fiber lasers at single-mode radiation. In the current work the results of the correct wavelength-scale electromagnetic analysis of DBR and DFB fiber lasers radiation are presented. The relevant wavelength-scale analysis is performed by the method of single expression [3]. A stable single-mode radiation from DBR laser can be observed at the specific lengths of a spacer - an amplifying piece of a fiber located between two FBGs (fiber Bragg gratings) serving as the laser mirrors. These specific lengths of the spacer should be as: an integer number of half and plus quarter wavelength in the spacer.

A stable single-mode radiation from DFB laser can be observed at π-shift in the middle of permittivity sinusoidal modulation of an amplifying fiber Bragg grating.

It is expected that the results of numerical analysis will be useful in designing stable single-mode radiating DBR and DFB lasers.

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corresponding author: e-mail: hovik@seua.am

Er^{3+} doped monolithic 1-D dielectric microcavity fabricated by rf-sputtering for coherent emission at 1.5 μm

A. Chiasera[1,*], F. Scotognella[2,3], B. Yann[4], G. Galzerano[5], A. Lukowiak[6], D.Ristic[7], G. Speranza[8,1], I. Vasilchenko[9], A. Vaccari[10], S. Valligatla[11], C. Meroni[12,1], S. Varas[1], L. Zur[13,1], M. Ivanda[7], G. C. Righini[13,14], S. Taccheo[15], R. Ramponi[5], M. Ferrari[1,13]

[1] IFN - CNR CSMFO Lab. & FBK CMM, via alla Cascata 56/C Povo, 38123 Trento, Italy.
[2] Politecnico di Milano, Dip. Fisica and IFN-CNR, Piazza Leonardo da Vinci 32, 20133, Milano, Italy
[3] Center for Nano Science and Technology@PoliMi, IIT, Via Giovanni Pascoli, 70/3, 20133, Milan, Italy
[4] Laboratoire FOTON (UMR CNRS 6082) Équipe Systèmes Photoniques, ENSSAT, CS 80518, F-22305 LANNION, France.
[5] IFN – CNR and Politecnico di Milano, Dip. Fisica, Piazza Leonardo da Vinci 32, 20133, Milano, Italy
[6] Institute of Low Temperature and Structure Research, PAS, 2 Okolna St., 50-422, Wroclaw, Poland
[7] Center of Excellence for Advanced Materials and Sensing Devices, Ruđer Bošković Institute, Bijenička c. 54, Zagreb, Croatia
[8] FBK CMM FMPS Unit, via Sommarive 18, Povo, 38123 Trento, Italy.
[9] Institute of High Technology Physics, Tomsk Polytechnic University, Tomsk, Russia.
[10] FBK CMM-ARES Unit, via Sommarive 18, Povo, 38123 Trento, Italy.
[12] Dipartimento di Fisica, Università di Trento, via Sommarive 14, Povo, 38123, Trento, Italy
[11] Institute for Integrative Nanosciences, IFW Dresden, Helmholtz Straße 20, 01069 Dresden, Germany.
[13] Enrico Fermi Center, Piazza del Viminale 1, 00184 Roma, Italy
[14] MiPLab. IFAC - CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
[15] College of Engineering, Swansea University, Singleton Park, Swansea, UK

We demonstrate that the rf-sputtering technique is suitable for the fabrication of high quality multilayer structures based on glass matrix. This paper reports the steps used in the fabrication protocols and the optical, spectroscopic, structural and morphologic results of Erbium activated 1-D photonic crystals, whereby it is possible to obtain coherent emission at 1.5 μm. 1-D Er^{3+} doped dielectric microcavity consists of 10 pairs of SiO_2/TiO_2 layers on each Bragg mirror with a central defect layer of SiO_2. Each layer is doped with Er^{3+}. The cavity is designed to present a cavity resonance at 1560 nm at 0° of detection that correspond to the $^4I_{13/2} \rightarrow ^4I_{15/2}$ Er^{3+} ions emission and a third order resonance placed at around 514 nm with 30° of incidence from the normal of the sample that is used to pump the sample with an Ar^+ laser line.

