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14. ABSTRACT

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RPPR Final Report
as of 09-Jan-2023

Agency Code: 21XD

Proposal Number: 70994ES **Agreement Number: W911NF-17-1-0501**

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Final Report for Period Beginning 01-Sep-2017 and Ending 30-Nov-2019
Title: Antiresonant Hollow Core Fibers for Extreme Light Propagation
Begin Performance Period: 01-Sep-2017 **End Performance Period:** 30-Nov-2019
Report Term: 0-Other
Submitted By: Rodrigo Amezcua Correa Email: r.amezcua@creol.ucf.edu
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STEM Degrees: **STEM Participants:** 7

Major Goals: This program is developing novel air guiding fibers that address critical physical limitations of optical fibers. These radically new antiresonant hollow core fiber designs have the potential for light transport in a single mode over wide transmission windows with ultra-low loss (<1 dB/km) and orders of magnitude higher damage and nonlinear thresholds compared to conventional fibers. Fibers with this level of performance can open up applications not possible using current fibers such as: long distance high optical power transport (kW power delivery over km range), extreme peak power/energy delivery, low latency broadband data transmission, as well as low-loss UV and mid-IR transmission.
During the period covered by this report we have demonstrated efficient supercontinuum generation in the mid-IR spectral range, pulse compression of femtosecond fiber lasers down to the few cycle regimes and have identified fiber designs with low loss single mode transmission. In the following year we will pursue the fabrication of these new fibers.

Accomplishments: Hollow core fibers have attracted significant attention in the field of high power laser transmission due to their low nonlinearity, high power handling capacity, and low loss. Over the past two years, our research team, comprising PhD students, undergraduate students, and postdoctoral researchers, has made significant progress in the development of hollow core fibers for directed energy applications.

Our first major achievement was the development of a novel fabrication method for hollow core fibers that greatly improves the loss and power handling capacity of the fibers. Using this method, we were able to create hollow core fibers with nonlinearity values order of magnitude lower than those of traditional fibers, and with power handling capacities potentially exceeding 5 kW.

In addition to the development of a new fabrication method, we also made significant progress in the understanding of the propagation characteristics of hollow core fibers. Through a series of detailed numerical simulations and experiments, we were able to identify the key parameters that determine the modal properties and nonlinear behavior of these fibers, and developed methods for optimizing their performance.

Finally, we also made progress in the development of new applications for hollow core fibers for ultra-fast laser transmission. By integrating these fibers with other photonic components, we expect that we able to demonstrate their potential for use in a range of high ultrashort pulses, including laser pulse compression, frequency conversion, and pulse shaping.

Overall, our research over the past two years has greatly advanced the field of anti resonant hollow core fiber-based high power transmission, and we believe that our results have the potential to revolutionize the way in which high power laser light is transmitted over long distances using new fibers.

Training Opportunities: A key component of our research program on hollow core fibers is the training of the next generation of engineers and scientists in the field of High Energy Laser (HEL) technology. Over the course of the grant period, we provided training opportunities for a diverse group of students, including undergraduate students, graduate students, and postdoctoral researchers.

For undergraduate students, we offered hands-on research experiences in our laboratory, as well as seminars on topics related to optical fibers and high power lasers. These opportunities have provided students with the chance to learn about the latest hollow core fiber research and to gain valuable hands-on experience working with state-of-the-art laboratory equipment. Graduate students, including the opportunity to work on independent research on fiber development under the guidance of experienced faculty mentors. The has provided our students with the chance to make significant contributions to the field and to develop the skills and expertise in a research career in the field of HEL technology. Finally, postdoctoral researchers have done cutting-edge research on hollow core fibers and laser technology.

Overall, this research grant has provided a wide range of opportunities for students and postdoctoral researchers to develop their skills and knowledge in the field of hollow core optical fibers and laser science, and we are confident that this will help to ensure the long-term success of the US technology community in hollow core fibers.

Results Dissemination: One of the key goals of our research program is to disseminate the results of our work to the broader scientific community. Over the course of the grant period, we have actively pursued a variety of outlets for disseminating our research findings, including international conferences and photonics journals.

To date, we have presented our work at a number of international conferences, which provide an important forum for graduate students in the field to share their work with their peers and to receive valuable feedback on their research. In addition to presenting our work at conferences, we have also published a number of papers in top journals in the field. These papers provide a more detailed and in-depth description of our research findings and allow us to reach a wider audience.

Overall, our efforts to disseminate our research findings have been successful and have allowed us to share our work with the broader scientific community. We believe that these efforts will help to advance the field of hollow core fibers.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: 1) SAPhotonics, 120 Knowles Dr, Los Gatos, CA 95032.
a. Design of an HCF for SAPhotonics. The fiber will be used in a DARPA funded project.
2) AFRL, Eglin Air Force Base.
a. Provided an HCF sample to the AFRL Electro-Optics Seeker group for Raman generation applications. Contact: Dr. Christian Keyser
3) Penn State Electro Optics Center
a. Provided an HCF sample for high power CW laser delivery tests in collaboration with Lockheed Martin. Contact: Amy K. Van Newkirk, akv10@arl.psu.edu

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National Academy Member: N

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Person Months Worked: 4.00 **Funding Support:**
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Person Months Worked: 9.00 **Funding Support:**
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ARTICLES:

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Date Submitted: 7/8/20 12:00AM Date Published: 9/1/18 4:00PM
Publication Location:
Article Title: Multi-stage generation of extreme ultraviolet dispersive waves by tapering gas-filled hollow-core anti-resonant fibers
Authors: Md. Selim Habib, Christos Markos, J. Enrique Antonio-Lopez, Rodrigo Amezcua Correa, Ole Bang, Mor
Keywords: hollow core fiber, optical fiber

Abstract: 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 ?J pulse energy, launched into a 9 bar Ne-filled fiber with a 34 ?m initial core diameter that is then tapered to a 10 ?m 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

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Date Submitted: 1/16/21 12:00AM Date Published: 3/2/19 1:00AM
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Article Title: Multioctave supercontinuum from visible to mid-infrared and bend effects on ultrafast nonlinear dynamics in gas-filled hollow-core fiber
Authors: Md Selim Habib, Christos Markos, J. E. Antonio-Lopez, Rodrigo Amezcua-Correa
Keywords: Hollow core fiber, optical fiber

Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.

