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Application-specific Specialty Optical Fibers: A new Paradigm in Fiber Designs

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Abstract

Specialty optical fiber for specific applications have become a new paradigm in guided wave photonics. In this invited presentation, we would review some of our application-specific specialty fiber designs for parabolic pulse generation to overcome nonlinear detriments, and all-fiber light sources for mid-IR and THz photonics.

1. Introduction

Optical fiber communication has seen phenomenal progress in last two decades with Tb/s transmission already demonstrated. To leverage on this remarkable progress more recently research on application-specific specialty fibers have emerged as a new paradigm in fiber designs. In recent years we have reported several new results in this emerging area of guided wave photonics. In this paper we shall review few of our relatively recent results.

Parabolic pulses (PP) are known to be special pulse shapes amenable to breaking-free propagation by countering detrimental strong nonlinear effects in guided wave propagation. These find many interesting applications including high power delivery, bio-medical imaging, etc. [1]. For mid-IR fiber optics, since the compatible glasses such as chalcogenides are highly nonlinear, high power laser propagation via PP is an attractive route to achieve stable pulse propagation through such nonlinear glass fibers in the mid-IR. We demonstrate through appropriate Bragg kind of microstructured fiber design for inducing rapidly varying but close to zero average dispersion with propagation through variation in fiber dimension along with consequential modulated nonlinearity, one can achieve stable pulse propagation in it. Additionally to mitigate the effect of third order dispersion (TOD), we incorporate transverse chirping in the fiber cladding.

In recent years mid-IR wavelength regime (2 ~ 10 μm) has attracted a lot of research in photonics. Some portions of this wavelength regime is also known as "molecular finger print" regime because of absorption exhibited by molecules like O_2, H_2O, CO, CO_2, NO, N_2O, OH, CH_4, HCL, etc. with well resolvable transitions. This wavelength regime is also of interest in the defense sector for high power delivery in applications like heat sinking missiles and counter measures, and thermal imaging in low power night vision, non-destructive soft tissue ablation in medical diagnostics, molecular absorption spectroscopy for monitoring combustion flow and gas dynamics, etc.

2. Specialty Fiber designs and Results

Our application-specific fibre designs have evolved on microstructured optical fibres (MOF) platform in various forms configurable around suitable materials having low transmission loss in a desired wavelength window(s). Key targets that underpin these designs involved inventing MOF geometries, which could be tailored for dispersion as well as nonlinearity management.

Towards Pulse-shaping

For PP generation, its propagation dynamics is studied by solving nonlinear Schrodinger equation (NLSE) under slowly varying pulse (of amplitude A) envelope approximation in a Bragg kind of 1D-MOF:

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}D(z)\frac{\partial^2 A}{\partial T^2} - i\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} + i\frac{\alpha}{2}A + \gamma(z)|A|^2 A = 0 \quad (1)$$

where β_2 and β_3 are respectively the second and third order dispersion coefficients ($\beta_2 > 0$), $D(z)$ is the longitudinally varying temporal dispersion profile where $D(0) = 1$, $\gamma(z)$ is the longitudinally varying nonlinear parameter and α is the loss coefficient. We solved the NLSE by the split-step Fourier method (SSFM) and by targeting a dispersion profile that oscillates with propagation along z about an average that is close to zero mimicking a ripple. Earlier we had shown that by introducing a transverse chirp, detrimental effect of third order dispersion (TOD) could be eliminated in such fiber designs [2]. Targeted fiber design was realized by considering a Bragg fiber with an aperiodic cladding and transverse chirp. Cross-sectional view of the chirped clad Bragg fiber is shown in Fig. 1 (a) and (b). Two chalcogenide glasses were chosen to form the microstructured fiber - *GeAsSe* as the low index core and bilayers of *AsSe/GeAsSe* as the claddings. Designed PP shaper is made up of concatenation of two fibers – F1 and F2, of which F1 would form the PP and F2 spliced with it would ensure its stable propagation. Cladding of both F1 and F2 consists of 6 bilayers, which are linearly chirped from the layer, which is next to the core till the outermost

