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Broadband light generation around 1300nm through spectrally recoiled solitons and dispersive waves

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We experimentally study the generation of broadband light around 1300nm from an 810nm Ti:Sapphire femtosecond pump laser. We use two photonic crystal fibers with a second infrared zero-dispersion wavelength (λ_{Z2}) and compare the efficiency of two schemes: In one fiber λ_{Z2}=1400nm and the light at 1300nm is composed of spectrally recoiled solitons. In the other fiber λ_{Z2}=1200nm and the light at 1300nm is composed of dispersive waves. © 2008 Optical Society of America

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The dispersion of photonic crystal fibers (PCFs) can be manipulated significantly by changing the air hole structure in the cladding. Index guiding PCFs can be designed to have zero-dispersion wavelength down in the visible (λ_{Z1}) and a second zero-dispersion wavelength (λ_{Z2}) in the infrared, if desired. The combination of a small mode area and a tailored dispersion profile in so-called highly nonlinear PCFs has led to a revolution in supercontinuum generation (SCG) with low pump energies.[1]

The nonlinear processes involved in SCG depend on the pumping scheme and are now generally well understood.[2] Supercontinuum light sources have become available commercially, and significant research is being aimed at improving the stability of the spectrum and at tailoring the spectrum, e.g., to have increased bandwidth and power content in the blue[3] or in wavelength regimes relevant for optical coherence tomography (OCT),[4,5] such as 800nm or 1000nm for ophthalmology (the eye) or 1300nm for highly scattering tissue.[6]

Here we focus on how to generate a broad, preferably Gaussian shaped, spectrum around 1300nm. One way to generate power at 1300nm is through degenerate four-wave mixing (FWM) of long pulses. However, FWM is typically inefficient, particularly if the Stokes wave is far from the pump.[7] Here we therefore consider how an 810nm femtosecond (fs) pump can be used to generate a broad spectrum around 1300nm.

One way to use a fs pump is to pump near λ_{Z1} in a conventional PCF with no λ_{Z2}, generate an octave spanning supercontinuum, and filter out the desired spectral part around 1300nm with a Gaussian filter.[8] This scheme also has low efficiency. Another way is to pump sufficiently far into the anomalous regime to generate a single fundamental soliton, and simultaneously avoid coupling too much energy into blue-shifted dispersive waves. Then let the soliton redshift due to the Raman effect until it reaches the desired wavelength. This was, e.g., done in a tapered PCF, where a 1300nm pump was shifted to 1.65μm with 60% efficiency.[9]

Recently there has been a lot of interest in pumping in the anomalous dispersion region in a PCF with two closely spaced zero-dispersion wavelengths.[10–13] In such fibers self-phase modulation (SPM) is dominant,[11,12] which leads to a strong depletion of the pump over just a few cm and efficient generation of two smooth spectra in the normal dispersion region below λ_{Z1} and above λ_{Z2}.[10–12]

Here we also use PCFs with two zero-dispersion wavelengths. However, because we want to transfer an 810nm fs pump to 1300nm, we need widely spaced zero-dispersion wavelengths,[12,14] and therefore SPM is no longer the dominant effect. In such PCFs soliton fission generates solitons that redshift towards λ_{Z2}, where they generate dispersive waves in the normal regime above λ_{Z2} and thereby experience a spectral recoil that cancels the Raman redshift.[15] Several recoiled solitons might therefore accumulate below λ_{Z2} and transfer a significant amount of power to red-shifted dispersive waves above λ_{Z2}. Depending on the fiber design the power at 1300nm could be made to consist og recoiled solitons or dispersive waves. The efficiency would, e.g., depend on the decay rate of the recoiled solitons, i.e., how much energy one soliton looses before the next one arrives. Here we experimentally compare the two schemes.