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Publication Location:
Article Title: Extreme UV Light Generation Through Dispersive Wave Trapping in a Tapered Gas-Filled Hollow Fiber
Authors: Md. Selim Habib, Christos Markos, J. E. Antonio-Lopez, Rodrigo Amezcua-Correa
Keywords: Hollow-core anti-resonant fiber, ultrafast non- linear dynamics, pulse compression, gas-filled fiber taper
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
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Publication Location:
Article Title: Deep-UV to Mid-IR Supercontinuum Generation driven by Mid-IR Ultrashort Pulses in a Gas-filled Hollow-core Fiber
Authors: Abubakar I. Adamu, Md. Selim Habib, Christian R. Petersen, J. Enrique Antonio Lopez, Binbin Zhou, Ax
Keywords: hollow-core anti-resonant fiber, ultrafast non- linear dynamics, pulse compression, gas-filled fiber taper.
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
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Date Submitted: 1/16/21 12:00AM Date Published: 2/1/19 10:00AM
Publication Location:
Article Title: Near-octave intense mid-infrared by adiabatic down-conversion in hollow anti-resonant fiber
Authors: Xiaoyue Ding, Md. Selim Habib, Rodrigo Amezcua-Correa, Jeffrey Moses
Keywords: mid-infrared light sources, hollow core fiber
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
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Publication Location:
Article Title: Single-mode, low loss hollow-core anti-resonant fiber designs
Authors: Md. Selim Habib, J. E. Antonio-Lopez, Christos Markos, Axel Sch&uuml;lzgen, Rodrigo Ame
Keywords: hollow-core antiresonant fiber
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
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Article Title: Watt-scale super-octave mid-infrared intrapulse difference frequency generation
Authors: Christian Gaida, Martin Gebhardt, Tobias Heuermann, Fabian Stutzki, Cesar Jauregui, Jose Antonio-Lo
Keywords: mid-infrared, hollow core fiber
Abstract: In this letter, we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynam- ics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-?m core HC-ARF to 18 ?m under 19-bar He, pumped at 800 nm with 6-?J pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.
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Article Title: Ultra-low Brillouin scattering in anti-resonant hollow-core fibers
Authors: Arjun Iyer, Wendao Xu, J. Enrique Antonio-Lopez, Rodrigo Amezcua Correa, William H. Renninger
Keywords: hollow core fiber
Abstract: Sensitive optical experiments in fiber, including for applications in communications and quantum information, are limited by the noise generated when light scatters from thermally excited guided-acoustic phonons. Novel fibers, such as microstructured fibers, offer control over both optical and acoustic waveguide properties, which can be designed to mitigate optomechanical noise. Here, we investigate the optomechanical properties of microstructured anti-resonant hollow-core fibers and demonstrate their promise as a low-noise fiber platform. By developing an ultra-sensitive spectroscopy technique, a seven capillary anti-resonant hollow-core fiber is found to exhibit record low optomechanical coupling (<10?4 W?1 m?1), in agreement with comprehensive numerical calculations. The largest scattering occurs from a guided acoustic mode in the air confined in the core of the fiber. Acoustic resonances in the silica, due to minimal overlap with the optical mode in the core, scatter a hundred tim
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Date Submitted: 1/17/21 12:00AM Date Published: 4/1/20 12:00AM
Publication Location:
Article Title: S2 Measurements Showing Suppression of Higher Order Modes in Confined Rare Earth Doped Large Core Fibers
Authors: Stefan Gausmann, Jose E. Antonio-Lopez, James Anderson, Steffen Wittek, Sanjabi Eznaveh Eznaveh
Keywords: hollow core fiber
Abstract: We present a detailed investigation on higher order mode suppression due to differential gain in large mode area step index fiber amplifiers with confined Yb doping using spatially and spectrally resolved imaging (S2). A novel active fiber with Yb doping confined to the central 30% of the core area is fabricated and its performance is directly compared to a fiber with a conventional homogeneously doped core with almost identical parameters. At high pump rates, S2 and beam pointing stability measurements clearly demonstrate fundamental mode operation of the confined doping few mode fiber, even under imperfect launching conditions and environmental perturbations. In addition, we discuss the mode content as a function of gain in co-pumped fiber amplifiers with and without confined rare earth core doping using a power propagation model for fibers with similar parameters to those used in our exper- iments. Our simulation results as well as amplification experiments indicate the great poten
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Publication Location:
Article Title: Design of Negative Curvature Hollow Core Fiber Based on Reinforcement Learning
Authors: Xiaowen Hu, Axel Schulzgen
Keywords: Negative curvature hollow core fiber, optical fiber design, reinforcement learning.
Abstract: In negative curvature hollow core fibers (NCHCFs), light guidance is based on the capillary structure in the cladding. To achieve desirable fiber propagation properties, various designs of the capillary structure have been proposed in literature. However, the design process so far depends more or less on experience. In this article, we propose a reinforcement learning (RL) based method of systematically optimizing the capillary structure to achieve low average confinement loss (CL) for a given operating wavelength range and core radius. We use a recurrent neural network (RNN) to interactively study the properties of different capillary structures. The wavelength averaged CLs of the resulting designs are more than one order of magnitude lower than the lowest average CL of prior designs in literature. The same approach can be applied to search for optimum capillary structures in terms of other fiber propagation properties such as bending loss (BL), higher order modes extinction ratio (HO
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Publication Location:
Article Title: Noise and spectral stability of deep-UV gas-filled fiber-based supercontinuum sources driven by ultrafast mid-IR pulses
Authors: Abubakar I. Adamu, Md. Selim Habib, Callum R. Smith, J. Enrique Antonio Lopez, Peter Uhd Jepsen, R
Keywords: hollow core fiber
Abstract: Deep-UV (DUV) supercontinuum (SC) sources based on gas-filled hollow-core fibers constitute perhaps the most viable solution towards ultrafast, compact, and tunable lasers in the UV spectral region, which can even also extend into the mid-infrared (iR). noise and spectral stability of such broadband sources are key parameters that define their true potential and suitability towards real-world applications. In order to investigate the spectral stability and noise levels in these fiber-based DUV sources, we generate an SC spectrum that extends from 180 nm (through phase-matched dispersive waves - DWs) to 4 ?m by pumping an argon-filled hollow-core anti-resonant fiber at a mid-IR wavelength of 2.45 ?m. We characterize the long-term stability of the source over several days and the pulse-to-pulse relative intensity noise (RIN) of the DW at 275 nm. The results indicate no sign of spectral degradation over 110 hours, but the RIN of the DW pulses at 275 nm is found to be as high as 33.3%. Num
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Article Title: Enhanced birefringence in conventional and hybrid anti-resonant hollow-core fibers
Authors: Md. Selim Habib, Abubakar I. Adamu, Christos Markos, Rodrigo Amezcua-Correa
Keywords: HCF, anti resonant fiber
Abstract: A hollow-core anti-resonant fiber (HC-ARF) design based on hybrid silica/silicon cladding is proposed for single-polarization, single-mode and high birefringence. We show that by adding silicon layers in a semi-nested HC-ARF, one of the polarization states can be strongly suppressed while simultaneously maintaining low propagation loss for other polarization states, single-mode and high birefiringence. The optimized HC-ARF design exhibits propagation loss, high birefringence, and polarization-extinction ratio of 0.05 dB/m, 0.5 × 10?4, >300 respectively for y-polarization while the loss of x-polarization is >5 dB/m at 1064 nm. The fiber also has low bend-loss and thus can be coiled to a small bend radii of 5 cm having ?0.06 dB/m bend loss.
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Publication Location:
Article Title: Impact of cladding elements on the loss performance of hollow-core anti-resonant fibers
Authors: Md. Selim Habib, Christos Markos, Rodrigo Amezcua-Correa
Keywords: HCF, anti resonant fiber
Abstract: A hollow-core anti-resonant fiber (HC-ARF) design based on hybrid silica/silicon cladding is proposed for single-polarization, single-mode and high birefringence. We show that by adding silicon layers in a semi-nested HC-ARF, one of the polarization states can be strongly suppressed while simultaneously maintaining low propagation loss for other polarization states, single-mode and high birefiringence. The optimized HC-ARF design exhibits propagation loss, high birefringence, and polarization-extinction ratio of 0.05 dB/m, 0.5 × 10?4, >300 respectively for y-polarization while the loss of x-polarization is >5 dB/m at 1064 nm. The fiber also has low bend-loss and thus can be coiled to a small bend radii of 5 cm having ?0.06 dB/m bend loss.
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Conference Location: Zurich
Paper Title: Supercontinuum generation from deep-UV to mid-IR in a noble gas-filled fiber pumped with ultrashort mid-IR pulses
Authors: Abubakar I. Adamu, Md. Selim Habib, Christian R. Petersen, Binbin Zhou, Axel Schülzgen, J. Enrique A
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Authors: Md. Selim Habib, Christos Markos, A. Isa Adamu, J. E. Antonio-Lopez, and Rodrigo Amezcua-Correa
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Authors: Arjun Iyer, Wendao Xu, J. Enrique Antonio-Lopez, Rodrigo Amezcua Correa, and William H. Renninger
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Rodrigo AMEZCUA CORREA
Signature Date: 1/8/23 10:28PM

