Multi-stage generation of extreme ultraviolet dispersive waves by tapering gas-filled hollow-core anti-resonant fibers

In this work, we numerically investigate an experimentally feasible design of a tapered Ne-filled hollow-core anti-resonant fiber and we report multi-stage generation of dispersive waves (DWs) in the range 90-120 nm, well into the extreme ultraviolet (UV) region. The simulations assume a 800 nm pump pulse with 30 fs 10 µJ pulse energy, launched into a 9 bar Ne-filled fiber with a 34 µm initial core diameter that is then tapered to a 10 µm core diameter. The simulations were performed using a new model that provides a realistic description of both loss and dispersion of the resonant and anti-resonant spectral bands of the fiber, and also importantly includes the material loss of silica in the UV. We show that by first generating solitons that emit DWs in the far-UV region in the pre-taper section, optimization of the following taper structure can allow re-collision with the solitons and further up-conversion of the far-UV DWs to the extreme-UV with energies up to 190 nJ in the 90-120 nm range. This process provides a new way to generate light in the extreme-UV spectral range using relatively low gas pressure.
**Research output: Research - peer-review › Journal article – Annual report year: 2018**

**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 (As2 Se3)-based optical windows. Using rigorous coupled-wave analysis, we identify a relief design optimized for high transmittance (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.

**General information**

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Organisations: Department of Micro- and Nanotechnology, Polymer Micro & Nano Engineering, Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Surface Engineering

Contributors: Lotz, M. R., Petersen, C. R., Markos, C., Bang, O., Jakobsen, M. H., Taboryski, R. J.

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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**

State: Published

Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, NKT Group
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.

General information
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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, NKT Group
Contributors: Dasa, M. K., Markos, C., Maria, M., Gonzalo, I. B., Petersen, C. R., Jain, D., Moselund, P. M., Bang, O.
Number of pages: 2
Pages: 1-2
Hollow-core fiber with nested anti-resonant tubes for low-loss THz guidance

A hollow-core fiber with nested anti-resonant node-free cladding tubes suitable for broadband THz guidance with low transmission losses is proposed. It is shown that the tube separation and tube thickness of the inner elements have a significant effect on the confinement loss and effective material loss of the fiber in the THz band. Using TOPAS copolymer, the proposed fiber was optimized for operation at 1 THz and it is predicted from numerical simulations that loss can be reduced to as low as 0.05 dB/m with a 0.6 THz wide dispersion flattened bandwidth.
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.

**General information**
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**Organisations:** Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation
**Contributors:** Markos, C., Petersen, C. R.
**Number of pages:** 6
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**Visible to Mid-infrared Supercontinuum Generation Using a Gas-filled Hollow-core Fiber**
Broadband supercontinuum generation spanning 0.58–5.0 μm is numerically presented using a Xe-filled nested hollow-core anti-resonant fiber under 7 bar pressure, pumped at 3 μm with 100 fs pulses and 15 μJ pulse energy.

**General information**
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*Organisations:* Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, University of Central Florida
**Contributors:** Habib, M. S., Markos, C., Adamu, A. I., Antonio-Lopez, J. E., Amezcua-Correa, R.
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**Publication date:** 2018

**Visible to Mid-infrared Supercontinuum Generation Using a Gas-filled Hollow-core Fiber**
Broadband supercontinuum generation spanning 0.58–5.0 μm is numerically presented using a Xe-filled nested hollow-core anti-resonant fiber under 7 bar pressure, pumped at 3 μm with 100 fs pulses and 15 μJ pulse energy.

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*State:* Published
*Organisations:* Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, University of Central Florida
**Contributors:** Habib, M. S., Markos, C., Adamu, A. I., Antonio-Lopez, J. E., Amezcua-Correa, R.
**Number of pages:** 2
**Pages:** 1-2
**Publication date:** 2018

**Charaterization of Industrial Coolant Fluids and Continuous Ageing Monitoring by Wireless Node-Enabled Fiber Optic Sensors**
Environmentally robust chemical sensors for monitoring industrial processes or infrastructures are lately becoming important devices in industry. Low complexity and wireless enabled characteristics can offer the required flexibility for sensor deployment in adaptable sensing networks for continuous monitoring and management of industrial assets. Here are presented the design, development and operation of a class of low cost photonic sensors for monitoring the ageing process and the operational characteristics of coolant fluids used in an industrial heavy machinery infrastructure. The chemical, physical and spectroscopic characteristics of specific industrial-grade coolant fluids were analyzed along their entire life cycle range, and proper parameters for their efficient monitoring were identified. Based on multimode polymer or silica optical fibers, wide range (3-11) pH sensors were developed by employing sol-gel derived pH sensitive coatings. The performances of the developed sensors were characterized and compared, towards their coolants' ageing monitoring capability, proving their efficiency in such a demanding application scenario and harsh industrial environment. The operating characteristics of this type of sensors allowed their integration in an autonomous wireless sensing node, thus enabling the future use of the demonstrated platform in wireless sensor networks for a variety of industrial and environmental monitoring applications.
Curvature and position of nested tubes in hollow-core anti-resonant fibers

Hollow-core anti-resonant (HC-AR) fibers where a symmetric distribution of cladding tubes compose a “negative-curvature” core boundary have extraordinary optical properties, such as low transmission loss, wide transmission bands and weak power overlap between the core modes and the silica parts [1], especially when smaller tubes are “nested” inside the larger tubes [2, 3]. Here we investigate the role of curvature and position of the nested tube and we show that the position of the nested tube has a much more pronounced effect compared to the curvature on the overall performance and single-mode operation of the fiber.