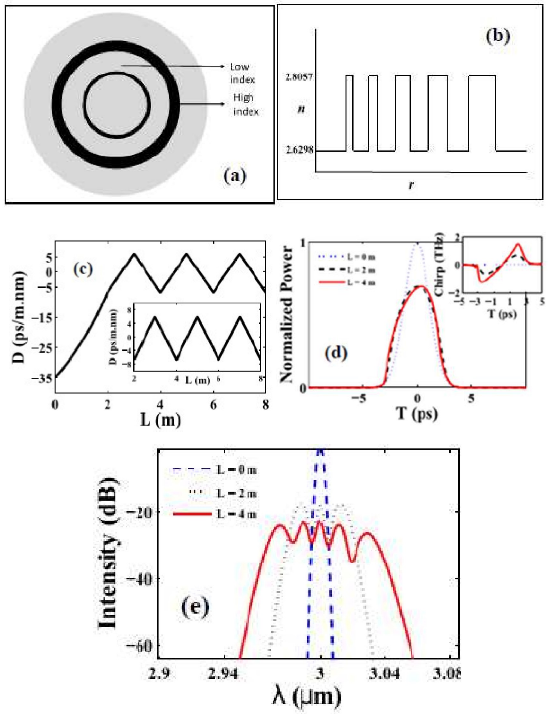

Figure 1 (a) Schematic of the chirped clad Bragg fiber cross-section; (b) refractive index profile of the Bragg fiber; (c) dispersion profile of the designed fiber – inset shows zero dispersion crossing of F2; (d) input temporal pulse power profile (dashed curve) along with evolution of output pulse power profiles at different fiber lengths; (e) corresponding spectral evolution at different fiber lengths.

layer (see Fig. 1(b)). Input is taken as a Gaussian pulse of peak power 150 W and FWHM 2.5 ps. Formation of parabolic pulse is shown in Fig. 1 (d). A close investigation of pulse propagation reveals that PPs are formed after about 1.5 m of the total fiber length with a misfit parameter M = 0.019 and propagates self-similarly. At the end of 4 m, a PP with FWHM ~ 4 ps is obtained as the output. A 3-dB spectral broadening of ~ 43 nm can be seen from Fig. 1(e). Details of our work in this direction can be found in [3].

Towards Mid-IR light Generation

On the mid-IR photonics front, several specialty fiber designs were reported by us for applications as all-fiber sources at different wavelength regime of mid-IR. Key targets that underpin these designs involved inventing MOF geometries, which would yield zero dispersion wavelengths (λ_{ZD}) in the neighbourhood of commercially available high power pump laser sources. One such typical MOF design is depicted in Fig. 2 (a) having chalcogenide material As_2S_3 as the host in which air holes are embedded in the cladding [4]. Design optimization led to diameter of the holes in the second ring to be different from the rest. Figure 2 (b) depicts dispersion spectrum of the designed MOF, which yielded a λ_{ZD} close to that of Tm-doped fibre lasers. Amplification factor (AF_s) i.e. gain signature at the signal wavelength region is plotted in Fig. 2 (c) to demonstrate narrow bandwidth (BW) of the generated signal for a pump power of 5W. Corresponding results for a broadband all-fibre mid-IR source is shown in Fig. 2 (d) for which the holey cladding of the designed MOF of the above type is filled with borosilicate rods (thermally compatible) to reduce the fiber's effective numerical aperture. This demonstrates example of a broad band all-fiber mid-IR source of BW ~ 80 nm spanning MWIR wavelength range from 3.1 ~ 3.9 μm achieved with a pump power of 5W from an Er-doped ZBLAN fibre laser emitting at ~ 2.8 μm [4]. In both the cases required fibre length is about a meter or less.

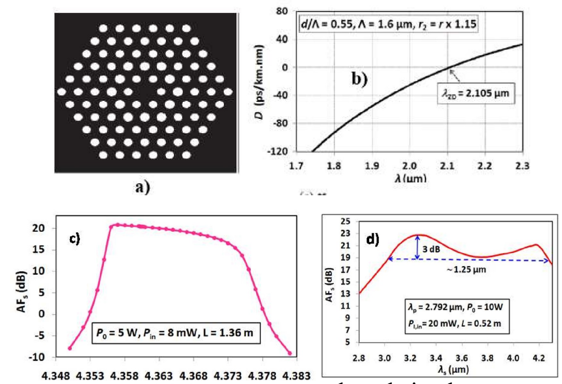

Figure 2 (a) Schematic cross-section of the chalcogenide material-based MOF; (b) its dispersion spectrum; (c) Gain spectrum of a narrow band all-fiber mid-IR source; (d) corresponding gain spectrum of a broad band mid-IR source.

Towards Pulse-preserving Wide Continuum Generation

A dispersion oscillating Bragg fiber at 2.8 μm has been designed for the realization of pulse reshaping and wide continuum [6, 7]. For this, we have chosen two chalcogenide glasses – *GeAsSe* (R.I. =2.6298 @ 2.8 μm) and *AsSe* (R.I. =2.8057 @ 2.8 μm). These glasses are mechanically and thermally compatible. For this design, we have considered 3 bi-layers composed of *AsSe/GeAsSe* that surround the *GeAsSe* made core. Pulse shaping and the stable propagation have been achieved by two tailor made fibers. The first part of the fiber, termed as F1, has its input cross-section as follows: core radius = 4.5 μm, thickness of first layer (d_1) = 0.695 μm, and thickness of second layer (d_2) = 2.94 μm, respectively; further, F1 is down-tapered with taper-ratio 0.81 over next 2 m length of the fiber. The sole purpose of F1 design is for pulse reshaping. The second part of the fiber, namely F2, is strictly designed for stable pulse propagation which is based on the dispersion oscillating scheme with an average dispersion close to zero. Starting from the end cross-sectional parameters of F1, a meter long down-tapered fiber (taper-ratio = 0.98) has been designed in a way where the dispersion profile starts from initial normal regime, crosses the zero and reaches anomalous regime with the average value around zero. Further, another identical fiber is joined to it so that the identical cross-sections are spliced together and such continuous splicing results in a dispersion oscillating profile. The custom designed Bragg fiber serves the purpose of pulse shaping and stable delivery over longer distance compared to any of its counterpart fibers with all possible dispersion profiles.

At the input end of the fiber, we have fed a Gaussian pulse of peak power = 200 W and FWHM = 1.5 ps. After propagating 2 m of the initial fiber length, the input Gaussian pulse has been converted into a parabolic pulse with its characteristic linear chirp within the pulse duration. In this specialty fiber we have achieved significant spectral broadening when the pulse shape has been preserved. The continuum is however limited in terms of width. A sample result to demonstrate the spectral broadening through such specialty fiber is shown in Fig. 2.

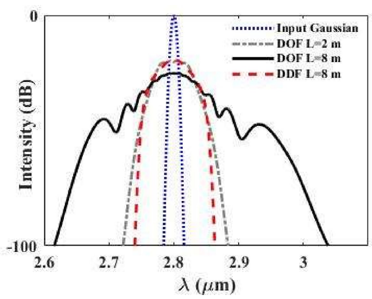

Figure 3 Continuum generation - spectral width of the input and output pulses from DOF and DDF at various fiber lengths.

Towards All-fiber THz source

Our work on specialty fibers for applications in THz domain involved exploitation of wavelength translation in plastic–based tailored fiber designs for generation of THz waves. Terahertz (THz) waves or T-rays, ranging from 0.1 ~ 10 THz (3 mm ~ 30 μm), fill the gap between microwaves and optical waves [8]. THz waves find extensive applications in medical treatment, spectroscopy, imaging, sensing, security, defense, and astronomy. Last 10 to 15 years has seen a significant surge in research on THz generation and its transmission via wave-guiding. Electronic based THz generation is limited by high metallic losses and lack of efficient electro-optic devices, whereas optics-based THz generation is limited by the absence of suitable host/doping materials for lasing and low overlap between optical and THz waves for NL frequency conversion. In [9] we reported an all-fiber terahertz (THz) radiation source by exploiting nonlinear parametric process in a specialty microstructured-core double-clad plastic fiber (MC-DCPF). The required phase-matching condition is satisfied through suitable tailoring of the fiber dispersion and nonlinear properties of the designed fiber when pumped at high-power from a CO_2 laser concomitantly with a CO laser of much lower power acting as a seed. Fiber design is shown in Fig. 4 with corresponding explanations in the figure caption.

