

14 GHz visible supercontinuum generation: calibration sources for astronomical spectrographs

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Abstract: We report the use of a specially designed tapered photonic crystal fiber to produce a broadband optical spectrum covering the visible spectral range. The pump source is a frequency doubled Yb fiber laser operating at a repetition rate of 14 GHz and emitting sub-5 pJ pulses. We experimentally determine the optimum core diameter and achieve a 235 nm broad spectrum. Numerical simulations are used to identify the underlying mechanisms and explain spectral features. The high repetition rate makes this system a promising candidate for precision calibration of astronomical spectrographs.

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1. Introduction

Offering long path lengths, extremely low transmission losses and a well-defined guided mode, single-mode optical fibers have proven to be a convenient test-bed for nonlinear optics. The advent of photonic crystal fibers (PCFs) has extended the range of possibilities by offering smaller mode areas and greatly extended control of group velocity dispersion (GVD) [1]. The ability to shift the zero-dispersion wavelength (ZDW) to match that of common near-infrared laser systems has led to the efficient generation of bright octave-spanning sources [2–4], with applications in, e.g., biology [5] and frequency metrology [6]. The ability to precisely adjust the GVD over a broad wavelength range has enabled the development of efficient photon-pair sources using four-wave mixing [7] and studies of pulse breakup and soliton formation in regions of anomalous dispersion, involving effects such as the soliton self-frequency shift and dispersive wave generation [8].

In this work we use tapered PCFs to broaden the spectrum of a high repetition rate laser frequency comb (LFC). Our motivation is to extend the potential of the frequency comb as a wavelength calibrator for applications in astro-metrology.

The precise redshift measurement of an astronomical object requires accurate monitoring of a large set of absorption lines distributed over a wide range of its spectrum. For example, the discovery of extra-solar planets is largely based upon the measurement of small variations in the Doppler shift of stellar absorption lines [9, 10]. The detection of an earth-like planet would require new calibration sources outperforming current thorium-argon calibration lamps and iodine absorption cells [10, 11]. Even higher precision and long term stability is required for red-shift surveys of distant quasars to observe directly the accelerated cosmic expansion [12]. The ability to perform such precise measurements of quasar spectra would also greatly help to pursue the hints for a temporal variation of fundamental constants [13].

For these applications, the use of a LFC as a calibration source appears to be well suited due to its high degree of stability and spectral uniformity [14, 15]. Its spectrum consists of equally spaced narrow lines serving as an optical frequency standard of extreme precision [6]. The line spacing of the LFC – corresponding to its pulse repetition rate – can be increased by the use of Fabry-Pérot-cavities [15–17] and thereby adapted to the resolving power of the best astronomical spectrographs [18]. The highest precision is achieved when the mode separation

approximately equals three resolution elements of the spectrograph, resulting in an optimum repetition rate of typically 10 to 30 GHz [14].

Spectral broadening of a fiber-based LFC filtered to such high repetition rates has already been successfully demonstrated in the IR [19]. For operation in the visible region frequency doubling of such a source significantly reduces the available pulse energy typically to the low-pJ regime. As a result, the challenge lies in the increase of the LFC spectral width to match the full optical bandwidth of a precision astronomical instrument. We demonstrate that tapering of suspended silica-strand PCFs creates devices suitable for broadening low-energy pulses sufficiently to cover the precision spectrograph HARPS (High Accuracy Radial velocity Planet Searcher) over most of its bandwidth, ranging from 380 - 690 nm [20]. We discuss the impact of small core size changes on the shape and width of the spectrum.