Determining the refractive index dispersion and thickness of hot-pressed chalcogenide thin films from an improved Swanepoel method

The well-known method presented by Swanepoel can be used to determine the refractive index dispersion of thin films in the near-infrared region from wavelength values at maxima and minima, only, of the transmission interference fringes. In order to extend this method into the mid-infrared spectral region (our measurements are over the wavelength range from 2 to 25 Å Âµm), the method is improved by using a two-term Sellmeier model instead of the Cauchy model as the dispersive equation. Chalcogenide thin films of nominal batch composition As40Se60 (at.%) and Ge16As24Se15.5Te44.5 (at.%) are prepared by a hot-pressing technique. The refractive index dispersion of the chalcogenide thin films is determined by the improved method with a standard deviation of less than 0.0027. The accuracy of the method is shown to be better than 0.4% at a wavelength of 3.1 Å Âµm by comparison with a benchmark refractive index value obtained from prism measurements on Ge16As24Se15.5Te44.5 material taken from the same batch.
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, SelenOptics, Université de Rennes
Contributors: Petersen, C. R., Engelsholm, R. D., Markos, C., Brilland, L., Troles, J., Bang, O.
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Generation of multiple VUV dispersive waves using a tapered gas-filled hollow-core anti-resonant fiber

Hollow-core anti-resonant (HC-AR) fibers are perhaps the best platform for ultrafast nonlinear optics based on light-gas interactions because they offer broadband guidance and low-loss guidance. The main advantage of using gases inside HC fibers is that both the dispersion and nonlinearity can be tuned by simply changing the pressure of the gas [1]. The emission of efficient dispersive wave (DW) in the deep-UV has been already observed in a uniform Ar-filled hollow-core fiber with tunability from 200 to 320 nm by changing the gas pressure and pulse energy [2]. In the quest of optimizing the nonlinear process to further blue-shift the generated DWs towards vacuum ultra-violet (VUV), here we numerically demonstrate for the first time (to the best of our knowledge) how the use of a tapered Ar-filled HC-AR fiber leads to multiple DWs in the extreme wavelength region from 143 to 280 nm.

General information
State: Published
Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Plasmonics and Metamaterials, Ultrafast Infrared and Terahertz Science
Hybrid photonic-crystal fiber

This article offers an extensive survey of results obtained using hybrid photonic-crystal fibers (PCFs) which constitute one of the most active research fields in contemporary fiber optics. The ability to integrate novel and functional materials in solid- and hollow-core PCFs through various postprocessing methods has enabled new directions toward understanding fundamental linear and nonlinear phenomena as well as novel application aspects, within the fields of optoelectronics, material and laser science, remote sensing, and spectroscopy. Here the recent progress in the field of hybrid PCFs is reviewed from scientific and technological perspectives, focusing on how different fluids, solids, and gases can significantly extend the functionality of PCFs. The first part of this review discusses the efforts to develop tunable linear and nonlinear fiber-optic devices using PCFs infiltrated with various liquids, glasses, semiconductors, and metals. The second part concentrates on recent and state-of-the-art advances in the field of gas-filled hollow-core PCFs. Extreme ultrafast gas-based nonlinear optics toward light generation in the extreme wavelength regions of vacuum ultraviolet, pulse propagation, and compression dynamics in both atomic and molecular gases, and novel soliton-plasma interactions are reviewed. A discussion of future prospects and directions is also included. Optical fibers provide much more than a means to transport light between different locations. This article reviews how integration of functional fluid, solid, and gaseous materials in photonic-crystal fibers enables control of their linear and nonlinear properties with applications in optoelectronics, sensing, and laser-matter interactions.
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

General information
State: Published
Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, SelenOptics, NKT Group
Low Loss Polycarbonate Polymer Optical Fiber for High Temperature FBG Humidity Sensing

We report the fabrication and characterization of a polycarbonate (PC) microstructured polymer optical fiber (mPOF) Bragg grating (FBG) humidity sensor that can operate beyond 100°C. The PC preform, from which the fiber was drawn, was produced using an improved casting approach to reduce the attenuation of the fiber. The fiber loss was found reduced by a factor of two compared to the latest reported PC mPOF [20], holding the low loss record in PC based fibers. PC mPOFBG was characterized to humidity and temperature, and a relative humidity (RH) sensitivity of 7.31±0.13 pm/% RH in the range 10–90% RH at 100°C and a temperature sensitivity of 25.86±0.63 pm/°C in the range 20–100 °C at 90% RH were measured.

General information
State: Published
Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Department of Mechanical Engineering, Manufacturing Engineering
Contributors: Woyessa, G., Fasano, A., Markos, C., Rasmussen, H. K., Bang, O.
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Scopus rating (2015): CiteScore 2.62 SJR 1.19 SNIP 1.266
Web of Science (2015): Impact factor 1.945
Web of Science (2015): Indexed yes
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Scopus rating (2014): CiteScore 2.78 SJR 1.421 SNIP 1.583
Web of Science (2014): Impact factor 2.11
Web of Science (2014): Indexed yes
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Scopus rating (2013): CiteScore 2.95 SJR 1.495 SNIP 1.548
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Scopus rating (2008): SJR 1.975 SNIP 1.864
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 2.224 SNIP 1.678
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Web of Science (2006): Indexed yes
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Web of Science (2005): Indexed yes
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Multiple soliton compression stages in mid-IR gas-filled hollow-core fibers

The light confinement inside hollow-core (HC) fibers filled with noble gases constitutes an efficient route to study interesting soliton-plasma dynamics [1]. More recently, plasma-induced soliton splitting at the self-compression point was observed in a gas-filled fiber in the near-IR [2]. However, the role of the plasma is so far not investigated in the mid-IR. This range is interesting because the photon energy is much lower, and thereby the plasma formation dynamics will be different, and because the mid-IR is currently being explored for generating few-cycle pulses and for supercontinuum generation. Here we investigate the soliton-plasma dynamics in a mid-IR pumped Xe-filled HC silica fiber based on the so-called anti-resonant (AR) effect. We find a novel soliton dynamics scenario where multiple soliton self-compression stages are observed.

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Photo Contest 2017
HONORABLE MENTION
"Top view of a soft-glass fiber preform while it is inside the furnace of a brand new 6-meter fiber fabrication draw tower facility (at DTU Fotonik) at around 1000 degrees Celsius."
—Christos Markos, DTU Fotonik, Technical University of Denmark

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Reconfigurable opto-thermal graded-index waveguiding in bulk chalcogenide glasses

In the absence of suitable deposition processes, the fabrication of graded-index chalcogenide waveguides or fibers remains an outstanding challenge. Here, by exploiting the strong thermo-optic effect present in chalcogenide glasses, we experimentally demonstrate non-permanent optically-induced waveguides in bulk As2Se3 rods using a 1.55 μm wavelength laser. This single-step process can be used not only to self-trap the writing beam, but also to guide another optical beam at a different wavelength in the opto-thermally inscribed waveguide channel. These results could pave the way towards harnessing nonlinear effects in graded-index chalcogenide guided settings. (C) 2017 Optical Society of America

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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, University of Central Florida
Contributors: Shabahang, S., Nye, N. S., Markos, C., Christodoulides, D. N., Abouraddy, A. F.
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Simultaneous measurement of temperature and humidity with microstructured polymer optical fiber Bragg gratings

A microstructured polymer optical fiber (mPOF) Bragg grating sensor system for the simultaneous measurement of temperature and relative humidity (RH) has been developed and characterized. The sensing head is based on two in-line fiber Bragg gratings recorded in a mPOF. The sensor system has a root mean square deviation of 1.04 % RH and 0.8 °C in the range 10 to 90% RH and 20 to 80 °C. The proposed sensor system is easy to fabricate, cheap and compact.

Soliton-plasma nonlinear dynamics in mid-IR gas-filled hollow-core fibers

We investigate numerically soliton-plasma interaction in a noble-gas-filled silica hollow-core anti-resonant fiber pumped in the mid-IR at 3.0 μm. We observe multiple soliton self-compression stages due to distinct stages where either the self-focusing or the self-defocusing nonlinearity dominates. Specifically, the parameters may be tuned so the competing plasma self-defocusing nonlinearity only dominates over the Kerr self-focusing nonlinearity around the soliton self-compression stage, where the increasing peak intensity on the leading pulse edge initiates a competing self-defocusing plasma nonlinearity acting nonlocally on the trailing edge, effectively preventing soliton formation there. As the plasma switches off after the self-compression stage, self-focusing dominates again, initiating another soliton self-compression stage in the trailing edge. This process is accompanied by supercontinuum generation spanning 1-4 μm. We find that the spectral coherence drops as the secondary compression stage is initiated. (C) 2017 Optical Society of America
Soliton-plasma nonlinear dynamics in mid-IR gas-filled hollow-core fibers

This publisher's note corrects Eq. (1) of Opt. Lett. 42, 2232 (2017) OPLEDP0146-9592 10.1364/OL.42.002232.