Final Report for Contract Number: **W911NF1710501 -** Dates Covered: **Sep, 01 2017 to Nov, 30 2019**

Cover page

The cover page of both the full complied report and each university's individual report should contain the follow:

1. **Period covered by report:** 09/01/2017 to 11/30/2019
2. **Proposal Title:** Antiresonant Hollow Core Fibers for Extreme Light Transport
3. **Contract/grant number:** W911NF-17-1-0501
4. **Authors of report:** Rodrigo Amezcua Correa
5. **Performing Organization and address:**
6. **Key words:** Hollow core fibers, nonlinear fiber optics, antiresonant fiber, optical fiber desing and fabrication
7. **Abstract – 200 words.** Should include the following components: Specific aims, results of finding and their significance, and plans for the coming year:

This program is developing novel air guiding fibers that address critical physical limitations of optical fibers. These radically new antiresonant hollow core fiber designs have the potential for light transport in a single mode over wide transmission windows with ultra-low loss (<1 dB/km) and orders of magnitude higher damage and nonlinear thresholds compared to conventional fibers. Fibers with this level of performance can open up applications not possible using current fibers such as: long distance high optical power transport (kW power delivery over km range), extreme peak power/energy delivery, low latency broadband data transmission, as well as low-loss UV and mid-IR transmission.

Technical report

I. Hollow core fiber development

Recently, Hollow-core anti-resonant (HC-AR) fibers have been extensively studied and developed by several research groups due to their extraordinary ability of light guidance in an air-core, low-loss, and wide transmission bandwidth. One of the unique features of hollow-core fiber is that >99.99% can be guided in the central air-core with only a tiny fraction of light overlapping with the surrounding glass structure, hence increasing the optical damage threshold and reducing material absorption significantly. The guiding mechanism of this fiber relies on the combination of a inhibited coupling (IC) between the core and cladding modes and the anti-resonance. The coupling between the core mode and cladding modes can be made strongly inhibited (phase mismatched) by suitably arranging the anti-resonant tubes in the cladding, which results in low loss and much broader spectral bandwidths. In order to control the modal content and attenuation, several types of HC-AR fibers have been proposed, investigated, and fabricated to date, including HC-AR fibers with circular anti-resonant tubes, "ice-cream cone" shape anti-resonant tubes, elliptical anti-resonant tubes, and nested anti-resonant tubes.

During the reported period, we proposed a 5-tube nested HC-AR fiber with propagation loss <1 dB/km and single-mode operation at telecommunication wavelengths. In order to get full information on modal contents of the fibers, we thoroughly investigate the propagation losses of the fundamental mode (FM) and higher-order modes (HOMs) as a function of the cladding parameters. We reveal that a proper selection of the number of the cladding anti-resonant tubes and the cladding geometry is crucial for minimizing propagation loss and for effectively single-mode operation. We have demonstrated for the first time, to the best of our knowledge, that a 5-tube cladding arrangement exhibits ultra-loss, wider transmission band and stronger HOMs suppression than cladding designs with different numbers of antiresonant tubes.

