Highly-Efficient, Octave Spanning Soliton Self-Frequency Shift Using a Photonic Crystal Fiber with Low OH Loss

Stephen A. Dekker(1), Ravi Pant(1), Alexander C. Judge(1), C. Martijn de Sterke(1) Benjamin J. Eggleton(1), Itanrichi Gris-Sánchez(2), Jonathan C. Knight(2)

(1)Centre for Ultrahigh-Bandwidth Devices for Optical Systems, Institute for Photonics and Optical Science, School of Physics, The University of Sydney, NSW 2006, Australia.

(2)Centre for Photonics and Photonic Materials, Dept. of Physics, University of Bath, Bath BA2 7AY, UK.

Author email address: sdekker@physics.usyd.edu.au

Abstract: We report the first demonstration of octave spanning soliton self-frequency shift in a OH absorption reduced fiber with widely-spaced zero-dispersion wavelengths. To our knowledge, this is the largest reported frequency tuning for a fiber-based source.

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1. Introduction and Background

Pulsed, wavelength tunable sources are desirable for numerous applications in areas such as communications, analog-to-digital conversion and spectroscopy [1, 2]. The Soliton Self-Frequency Shift [3] (SSFS), which is a result of the red-shift induced by intra-pulse Raman scattering, is ideal for realizing such sources. A wavelength tunable source employing the SSFS is attractive because the red-shift can be continuously tuned by varying the power of the input pulse, it can provide a very large tuning range, and it leads to sources with short output pulses (~10’s fs width).

There have been several demonstrations of the SSFS in different types of silica fiber [4, 5]. The maximum shift achievable in these experiments is limited on the long wavelength side by the intrinsic absorption of silica at wavelengths above λ ≈ 2 μm [5]. Since the SSFS requires anomalous dispersion [6], the separation of the first and second zero-dispersion wavelengths, λZD1 and λZD2, also limits the achievable red-shift. The λZD1 can be lowered by using Photonic Crystal Fibers (PCFs) with small cores, but this tends to increase the OH loss peak around a wavelength λ ≈ 1400 nm [7], thus, in effect, creating an upper limit on the SSFS when pumping at shorter wavelengths.

Here we present the first experimental demonstration of octave spanning soliton self-frequency shift in which pulses from a mode-locked Ti:Sapphire laser at a wavelength λ = 783 nm are shifted to λ = 1650 nm in a PCF. The efficiency of this process is 54%; this fraction of the output energy is contained in the most red-shifted soliton. The concept of the octave spanning SSFS is shown in Fig. 1: widely spaced zero-dispersion wavelengths ensure a large wavelength interval with anomalous dispersion, which, in principle, is available for the SSFS. However, in commercially available fibers with these parameters the high loss associated with the OH peak around a wavelength of 1400 nm prevents this full interval from being exploited. In contrast, we used a specially designed PCF which combines a reduced OH loss peak with widely spaced zero dispersion wavelengths, allowing almost the entire interval with anomalous dispersion to be exploited.

Our PCF had a length of 22 m, a core diameter of 1.5 μm, and a peak OH-associated attenuation of 0.09 dB/m; an SEM of the fiber’s core area is shown in the inset of Fig. 1. Using the SEM of the fiber cross-section and a
commercially available finite-element software package, the anomalous dispersion region was calculated to range from $\lambda_{2D1} = 700$ nm to $\lambda_{2D2} = 1870$ nm (see Fig. 1). This window, wherein the nonlinear coefficient varies monotonically from $\gamma = 0.11 \text{ (Wm)}^{-1}$ at $\lambda_{2D1}$ to $\gamma = 0.03 \text{ (Wm)}^{-1}$ at $\lambda_{2D2}$, permits an SSFS over an octave for an input wavelength of 783 nm.

2. Fiber fabrication

The fiber was fabricated using the stack-and-draw process but with additional steps to reduce spectral attenuation. Previously published data on attenuation in such small-core PCF’s shows a strong increase in the spectral attenuation for core diameters below about 2 $\mu$m, due to extrinsic OH contamination during stacking, and structural damage to the silica matrix during the drawing. These together cause the increased attenuation both at the OH overtones and at other wavelengths within the transparency window of silica. Previous efforts to reduce these effects using halogen-based dehydration were only partially successful [7]. In our fibers we greatly reduced these effects by annealing the preform in a dry environment immediately prior to fiber drawing [8], which allowed us to fabricate low attenuation, small-core fibers with zero dispersion wavelengths suitable for a large SSFS in the near-IR.

3. Experiment and Results

The experimental setup is shown schematically in Fig. 2. Pulses from a mode-locked Ti:Sapphire laser with a repetition rate of 83 MHz and centre wavelength of 783 nm were launched into the PCF using a 40× microscope objective. An optical isolator was used at the laser output to avoid feedback. The pulse width, measured using an autocorrelator, had a full-width at half-maximum of 260 fs, assuming a Gaussian pulse. Simultaneous measurements of the pulse spectrum show that the pulses had a linear chirp with a chirp parameter $C \approx 2.4$. Due to the birefringence of our PCF, a quarter-wave plate was used to optimize the input polarization such that the red-shift was maximized at the highest input power. Subsequently, the input power was tuned using a variable attenuator and the output spectrum recorded using an optical spectrum analyzer.

Figure 3 shows output spectra for different input powers. The wavelength of the strongest soliton increases continuously as the input power varies from 4 mW to 155 mW. At the highest power it has a wavelength of $\lambda = 1650$ nm, a red-shift of more than an octave relative to the pump wavelength of 783 nm. To the best of our knowledge, this is a record frequency shift obtained in an SSFS experiment, and the first time an octave shift has been achieved.

4. Conclusions

We have demonstrated a record SSFS over more than an octave, from 783 nm to 1650 nm using a PCF with reduced OH loss. For the largest SSFS observed, the fraction of the output energy in the most red-shifted soliton is 54%. This is thus a high efficiency, pulsed source with wavelength tunable over more than an octave. It is likely that by further optimizing the input pulse, which in our experiments was linearly chirped, even larger shifts can be observed.

References