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Scopus rating (2016): CiteScore 3.54 SJR 1.769 SNIP 1.549
Web of Science (2016): Impact factor 3.416
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.53 SJR 2.013 SNIP 1.53
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Toward single-mode UV to near-IR guidance using hollow-core antiresonant silica fiber

Hollow-core anti-resonant (HC-AR) fibers with a "negative-curvature" of the core-cladding boundary have been extensively studied over the past few years owing to their low loss and wide transmission bandwidths. The key unique feature of the HC-AR fiber is that the coupling between the core and cladding modes can be made anti-resonant (strongly inhibited) by suitably arranging the anti-resonant tubes in the cladding, which results in low loss and broad spectral bandwidths. HC-AR fibers have been fabricated aimed at visible, near-or mid-IR transmission [1-4]. Here we fabricate and characterize a silica HC-AR fiber having a single ring of 7 non-touching capillaries, designed to have effectively single-mode operation and low loss from UV to near-IR.

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Zeonex microstructured polymer optical fiber: fabrication friendly fibers for high temperature and humidity insensitive Bragg grating sensing

In the quest of finding the ideal polymer optical fiber (POF) for Bragg grating sensing, we have fabricated and characterized an endlessly single mode microstructured POF (mPOF). This fiber is made from cyclo-olefin homopolymer Zeonex grade 480R which has a very high glass transition temperature of 138 °C and is humidity insensitive. It represents a significant improvement with respect to the also humidity insensitive Topas core fibers, in that Zeonex fibers are easier to manufacture, has better transmittance, higher sensitivity to temperature and better mechanical stability at high temperature. Furthermore, Zeonex has very good compatibility with PMMA in terms of dilatation coefficients for co-drawing applications. The Zeonex mPOF has a core and cladding diameter of 8.8 µm and 150 µm, respectively, with a hole to pitch ratio of 0.4 and a minimum propagation loss of 2.34 ± 0.39 dB/m at 690.78 nm. We have also inscribed and characterized fiber Bragg gratings (FBGs) in Zeonex mPOFs in the low loss 850 nm spectral band.

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Zeonex-PMMA microstructured polymer optical FBGs for simultaneous humidity and temperature sensing

In this Letter, we report for the first time, to the best of our knowledge, the fabrication and characterization of a Zeonex/PMMA microstructured polymer optical fiber (mPOF) Bragg grating sensor for simultaneous monitoring of relative humidity (RH) and temperature. The sensing element (probe) is based on two separate in-line fiber Bragg gratings (FBGs) inscribed in the fabricated mPOF. A root mean square deviation of 0.8% RH and 0.6°C in the range of 10%-90% RH and 20°C-80°C was found. The developed mPOFBG sensor constitutes an efficient route toward low-cost, easy-to-fabricate and compact multi-parameter sensing solutions.

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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Department of Mechanical Engineering, Manufacturing Engineering
Contributors: Woyessa, G., Pedersen, J. K. M., Fasano, A., Nielsen, K., Markos, C., Rasmussen, H. K., Bang, O.
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Web of Science (2017): Impact factor 3.589
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.54 SJR 1.769 SNIP 1.549
Web of Science (2016): Impact factor 3.416
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.53 SJR 2.013 SNIP 1.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.86 SJR 2.429 SNIP 1.997
Web of Science (2014): Impact factor 3.292
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.95 SJR 2.441 SNIP 2.058
Web of Science (2013): Impact factor 3.179
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.52 SJR 2.577 SNIP 1.92
Web of Science (2012): Impact factor 3.385
ISI indexed (2012): ISI indexed yes
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BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.69 SJR 2.519 SNIP 2.453
Web of Science (2011): Impact factor 3.399
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.637 SNIP 2.263
Web of Science (2010): Impact factor 3.318
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 3.077 SNIP 2.658
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 3.354 SNIP 2.384
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.443 SNIP 2.157
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 3.126 SNIP 2.319
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 3.245 SNIP 2.451
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Scopus rating (2004): SJR 3.523 SNIP 2.726
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Scopus rating (2003): SJR 3.725 SNIP 2.626
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Scopus rating (2002): SJR 3.571 SNIP 2.415
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 3.776 SNIP 2.273
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 4.157 SNIP 1.716
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Scopus rating (1999): SJR 3.926 SNIP 1.685
A Novel Low-Loss Diamond-Core Porous Fiber for Polarization Maintaining Terahertz Transmission

We report on the numerical design optimization of a new kind of relatively simple porous-core photonic crystal fiber (PCF) for terahertz (THz) waveguiding. A novel twist is introduced in the regular hexagonal PCF by including a diamond-shaped porous-core inside the hexagonal cladding. The numerical results obtained from an efficient finite-element method, which confirms a high birefringence of the order 10^{-2} and low effective material loss of 0.07 cm^{-1} at 0.7-THz operating frequency. The proposed PCF is anticipated to be useful in polarization sensitive THz appliances.