Figure 12(a) shows the geometry of a 5-tube HC-AR fiber used in our investigations. We considered a core diameter of 30.5 μm (D_c) and a silica wall thickness of t = 1120 nm, which is identical to the fiber structure reported in [10]. The inner nested tube has a diameter $d = D/2$ and wall thickness of t = 1120 nm. The outer tubes are separated by a gap distance, g forming a node-free core boundary. The node-free configuration provides better loss properties and flatter transmission spectra compared to closed core boundary structures [3]. The numerical analyses were performed using a finite-element based COMSOL mode solver. In order to accurately model the leakage loss of the fiber, we used perfectly-matched layers (PML) outside the fiber domain, and both mesh size and PML parameters were optimized according to prior studies.

We first compare the propagation loss of nested HC-AR fibers with 5, 6, and 7 tubes. The calculated propagation loss spectra and near-field profiles of the fundamental modes for the three fiber designs are presented in Fig.13. In these calculations, the power overlap with the silica walls was used to estimate the effective material loss. Material loss was then added to the leakage loss and SSL in order to obtain the total propagation loss. The SSL arises from imperfections of the fiber which result in light scattering from the air-glass interfaces.

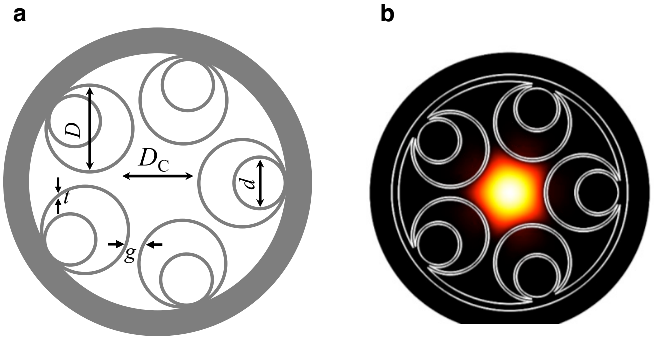

Fig. 12. (a) Geometry of the proposed 5-tube HC-AR fiber. The fiber has a core diameter D_c = 30.5 μm, a uniform silica wall thickness t = 1120 nm, and outer tube separation, g. The diameter of the inner nested tubes d is defined by $d = D/2$. (b) Mode field profile of the fundamental mode at 1550 nm.

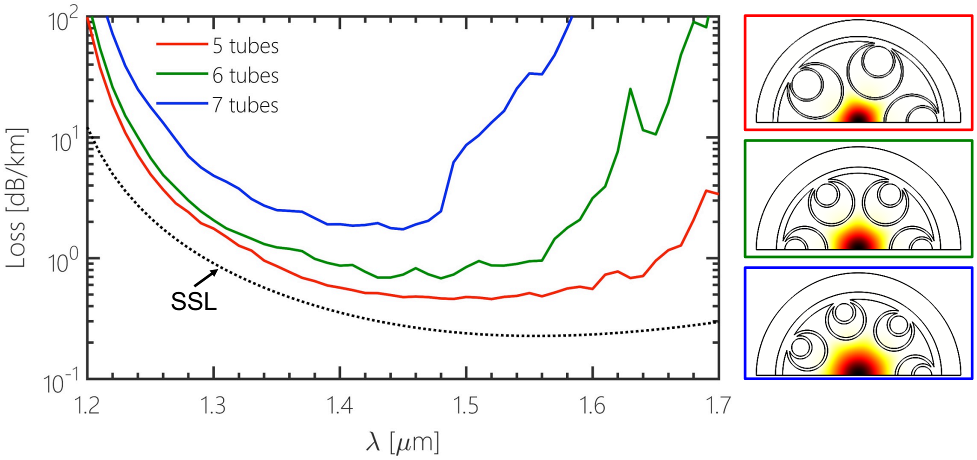

Fig. 13. Calculated loss spectra of nested HC-AR fibers with five, six, and seven tubes. All fibers have the same core diameter D_c = 30.5 μm, a uniform silica strut thickness t = 1120 nm, and same gap distance g. The black dashed line represents surface scattering loss. The color of the frame corresponds to the color of line of the plot.

However, HC-AR fibers exhibit low SSL as compared to HC-PBG because the field intensities at the air-glass interfaces are relatively low [6]. The SSL was calculated accordingly to the method reported in [3]. We calculated SSL of ~0.23 dB/km at 1.55 μm. The solid red line shows the propagation loss of a 5-tube nested HC-AR fiber with a loss level of ~0.52 dB/km at 1.55 μm. The solid green line is the propagation loss of the 6-tube nested HC-AR fiber. In this case the propagation loss is ~2 dB/km at 1.55 μm. The solid green line corresponds to the D-shaped HC-AR fiber with ~0.95 dB/km loss at 1.55 μm. Finally, the solid blue line depicts the loss spectrum of 7-tube nested HC-AR fiber with a loss value of ~33 dB/km at 1.55 μm. The results in Fig. 2 clearly indicate that the 5-tube HC-AR fiber shows improved loss performance (lower loss and broader transmission window) compared to 6 and 7-tube fibers.