2. Experimental details

The source of our frequency comb is a Yb fiber laser with a repetition rate of 250 MHz and a central wavelength of 1030 nm. Its mode spacing is increased to 14 GHz by means of three Fabry-Pérot cavities with a finesse of about 400. The first cavity possesses a free spectral range of 2 GHz followed by two cavities with a 14 GHz mode spacing. They are stabilized with the help of an auxiliary CW-laser as described in [21]. The strongest of the attenuated modes are at ± 2 GHz next to each transmitted mode and are attenuated by 80 dB. Other unwanted laser modes are suppressed even further which is highly desirable to prevent their later intensification by spectral broadening in the tapered PCF [22]. After the cavities, the light is amplified to 6 W, resulting in a slight shift of the central wavelength to 1060 nm. The optical pulses are then compressed to 100 fs and frequency doubled in a 3 mm long LBO crystal. An average power of 120 mW at a central wavelength of 530 nm with 5 nm bandwidth is obtained. Higher conversion efficiency is possible with longer crystals at the expense of a reduced phase matching bandwidth.

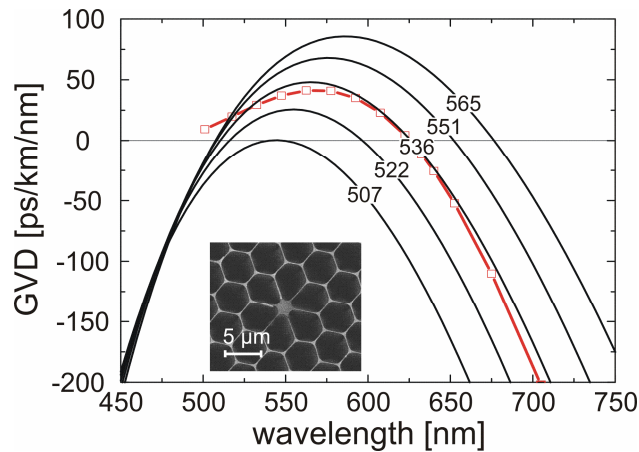


Fig. 1. (Color online) Calculated GVD of tapered PCFs for different core sizes (black lines; labels correspond to core diameters in nm). The red squares indicate the measured GVD values of a tapered PCF with a 536 nm core diameter. The inset shows an SEM image of the untapered PCF.

The flame-brush technique [23] was used to taper a PCF made in Erlangen with a core diameter of 2.0 μm down to various other core diameters. During this process a small flame sweeps to and fro along the fiber while it is pulled apart by two linear translation stages. This results in a central taper waist where the fiber diameter is reduced to a constant size. The inset of Fig. 1 shows a scanning electron micrograph of the untapered PCF structure, the geometry of which was preserved during the tapering process. The core is suspended by 6 silica membranes each ~ 100 nm thick. The action of the PCF can be accurately modelled as a silica strand, the microstructured cladding having little influence on the GVD of the fundamental

core mode. Figure 1 shows GVD curves for a series of different core diameters ranging from 507 to 565 nm, calculated by means of a silica strand model [24]. The GVD of a 536 nm taper was measured by white light interferometry and is plotted next to the simulated GVD curves. There is good agreement between experiment and theory, a region of anomalous dispersion appearing in the visible. In general, small changes in core diameter lead to strong variations in the position of the ZDWs, strongly determining the spectral reshaping of the input pulse.

3. Spectral broadening

100 fs (FWHM) pulses were launched into tapered samples with 30-cm-long taper waist, short untapered sections (between 2 and 5 cm long) at each end allowing launch efficiencies of ~50%. The average launched power was ~60 mW in all cases. The resulting output spectra, recorded using an optical spectrum analyzer, are shown in Fig. 2. It is clear that small changes in core diameter cause strong variations in the output spectrum, which however remains relatively flat between ~450 and ~600 nm. For certain core sizes an additional radiation band appears in the red spectral range. The widest spectrum (235 nm at the -20 dB level) occurs at a core diameter of 536 nm, with ZDWs at 510 nm and 620 nm.