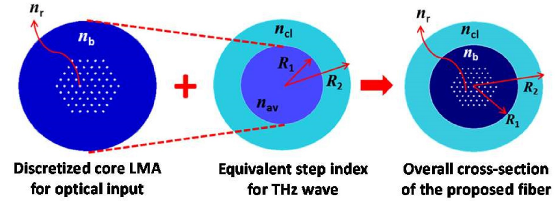

Figure 4. (a) Effective cross-section of the designed fiber for optical waves. The core is formed by hexagonally arranged 4 rings of high index rods of radius of 1 μm (white circles) and of pitch = 30 μm in a uniform lower index background of much wider cross-section (dark blue color), which effectively forms the cladding; (b) Effective cross-section for the THz wave, where core of radius R_1 is formed by an average index (n_{av}, light purple color) with uniform cladding (2nd clad, shown in light blue color); (c) The combined cross-section of the proposed MC-DCPF [9].

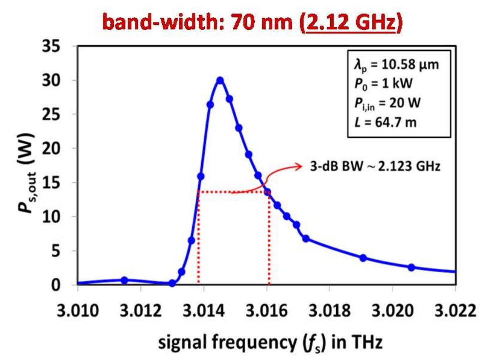

Figure 5 Output spectrum of the generated THz wave having 3-dB phase-matching band-width of ~2.12 GHz (≈ 70 nm).

3. Conclusion

In this paper, we reviewed some of our recent specialty fiber designs for applications in mid-IR and THz photonics. Sample results for parabolic pulse and continuum generation, all-fiber narrow band and broad band mid-IR sources, and all-fiber THz sources are presented.

4. References

1. A. Barh, S. Ghosh, R. K Varshney, and B. P. Pal, "A tapered chalcogenide microstructured optical fiber for mid-IR parabolic pulse generation: Design and Performance Study", *IEEE J. Special Top. Quant. Electron*. **20**, 2014, 7500507,

2. S. Ghosh, R. K. Varshney, B. P. Pal, and G. Monnom, "A Bragg-like chirped clad all-solid microstructured

optical fiber with ultra-wide bandwidth for short pulse delivery and pulse reshaping," *Opt, Quant. Electron.* **42,** 2010, 1.

3. P. Biswas, B. P. Pal, A. Biswas, and S. Ghosh, "Towards self-similar propagation of optical pulses in a dispersion tailored, nonlinear and segmented Bragg fiber at 2.8 μm", *IEEE Photon. J.* **9**, 2017, 7104412.

4. A. Barh, S. Ghosh, G. P. Agrawal, R. K. Varshney, I. D. Aggarwal, and B. P. Pal, "Design of an efficient mid-IR light source using chalcogenide holey fibers: a numerical study", *J. OPT. (IOP)*. **15**, 2013, 035205.

5. A. Barh, S. Ghosh, R. K. Varshney, and B. P. Pal, 2013, "An efficient broad-band mid-wave IR fiber optic light source: Design and performance simulation", *Opt. Exp*. **21**, 2013, 9547.

6. Y. Liu, H. Tu, and S. A. Boppart, "Wave-breaking-extended fiber supercontinuum generation for high compression ratio transform-limited pulse compression," *Opt. Lett*. **37**, 2012, 2172.

7. K. Nagasaka, T. H. Tuan, T. Cheng, M. Matsumoto, H. Tezuka, T. Suzuki, and Y. Ohishi, "Supercontinuum generation in the normal dispersion regime using chalcogenide double-clad fiber," *App. Phys. Exp.* **10**, 2017, 032103.

[8] X. C. Zhang, "Terahertz wave imaging: horizons and hurdles," Phys. in Medicine and Biology **47**, 2002, 3667.

[9] A. Barh, R. K. Varshney, G. P. Agrawal, B. M. A. Rahman, and B. P. Pal, "Plastic fiber design for THz generation through wavelength translation", *Opt. Letts.* **40**, 2015, 2107.