General information
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Organisations: Department of Photonics Engineering, Ultrafast Infrared and Terahertz Science, Fiber Sensors and Supercontinuum Generation, Rajshahi University of Engineering and Technology
Contributors: Islam, R., Habib, S., Hasanuzzaman, G. K. M., Rana, S., Sadath, M. A., Markos, C.
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Scopus rating (2015): CiteScore 2.62 SJR 1.19 SNIP 1.266
Web of Science (2015): Impact factor 1.945
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BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 2.78 SJR 1.421 SNIP 1.583
Web of Science (2014): Impact factor 2.11
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
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Web of Science (2013): Impact factor 2.176
ISI indexed (2013): ISI indexed yes
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ISI indexed (2012): ISI indexed yes
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BFI (2011): BFI-level 2
Characterising refractive index dispersion in chalcogenide glasses

Much effort has been devoted to the study of glasses that contain the chalcogen elements (sulfur, selenium and tellurium) for photonics’ applications out to MIR wavelengths. In this paper we describe some techniques for determining the refractive index dispersion characteristics of these glasses. Knowledge of material dispersion is critical in delivering step-index fibres including with high numerical aperture for mid-infrared supercontinuum generation.
We describe the fabrication of a polycarbonate (PC) micro-structured polymer optical fiber (mPOF) and the writing of fiber Bragg gratings (FBGs) in it to enable strain and temperature measurements. We demonstrate the photosensitivity of a dopant-free PC fiber by grating inscription using a UV laser. We further show that PC Bragg gratings can be extended up to at least 3% without affecting the initial functionality of the micro-structured fiber. The response of PC FBGs to temperature up to 125°C is also investigated. Polycarbonate has good mechanical properties and its high temperature resistance might extend the range of application of polymeric FBGs.

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, Department of Photonics Engineering, Federal Institute for Materials Research and Testing
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Bibliographical note
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Research output: Research - peer-review › Article in proceedings – Annual report year: 2016

Creation of a microstructured polymer optical fiber with UV Bragg grating inscription for the detection of extensions at temperatures up to 125°C
We describe the fabrication of a polycarbonate (PC) micro-structured polymer optical fiber (mPOF) and the writing of fiber Bragg gratings (FBGs) in it to enable strain and temperature measurements. We demonstrate the photosensitivity of a dopant-free PC fiber by grating inscription using a UV laser. We further show that PC Bragg gratings can be extended up to at least 3% without affecting the initial functionality of the micro-structured fiber. The response of PC FBGs to temperature up to 125°C is also investigated. Polycarbonate has good mechanical properties and its high temperature resistance might extend the range of application of polymeric FBGs.
Fabrication and characterization of polycarbonate microstructured polymer optical fibers for high-temperature-resistant fiber Bragg grating strain sensors

Here we present the fabrication of a solid-core microstructured polymer optical fiber (mPOF) made of polycarbonate (PC), and report the first experimental demonstration of a fiber Bragg grating (FBG) written in a PC optical fiber. The PC used in this work has a glass transition temperature of 145°C. We also characterize the mPOF optically and mechanically, and further test the sensitivity of the PC FBG to strain and temperature. We demonstrate that the PC FBG can bear temperatures as high as 125°C without malfunctioning. In contrast, polymethyl methacrylate-based FBG technology is generally limited to temperatures below 90°C.

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Federal Institute for Materials Research and Testing
Contributors: Fasano, A., Woyessa, G., Stajanca, P., Markos, C., Stefani, A., Nielsen, K., Rasmussen, H. K., Krebber, K., Bang, O.
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Scopus rating (2016): CiteScore 2.74 SJR 1.042 SNIP 1.23
Web of Science (2016): Impact factor 2.591
Web of Science (2016): Indexed yes
Scopus rating (2015): CiteScore 3.07 SJR 1.34 SNIP 1.351
Web of Science (2015): Impact factor 2.657
Web of Science (2015): Indexed yes
Scopus rating (2014): CiteScore 3.17 SJR 1.521 SNIP 1.623
Web of Science (2014): Impact factor 2.844
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Scopus rating (2012): CiteScore 2.58 SJR 1.609 SNIP 1.774
Web of Science (2012): Impact factor 2.616
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Web of Science (2011): Impact factor
Web of Science (2011): Indexed yes

Bibliographical note
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Modulation-instability biosensing using an As2S3 chalcogenide tapered fiber

We demonstrate an experimentally feasible biosensor design based on As2S3 chalcogenide tapered fiber. Pumping the fiber close to 1064 nm, a record sensitivity up to ~18 nm/nm was predicted.

M-type fiber for exploiting higher-order-modes dispersion for application in mid-IR supercontinuum generation

We demonstrate an M-type fiber suitable for launching higher-order-modes (such as LP02&LP03) as core-confined-modes, while guiding LP01 and other lower-order-modes in a ring. The M-type fiber can shift the zero-dispersion-wavelength of bulk-material by several 1000 nanometers.
**Polymer Optical Fibre Bragg Grating Humidity Sensor at 100ºC**

We have demonstrated a polymer optical fibre Bragg grating humidity sensor that can be operated up to 100ºC. The sensor has been fabricated from a polycarbonate (PC) microstructured polymer optical fibre Bragg grating (mPOFBG). PC mPOFBG gave a relative humidity (RH) sensitivity of 6.95±0.83 pm/% RH in the range 10-90% RH at 100ºC and a temperature sensitivity of 25.94±0.47 pm/ºC in the range 20 - 100 ºC at 90% RH. Despite PC mPOFBGs shows smaller humidity sensitivity compared to PMMA mPOFBGs, they can be used to sense humidity beyond the operating temperature limit of PMMA mPOFBGs.