In order to better understand the modal contents of HC-AR fibers, we show contour plots of the FM and HOMs propagation loss as a function of normalized tube diameter (D/D_c) and normalized nested tube diameter (d/D) for a 5-tube nested fiber in Fig. 3. From these maps it is possible to identify design regions for low loss and effectively single-mode operation. It is evident from Fig. 3(b) that the FM loss remains <1 dB/km in the range of $0.7< D/D_c <1.15$ and $0.5< d/D<0.7$. For a normalized tube diameter, $D/D_c<0.68$, the FM mode loss progressively increases with decreasing values of d/D. Figure. 3(c) shows the loss of HOMs (lowest loss among the LP_{11} and LP_{21} modes). The HOM loss can be made as high as 6000 dB/km for $D/D_c \simeq 1.13$ and $d/D \simeq 0.68$ while maintaining the FM loss below 0.5 dB/km. This large loss value of HOMs is due to the strong coupling between HOMs and cladding modes . Our results indicate that HOMs can be strongly suppressed by properly engineering the anti-resonant cladding structure. In addition, Figure 3(d) shows the calculated higher-order mode extinction ratio (HOMER), which is defined as the ratio between the propagation loss of the HOM with the lowest loss and the propagation loss of the fundamental mode. For $D/D_c \simeq 1.13$ and $d/D \simeq 0.68$, the HOMER is >12000. To the best of our knowledge, this is the highest reported HOMER value in any HC-AR fiber. The calculated HOMER for 6-tube HC-AR fiber is ~200 which is far lower than 5-tube nested HC-AR fiber. The 5-tube nested HC-AR fiber exhibits small bend loss of 1 dB/km at 5 cm bend radius, and also insensitive to tight bend condition.

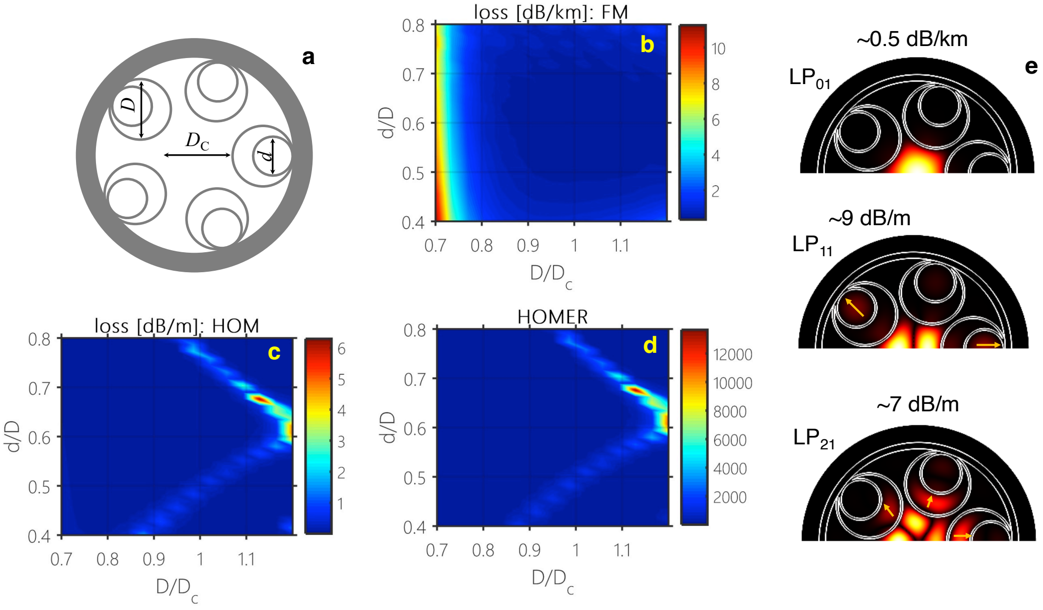

Fig. 3. (a) Geometry of a nested HC-AR fiber with five anti-resonant tubes. Calculated total propagation loss of (b) LP_{01}-like FM and (c) HOMs. (d) HOMER as a function of d/D with different values of D/D_c. (e) Mode field profile of LP_{01}, LP_{11}, and LP_{21} at $D/D_c \simeq 1.05$ and $d/D \simeq 0.68$. The light leakage into the cladding for HOMs are indicated by arrows. HOM loss in (c) is defined as the lowest loss among the four LP modes (LP_{11}^a, LP_{11}^b, LP_{21}^a, and LP_{21}^b). All simulations are performed at 1.55 μm. The fiber has a fixed core diameter $D_c = 30.5$ μm and a uniform silica strut thickness $t = 1120$ nm.

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The results presented here indicate that precisely engineering the cladding of AR-HCF is crucial for achieving ultra-low loss and effective single-mode operation and could lead to novel designs with improved performance.

II. Machine learning for the design of hollow core fibers

In negative curvature hollow core fibers (NCHCFs), light guidance is based on the capillary structure in the cladding. To achieve desirable fiber propagation properties, various designs of the capillary structure have been proposed in literature. However, the design process so far depends more or less on experience. In this article, we propose a reinforcement learning (RL) based method of systematically optimizing the capillary structure to achieve low average confinement loss (CL) for a given operating wavelength range and core radius. We use a recurrent neural network (RNN) to interactively study the properties of different capillary structures. The wavelength averaged CLs of the resulting designs are more than one order of magnitude lower than the lowest average CL of prior designs in literature. The same approach can be applied to search for optimum capillary structures in terms of other fiber propagation properties such as bending loss (BL), higher order modes extinction ratio (HOMER), overlap of the optical mode with the capillary structure, or a trade-off among these properties.

During the reported period, we have proposed a novel method to find NCHCF designs with low CLs for a given core radius and operating wavelength range. We decompose the capillary cladding structures to segments of rings. By appending those segments, we construct a set containing 1,000,000 NCHCF designs. An RL method, in which an RNN and an FEM based modal solver interact with each other, has been used to search for the optimum design. The RNN selects a design while the FEM based modal solver provides the CL calculation of that design, which is in turn used to train the RNN. The resulting best NCHCF designs show low CLs over the entire operating wavelength span. The average CLs of the designs are more than one order of magnitude lower than the lowest average CL of designs in literature. The proposed method can also be used to study the optimum NCHCF designs in terms of BL, HOMER, overlap of the optical mode with the capillary structure or a combination of NCHCF properties.

III. UV Generation in gas filled hollow core fibers

Ultraviolet (UV) light is a key tool in a wide range of scientific and technological applications, including semiconductor manufacturing, material processing, and medical treatment. However, current UV light sources are limited by their low efficiency, high cost, and/or narrow tuning range, which hinders their widespread adoption in many applications.

