accepted as a Postdeadline paper at
CLEO-PR 2005, 11-15 July 2005, Tokyo

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Broadband supercontiuum generation in an extremely nonlinear extruded lead silicate holey fiber using weak fs pulses

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Abstract

Broadband supercontinuum generation at 1.06 µm spanning > 1000 nm and extending to the visible is observed in a dispersion optimized holey fiber with a record-high nonlinearity (1860 $W^{-1}km^{-1}$ at 1.55 µm), for launched pulse energies < 100 pJ.

Introduction

Supercontinuum generation (SCG) in holey fibers (HFs) has attracted significant interest over the recent years, mainly because of the capability of these fibers to offer effective nonlinearities that exceed by far what can normally be achieved using conventional fiber technology. However, SCG becomes more efficient when the fiber is pumped at a wavelength near to its zero-dispersion wavelength. Because of the extreme waveguiding conditions of highly nonlinear HFs, it is possible to alter the magnitude and slope of their dispersion profile by suitable modification of the fiber design. Shifting the zero-dispersion wavelength of a nonlinear HF to a region where there are convenient laser sources available enhances the efficiency of the SCG process.

Non-silica soft glasses offer as much as 100 times higher material nonlinearity than pure silica, and are therefore strong candidates for the fabrication of nonlinear fibers. To this end, we recently reported the fabrication of a lead silicate (SF57) HF with a record-high effective nonlinearity of 1860 $W^{-1}km^{-1}$ (measured at 1.55 µm) and a zero dispersion wavelength at ~1 µm, and demonstrated its suitability for SCG using a commercial and relatively low power fs pulse source operating at 1.06 µm [1]. In this paper we report on experiments using this HF exhibiting optimized SCG performance, and present numerical simulations that confirm the role of the tailored dispersion profile of the fiber on the nonlinear processes. By launching 200 fs pulses of just a few tens of pJ energy into a 60 cm piece of HF we have generated a bandwidth of ~1000 nm that extended to the visible wavelengths.

Fiber properties

An SEM image of the HF we used in our experiments is shown in Fig.1a. The material of the fiber (SF57) is the most nonlinear among the commercially available lead silicate glasses, with a nonlinear refractive index of $4.1 \cdot 10^{-19}$ m^2/W at 1.06 µm [2]. Because of the low softening temperature of this glass (~500°C) and its excellent thermal stability characteristics it is possible to apply extrusion techniques for the fabrication of reproducible and high quality fiber preforms. The fiber fabrication followed the three-step procedure previously reported in Refs. [3, 4].

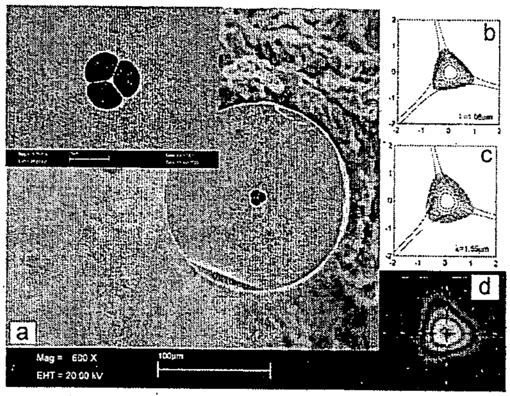

Fig. 1: (a) SEM image of the small core extruded lead silicate HF with 1 µm core. Predicted mode profiles at (b) 1.06 µm and (c) 1.55 µm and (d) measured mode profile at 1 µm.

The fiber design we have followed allows the production of extremely small-core high-NA HFs and provides high optical isolation for the core from the outer glass region by three fine struts. In the experiments described herein, we have used a HF with a measured core diameter of 1 µm. The dispersion of this HF is estimated to be anomalous at 1.06 µm and have a value of < 50 ps/(nm·km), and the zero-dispersion wavelength to be at ~945 µm. The role of the fiber design to the dispersion tailoring of this HF can be appreciated if one considers that the zero-dispersion wavelength for SF57 is ~1.97 µm.

Inspection of the guidance characteristics of the HF at both 1 µm and 1.55 µm, both by imaging the near-field of the guiding mode with an infrared camera (Fig.1d) and by theoretically calculating the mode profile from the SEM image (Fig.1b-c) revealed that the fiber guides a single triangular-shaped mode. A white light loss measurement showed an attenuation loss of 2.1 dB/m at 1.06 μm and 2.3 dB/m at 1.55 μm. The effective nonlinear coefficient, γ, of the HF was measured as 1860 $W^{-1}km^{-1}$ at 1.55 μm, establishing it as the most nonlinear fiber ever produced [1]. (Note that because of the dependence of γ on the wavelength, this value corresponds to > 3000 $W^{-1}km^{-1}$ at 1.06 μm.)