**General information**

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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Department of Mechanical Engineering, Manufacturing Engineering
Contributors: Woyessa, G., Fasano, A., Markos, C., Rasmussen, H. K., Bang, O.
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**Single mode step-index polymer optical fiber for humidity insensitive high temperature fiber Bragg grating sensors**

We have fabricated the first single-mode step-index and humidity insensitive polymer optical fiber operating in the 850 nm wavelength ranges. The step-index preform is fabricated using injection molding, which is an efficient method for cost effective, flexible and fast preparation of the fiber preform. The fabricated single-mode step-index (SI) polymer optical fiber (POF) has a 4.8µm core made from TOPAS grade 5013S-04 with a glass transition temperature of 134°C and a 150 µm cladding made from ZEONEX grade 480R with a glass transition temperature of 138°C. The key advantages of the proposed SIPOF are low water absorption, high operating temperature and chemical inertness to acids and bases and many polar solvents as compared to the conventional poly-methyl-methacrylate (PMMA) and polystyrene based POFs. In addition, the fiber Bragg grating writing time is short compared to microstructured POFs.

**General information**

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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Department of Mechanical Engineering, Manufacturing Engineering
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Web of Science (2017): Indexed yes
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Web of Science (2016): Impact factor 3.307
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Single_mode_step_index_polymer_optical_fiber_for_humidity_insensitive_high_temperature_fiber_Bragg_grating_sensors.pdf
Temperature insensitive hysteresis free highly sensitive polymer optical fiber Bragg grating humidity sensor

The effect of humidity on annealing of poly (methyl methacrylate) (PMMA) based microstructured polymer optical fiber Bragg gratings (mPOFBGs) and the resulting humidity responsivity are investigated. Typically annealing of PMMA POFs is done in an oven without humidity control around 80°C and therefore at low humidity. We demonstrate that annealing at high humidity and high temperature improves the performances of mPOFBGs in terms of stability and sensitivity to humidity. PMMA mPOFBGs that are not annealed or annealed at low humidity level will have a low and highly temperature dependent sensitivity and a high hysteresis in the humidity response, in particular when operated at high temperature. PMMA mPOFBGs annealed at high humidity show higher and more linear humidity sensitivity with negligible hysteresis. We also report how annealing at high humidity can blue-shift the FBG wavelength more than 230 nm without loss in the grating strength.

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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.48 SJR 1.532 SNIP 1.544
Web of Science (2016): Impact factor 3.307
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.78 SJR 1.91 SNIP 1.674
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.18 SJR 2.313 SNIP 2.124
Web of Science (2014): Impact factor 3.488
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.38 SJR 2.337 SNIP 2.196
Web of Science (2013): Impact factor 3.525
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.85 SJR 2.562 SNIP 2.108
Web of Science (2012): Impact factor 3.546
ISI indexed (2012): ISI indexed yes
Thermo-tunable hybrid photonic crystal fiber based on solution-processed chalcogenide glass nanolayers

The possibility to combine silica photonic crystal fiber (PCF) as low-loss platform with advanced functional materials, offers an enormous range of choices for the development of fiber-based tunable devices. Here, we report a tunable hybrid silica PCF with integrated As2S3 glass nanolayers inside the air-capillaries of the fiber based on a solution-processed glass approach. The deposited high-index layers revealed antiresonant transmission windows from similar to 500 nm up to similar to 1300 nm. We experimentally demonstrate for the first time the possibility to thermally-tune the revealed antiresonances by taking advantage the high thermo-optic coefficient of the solution-processed nanolayers. Two different hybrid fiber structures, with core diameter 10 and 5 μm, were developed and characterized using a supercontinuum source. The maximum sensitivity was measured to be as high as 3.6 nm/°C at 1300 nm. The proposed fiber device could potentially constitute an efficient route towards realization of monolithic tunable fiber filters or sensing elements.

General information
State: Published
Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation
Zeonex Microstructured Polymer Optical Fibre Bragg Grating Sensor
We fabricated an endlessly single mode and humidity insensitive Zeonex microstructured polymer optical fibre (mPOF) for fibre Bragg grating (FBG) temperature and strain sensors. We inscribed and characterise FBGs in Zeonex mPOF for the first time.

General information
Antiresonant guiding in a poly(methyl-methacrylate) hollow-core optical fiber

Strong antiresonant reflecting optical waveguiding is demonstrated in a novel poly (methyl-methacrylate) (PMMA) hollow-core fiber. The transmission spectrum of the fiber was characterized using a supercontinuum source and it revealed distinct resonances with resonant dips as strong as ~20 dB in the wavelength range 480-900 nm, where PMMA has low absorption. The total propagation loss of the fiber was measured to have a minimum of ~45 dB m⁻¹ at around 500 nm. The thermal sensitivity of the fiber is 256 ± 16 pm °C⁻¹, defined as the red-shift of the resonances per °C, which is three times higher than the sensitivity of polymer fiber Bragg gratings.
Humidity insensitive step-index polymer optical fibre Bragg grating sensors
We have fabricated and characterised a humidity insensitive step index (SI) polymer optical fibre (POF) Bragg grating sensors. The fibre was made based on the injection molding technique, which is an efficient method for fast, flexible and cost effective preparation of the fibre preform. The fabricated SIPOF has a core made from TOPAS with a glass transition temperature of 134 degrees C and a cladding from ZEONEX with a glass transition temperature of 138 degrees C. The main advantages of the proposed SIPOF are the low water absorption and good chemical resistance compared to the conventional poly-methyl-methacrylate (PMMA) based SIPOFs. The fibre has a minimum loss of similar to 6dB/m at 770nm.

General information
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Organisations: Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Department of Mechanical Engineering, Manufacturing Engineering, Department of Management Engineering
Contributors: Woyessa, G., Fasano, A., Stefani, A., Markos, C., Nielsen, K., Rasmussen, H. K., Bang, O.
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Publisher: SPIE - International Society for Optical Engineering
Nonlinear Label-Free Biosensing With High Sensitivity Using As$_2$S$_3$ Chalcogenide Tapered Fiber

We demonstrate an experimentally feasible fiber design, which can act as a highly sensitive, label-free, and selective biosensor using the inherent high nonlinearity of an As$_2$S$_3$ chalcogenide tapered fiber. The surface immobilization of the fiber with an antigen layer can provide the possibility to selectively capture antibody biomolecules. This increase of the layer thickness directly affects the group velocity dispersion of the fiber and, thus, the modulation instability (MI) gain spectrum changes (location of the anti-Stokes and Stokes wavelengths) when pumping the fiber close to the zero-dispersion wavelength. The sensitivity of the sensor was predicted to be $\sim$18 nm/\(\text{nmm}\), defined as the shift in resonance wavelength per nanometer biolayer thickness, which is almost twice the current record sensitivity of nonlinear MI-based fiber optical biosensors. Importantly, due to the strong nonlinearity of As$_2$S$_3$, this high sensitivity can be obtained using a low-power 1064-nm microchip laser.
Photonic-crystal fibre: Mapping the structure

The demonstration of real-time and non-destructive Doppler-assisted tomography of the internal structure of photonic-crystal fibres could aid the fabrication of high-quality fibres with enhanced performance.
Production and Characterization of Polycarbonate Microstructured Polymer Optical Fiber Bragg Grating Sensor

We present the fabrication and characterization of a polycarbonate (PC) microstructured polymer optical fiber (mPOF) and the writing of a fiber Bragg grating (FBG) in it to obtain a polymer optical FBG sensor. The manufacturing process of the PC mPOF consists of multiple consecutive stages, such as casting of polymer granulates into a solid rod, machining and drilling of a 3-ring hexagonal lattice of holes into it, and finally drawing into fiber. We demonstrate that the obtained PC mPOF is photosensitive and FBGs can be conveniently inscribed into it, thereby enabling FBG-based temperature and strain sensing. The PC optical fibers are for some applications an attractive alternative to conventional materials used in POF fabrication, such as polymethyl methacrylate (PMMA). In general, PC can be used at temperature up to 120 °C and breaks at considerably higher strains than PMMA.

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, Department of Photonics Engineering, Fiber Sensors and Supercontinuum Generation, Federal Institute for Materials Research and Testing
Contributors: Fasano, A., Woyessa, G., Stajanca, P., Markos, C., Stefani, A., Nielsen, K., Rasmussen, H. K., Krebber, K., Bang, O.
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Thermally tunable bandgaps in a hybrid As2S3/silica photonic crystal fiber

We report the fabrication and characterization of a hybrid silica photonic crystal fiber (PCF) with integrated chalcogenide glass layers and we show how the bandgaps of the fiber can be thermally tuned. The formation of the high-index chalcogenide films on the inner surface of the PCF holes revealed resonances as strong as similar to 35 dB both in the visible and infrared regime. Temperature measurements indicate that the transmission windows can be tuned with a sensitivity as high as similar to 3.5 nm/°C. The proposed fiber has potential for all-fiber filtering and temperature sensing.

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Bragg grating writing in PMMA microstructured polymer optical fibers in less than 7 minutes

We demonstrate fiber Bragg grating (FBG) writing in PMMA microstructured Polymer Optical Fibers (mPOFs) using UV Phase Mask technique with writing times shorter than 10 min. The shortest writing time was 6 minutes and 50 seconds and the longest writing time was 8 min and 50 sec. The FBGs were written in a 125 x00B5;m PMMA mPOF having 3-rings of holes, the reflection peaks were centred at 632.6 nm and have a reflectivity as high as 26 dB. We also demonstrate how the writing dynamics depends on the intensity of the writing beam.