One promising approach for the generation of extreme UV (EUV) light is through the use of dispersive wave trapping in a tapered gas-filled hollow fiber. This approach involves the generation of a dispersive wave through four-wave mixing in the HCF, which is then trapped in a small region of the fiber through the use of a taper. we demonstrate how the soliton– plasma interaction initiates trapping of the generated dispersive waves (DWs) in an experimentally feasible tapered He-filled hollow-core anti-resonant fiber (HC-ARF). We show that the taper gradient strongly influences the pulse trapping dynamics and thus determines the intensity and blueshift of the trapped DW. This process leads to an efficient DW generation down to 100 nm with a 3.4-octave supercontinuum spanning 100–1150 nm (2.73 PHz) by tapering a 36-µm core HC-ARF to 18 µm under 19-bar He, pumped at 800 nm with 6-µJ pulse energy. The proposed fiber taper structure could be an alternative route to generate light in the extreme ultra-violet (EUV) spectral range using moderate gas pressure and relatively low pulse energy.

We have numerically demonstrated the generation of multiple DWs in the VUV wavelength region in a tapered He-filled HC-ARF. The mechanism behind the DWs emission in the VUV region relies exclusively upon the DW trapping in a gravity-like potential formed by the soliton-plasma nonlinear interaction in the adiabatically and a smaller taper ratio. Here, we demonstrate for the first time that the taper profile has a crucial role on the generated intensity and blue-shift of the DW trapped by the soliton-plasma, indicating that careful design of the taper profile is crucial for efficient VUV light generation.

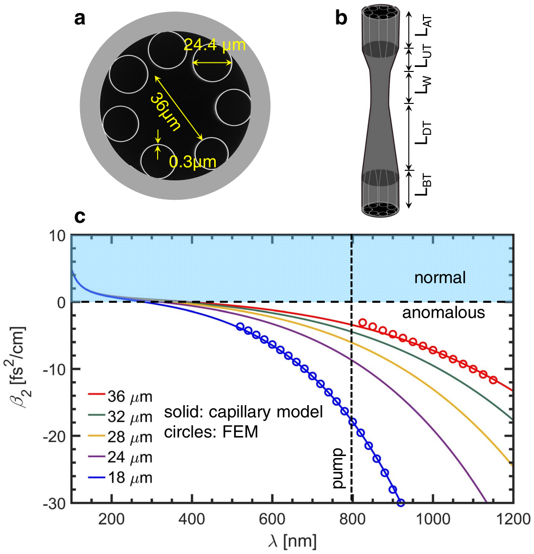

Fig. 1. (a) SEM image of HC-ARF. (b) Sketch of the longitudinal sections of the HC-ARF taper. (c) Group velocity dispersion (GVD) vs. wavelength under 19 bar He for different core diameters calculated using capillary model (solid line) and finite-element method (circle).

Fig. 1(a) shows a scanning electron microscope (SEM) image of the HC-ARF fabricated in house with a core diameter of 36 µm, wall thickness of 300 ± 5 nm, and an average capillary diameter of 24.4 µm. The wall thickness was chosen to be 300 nm so that it gives high transmission at pump wavelength of 800 nm. In our calculations, we used the SEM image to model the fiber because this will allow us to estimate a realistic dispersion profile. The effective mode index of LP_{01}-mode of an evacuated HC-ARF was calculated using a modified capillary model (MCM) in which wavelength dependent of the core radius is assumed according to [17], and fiber resonance effect has been neglected for simplicity. Fig. 1(b) illustrates the taper profile of the HC-ARF used in this work. The length of the uniform input section (L_{BT}), down-taper section (L_{DT}), uniform waist section (L_W), up-taper section (L_{UT}), and the fiber length after the taper section (L_{AT}) are 20 cm, 5 cm, 5 cm, 3 cm, and 7 cm, respectively. The core diameters before the taper transition and at the taper waist are 36 µm and 18 µm, respectively. We choose a moderate core diameter of the down-taper section of 18 µm in order to avoid the influence of loss on the DW in the EUV regime. The finite-element calculated loss of the 18 µm core fiber section is <0.5 dB/m and <1 dB/m at 800 nm and 1200 nm, respectively. Moreover, a few cm long down-taper and up-taper transitions were used. Therefore, we believe that the impact of the propagation loss on the overall supercontinuum spectrum can be neglected and hence the loss is not included in our calculations. In our model, we assume a more realistic taper profile in which the taper transition to be decaying with an exponential profile: $r(z) = r_0 e^{-z/L_0}$, where r_0 is the initial fiber diameter, L_0 is a fixed length of the fiber is assumed to be uniformly heated and stretched, and z is the distance along the taper transition. We choose the length of the taper transition sections (L_{DT} and L_{UT}) such that it follows adiabatic criterion. Fig. 1(c) shows the group- velocity dispersion (GVD) using MCM under 19 bar of He for different core diameters. As a comparison, we also calculated the GVD using finite-element method for two different core diameters: 36 µm (red circle) and 18 µm (blue circle) indicating the good agreement between the two different calculation approaches.

The optical pulse propagation was calculated using a generalized nonlinear Schrödinger equation which also includes free-electron effects expressed as:

$$(i\partial + D(i\partial) + \gamma|A|^2 - {\omega^2}_p + i^{A_{eff} I_p \partial_t N_e})A=0, (1) \; {}^{z\ t} \; 2\omega_0 c \; 2|A|^2$$

where A is the complex field envelope, t is the time in the reference frame moving with the pump group velocity, D is the full dispersion operator, c is the velocity of light in vacuum, γ is the Kerr nonlinear coefficient of the gas, ω_0 is the central angular frequency of the input pulse, ω_p is the plasma frequency, m_e is the mass of an electron, ε_0 is the free space permittivity, A_{eff} is the effective mode area of the fiber, I_p is the ionization energy of the gas, N_e is the free electron density. Raman contribution of silica was neglected in our calculations due to the very low light-glass overlap ($\ll$1%). In our system, the peak intensity at the maximum compression point reaches as high as ~300 TW/cm^2 and tunneling ionization dominates over multiphoton ionization. Therefore, in our ionization calculation, we use quasi-static tunneling based on on Ammosov, Delone, and Krainov (ADK) model.

Fig. 2 shows the spectral, temporal, intensity and free electron density evaluation of a tapered HC-ARF under 19 bar pressure of He pumped in the anomalous dispersion regime at 800 nm with 30 fs pulse duration and 6 µJ energy pulse which corresponds to a soliton order of ~4.4. In our simulations, we choose a lighter gas (He) than for example Argon because it shifts the zero-dispersion wavelength towards further into the blue as well as the resonant DW. A moderate pressure is

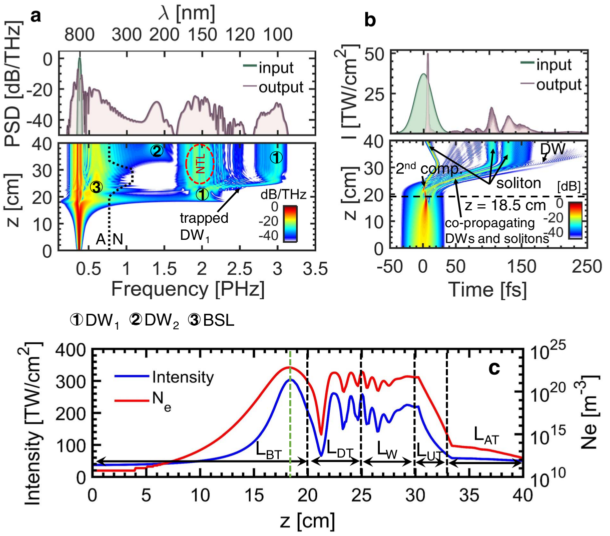

Fig. 2. Simulated (a) power spectral density (PSD), (b) temporal intensity profile, and (c) intensity (left) and free electron density (N_e) as a function of fiber length for a 6 μJ, 30 fs long pulse in an He-filled under 19 bar for a tapered HC-ARF. A: anomalous dispersion, N: normal dispersion, DW: dispersive wave, BSL: blue shifted soliton, NTL: non-trapped light.

chosen in order to compensate for the low nonlinearity of He. One of the main advantages of considering tapering is that while the initially straight gas-filled HC-ARF allows the generation of DW in the UV region; the subsequent tapering section is then significantly moves the DW radiation towards the VUV. The spectral and temporal evolution is shown in Fig. 2(a-b) in which the pulse undergoes a strong soliton self-compression due to the combined effect of anomalous dispersion and self-phase modulation. The pulse is compressed down to a single cycle duration of <2 fs with peak intensity ~300 TW/cm^2 after propagating 18.5 cm well before the taper transition starts at 20 cm. Such high intensity pulse of ~300 TW/cm^2 is enough to ionize the gas and form a plasma. It can be seen from Fig. 2(a) that at the maximum temporal compression point a blue-shifted spectrum was found and a strong DW is formed at ~150 nm which is due to the strong overlap between the soliton and the DW. The power spectral density was calculated as, $PSD = \frac{c}{\lambda^2} |E(z,\lambda)|^2 f_{rep}$, where f_{rep} is the seed laser repetition rate. The spectrum mainly extends towards blue due to the plasma formation. We also observed that when the ionization is turned off, the DW is emitted at ~130 nm. The DW is formed at longer wavelengths for the ionization case because the pump soliton shifts toward the blue side. In the taper down transition section (fiber length: 20-25 cm), the GVD changes and the ZDW shifts further toward the shorter wavelength from 399 nm to 278 nm. In the down taper section, the soliton slows down due to the decreased group velocity (GV). Due to the decreased GV, the soliton catches up the DW while shifting it further down to 100 nm through the group velocity matching (GVM) after propagation of ~ 24 cm. Finally, another DW emission is observed at around 280 nm in the up taper section after ~ 38 cm (see DW_2 in Fig. 2(a)). Fig. 2(c) shows the intensity and free electron density generation with respect the propagation distance. It can be seen from Fig. 2(c) that both intensity and free electron density increases at the maximum compression point at z = 18.5 cm (green broken line). After the self-soliton compression point, both the intensity and generation of free electrons drop below the ionization threshold level. We found another soliton self-compression stage at around 22.5 cm.

During this period, we report for the first time how the soliton- plasma trapping of DWs in a tapered He-filled HC-ARF can lead to an efficient DW down in the EUV. Our numerical modeling relies upon experimentally feasible parameters and predicts that the shortest EUV light can be generated at ~100 nm with a supercontinuum spanning 100-1150 nm via pulse trapping effect by tapering a 36 µm core fiber down to 18 µm. We demonstrated that the taper profile plays a crucial role for generating DWs with an additional degree of freedom compared to a uniform fiber. The intensity of the DW relies on the taper gradient. When the taper gradient is decreased, the soliton tends to deliver more energy to the corresponding DW which is due to the GAM between the soliton and DW. We believe that the results presented could be very useful to the fiber-optics community towards generation and development of compact, bright, tunable, spatially coherent light source in the EUV range.

IV. Brillouin Scattering in Anti-Resonant Hollow-Core Fibers

Optomechanical interactions, in which light and mechanical waves interact with each other, are an important area of research with potential applications in a wide range of fields, including sensing, cooling, and quantum information processing. However, most optomechanical systems have relatively strong optomechanical coupling, which can limit their performance in noise-sensitive applications. During this project, we investigated optomechanical interactions in anti-resonant hollow-core fibers, for the first time. Experiments and corresponding theoretical calculations reveal weak optomechanical coupling, which suggests that anti-resonant hollow-core fibers are well-suited for noise-sensitive applications.

