Accepted version of a published manuscript

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Published in:

Laser Physics, Volume 29, January 2019

Received: 11 June 2018

Accepted: 22 November 2018

Available online: 9 January 2019.

DOI: <https://doi.org/10.1088/1555-6611/aaf640>

This is the accepted version of a published article. For citing please follow to the link for the final authenticated version of the article: <https://doi.org/10.1088/1555-6611/aaf640>

Research funding:

ARRS - Slovenian Research Agency (P2-0270, P2-0392) Projects L2-8183, L2-9240.

The article relates to SPS Operation entitled Building blocks, tools and systems for future factories – GOSTOP.

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Abstract

In this paper the generation of visible spectrum via optimized supercontinuum generation in tapered ordinary fibers by ultrashort laser pulses is presented. The tunability of the visible part of the spectra is achieved by changing the pump pulse duration during operation. The optimization of the supercontinuum generation is carried out by the investigation of the taper geometry with the emphasis on the downtapering section length. Its increase is found to be correlated to higher intensity in the visible part of the spectra. This is further supported by the results on spectra evolution before it enters the taper waist where an important transfer of the pump power to the shorter wavelengths is found.

Keywords: Fiber lasers, Supercontinuum generation, Ytterbium-doped fiber amplifiers

1. Introduction

Supercontinuum laser sources covering the visible part of the electromagnetic spectrum have a broad range of applications, e. g. optical coherence tomography [1], stimulated emission depletion microscopy [2], Förster resonance energy transfer (FRET), and fluorescence lifetime imaging (FLIM) [3], where high-intensity light is needed.

The dynamics of supercontinuum generation (SCG) has been extensively investigated both theoretically and experimentally in the last two decades [4]–[8]. Extreme spectral broadening can be achieved using CW [9], ns [10], ps [11], or fs [12], [13] laser sources coupled to highly nonlinear waveguides. Prevalent SCG waveguides are silica-based, generating spectra spanning from around 400 nm to 2000 nm [14].

Fiber-based high-power laser sources are preferred as a compact alternative to bulk lasers [15] as they can be directly spliced with fiber nonlinear waveguides - photonic-crystal fibers (PCFs) or tapered ordinary fibers (TOFs) - to obtain a highly efficient SC source [16]. This is especially true for fiber CW and nanosecond sources [17], which can be realized in all-fiber design, in the last case using the gain-switching approach [18]. Ultrashort sources have to be used when employing centimeter-length nonlinear waveguides as CW supercontinuum requires highly nonlinear waveguides at least a couple of tens of meters long [9]. The peak powers needed when using short nonlinear waveguides are over several kW. A special master oscillator power amplifier (MOPA) design [19] is required to provide the adequate power [20], [21].

For femtosecond pulses, laser source is based on mode-locked seed connected to the above-mentioned MOPA system encompassing a free space compressor at the end.

The supercontinuum nonlinear dynamics depends on the geometry of nonlinear waveguide and laser pulse parameters, i.e. pulse duration, central wavelength, pulse peak power, and chirp of the pulse [22]–[24]. Although the same nonlinear optical processes drive SCG in PCFs and TOFs, their corresponding geometries and manufacturing processes are different. PCFs have to be fabricated using advanced manufacturing process owing to their complex geometrical structure.

In contrast, TOFs can be manufactured on a glass processor or by etching [25] using readily available conventional, i.e. telecommunication, optical fibers. Its geometrical parameters can be precisely adjusted in a lab setting with low manufacturing costs when compared with PCFs. Unfortunately, mechanical stability of micrometer taper waists usually limits their lengths up to 10 cm. One can increase the interaction length by splicing several TOFs together, thus generating broader spectra. TOFs can be spliced or made directly on the output of fiber-based laser sources using conventional fiber processing devices to form an all-fiber SCG source. Apart from the use of TOFs in SCG, their properties are exploited in numerous applications [26] in e. g. as label-free biosensors [27] or atom traps [28]. For efficient SCG, a study of the taper geometry and laser pulse parameters is necessary.

Spectra generated in TOFs are mainly influenced by geometrical parameters, i. e. the lengths of transition regions from untapered fiber to taper waist (downtapering and uptapering section), taper waist length and taper waist diameter. One study presented the influence of waist diameter profile of TOFs on SCG [29]. Another study in PCFs presented the influence of downtapering section and uptapering section length on the generated power in the blue edge of the spectra [8]. It has to be noted PCFs were already in the anomalous dispersion regime and tapering just increased their anomalous dispersion. When tapering an ordinary telecommunications fiber the group velocity dispersion changes from normal to anomalous dispersion in the downtapering section when using Ytterbium based lasers as a pump source. In the soliton fission regime a numerical simulation of SCG in TOFs up to 10 kW peak powers has been reported [24].