Luminescence spectroscopy put in evidence that the erbium emission from the microcavity related to the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of the Er^{3+} ions is centered at 1560 nm, at excitation power at 514.5 nm above 30 mW. It exhibits a Full Width at Half Maximum FWHM of ~ 1.0 ± 0.1 nm, that corresponds to the resolution of the detection apparatus. In the case of excitation power below 30 mW, the FWHM corresponds to 2.5 ± 0.1 nm. The behavior of the emission intensity at emission wavelength of 1560 nm and FWHM as a function of different 514.5 nm excitation powers, with a detection angle of 0° and an excitation angle of 30°, is nonlinear. Simultaneously there is a narrowing of the FWHM from 2.5 nm at low pump power to approximately 1 nm, which is limited by a spectral resolution of our experimental set up.

This research is performed in the framework of the projects COST MP1401 (2014-2018).

* alessandro.chiasera@cnr.ifn.it

Tailoring of geometries in Er^{3+} doped 1-D dielectric microcavity fabricated by Rf-Sputtering for the optimization of coherent emission at 1.5 μm

C. Meroni[1,2,*], A. Chiasera[2], F. Scotognella[3,4], Y.G. Boucher[5],
A. Lukowiak[6], G. Speranza[7,2], S. Varas[2], L. Zur[8,2], S. Taccheo[9], M. Ferrari[2,8]

[1]Dipartimento di Fisica, Università di Trento, via Sommarive 14, Povo, 38123, Trento, Italy
[2]IFN - CNR CSMFO Lab. & FBK CMM, via alla Cascata 56/C Povo, 38123 Trento, Italy.
[3]Politecnico di Milano, Dip. Fisica and IFN-CNR, Piazza Leonardo da Vinci 32, 20133, Milano, Italy
[4]Center for Nano Science and Technology@PoliMi, IIT, Via Giovanni Pascoli, 70/3, 20133, Milan, Italy
[5]Laboratoire FOTON (UMR CNRS 6082) Équipe Systèmes Photoniques, ENSSAT, CS 80518, F-22305 LANNION, France.
[6]Institute of Low Temperature and Structure Research, PAS, 2 Okolna St., 50-422, Wroclaw, Poland
[7]FBK CMM FMPS Unit, via Sommarive 18, Povo, 38123 Trento, Italy.
[8]Enrico Fermi Center, Piazza del Viminale 1, 00184 Roma, Italy
[9]College of Engineering, Swansea University, Singleton Park, Swansea, UK

Among different approaches and geometries, 1-D photonic crystals are the simplest photonic band-gap device exploitable to manipulate the emission and absorption properties of rare earth ions.

However, to obtain and optimize stimulated emission from these systems, a careful tailoring and optimization of the numerous parameters involved, such as the geometry and the materials, is needed. Rf-Sputtering technique allows to control precisely the various steps of the fabrication process of the cavities. In this paper, we present different approaches that are used to improve the spectroscopic features of Er^{3+} doped monolithic 1-D photonic crystals.

The Er^{3+} doped dielectric 1-D microcavities were fabricated by Rf Sputtering technique. The microcavities are formed by half wave Er^{3+} doped SiO_2 active layer, inserted between two active Bragg reflectors that consist of a certain number, depending on the sample, of pairs of SiO_2/TiO_2 layers also doped with Er^{3+} ions. The spectroscopic features of the samples have been investigated in the 1.5 μm region, with the purpose of emphasize the most convenient geometry. The emission intensity peak at 1535 nm presents a non-linear behavior with the pump power and a threshold at about 0.6 mW has been observed.

This research is performed in the framework of the projects COST MP1401 (2014-2018).