We study two highly nonlinear PCFs, NL-1.7-650 (fiber A) and NL-PM-760 (fiber N), fabricated by Crystal Fibre A/S. We measure the average hole diameter and pitch for the fibers from scanning electron microscopy (SEM) images and use these average dimensions to calculate the dispersion profiles numerically (see Fig.1). Fiber A has zero-dispersion at λ_{Z1}=725nm and λ_{Z2}=1390nm, whereas fiber N has zero-dispersion at λ_{Z1}=780nm and λ_{Z2}=1170nm. Thus, fiber A has anomalous dispersion and fiber N has normal dispersion in the region of inter-

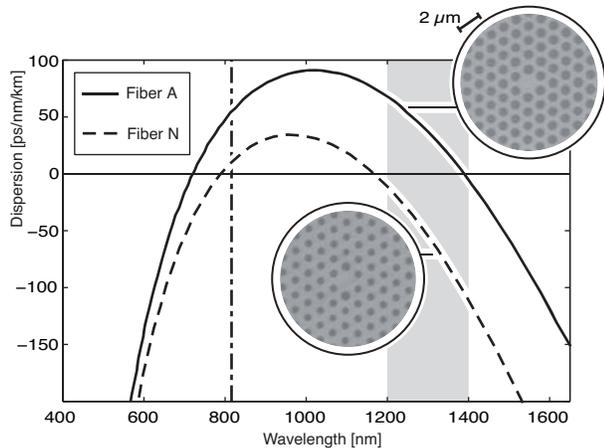est, 1200-1400nm, marked as the grey area in Fig.1.

Fig. 1. Dispersion curves for fiber A (solid) and N (dashed) calculated from the inserted SEM images. Fiber A (N) has zero dispersion at λ_{Z1}=725nm (780nm) and λ_{Z2}=1390nm (1170nm). The pump wavelength is marked with a vertical dash-dotted line.

The PCFs are pumped in the anomalous dispersion region by an 810nm Ti:Sapphire laser (FEMTOSOURCE Compact PRO, FEMTOLASERS) with a full width at half maximum (FWHM) spectral bandwidth of 130nm, and a repetition rate of 75MHz. The laser gives a transform limited pulse length of 11.4fs, which, due to the lenses in our setup, results in weakly positively chirped pulses at the fiber input with a FWHM of 21 fs. The coupling loss into the fiber is 3-4dB minimum. In Fig.2 we show the output spectra for different input powers. Up to 80% of the power is initially lost to blue-shifted dispersive waves in the normal regime below λ_{Z1}, which is unwanted for the power-transfer schemes we investigate.

After the initial loss of energy to dispersive waves the pump generates a number of solitons through soliton fission. The higher the input power is, the shorter the first generated lowest-order soliton will be, and the more it will be redshifted after a fixed propagation length.[2] This is what is observed in Fig.2. In fiber A we can clearly distinguish the lowest-order soliton for input powers above 30mW. Around 55mW the first soliton has reached λ_{Z2} and started to generate red-shifted dispersive waves.

For fiber N with a significantly narrower anomalous dispersion regime, red-shifted dispersive waves are generated already at 14mW input power, and no individual solitons can be clearly distinguished. In fact, even for low pump powers, the spectrum develops into a broad supercontinuum, which is explained by the fact that fiber N is being pumped much closer to λ_{Z1}. For fiber N the second zero-dispersion wavelength therefore acts more as a limiter of the supercontinuum generation, which could still be a desirable effect nevertheless.

In Fig.3 we show a contour plot of the measured output spectrum versus input power for different fiber lengths. For fiber A we see that with only 6cm of fiber one
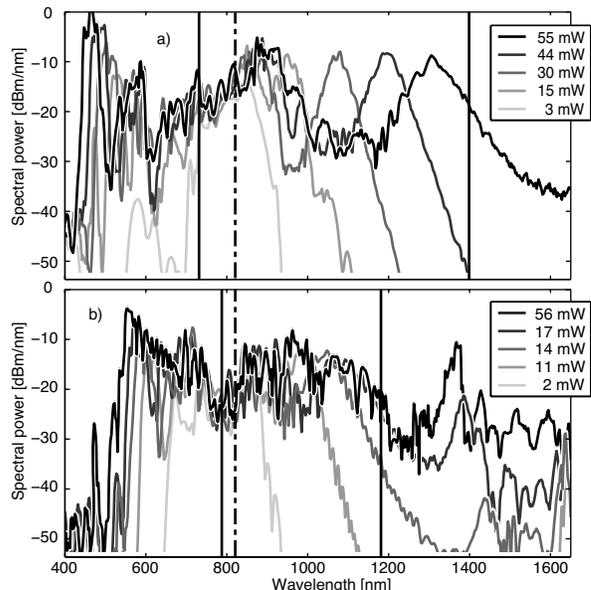

Fig. 2. