MIR supercontinuum in all-normal dispersion Chalcogenide photonic crystal fibers pumped with 2µm femtosecond laser

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Abstract: We demonstrate mid-infrared supercontinuum generation in an all-normal dispersion Chalcogenide PCF pumped by fiber laser. The -20dB bandwidth is 1.7~2.7µm dominated by self-phase modulation and optical wave breaking. Tapering is proposed to improve performance.

OCIS codes: (320.6629) Supercontinuum generation (190.4370) Nonlinear optics, fibers (060.5295) Photonic crystal fibers

1. Introduction

Over the past decades, supercontinuum generation (SCG) in the mid-infrared (MIR) has been well-studied both for sources and applications [1]. Particularly, chalcogenide glass (ChG) possessing ultrahigh nonlinearity and MIR transparency had drawn great attention. Indeed, the first SCG covering the whole "molecular fingerprint" band was demonstrated with a step-index ChG fiber [2]. A step-index ChG fiber typically has a zero-dispersion wavelength longer than 4µm due to the strong material dispersion, so most demonstrations on broadband SCG were performed with an optical parametric amplifier or oscillator (OPA/OPO) as pumping source [2]. Free-space OPA/OPOs are however highly sensitive to external perturbations, like vibration or temperature fluctuations. Thus, such SCG sources are difficult to put into real world applications. Two main strategies were utilized to overcome this problem. On the one hand, SCG in dispersion engineered ChG fibers was demonstrated [3]. On the other hand, step index ChG fibers with larger cores were pumped by cascaded SCG to reach longer wavelength [4]. Both schemes are effectively pumping the ChG fiber in the anomalous region.

More recently, the idea of SCG in all-normal dispersion (ANDi) fiber as accrued interest. When pumped in the anomalous region, soliton dynamics and modulation instability (MI) can lead to multiple pulses, shot-to-shot fluctuation and low coherent across the SC [1]. Contrarily, pumping an ANDi fiber with femtosecond pulses, soliton dynamics and MI formation can be eliminated, and SCG stays single pulsed [5, 6]. Ultrashort laser induced spectrum broadening in ANDi fiber is dominated by self-phase modulation (SPM) and optical-wave breaking (OWB) [5], resulting in high coherent and re-compressible SCG [6]. Also, confining the SCG in the spectrum of interest is beneficial for some applications [7]. Both SPM and OWB are elastic processes, leading to high efficiency. Last year, MIR SCG has been demonstrated in ANDi ChG fiber platforms; this fiber was pumped by OPO due to strong dispersion (> 600 ps^2/km at pump) [8].

Here, we demonstrated the first SCG in an ANDi ChG photonic crystal fiber (PCF). Utilizing the PCF structure, a relatively low dispersion can be achieved while maintaining single mode propagation. The PCF was pumped by a femtosecond fiber laser at 2.07µm (Tm-Ho band). Broad SC was recorded over approximately 1.7~2.7µm at -20dB with high long-term spectrum stability. Simulations indicate single pulse SC dominated by deterministic processes. Finally, we propose a new ANDi design which has better dispersion profile and nonlinear parameter.

2. Experimental setup and approach

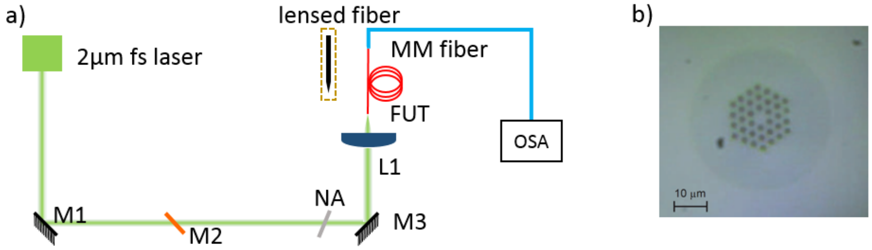

Figure 1. (a) Experimental setup. M1&M3: gold coated mirrors; M2: Dichroic mirror; NA: neutral density filter; L1: aspherical lens; FUT: fiber under test; (b) Cross-section of tested fiber (FUT1).

The experimental setup is sketched in Fig.1a. The femtosecond fiber laser center wavelength was fixed at 2.07µm. The repetition rate is 19.03MHz, pulse duration is approximately 80fs and average output power is 90mW, leading to an estimated peak power of 59.1kW. The laser has a collimated spot diameter of 4mm. Two gold coated mirrors (M1 and M3) are used to direct the beam. Dichroic mirror M2 passes 1850~2100nm and reflects 1500~1750nm. Between M2 and M3, a reflective neutral density filter was placed for pump power tuning. The filter has a small angle to avoid back reflection. A MIR aspherical lens (L1) focuses the laser into the fiber under test (FUT). The total optical path length before L1 is approximately 3m. A lensed fiber made on SMF-28 collects output during alignment. For SCG recording, a multimode (MM) fluoride fiber with 100μm core size replaces the lensed fiber. The spectrum is finally recorded on the optical spectrum analyzer (OSA), Yokogawa AQ6376.