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Contributors: Bundalo, I., Nielsen, K., Markos, C., Bang, O.
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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.48 SJR 1.532 SNIP 1.544
Web of Science (2016): Impact factor 3.307
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.78 SJR 1.91 SNIP 1.674
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BFI (2014): BFI-level 2
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Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.85 SJR 2.562 SNIP 2.108
Web of Science (2012): Impact factor 3.546
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Hybrid polymer photonic crystal fiber with integrated chalcogenide glass nanofilms

The combination of chalcogenide glasses with polymer photonic crystal fibers (PCFs) is a difficult and challenging task due to their different thermo-mechanical material properties. Here we report the first experimental realization of a hybrid polymer-chalcogenide PCF with integrated As2S3 glass nanofilms at the inner surface of the air-channels of a poly-methyl-methacrylate (PMMA) PCF. The integrated high refractive index glass films introduce distinct antiresonant transmission bands in the 480-900 nm wavelength region. We demonstrate that the ultra-high Kerr nonlinearity of the chalcogenide glass makes the polymer PCF nonlinear and provides a possibility to shift the transmission band edges as much as 17 nm by changing the intensity. The proposed fabrication technique constitutes a new highway towards all-fiber nonlinear tunable devices based on polymer PCFs, which at the moment is not possible with any other fabrication method.

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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.63 SJR 1.692 SNIP 1.354
Web of Science (2016): Impact factor 4.259
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 5.3 SJR 2.034 SNIP 1.597
Web of Science (2015): Impact factor 5.228
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Photo-induced changes in a hybrid amorphous chalcogenide/silica photonic crystal fiber

Photostructural changes in a hybrid photonic crystal fiber with chalcogenide nanofilms inside the inner surface of the cladding holes are experimentally demonstrated. The deposition of the amorphous chalcogenide glass films inside the silica capillaries of the fiber was made by infiltrating the nanocolloidal solution-based As25S75, while the photoinduced changes were performed by side illuminating the fiber near the bandgap edge of the formed glass nanofilms. The photoinduced effect of the chalcogenide glass directly red-shifts the transmission bandgap position of the fiber as high as similar to 20.6 nm at around 1600 nm wavelength, while the maximum bandgap intensity change at similar to 1270nm was -3dB.

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PMMA mPOF Bragg gratings written in less than 10 min
Fiber Bragg grating (FBG) writing in PMMA microstructured Polymer Optical Fibers (mPOFs) using the UV Phase Mask technique is a time consuming process requiring about 40 minutes to inscribe a grating in an undoped fiber. Here we demonstrate the FBG inscription with the writing times shorter than 10 min. By careful aligning and increasing the beam intensity in the core of the fiber, writing times as short as 6 minutes and 50 second were achieved. The FBGs were written in a 125 μm PMMA mPOF having 3-rings of holes, the reflection peaks were centred at 632.6 nm and have a reflectivity as high as 26 dB. We also demonstrate how the writing dynamics depends on the intensity of the writing beam.

THz waveguides, devices and hybrid polymer-chalcogenide photonic crystal fibers
In this contribution, we review our recent activities in the design, fabrication and characterization of polymer THz waveguides. Besides the THz waveguides, we finally will also briefly show some of our initial results on a novel hybrid polymer photonic crystal fiber with integrated chalcogenide glass layers.
polymer photonic crystal Øber with integrated chalcogenide glass layers.

High-Tg TOPAS mPOF strain sensing at 110 degrees

We demonstrate a mPOF made of high-Tg TOPAS grade 5013 with Tg = 135°C. We inscribe FBGs into the fiber and demonstrate strain sensing of 2.5% strain at 98°C, further we also demonstrate strain sensing at a record high temperature of 110°C. The Bragg wavelengths of the FBGs are around 860 nm, where the propagation loss is 5.1dB/m, close to the fiber loss minimum of 3.67dB/m at 787nm.

High-Tg TOPAS microstructured polymer optical fiber for fiber Bragg grating strain sensing at 110 degrees

We present the fabrication and characterization of fiber Bragg gratings (FBGs) in an endlessly single-mode microstructured polymer optical fiber (mPOF) made of humidity-insensitive high-Tg TOPAS cyclic olefin copolymer. The mPOF is the first made from grade 5013 TOPAS with a glass transition temperature of Tg = 135°C and we experimentally demonstrate high strain operation (2.5%) of the FBG at 98°C and stable operation up to a record high temperature of 110°C. The Bragg wavelengths of the FBGs are around 860 nm, where the propagation loss is 5.1dB/m, close to the fiber loss minimum of 3.67dB/m at 787nm.
Projects:

**Gas-filled Hollow-Core Photonic Crystal Fibers for sensing applications and ultrafast non-linear optics**
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Bang, O., Supervisor, Department of Photonics Engineering

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Award relations: Gas-filled Hollow-Core Photonic Crystal Fibers for sensing applications and ultrafast non-linear optics  
Project: PhD

**High-power visible-near-IR Supercontinuum sources for spectroscopic photoacoustic microscopy**
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Award relations: High-power visible-near-IR Supercontinuum sources for spectroscopic photoacoustic microscopy  
Project: PhD

**Speciality and Microstructured Polymer Optical FBG Sensors**
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