Optimized SCG at 1.06 μm

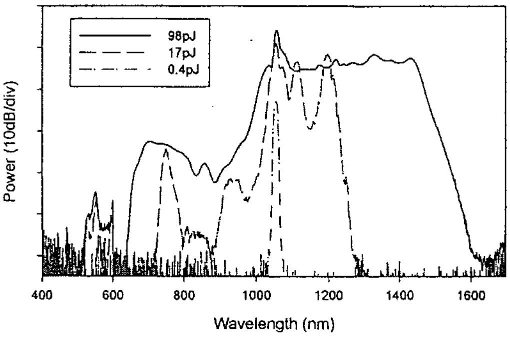

Fig.2: Optical spectra obtained for various launched pulse energies.

For our SCG experiments we used a mode-locked diode pumped Nd:glass laser to launch 200 fs pulses at a repetition rate of 80 MHz and a wavelength of 1.06 μm with pulse energies up to 100 pJ into a short length (~60 cm) of this HF. Fig.2 illustrates the spectra obtained at various launched powers. For modest power levels (launched pulse energies below ~20 pJ) we saw clear evidence of Raman soliton formation, an indication that this HF has anomalous dispersion at the wavelength of operation. However, the presence of four wave mixing and the generation of new components at shorter wavelengths relative to the pump is an indication that the zero-dispersion wavelength is close to the predicted wavelengths. At higher pulse energies (~100 pJ) the spectral components in the HF spanned more than one octave and extended significantly into the shorter IR/visible wavelength regions of the spectrum. We achieved a spectral broadening in excess of 1000 nm for launched pulse energies as low as 98 pJ. We expect even broader spectra to be observed if we use an even shorter length of fiber, because of the significant fiber loss on both long and short wavelength ends of the spectrum.

Modeling of SCG

We have performed modeling of the SCG to explain the behavior that we observe in the experiment. As the absolute Raman gain of SF57 is not well established, we performed independent micro-Raman measurements on a bulk piece of glass to estimate the Raman gain spectrum. An example of our simulation result for 30 pJ launched pulse energy is shown in Fig.3. The general behavior noticed in both experiment and simulation is very similar. Several of the discrepancies observed can be justified as follows: The much higher power measured in the experiment relative to the simulation could be accounted for light traveling in the cladding of the HF rather than its core (note that the HF was uncoated). This also explains the peak observed at the pump wavelength in the experimental data. The simulation has taken into account the propagation of only one pulse. It has been shown that even small pulse amplitude fluctuations are sufficient to result in smearing of the output spectrum and a flat averaged spectral response. Finally, the simulation predicts that the power of the shorter wavelength components should be higher than what we measure and we are currently investigating this. We believe that much of this is due to the fact that the fiber patchcord we used to connect the HF output to the spectrum analyzer has a cut-off wavelength at ~980 nm, which might cause the detected power levels to be lower for the wavelengths of multi-mode operation.

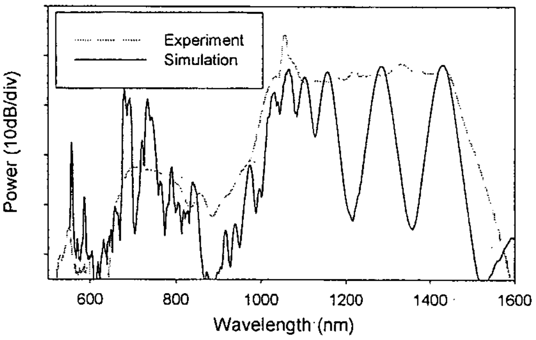

Fig.3: Simulated and experimental optical spectra at the output of the SCG system.

Conclusion

We have used a small-core lead silicate HF with a record-high effective nonlinearity coefficient (γ = 1860 $W^{-1}km^{-1}$ at 1.55 μm) and tailored dispersion characteristics (zero-dispersion wavelength at ~1 μm) to generate a broadband supercontinuum at 1.06 μm extending either side of the pump wavelength. Using just ~98 pJ energy pulses in a 60 cm piece of this HF we observed a spectrum spanning over 1000 nm.

References

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