Deep-UV to Mid-IR Supercontinuum Generation driven by Mid-IR Ultrashort Pulses in a Gas-filled Hollow-core Fiber

Supercontinuum (SC) generation based on ultrashort pulse compression constitutes one of the most promising technologies towards ultra-wide bandwidth, high-brightness, and spatially coherent light sources for applications such as spectroscopy and microscopy. Here, multi-octave SC generation in a gas-filled hollow-core antiresonant fiber (HC-ARF) is reported spanning from 200 nm in the deep ultraviolet (DUV) to 4000 nm in the mid-infrared (mid-IR) having an output energy of 5 μJ. This was obtained by pumping at the center wavelength of the first anti-resonant transmission window (2460 nm) with ~100 fs pulses and an injected pulse energy of ~8 μJ. The mechanism behind the extreme spectral broadening relies upon intense soliton-plasma nonlinear dynamics which leads to efficient soliton self-compression and phase-matched dispersive wave (DW) emission in the DUV region. The strongest DW is observed at 275 nm which corresponds to the calculated phase-matching wavelength of the pump. Furthermore, the effect of changing the pump pulse energy and gas pressure on the nonlinear dynamics and their direct impact on SC generation was investigated. This work represents another step towards gas-filled fiber-based coherent sources, which is set to have a major impact on applications spanning from DUV to mid-IR.
mid-infrared spectral-domain optical coherence tomography system operating at a central wavelength of 4 µm and an axial resolution of 8.6 µm is demonstrated. The system produces two-dimensional cross-sectional images in real time enabled by a high-brightness 0.9- to 4.7-µm mid-infrared supercontinuum source with a pulse repetition rate of 1 MHz for illumination and broadband upconversion of more than 1-µm bandwidth from 3.58–4.63 µm to 820–865 nm, where a standard 800-nm spectrometer can be used for fast detection. The images produced by the mid-infrared system are compared with those delivered by a state-of-the-art ultra-high-resolution near-infrared optical coherence tomography system operating at 1.3 µm, and the potential applications and samples suited for this technology are discussed. In doing so, the first practical mid-infrared optical coherence tomography system is demonstrated, with immediate applications in real-time non-destructive testing for the inspection of defects and thickness measurements in samples that exhibit strong scattering at shorter wavelengths.

GLS and GLSSe ultrafast laser inscribed waveguides for mid-IR supercontinuum generation

Using the ultrafast laser inscription technique, buried channel waveguides have been fabricated in gallium lanthanum sulfide and gallium lanthanum sulfide selenide glasses to demonstrate the suitability of the materials for supercontinuum generation in the mid-IR. Supercontinuum generation was performed using 100 femtosecond pump pulses with microJoule pulse energies and a center wavelength of 4.6 µm, which is in the anomalous dispersion regime for these waveguides. Under such pump conditions, supercontinuum was obtained covering a 25-dB-bandwidth of up to 6.1 µm with a long-wavelength edge of 8 µm. To our knowledge, this represents the broadest and the longest-wavelength IR supercontinuum generated from an ultrafast laser inscribed waveguide to date.
Supercontinuum laser for spectroscopic photoacoustic imaging of lipids in the extended near-infrared region

The ability of spectroscopic photoacoustic imaging to enable functional information on top of the structural information of the tissue makes it a promising tool for detection and monitoring of numerous diseases. In the current work, we demonstrate a cost-efficient high-power supercontinuum laser source based on a telecom range diode laser system and few meters of a standard optical fiber for spectroscopic photoacoustic imaging of lipids in the extended near-infrared region.

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Direct nanoimprinting of moth-eye structures in chalcogenide glass for broadband antireflection in the mid-infrared

Fresnel reflection at the boundary between two media of differing refractive indices is a major contributing factor to the overall loss in mid-infrared optical systems based on high-index materials such as chalcogenide glasses. In this paper, we present a study of broadband antireflective moth-eye structures directly nanoimprinted on the surfaces of arsenic triselenide (As2Se3)-based optical windows. Using rigorous coupled-wave analysis, we identify a relief design optimized for high transmittance (<1% reflectance) at 6 μm, which when nanoimprinted features a transmittance improvement (ΔT > 12%) in the 5.9–7.3 μm spectral range as well as improved omnidirectional properties. Finally, we demonstrate the adaptability of nanoimprinted surface reliefs by tailoring the nanostructure pitch and height, achieving both extremely broadband antireflective and highly efficient antireflective surface reliefs. The results and methods presented herein provide an efficient and scalable solution for improving the transmission of bulk optics, waveguides, and photonic devices in the mid-infrared.

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Organisations: Department of Micro- and Nanotechnology, Polymer Micro & Nano Engineering, Department of Photonics Engineering, Fiber Sensors & Supercontinuum, Surface Engineering
Contributors: Lotz, M. R., Petersen, C. R., Markos, C., Bang, O., Jakobsen, M. H., Taboryski, R. J.
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Ge22As20Se58 glass ultrafast laser inscribed waveguides for mid-IR integrated optics

Ultrafast laser inscription has been used to produce channel waveguides in Ge22As20Se58 glass (GASIR-1, Umicore N.V). The mode field diameter and waveguide losses at 2.94 μm were measured along with the waveguide dispersion in the 1 to 4.5 μm range, which is used to estimate the zero-dispersion wavelength. Z-scan measurements of bulk samples have also been performed to determine the nonlinear refractive index. Finally, midIR supercontinuum generation has been shown when pumping the waveguides with femtosecond pulses centered at 4.6 μm. Supercontinuum spanning approximately 4 μm from 2.5 to 6.5 μm was measured which, to the best of the authors' knowledge, represents the broadest and the deepest IR supercontinuum from an ultrafast laser inscribed waveguide to date. This work, combined with the long wavelength transmission of GASIR-1 up to 15 μm, paves the way for realizing further ultrafast laser inscribed waveguide devices in GASIR-1 for mid-IR integrated optics applications. Published by The Optical Society under the terms of the Creative Commons Attribution 4.0 License.

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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, Fraunhofer Centre for Applied Photonics, Heriot-Watt University
Contributors: Morris, J. M., Mackenzie, M. D., Petersen, C. R., Demetriou, G., Kar, A. K., Bang, O., Bookey, H. T.
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High-pulse energy supercontinuum laser for high-resolution spectroscopic photoacoustic imaging of lipids in the 1650-1850 nm region

We propose a cost-effective high-pulse energy supercontinuum (SC) source based on a telecom range diode laser-based amplifier and a few meters of standard single-mode optical fiber, with a pulse energy density as high as ~25 nJ/nm in the 1650-1850 nm regime (factor >3 times higher than any SC source ever used in this wavelength range). We demonstrate how such an SC source combined with a tunable filter allows high-resolution spectroscopic photoacoustic imaging and the spectroscopy of lipids in the first overtone transition band of C-H bonds (1650-1850 nm). We show the successful discrimination of two different lipids (cholesterol and lipid in adipose tissue) and the photoacoustic cross-sectional scan of lipid-rich adipose tissue at three different locations. The proposed high-pulse energy SC laser paves a new direction towards compact, broadband and cost-effective source for spectroscopic photoacoustic imaging.

General information
High Pulse Energy Supercontinuum Laser for Photoacoustic Detection and Identification of Lipids in the 1650-1850 nm Wavelength Region

Lipids are highly coveted for the interrogation of fatal chronic diseases. We propose cost-efficient high pulse energy supercontinuum source, using telecom range diode laser and standard optical fiber for photoacoustic detection and identification of lipids.

Mid-infrared fiber-coupled supercontinuum spectroscopic imaging using a tapered chalcogenide photonic crystal fiber

We present the first demonstration of mid-infrared spectroscopic imaging of human tissue using a fiber-coupled supercontinuum source spanning from 2-7.5 μm. The supercontinuum was generated in a tapered large mode area chalcogenide photonic crystal fiber in order to obtain broad bandwidth, high average power, and single-mode output for good imaging properties. Tissue imaging was demonstrated in transmission by raster scanning over a sub-mm region of paraffinized colon tissue on CaF2 substrate, and the signal was measured using a fiber-coupled grating spectrometer. This demonstration has shown that we can distinguish between epithelial and surrounding connective tissues within a paraffinized section of colon tissue by imaging at discrete wavelengths related to distinct chemical absorption features.
Mid-infrared multispectral tissue imaging using a chalcogenide fiber supercontinuum source
We present the first demonstration of mid-infrared supercontinuum tissue imaging at wavelengths beyond 5 μm using a fiber-coupled supercontinuum source spanning 2-7.5 μm. The supercontinuum was generated in a tapered large mode area chalcogenide photonic crystal fiber in order to obtain broad bandwidth, high average power, and single-mode output for diffraction-limited imaging performance. Tissue imaging was demonstrated in transmission at selected wavelengths between 5.7μm (1754 cm−1) and 7.3μm (1370 cm−1) by point scanning over a sub-mm region of colon tissue, and the results were compared to images obtained from a commercial instrument