*meroni@fbk.eu

Effects of gamma irradiation on phase-shifted grating based fiber laser

Haifeng Qi [a], Dan Sporea [b], Andrei Stancalie [b], Daniel Neguţ [c], Weitao Wang [a], Jian Guo [a], Zhiqiang Song [a], Chang Wang [a], and Gangding Peng [d]

[a] Shandong Key Laboratory of Optical Fiber Sensing Technologies, Laser Institute of Shandong Academy of Sciences, Jinan, Shandong, 250014, China

[b] National Institute for Laser, Plasma and Radiation Physics Center for Advanced Laser Technologies, Magurele, 077125, Romania

[c] Horia Hulubei" National Institute of Physics and Nuclear Engineering, Măgurele, 077125, Romania

[d] School of Electrical Engineering & Telecommunications, The University of New South Wales, NSW, 2052, Australia

The experimental study concerning the irradiation effects of gamma-ray on distributed feedback fiber laser (DFB-FL) was carried out. The obvious wavelength shift was observed without evident changes in reflectivity and bandwidth under the current experimental irradiation condition, up to 60 kGy gamma radiation. For DFB-FL, evident attenuation in output power was observed and the rising tendency of the attenuation under increasing irradiation dose was demonstrated as well.

The cavity of DFB-FL is a section of phase-shifted grating engraved on Er-doped optical fiber (Nufern, Esf3/125). The phased-shifted gratings studied in our experiment were fabricated with dithering phase mask technique and a 244 nm continuous UV laser (shown in Fig.1). The phase-shifted grating lengths of these samples were about 30 mm to 40 mm. The phase-shifted grating emits laser at the Bragg wavelength when it is pumped through a wavelength division multiplexer (WDM) with a 980 nm laser diode (LD). The schematic diagram for DFB-FL is illustrated in Fig. 3.

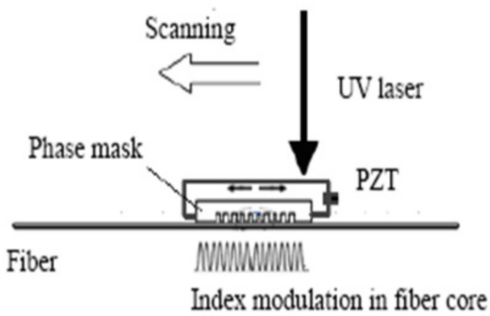

Fig. 1 Schematic diagram for grating fabrication technique

Fig. 2 Phase-shifted grating fabrication system

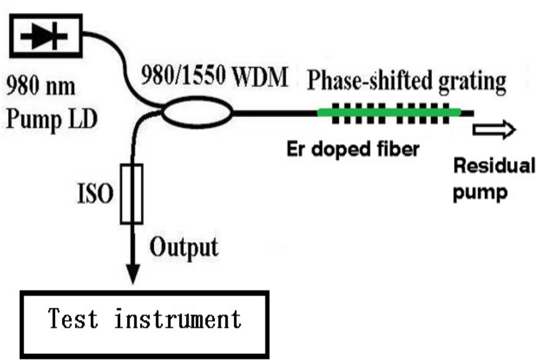

Fig. 3 Schematic diagram for DFB-FL

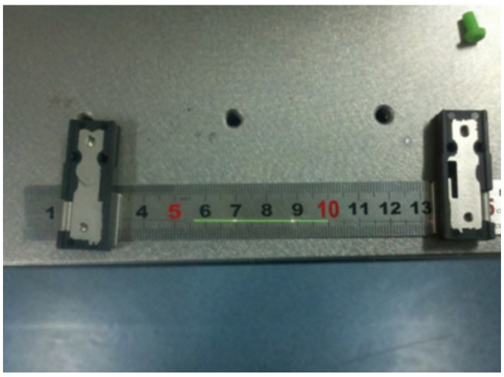

Fig.4 DFB-FL cavity

The DFB-FL samples prepared as above were irradiated under different gamma radiation doses in batches. The irradiation of the investigated samples was performed using the ^{60}Co the research irradiator type

GC-5000, BRIT (India), which has an irradiation chamber volume of 5000 cm^3 and is operated at "Horia Hulubei" National Institute of Physics and Nuclear Engineering. The sketch of the irradiator is illustrated in Fig. 5. The samples for irradiation were placed during the irradiation in the middle of the irradiation chamber and about 10 cm above the base. The samples were tested with varying gamma doses of 2, 12, 36, and 60 kGy at a dose rate of 4.4 kGy/h. The irradiation process was carried out at about 36 °C slightly above the room temperature. The irradiation dose and total dose were measured, off-line, with one standard deviation of 3.3 %, by using an ethanolchlorobenzen dosimetery system with oscillometric readout method. The system is traceable at the National Physical Laboratory, through RISOE HDRL.