To our knowledge this paper presents the findings of the first experimental study on

downtapering section length and pulse duration influence of the ultrashort laser pulses on SCG in TOFs using tens of kilowatts of peak power in the modulation instability regime. The results show influence of the geometrical parameters, especially downtapering section length. For this purpose, an ultrafast fiber MOPA laser source was developed capable of tuning the output visible spectrum during operation by tailoring the second-order dispersion of the seed pulse. This feature also enabled fine tuning of the visible part of SCG spectrum at a fixed repetition rate and average power.

2. Experimental setup

The laser source for supercontinuum generation was a compact fiber chirped pulse amplification (CPA) system in MOPA configuration, incorporated into the experimental setup as shown in figure 1.

Figure 1. Schematic of the experimental setup used for supercontinuum generation. CFBG stands for chirped fiber Bragg grating and AOM for acousto-optical modulator.

Seed laser was a fiber mode-locked laser with a pulse repetition rate of 30 MHz and approximately 1 mW of average power. Pulse duration of seed pulses at the output of the seed laser was 1.5 ps. Pulses from the seed laser had a center wavelength of 1030 nm and a full width at half maximum (FWHM) of 6.1 nm.

The pulses were then stretched using a tunable chirped fiber Bragg grating (CFBG) from 1.5 ps to 480 ps and amplified in two fiber amplification stages that were pumped with laser diodes at 976 nm [30], [31]. The repetition rate of the pulses in the second amplification stage was controlled using an acousto-optic modulator (AOM) [20]. Amplified pulses were externally compressed at the exit of the second amplification stage using a grating compressor. The dispersion of the compressor was kept constant. The shortest pulse duration achieved was 370 fs. The grating compressor could be replaced with a chirped volume Bragg grating allowing for an even more compact design [32].

With tunable CFBG, the second-order dispersion could be independently changed and therefore the compressed pulse duration could be tuned from 370 fs to 15 ps with either a positive or a negative linear chirp. The third-order dispersion was compensated for all pulse durations. Pulse duration was monitored during operation with an autocorrelator.

Compressed pulses from the grating compressor were coupled to a tapered fiber, produced from standard SMF-28 optical fiber. Supercontinuum spectra was measured with integrating sphere to avoid spectral dependant losses due to possible coupling misalignment into the optical fiber of the spectrometer.

3. Tapered fibers

Typically, tapered ordinary fibers consist of an input pigtail, a downtapering section, a taper waist, an uptapering section, and an output pigtail. The main effect of input pigtail is chirping of pulse due to SPM and temporal broadening due to normal dispersion. To keep the effect of the input pigtail the same in different tapers, the pigtail lengths have to be the same.

The effect of downtapering section is twofold. First, it determines the adiabaticity of the taper, that is the transmission efficiency of laser pulses into the fundamental mode in the waist [33]. Second, it affects the evolution of nonlinear processes as dispersion and mode confinement change with propagation of the pulse in the downtapering section.

To evaluate the influence of downtapering section on the nonlinear dynamics, we had to carefully consider the adiabatic transition to rule out power leakage that could affect the generated spectra. A consistent power transmission to the taper waist at different downtapering section lengths is important for comparable results regarding the nonlinear dynamics.

The general rule of thumb for optimizing power transmission is adiabaticity criterion as derived in [34]. This is the distance at which beat length Z_b , that is the distance on which considerable coupling occurs between modes, is equal to downtapering section length Z_t

$$Z_t = \frac{R}{\tan(\theta)}, \quad (1)$$

$$Z_b = \frac{2\pi}{\beta_1 - \beta_2}, \quad (2)$$

where R is change of radius of downtapering section, θ is angle of the downtapering section, β_1 is fundamental mode constant, and β_2 mode constant of dominant coupling mode for power loss. The combined equations (1) and (2) give upper boundary on the taper angle θ with respect to the diameter change of downtapering section and difference of two dominant modes involved in power loss. For our fiber, this rule suggests that our taper angle should be always less than 10 mrad [33]. Quantitative information on transmission has to be obtained numerically.

As a reference, we took the results in [33] where transmission losses of tapered SMF-28 fiber were studied at 780 nm. To achieve transmission of 99.9%, they report that taper angle has to be in the range of 6-1.5 mrad, depending on the cladding diameter. The critical area for power losses from the fundamental mode to higher modes occurs when the cladding diameter in the taper approaches 50 μm .

Considering the above-mentioned results, tapers were created using the glass processor Vytran GPX-3600. The overall length of downtapering section, taper waist, and uptapering section was limited to 90 mm because of Vytran processing unit.

The first step was drawing the fibers to reduce the cladding diameter from 125 μm to 10 μm , section “downtapering section 1” in figure 2. In tapers T1, T2, T3, and T5, second draw further reduced the diameter from 10 μm to 3 μm at an angle of 1.2 mrad over a 3 mm length corresponding to section “downtapering section 2” in figure 2. The geometries of drawn tapers and their corresponding taper angles are listed in TABLE I.

TABLE I
NOMENCLATURE USED FOR TAPERED FIBERS AND THEIR PROPERTIES

Taper name	Downtapering section 1 [mm]	Downtapering angle [mrad]	Uptapering section 1 [mm]	Uptapering angle [mrad]	Waist length [mm]
T1	15	3.8	15	3.8	40
T2	22	2.6			
T3	30	1.9			
T4-A ^a	30	1.9	15	3.8	2
T4-B ^a	15	3.8	30	1.9	

T5-A ^b	30	1.9	15	3.8
T5-B ^b	15	3.8	30	1.9

Letters A and B denote the end of the same taper fiber to which the light was coupled.

^a Taper waist for taper T4 had diameter 10 μm as opposed to tapers T1, T2, and T3 where taper waist was 3 μm in diameter.

^b Taper T5 had after the first draw the same geometry as T4, but it was additionally tapered to 3 μm in the waist.

Tapers T4 and T5 were drawn to study only the effect of downtapering sections on SCG. Downtapering section and uptapering section of any taper could be interchanged by coupling the laser source at either end of the taper denoted by letters A and B.

Figure 2. Schematic of tapers used in supercontinuum generation.

4. Results and discussion

4.1 Influence of pulse duration on generated spectra

Compressed pulse from the laser source is shown in figure 3. The pulse shape matches the one of hyperbolic secant squared. For this shape, the pulse duration calculated from autocorrelation trace is 370 fs. Using tunable pulse stretcher, we could tune the duration of a compressed pulse and therefore tune the supercontinuum spectra during laser operation.

Figure 3. Shortest obtained pulse from the fiber amplifier with the corresponding hyperbolic secant squared fit. The $\text{FWHM}_{\text{pulse}}$ denotes the pulse FWHM obtained from the autocorrelation. FWHM_{AC} denotes the autocorrelation FWHM.

The throughput of all tapers was around 75% at low pulse energies. The effect of coupling efficiency and adiabaticity of downtapering sections on SCG dynamics was therefore negligible.

Laser source parameters for all presented measurements in this paper were 400 kHz repetition rate, 370 fs long pulses, 14 mW average power, and 36 nJ pulse energy, unless otherwise noted for the pulse durations.

Using the ability to tune pulse duration, we investigated the effect of pulse duration on supercontinuum generation in taper T3. As presented in figure 4 we were able to tune supercontinuum by changing the second-order dispersion of tunable CFBG.

The change in supercontinuum spectra with respect to pulse duration is contributed to two main effects. First is the change in the peak power of the pulses. As all the pulses have the same energy, the shorter pulses consequently have higher peak powers. This means that the shorter pulses experience higher nonlinearities and therefore produce wider spectra. Second contribution to the supercontinuum spectrum shape can be based on the temporal slope of the pulses. The magnitude of optical nonlinearities is also dependent on the time derivative of the pulse intensity. The steeper the temporal pulse profile, the bigger is the effect of the optical nonlinearities. As the intensity of longer pulses changes slower in time compared to the intensity of shorter pulses, the effect of nonlinearities is higher with shorter pulses than with longer pulses. Taking both effects into account, wider spectrum can be achieved using shorter pulses.

By varying laser pulse durations, we could adjust the spectral power in the visible part of supercontinuum and tune its width during laser operation.

Figure 4. Supercontinuum generated in taper T3. We could adjust the output spectra by tuning the pulse duration with changing the second-order dispersion.

4.2 Influence of downtapering section length on generated spectra

Figure 5 displays the output spectra of three tapered fibers with different downtapering section lengths. We found that tapers with longer downtapering section (smaller taper gradients) generated supercontinuum with peak position further towards the blue part of the spectrum. We attribute this result to the slower change of zero-dispersion wavelength from near-infrared (approx 1.3 μm) in the untapered input pigtail fiber to visible wavelengths required to generate supercontinuum in the waist of the tapered fiber region. Because the change of zero dispersion wavelength is related to the waveguide diameter, the longer downtapering section means slower change of the fiber diameter and consequently slower change of the zero dispersion wavelength. This slower change enable more efficient energy transfer from primary pump wavelength to shorter wavelengths needed for supercontinuum generation in the waist of the tapered region. In other words, having a fast transition would mean, that the zero-dispersion wavelength would fall outside of the primary pump spectral range too quickly and therefore reducing the energy transfer efficiency, as the anomalous dispersion would not compensate for the pump pulse temporal broadening induced by the optical nonlinearities.

To confirm this, a pump spectra was measured after the downtapering section from 125 μm to 10 μm . An important difference was found when comparing spectra broadening

after 15 mm and 30 mm long transition as shown in figure 6. While the downtapering section length had an insignificant influence on the wavelengths longer than the primary pump wavelength, the power in the shorter part of the spectrum is shifting between spectral components. For T4 taper this can be seen in the peak at the 1007 nm which is becoming more pronounced when increasing the downtapering section length (Figure 6 (b)). This correspond to better power transfer from primary pump wavelength to the short edge of the pre-broadened spectrum before it enters the taper waist where it is broadened to the final supercontinuum. The result was confirmed with the measurements done on the T5 taper where after main transition from 125 μm to 10 μm another short transition to 3 μm was made. The same difference in power at the short wavelength edge as with the T4 taper was measured while the only impact of the short transition was the 2 nm shift of the peak to the 1005 nm.

Figure 5. Supercontinuum in three tapered ordinary fibers with different downtapering section lengths as presented in the legend. Spectra generated in tapers with longer downtapering sections (smaller angles) generate spectra further towards the blue part of the spectrum.

Figure 6. A comparison of the broadened spectra after downtapering section 1 for two downtapering section lengths of 30 mm (T4-A) and 15 mm (T4-B) made from 125 μm to 10 μm . A better power transfer to the shorter wavelengths of the spectra was found for the longer transition. A comparison was made to the double stage taper T5 where first region has the same characteristics as T4 while the second has additional short transition to the 3 μm . The same effect on the power conversion can be seen and shows the importance of the down taper from 125 μm to 10 μm .

The better conversion of the pump power to the shorter wavelengths is contributed to the laser pulse residing closer to the zero-dispersion wavelength while propagating down the longer downtapering section.

In general, characteristic nonlinear length scale has to be on the same length scale as difference in geometrical parameters for observable changes in the nonlinear dynamics. Characteristic nonlinear length changes throughout the downtapering section. The most important for the initial stage of SCG is characteristic nonlinear length near the critical part of the downtapering section where the taper's zero-dispersion wavelength is approaching pump wavelength. In our case, nonlinear lengths around the said critical downtapering section were less than 2 mm. A notable difference could therefore be observed as nonlinear length is comparable to the length differences of the said critical regions in our tapers.

5. Conclusion

In conclusion, we have presented supercontinuum generation in tapered ordinary fibers using ultrashort fiber laser source built for this purpose. The fiber source was capable of changing pulse width and chirp without changing the repetition rate or average power, all while keeping the dispersion of the compressor constant. This was done using a tunable stretcher based on fiber Bragg grating with controllable second-order dispersion. As the tunability of the pulse duration does not depend on the grating compressor a more compact solution is also possible, i.e. a chirped volume Bragg grating. Pulses at 400 kHz repetition rate and 14 mW average power at 1030 nm were coupled to TOFs to produce visible spectrum with a tunable short wavelength edge for more than 100 nm. Further, the findings of an experimental study of how downtapering section length influences SCG in TOFs using 36 nJ and 370 fs pulses were presented. Experiments were made on three 3 μm

diameter and 40 mm long tapers with different downtapering section lengths, which satisfied the criterion for adiabatic transition. The results show that longer downtapering section lengths produce better conversion of pump spectrum to visible spectrum with the peak moving nearer to 400 nm. The behavior was further supported by measurements done using tapers with negligible taper waist lengths. The results were presented with the argumentation that laser pulses propagating down the longer downtapering section reside closer to the zero-dispersion wavelength for an extended period of time when compared with those propagating down the shorter downtapering section. This allowed for more efficient extension of the generated supercontinuum to shorter wavelengths.

To our knowledge, we have shown for the first time the influence of downtapering section on supercontinuum generation in tapered single-mode fibers using ultrashort laser pulses.

Acknowledgments

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0270 and No. P2-0392 and projects L2-6780, L2-8183 and L2-9240). The article relates to SPS Operation entitled Building blocks, tools, and systems for future factories – GOSTOP.

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