Mid-IR Supercontinuum Generation in Ultrafast Laser Inscribed Waveguides
Supercontinuum from 2.5 to 6.5 μm has been generated in ULI waveguides pumped with femtosecond pulses centered at 4.6 μm. Dispersion measurements show the zero dispersion wavelength for the waveguides to be around 5.3 μm.
Multimaterial photonic crystal fibers
One of the main advantages of photonic crystal fibers (PCFs) is their ability to host novel functional materials in the airholes of the cladding. Here, we demonstrate a unique post-processing method which allows the integration of materials with significantly different thermo-mechanical properties inside the voids of silica PCF. We first present the material properties of silica, As2Se3 and polydimethylsiloxane (PDMS) in terms of their refractive indices and viscosity profile. The latter suggests that the proposed materials are not suitable for direct fiber drawing and thus we present the development of a multi-material As2Se3/PDMS/Silica PCF based on a solution-processed and pressure-assisting method. The integration of both As2Se3 chalcogenide glass films and PDMS was made in ambient conditions using a cost-effective approach. The deposition of the high-index chalcogenide glass films revealed distinct resonances in the visible and near-infrared region while the high thermo-optic coefficient of PDMS provides the ability to thermally control the intensity of the antiresonant bands. The proposed method opens new directions towards multimaterial silica-based PCFs for novel tunable devices and sensors.

Towards a table-top synchrotron based on supercontinuum generation
Recently, high brightness and broadband supercontinuum (SC) sources reaching far into the infrared (IR) have emerged with the potential to rival traditional broadband sources of IR radiation. Here, the brightness of these IR SC sources is compared with that of synchrotron IR beamlines and SiC thermal emitters (Globars). It is found that SC sources can deliver a brightness that is 5-6 orders of magnitude higher than Globars and 1-2 orders of magnitude higher than typical IR beamlines, matching the beamlines at least out to 10.6 μm (940 cm⁻¹). This means that these sources can now cover nearly all of the 800-5000 cm⁻¹ spectrum (2-12.5 μm) which is frequently used in IR spectroscopy and microscopy. To demonstrate applicability, such an IR SC source was used for transmission spectroscopy of highly scattering filtration membranes from 3500-1300 cm⁻¹, and transmission microscopy of colon tissue at 1538 cm⁻¹.
Efficient Mid-Infrared Supercontinuum Generation in Tapered Large Mode Area Chalcogenide Photonic Crystal Fibers
Mid-infrared supercontinuum spanning from 1.8-9 μm with an output power of 41.5 mW is demonstrated by pumping tapered large mode area chalcogenide photonic crystal fibers using a 4 μm optical parametric source.

Increased mid-infrared supercontinuum bandwidth and average power by tapering large-mode-area chalcogenide photonic crystal fibers
The trade-off between the spectral bandwidth and average output power from chalcogenide fiber-based mid-infrared supercontinuum sources is one of the major challenges towards practical application of the technology. In this paper we address this challenge through tapering of large-mode-area chalcogenide photonic crystal fibers. Compared to previously reported step-index fiber tapers the photonic crystal fiber structure ensures single-mode propagation, which improves the beam quality and reduces losses in the taper due to higher-order mode stripping. By pumping the tapered fibers at 4 μm using a MHz optical parametric generation source, and choosing an appropriate length of the untapered fiber segments, the output could be tailored for either the broadest bandwidth from 1 to 11.5 μm with 35.4 mW average output power, or the highest output power of 57.3 mW covering a spectrum from 1 to 8 μm. (C) 2017 Optical Society of America
Spectroscopy is the study of how light interacts with molecules, which can be used to identify various substances in for example foods and medicine, by observing which parts of the light is absorbed after interaction with the sample. Especially infrared light, more precisely the mid infrared part of the spectrum, is of interest because almost all molecules display distinct absorption fingerprints in this region. Current instrumentation however relies on thermal light sources, much like the well-known incandescent light bulb, which has very limited brightness and limited possibilities for manipulating and using the light in different applications. This dissertation presents the past three years of my work with developing an alternative light source that has the broad spectral bandwidth of a lamp, and high power focused in a tight spot similar to a laser. Such a mid-infrared light source can be achieved through a process known as supercontinuum generation.