We used a ARHCF consisting of 7 non-touching capillaries (Fig.1(a)). In optomechanical studies of photonic bandgap hollow-core PCFs, previously, the acoustic modes in the air confined to the core were found to closely resemble that of guided modes in an air-filled hollow rigid cylinder [8]. Since ARHCF also resembles a hollow cylinder but with 7 additional thin capillaries, the acoustic modes in the core of ARHCF are expected to have the structure of acoustic modes of a rigid hollow cylinder perturbed by the thin capillaries. We numerically solve for the guided acoustic modes of the ARHCF with 2D finite element simulations of the fiber cross-section. Simulations indeed reveal a class of Bessel-like modes in the air in the core of the fiber. Optomechanical coupling, neglecting radiation pressure effects, is determined by calculating the overlap of the acoustic displacement with the optical force distribution calculated from the simulated optical mode. The largest Brillouin coupling (gain~ 3 x 10^{-5} $W^{-1}m^{-1}$), is predicted for a Bessel-like mode in air at ~9.4 MHz (Fig.1(c)). This mode has the strongest overlap with the forces produced by the optical mode (Fig.1(b)). The higher-order Bessel-like acoustic modes in air have a considerably lower overlap with the optical force, which results in a comparatively smaller optomechanical coupling. Finally, the acoustic modes confined to the glass have negligible overlap with the optical forces resulting in lower coupling by more than an order of magnitude. Experimental observations and numerical predictions demonstrate a weak optomechanical response from air in the fiber core and a measurement-limited response from acoustic excitations in the silica microstructure.

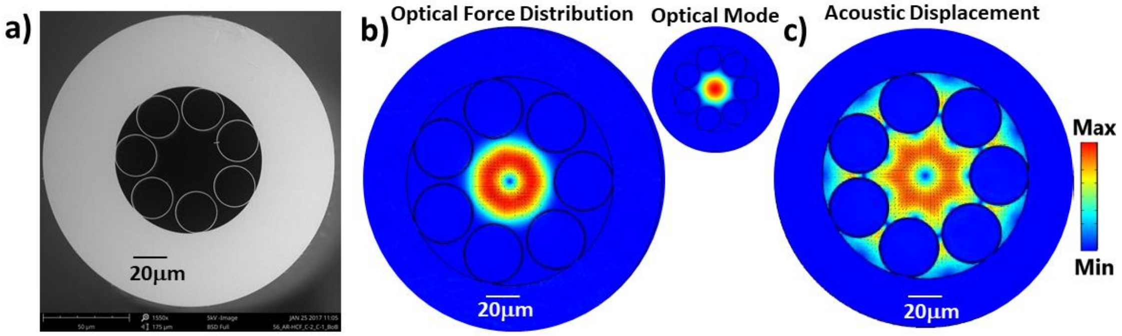

Fig. 1: a) SEM fiber cross-section of the ARHCF, b) simulated force distribution from the fundamental optical mode (inset), and c) the dominant acoustic mode in air.

I. Mid-IR supercontinuum generation in antiresonant hollow core fibers

Hollow-core antiresonant (HC-AR) fibers are a versatile plat- form for investigating ultrafast nonlinear optics in gas-filled fibers because of their broadband guidance, low loss (near-IR to mid-IR), high damage threshold, and weak and anomalous dispersion. The possibility of filling these fibers with gases bestows them with a nonlinearity and dispersion that can be adjusted with pressure. Moreover, gases have several distinct advantages over solid nonlinear materials such as higher damage thresholds, and extremely wide transparency ranges, and they are also considered a self-healing media due to their ability to recombine after ionization. In previous works, light–gas interaction and soliton dynamics in noble gas-filled HC fibers of Kagome type (also known as inhibited-coupling fibers) have been extensively studied in the near-IR. The prospect for further increas- ing the bandwidth by fiber tapering was also demonstrated. However, limited studies on light–gas inter- action have been performed in the mid-IR spectral regime. The mid-IR region is attractive mainly because most molecules display their fundamental vibrational absorptions in this wavelength range.

Therefore, mid-IR supercontinuum sources are currently of great technical and scientific interest due to their wide range of potential applications such as early cancer diagnostics, food quality control, medical surgery, and thermal and photoacoustic imaging or spectroscopy. The supercontinuum sources, both in the visible, near-IR, and mid-IR, have so high brightness that they outperform square km-sized synchrotrons, as demonstrated recently. Moreover, near-IR to mid-IR supercontinuum sources find applications in the extremely im- portant imaging modalities of hyperspectral imaging, photoacoustic sensing of glucose, and optical coherence tomography imaging, as well as in disease detection. One of the most challenging aspects of generating supercontinuum in the mid-IR using silica-based fibers is that silica glass has a high attenuation beyond 3 µm. Nonetheless, the high attenuation of silica in the mid-IR was overcome with the development of HC fibers, which enabled high light con- finement in the core (∼99.99%) and therefore loss levels in the order of dB/m. These efforts lead to the demonstration of minimum propagation loss of 34 dB/km at 3050 nm and light guidance beyond 5 µm. Despite their unique optical properties, HC-AR fibers have been found to be sensitive to bend perturbations. The best bend performance of HC-AR fibers has been recently experimentally demonstrated in the mid-IR with a loss of 0.3 dB/m at a 8 cm bend radius. However, to the best of our knowledge, the effect of bending on ultrafast nonlinear propagation dynamics has never been investigated, and it still remains unknown. In this period we numerically show multiple octave-spanning supercontinua covering the 400–5000 nm spectral range using a 25 cm nested HC-AR fiber. It should be noted that our numerical simulations consider experimental feasible parame- ters, i.e., 100 fs pulse duration and 15 µJ pulse energy at 3 µm (Spitfire Pro, Spectra Physics). Towards the development of compact mid-IR supercontinuum sources, coiling of fiber with relatively small bending radius is perhaps a crucial step. It has been shown experimentally that it is possible to coil HC-AR fiber tightly (bend radius <5 cm) with minimum loss of 0.2 dB/m. In addition, bending of the fiber is a well-known experimental method to suppress the higher order modes, making the fiber effectively single-mode. We consider two different HC-AR fibers with the same core diameter but one with nested HC-AR fiber (smaller capillaries are nested inside the tubes defining the core boundary) and a second fiber without nested capillaries. This way, we can determine whether a nested fiber structure (which imposes fab- rication challenges) could have a direct impact on the performance. Our numerical results predict that the blue edge of the supercontinuum is affected at a critical bend radius of ∼12 cm, whereas both the short and long wavelength edge of the super- continuum are strongly affected for a bend radius smaller than 5 cm. Our investigations also indicate that the nested HC-AR fiber and the non-nested HC-AR fiber show similar nonlinear propagation dynamics when a short section of fiber (25 cm) is considered, although the former has lower loss than the latter.