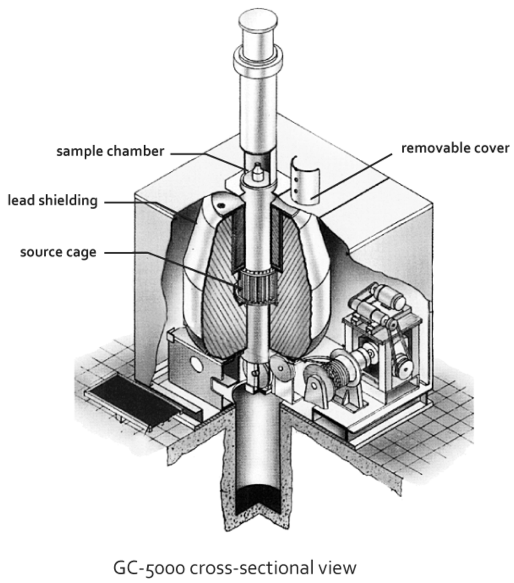

Fig. 5 Sketch of the gamma irradiation

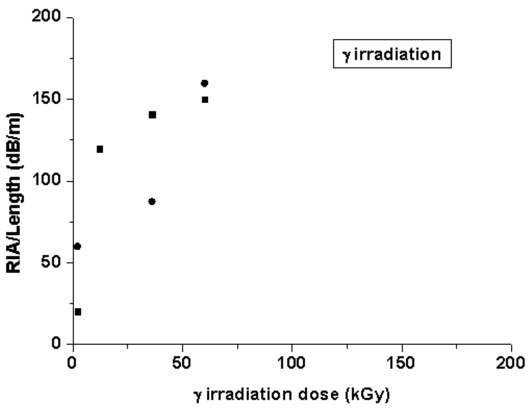

Fig. 6 Gamma radiation effect on DFB-FL output power

All results of gamma induced power loss of DFB-FLs are summarized in Table 1.

Table 1 LASER EFFICIENCY DECREASE WITH THE INCREASE IRRADIATION DOSE FOR GAMMA IRRADIATION

γ dose (kGy)	**Sample Code**	**Length (mm)**	**Output power before irradiation (μW)**	**Output power after irradiation (μW)**	**Difference (μW)**	**RIA (dB)**	**RIA/Length (dB/m)**
2	DFB-01	40	73	60.6	-12.4	0.81	20.25
	DFB-09	44	18	9.8	-8.2	2.64	60
12	DFB-10	40	187	62	-125	4.79	119.8
	DFB-02	40	Broken		-	-	-
36	DFB-11	40	160	43.8	-116.2	5.63	140.8
	DFB-03	45	240	97	-143	3.93	87.3
60	DFB-12	40	149	37.5	-111.5	6.0	150
	DFB-04	35	135	37.3	-97.7	5.59	159.7

For these DFB-FLs, the radiation induced power loss was observed and found to be nearly proportional to the irradiation dose, for gamma irradiation, as shown in Fig.6. From the experimental results, the radiation induced power loss in DFB-FL increases with the increasing doses of gamma radiation. This suggests that the semi-quantitative radiation dosimetry by DFB-FL is possible. Since the laser cavity of DFB-FL has a section of pigtail fiber about 0.5 m at the output port which was also irradiated by the same radiation dose,

the radiation induced laser attenuation must include RIA of pigtail fiber at both 1550 nm and 980 nm. The RIA of pigtail fiber at 980 nm led to the reduction of pump power entering into laser cavity. The RIA of pigtail fiber at 1550 nm led to the reduction of laser emission arriving at power meter. Since the negligible changes in grating strength mentioned before, the increase of cavity loss could be decided which led to the laser efficiency decrease. As for the specific cavity loss of DFB-FL, the radiation induced difference in characteristics of the Er-doped fiber should be measured in the meantime. Hence, the quantitative measurement of the used fiber characteristics need be carried out in the future investigation.

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