Supercontinuum generation is a spectacular process in which an intense single color laser line can generate new colors by propagation in a nonlinear medium, such as a glass optical fiber. The theory of supercontinuum generation is therefore presented as well as experimental and numerical results. Several different configurations of lasers and fibers are investigated, together with techniques for increasing the power, such as imprinting of anti-reflective structures and reducing the diameter of the fiber to increase the nonlinearity and thus efficiency of the supercontinuum generation. Finally the light sources are put to the test in a series of proof-of-concept demonstrations, designed to benefit from the unique properties of supercontinuum light sources. It is believed that such a source can find application within for example food analysis and diagnosis of early-stage skin cancer.
Mid-IR supercontinuum generation beyond 7 μm using a silica-fluoride-chalcogenide fiber cascade

We report on an experimental demonstration of mid-infrared cascaded supercontinuum generation in commercial silica, fluoride, and chalcogenide fibers as a potentially cheap and practical alternative to direct pumping schemes. A pump continuum up to 4.4 μm was generated in cascaded silica and fluoride fibers by an amplified 1.55 μm nanosecond diode laser. By pumping a commercial Ge10As22Se68 single-material photonic crystal fiber with 135.7 mW of the pump continuum from 3.5- 4.4 μm, we obtained a continuum up to 7.2 μm with a total output power after the collimating lens of 54.5 mW, and 3.7 mW above 4.5 μm.

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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum
Contributors: Petersen, C. R., Moselund, P. M., Petersen, C., Møller, U. V., Bang, O.
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Volume: 9703
Publisher: SPIE - International Society for Optical Engineering
Refractive index and dispersion control of ultrafast laser inscribed waveguides in gallium lanthanum sulphide for near and mid-infrared applications

The powerful ultrafast laser inscription technique is used to fabricate optical waveguides in gallium lanthanum sulphide substrates. For the first time the refractive index profile and the dispersion of such ultrafast laser inscribed waveguides are experimentally measured. In addition the Zero Dispersion Wavelength of both the waveguides and bulk substrate is experimentally determined. The Zero Dispersion Wavelength was determined to be between 3.66 and 3.71 μm for the waveguides and about 3.61 μm for the bulk. This work paves the way for realizing ultrafast laser inscribed waveguide devices in gallium lanthanum sulphide glasses for near and mid-IR applications. (C) 2016 Optical Society of America

Spectral-temporal composition matters when cascading supercontinua into the mid-infrared

Supercontinuum generation in chalcogenide fibers is a promising technology for broadband spatially coherent sources in the mid-infrared, but it suffers from discouraging commercial prospects, mainly due to a lack of suitable pump lasers. Here, a promising approach is experimentally demonstrated using an amplified 1.55 μm diode laser to generate a pump continuum up to 4.4 μm in cascaded silica and fluoride fibers. We present experimental evidence and numerical simulations confirming that the spectral-temporal composition of the pump continuum is critical for continued broadening in a chalcogenide fiber. The fundamental physical question is concerned with the long-wavelength components of the pump spectrum, which may consist of either solitons or dispersive waves. In demonstrating this we present a commercially viable fiber-cascading configuration to generate a mid-infrared supercontinuum up to 7 μm in commercial chalcogenide fibers.

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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, Heriot-Watt University, Universite Laval, University of Southampton
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General information
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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, NKT Group
Towards the mid-infrared optical biopsy

We are establishing a new paradigm in mid-infrared molecular sensing, mapping and imaging to open up the mid-infrared spectral region for in vivo (i.e. in person) medical diagnostics and surgery. Thus, we are working towards the mid-infrared optical biopsy (‘opsy’ look at, bio the biology) in situ in the body for real-time diagnosis. This new paradigm will be enabled through focused development of devices and systems which are robust, functionally designed, safe, compact and cost effective and are based on active and passive mid-infrared optical fibers. In particular, this will enable early diagnosis of external cancers, mid-infrared detection of cancer-margins during external surgery for precise removal of diseased tissue, in one go during the surgery, and mid-infrared endoscopy for early diagnosis of internal cancers and their precision removal.