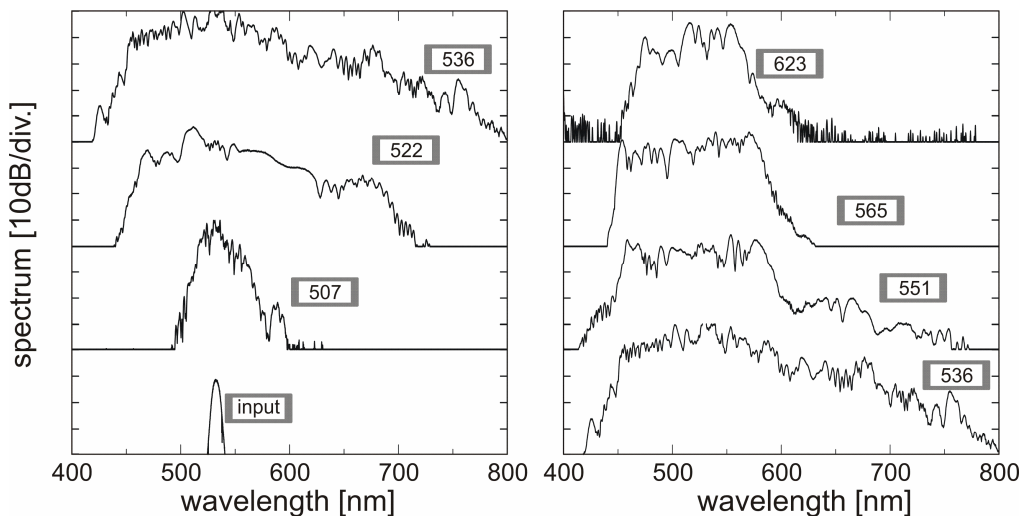


Fig. 2. Spectral broadening (logarithmic plot) of 4.3 pJ pulses traversing 30 cm long pieces of the tapers shown in Fig. 1. The numbers correspond to the taper-waist core diameter in nm.

The spectral shape is affected by the position of these two ZDWs relative to the pump wavelength. Reducing the core diameter below 536 nm shifts both ZDWs towards each other, the region of anomalous dispersion shrinking to zero at 507 nm. At this point soliton formation is prevented, spectral broadening is governed purely by self-phase modulation [25], the absence of dispersive wave generation limiting the spectral width to ~50 nm (-20 dB level).

The ZDWs dictate the spectral positions of the dispersive waves [8], the core diameter strongly affecting the position of the long-wavelength ZDW (due to waveguide dispersion), whereas material dispersion dominates the short-wavelength ZDW, which remains relatively unaffected by changes in core diameter. The position of the red ZDW shapes the long-wavelength edge of the broadened spectra, the dispersive wave band moving into the IR as the core diameter increases. The conversion efficiency falls as the detuning of the dispersive wave frequency from the pump frequency rises. This causes the red radiation band to vanish at larger core diameters (Fig. 2b).

4. Numerical simulations

Figure 3 shows the simulated propagation of a 10 pJ 100 fs pulse in a 30-cm-long taper waist with a uniform core diameter of 536 nm, with untapered input and output sections each 2 cm long. The GVD in the tapered section is $\sim 4.3 \text{ ps}^2/\text{km}$ at the pump wavelength (530 nm). The generalized nonlinear Schrödinger equation was used [25]:

$$\frac{\partial A(z, \tau)}{\partial z} = D[A(z, \tau)] + i \left(\gamma(\omega_0) + i\gamma_1 \frac{\partial}{\partial \tau} \right) \times \left(A(z, \tau) \int_{-\infty}^{\infty} R(t) |A(z, \tau)|^2 dt \right)$$

where $A(z, t)$ is the complex time-domain envelope of the electric field, $\tau = t - z/v_g$ is the time in a reference frame moving with the group velocity of the pulse, t is the physical time and v_g the group velocity. The operator D takes care of the group velocity dispersion. The function $R(t)$ includes the Kerr and Raman effects in fused silica (for more details see [3,25]). The nonlinearity of the PCF is introduced by the nonlinear coefficient $\gamma(\omega_0) = n_2(\omega_0)\omega_0/c/A_{\text{eff}}(\omega_0)$, evaluated at the center frequency of the input pulse. Here, n_2 is the nonlinear index of refraction ($2.7 \times 10^{-20} \text{ m}^2/\text{W}$ for silica) and A_{eff} is the effective area of the fundamental mode. The time derivative accounts for self-steepening and $\gamma_1 = \partial\gamma/\partial\omega$ is the first order correction to the nonlinear coefficient.