Two PCFs with slightly different air hole size were tested in this experiment, referred to as FUT1 and FUT2 in the following text. FUT1 (Fig.1b) has a pitch-hole ratio of 0.58, 20 cm length and linear loss of 0.6dB/m at 1550nm. FUT2 has a pitch-hole ratio of 0.49, a slightly larger dispersion at 2.07μm and length of 80cm. Both FUTs have a core diameter of about 4μm. The pump input coupling loss was about 3dB.

3. Results and analysis

The FUT1 dispersion was measured by a low-coherence interferometry method. Experimentally retrieved dispersion data is shown in Fig.2a. Experimental data and simulation matches perfectly, indicating precise simulation and effectively single mode operation of the PCF. The group velocity dispersion (GVD) β_2 was measured to be about 350ps^2/km at the pumping wavelength of 2.07μm. In addition, no clear trace of birefringence was noticed at the measured wavelength band. The fiber is in the ANDi region until approximately 2.9μm owing to the strong material dispersion of GeAsSe.

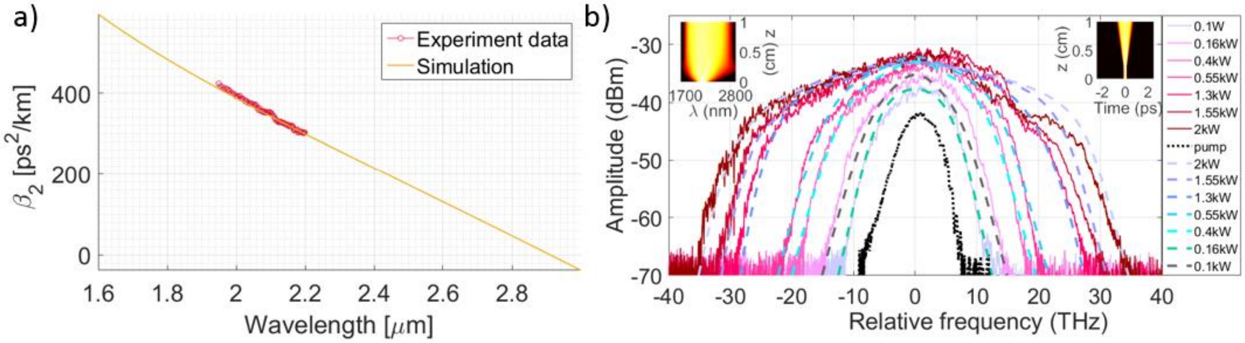

Figure 2. (a) Dispersion measurement and simulation of FUT1; (b) SCG measurement (solid line), simulation (dashed line) and input laser. Inset: simulated pulse evolution in time and wavelength, at 2kW peak power. The x-axis is a relative frequency centered at 145THz

The attenuated laser spectrum was recorded as a reference. The laser average power in FUT1 was progressively increased until approximately 10mW, i.e. a maximum coupled peak power of 2kW. A relatively symmetric spectral broadening, centered at the pump wavelength, is expected from an SPM and OWB dominated SCG. To illustrate this effect, the SCG is plotted in the frequency domain (THz) in Fig.2b, corresponding to approximately 1.7~2.7μm at -20dB. Generalized nonlinear Schrodinger equation (GNLSE) numerically simulates the pulse evolution [1] in time and wavelength region. The simulated result was fitted to each pump level by tuning only the peak power accordingly to the average power. From our previous work [9], the fiber has a nonlinear parameter of approximately 1.4 (W·m)$^{-1}$ and less than 0.6dB/m linear loss over the whole bandwidth. The drop centered at 1800nm is likely due to absorption from CH_2Cl_2, which was used during the polymer striping process.

As shown in Fig.2b, no spectrum split/fission related dynamics appears during pump increase. Indeed, the SCG in attributed to SPM and OWB at the beginning of fiber length (<1cm). Then, due to the ultrahigh normal GVD of the GeAsSe PCF, no noticeable nonlinear spectrum evolution occurs afterwards as the strong time domain broadening quickly inhibited nonlinear effects (see inset of Fig.2b). The perfect fitting of the recorded spectra with GNLSE at every pump level. This spectrum expansion is expected to be dominated by SPM and OBW, resulting in a coherent, single pulse and re-compressible SCG.

Similar tests were performed with FUT2, which has a similar dispersion (β_2 = 400ps^2/km at 2.07μm) and the results are depicted in Fig.3a. A deep water absorption peak centered at 1950nm is due to the longer time storage in an unprotected environment with respect to FUT1. In addition, a much stronger water absorption lies in 2400~3400nm [10], resulting in the bandwidth reduction on the long wavelength side. However, as expected, a similar overall behavior as for FUT1 is observed. The long-term stability of the SC was finally assessed using the AQ 6375 OSA, which has a faster sweep and higher sensitivity. We would expect that a SGC dominated by SPM and OWB should be stable over long time, since both effects are “self-seeded”. Over 700 traces were recorded for 40 min of continuous operation. The recorded data was superimposed in Fig3.b and clearly shows great spectrum stability, meaning no photon darkening or multiphoton absorption, confirming the potential long-term operation of such system. For our demonstration, the main source of instability is the fluctuation in coupling efficiency.

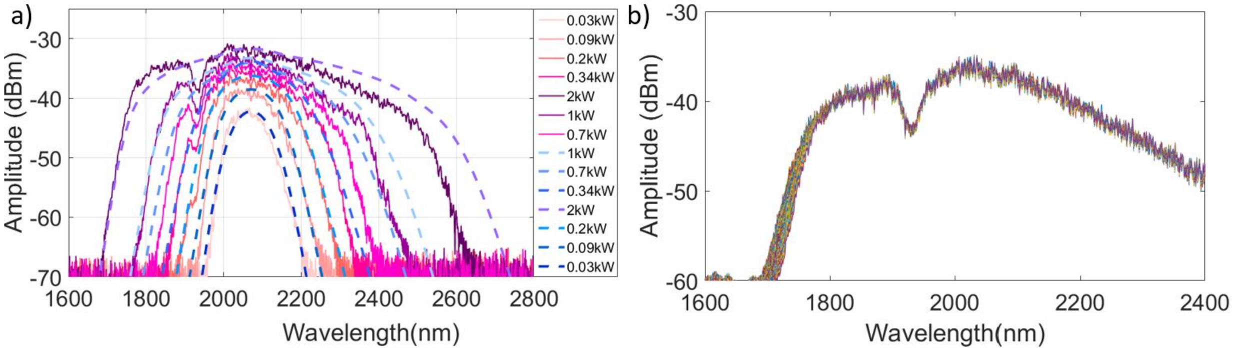

Figure 3. (a) SCG measurement (solid line), simulation (dashed line) and input laser; (b) superimposed spectrum of 700 traces

A broader MIR SCG in an ANDi fiber is more desirable in order to reach shorter pulse compression and broader spectral coverage. In addition, the fiber length has to be as short as possible to avoid strong pulse broadening in time. For this purpose, a larger nonlinear coefficient γ and less dispersion is desirable and which both can be achieve through tapering the current PCF. Commercially avaible GeAsSe PCF has an air-pitch ratio of ~0.5. Dispersion simulation was performed for a GeAsSe PCF with air-pitch ratio of 0.5 tapered to a waist diameter of 2.5µm. The results are shownin Fig.4a. Clearly, the tapered PCF is still ANDi, thanks to the strong material dispersion. Pumping at the same wavelength, 2.07µm, 1kW in peak, and 2cm in length, the simulated SCG in Fig4.b. The 3dB amplitude is 1690~2640nm, leading to a bandwidth of 950nm.

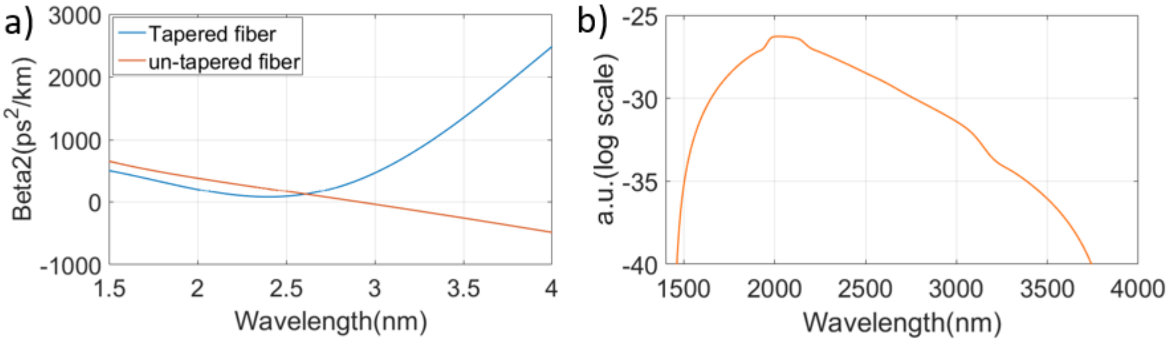

Figure 4. (a) Dispersion simulation of taper fiber; (b) SCG simulation of the tapered fiber; pumped with 1kW in peak

4. Conclusion

In conclusion, we have demonstrated experimentally SCG in an ANDi ChG PCF for the first time. A broad range from 1.7~2.7µm at -20dB was covered and matches well with simulations. A new design was proposed based on commercially available fiber and SCG on this design was simulated. The overall SCG power in FUT was about 4mW, with 5mW pump power coupled.

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