The mid-infrared spectral region has previously lacked portable, bright sources. We set a record in demonstrating extreme broad-band supercontinuum generated light 1.4 to 13.3 microns in a specially engineered, high numerical aperture mid-infrared optical fiber. The active mid-infrared fiber broadband supercontinuum for the first time offers the possibility of a bright mid-infrared wideband source in a portable package as a first step for medical fiber-based systems operating in the mid-infrared. Moreover, mid-infrared molecular mapping and imaging is potentially a disruptive technology to give improved monitoring of the environment, energy efficiency, security, agriculture and in manufacturing and chemical processing. This work is in part supported by the European Commission: Framework Seven (FP7) Large-Scale Integrated Project MINERVA: MId-to-NEaR-infrared spectroscopy for improVed medical diAgnostics (317803; www.minerva-project.eu).

General information

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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, University of Nottingham, University of Exeter, Gloucestershire Royal Hospital, Gooch and Housego Ltd., NKT Group, Vivid Components Ltd., LISA Laser Products GmbH
Publication date: 2016
Mid-infrared supercontinuum generation in the fingerprint region

The mid-infrared spectral region is of great technical and scientific interest because most molecules display fundamental vibrational absorptions in this region, leaving distinctive spectral fingerprints. Here, we demonstrate experimentally that launching intense ultra-short pulses with a central wavelength of either 4.5 µm or 6.3 µm into short pieces of ultra-high numerical-aperture step-index chalcogenide glass optical fibre generates a mid-infrared supercontinuum spanning 1.5 µm to 11.7 µm and 1.4 µm to 13.3 µm, respectively [1]. This is the first experimental demonstration to truly reveal the potential of fibres to emit across the mid-infrared molecular fingerprint region, which is of key importance for applications such as early cancer diagnostics, gas sensing and food quality control.

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Source: PublicationPreSubmission
Mid-infrared supercontinuum generation spanning more than 11 μm in a chalcogenide step-index fiber

Supercontinuum generation covering an ultra-broad spectrum from 1.5-11.7μm and 1.4-13.3μm is experimentally demonstrated by pumping an 85mm chalcogenide step-index fiber with 100fs pulses at a wavelength of 4.5μm and 6.3μm, respectively.

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Multi-milliwatt mid-infrared supercontinuum generation in a suspended core chalcogenide fiber

A low-loss suspended core As38Se62 fiber with core diameter of 4.5 μm and a zero-dispersion wavelength of 3.5 μm was used for mid-infrared supercontinuum generation. The dispersion of the fiber was measured from 2.9 to 4.2 μm and was in good correspondence with the calculated dispersion. An optical parametric amplifier delivering 320 fs pulses with a peak power of 14.8 kW at a repetition rate of 21 MHz was used to pump 18 cm of suspended core fiber at different wavelengths from 3.3 to 4.7 μm. By pumping at 4.4 μm with a peak power of 5.2 kW coupled to the fiber a supercontinuum spanning from 1.7 to 7.5 μm with an average output power of 15.6 mW and an average power >5.0 μm of 4.7 mW was obtained.

General information
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DOIs:
10.1364/OE.23.003282
Two-octave mid-infrared supercontinuum generation in As-Se suspended core fibers

A more than two-octave mid-infrared supercontinuum with an average output power of 15.6 mW covering 1.7-7.5 μm (1,333-5,900 cm\(^{-1}\)) is generated in a low-loss As\(_{38}\)Se\(_{62}\) suspended core fiber with core diameter of 4.5 μm.

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Broadband Mid-infrared Supercontinuum Generation in Suspended Core Chalcogenide Fibers

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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, Australian National University, Perfors, Université de Rennes
Contributors: Yu, Y., Gai, X., Møller, U. V., Kubat, I., Petersen, C. R., Brilland, L., Méchin, D., Troles, J., Bang, O., Luther-Davies, B.
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Research output: Contribution to conference – Conference abstract for conference – Annual report year: 2014 – Research – peer-review

High Average Power Mid-infrared Supercontinuum Generation in a Suspended Core Chalcogenide Fiber

Mid-infrared supercontinuum spanning from 2.0 to 6.1 μm is generated in a 9 cm suspended core chalcogenide fiber by pumping close to the fiber zero-dispersion wavelength at 3.5 μm with an OPA system