The short untapered input section, which has a core diameter of 2 μm , does not significantly affect the temporal shape of the pulse at the start of the tapered section. The nonlinear coefficient in the taper waist is $1.1 \text{ W}^{-1}\text{m}^{-1}$, yielding a soliton order $N = 8$. At ~ 10 cm from the start of the tapered section, the pulse spectrum broadens extensively. Fission of the $N = 8$ soliton leads to breakup into fundamental solitons [8]. At the same time, dispersive waves are generated at ~ 435 and ~ 740 nm. The first ejected soliton has the shortest duration (13 fs in the simulations) so would undergo the strongest soliton self-frequency red-shift [8] if the presence of the ZDW at 620 nm did not cancel it. As a consequence, the soliton emits dispersive radiation at around 700 nm [3].

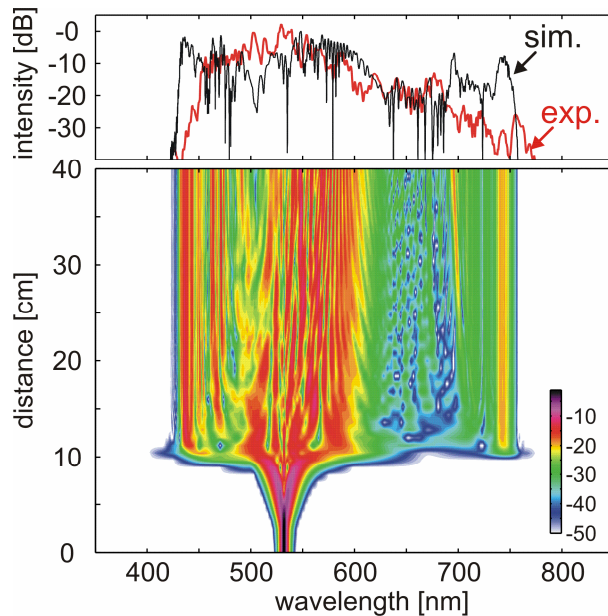


Fig. 3. (Color online) Simulated pulse propagation in a 40 cm long tapered PCF. The device had 2 cm long untapered sections at both ends and 1 cm long transitions, all of which are included in the simulations. The core diameter at the taper waist is 536 nm. The top figure shows the experimental and simulated spectrum at the fibre output.

5. Conclusion

A nearly octave-spanning frequency comb in the visible spectral range can be produced by pumping a tapered PCF with 4.3 pJ pulses at 530 nm at a repetition rate of 14 GHz. The spectral broadening is achieved by soliton formation and concomitant emission of dispersive waves. Compared to previous experiments with 35 fs pulses [3], the longer pulse duration reduces the energy transfer into the dispersive waves and generates a very flat spectrum. As only 6 W of the 12 W of the infra-red power available in our setup was used, it should be possible to maintain the calibration bandwidth up to repetition rates as high as 28 GHz. In a first experiment we observed the coherence of the optical spectrum by beating the LFC with a narrowband 532 nm cw laser, showing the preservation of the comb structure. The coherence and side-band suppression of the emitted spectrum will be presented elsewhere [26], showing that the light source may prove useful in the calibration of high-resolution astronomical spectrographs – the demonstrated -20 dB bandwidth of 235 nm corresponds to 76% of the bandwidth of HARPS [20]. In a next step we plan to further increase the spectral bandwidth and improve its flatness by shaping the spectrum with a spatial light modulator [17, 27].