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Publication date: 2014

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Mid-infrared supercontinuum covering the 1.4–13.3 μm molecular fingerprint region using ultra-high NA chalcogenide step-index fibre

The mid-infrared spectral region is of great technical and scientific interest because most molecules display fundamental vibrational absorptions in this region, leaving distinctive spectral fingerprints. To date, the limitations of mid-infrared light sources such as thermal emitters, low-power laser diodes, quantum cascade lasers and synchrotron radiation have precluded mid-infrared applications where the spatial coherence, broad bandwidth, high brightness and portability of a supercontinuum laser are all required. Here, we demonstrate experimentally that launching intense ultra-short pulses with a central wavelength of either 4.5 μm or 6.3 μm into short pieces of ultra-high numerical-aperture step-index chalcogenide glass optical fibre generates a mid-infrared supercontinuum spanning 1.5 μm to 11.7 μm and 1.4 μm to 13.3 μm, respectively. This is the first experimental demonstration to truly reveal the potential of fibres to emit across the mid-infrared molecular ‘fingerprint region’, which is of key importance for applications such as early cancer diagnostics, gas sensing and food quality control.

Mid-infrared supercontinuum generation in a suspended core chalcogenide fiber

The mid-infrared spectral region is of great interest because virtually all organic compounds display distinctive spectral fingerprints herein that reveal chemical information about them [1], and the mid-infrared region is therefore of key importance to many applications, including food quality control [2], gas sensing [3] and medical diagnostics [4]. We have used a low-loss suspended core As38Se62 fiber with core diameter of 4.5 μm and a zero-dispersion wavelength of 3.5 μm to generate mid-infrared supercontinuum by pumping with an optical parametric amplifier delivering 320 fs pulses with a peak power of ~5.5 kW at a repetition rate of 21 MHz at different wavelengths from 3.3 to 4.7 μm. By pumping at 4.4 μm with a peak power of 5.2 kW coupled to the fiber a supercontinuum spanning from 1.7 to 7.5 μm with an average output power of 15.6 mW was obtained. Figure 1 shows the results obtained when pumping at 3.5 μm. We have recently demonstrated a record-breaking supercontinuum spanning from 1.4–13.3 μm in a step-index chalcogenide fiber [5]. The results in this presentation are however to our knowledge the first reported supercontinuum generated beyond 6 μm in a chalcogenide microstructured optical fiber.
Mid-infrared supercontinuum generation in concatenated fluoride and chalcogenide glass fibers covering more than three octaves

Supercontinuum is generated in concatenated ZBLAN and As2Se3 fibers. Initially, a 0.9-4.1mm supercontinuum is obtained by pumping the ZBLAN fiber with a Tm laser, which then continues to broaden to 0.9-9um in As2Se3 fiber.

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Contributors: Kubat, I., Petersen, C. R., Møller, U. V., Seddon, A., Benson, T., Brilland, L., Méchin, D., Moselund, P. M., Bang, O.
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Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2014 › Research › peer-review

Supercontinuum based mid-IR imaging spectroscopy for cancer detection

The mid-infrared (IR) spectral region is of significant technical and scientific interest because most molecules display fundamental vibrational absorptions in this region, leaving distinct spectral fingerprints. To date, the limitations of mid-IR light sources, such as thermal emitters, low-power laser diodes, quantum cascade lasers and synchrotron radiation, have precluded mid-IR applications where the spatial coherence, broad bandwidth, high brightness and portability of a supercontinuum laser are all required. In an international collaboration in the EU project MINERVA [minerva-project.eu] DTU Fotonik has now demonstrated the first optical fiber based broadband so-called supercontinuum light source, which covers 1.4-13.3 μm and thereby most of the molecular fingerprint region [1]. This ultra-fast light source is the basic component in the mid-IR camera developed in MINERVA for early cancer detection with mid-IR imaging spectroscopy.

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Contributors: Bang, O., Møller, U. V., Kubat, I., Petersen, C. R.
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Research output: Chapter in Book/Report/Conference proceeding – Conference abstract in proceedings – Annual report year: 2014 › Research › peer-review

Supercontinuum generation from ultraviolet to mid-infrared

The advent of photonic crystal fibers (PCFs) has paved the road for commercial high-power supercontinuum light sources. The air-hole structuring in the PCF manipulates the properties of light and gives a tremendous degree of design freedom, which has enabled pushing the properties of PCFs to limits that can never be achieved with standard step index fibers. For example, one can move the zero dispersion wavelength (ZDW) into the visible [1] and make them endlessly single moded [2]. For efficient supercontinuum generation it is of great importance that the pump wavelength is close to the ZDW. We demonstrate how the spectral blue-edge can be manipulated by careful fiber design and tapering of the PCF enabling supercontinuum generation spanning all the way from 380 nm to 2.4μm [3]. We discuss the limiting factors of the supercontinuum bandwidth. Furthermore, we discuss how the fiber tapering influences the intensity noise of the supercontinuum source [4].
Supercontinuum sources based on silica fibers are limited to the material loss edge at 2.4 μm. However, for wavelengths beyond 2.4 μm the attenuation of light in silica fibers is greatly increased making them useless for the mid-infrared region. Instead, other fiber materials such as fluoride-based glasses (ZBLAN) and chalcogenide glasses can be used for mid-infrared supercontinuum generation. We will show supercontinuum generation in ZBLAN fibers covering 1.5-4.5 μm [5] and super-continuum generation in microstructured chalcogenide fibers out to 9 μm. We discuss the prospects for extending the supercontinuum generation beyond 10 μm and highlight useful applications such as cancer detection and food analysis.

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Supercontinuum light sources for food analysis
In Light & Food, a 30M DKK project funded by Innovationsfonden where DTU Fotonik has joined forces with University of Copenhagen, Aarhus University, FOSS and NKT, the vision is to develop a platform of analytical solutions to optimization of sustainable food production, both in the field and in the factory. These solutions will combine bright and broadband infrared light sources, so-called supercontinuum light sources, with spectroscopy, chemometrics and processing expertise and thereby contribute to increased food quality through faster and more precise analysis of grains, soils and dairy products. One track of Light & Food will target the mid-infrared spectral region. To date, the limitations of mid-infrared light sources, such as thermal emitters, low-power laser diodes, quantum cascade lasers and synchrotron radiation, have precluded mid-IR applications where the spatial coherence, broad bandwidth, high brightness and portability of a supercontinuum laser are all required. DTU Fotonik has now demonstrated the first optical fiber based broadband supercontinuum light source, which covers 1.4-13.3μm and thereby most of the molecular fingerprint region.

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Thulium pumped mid-infrared 0.9–9μm supercontinuum generation in concatenated fluoride and chalcogenide glass fibers
We theoretically demonstrate a novel approach for generating Mid-InfraRed SuperContinuum (MIR SC) by using concatenated fluoride and chalcogenide glass fibers pumped with a standard pulsed Thulium (Tm) laser (T<sub>FWHM</sub>≈3.5ps, P<sub>P</sub>≈20kW, ν<sub>R</sub>≈30MHz, and P<sub>avg</sub>≈2W). The fluoride fiber SC is generated in 10m of ZBLAN spanning the 0.9–4.1μm SC at the −30dB level. The ZBLAN fiber SC is then coupled into 10cm of As2Se3 chalcogenide Microstructured Optical Fiber (MOF) designed to have a zero-dispersion wavelength (λ<sub>ZD</sub>) significantly below the 4.1μm Infrared (IR) edge of the ZBLAN fiber SC, here 3.55μm. This allows the MIR solitons in the ZBLAN fiber SC to couple into anomalous dispersion in the chalcogenide fiber and further redshift out to the fiber loss edge at around 9μm. The final 0.9–9μm SC covers over 3 octaves in the MIR with around 15mW of power converted into the 6–9μm range.

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Activities:

**Generation and Applications of High Average Power Mid-IR Supercontinuum in Chalcogenide Fibres**

Period: 20 Oct 2016  
Christian Rosenberg Petersen (Invited speaker)  
Department of Photonics Engineering  
Fiber Sensors & Supercontinuum

**Description**
Invited talk on our recent work with mid-infrared supercontinuum generation in the session: Symposium on Mid-Infrared Fiber Sources I (FTh4A)

**Links:**  
http://dx.doi.org/https://doi.org/10.1364/FIO.2016.FTh4A.2

**Related event**

**Frontiers in Optics 2016**  
17/10/2016 — 21/10/2016  
Rochester, NY, United States  
Keywords: Mid infrared supercontinuum  
Activity: Talks and presentations › Conference presentations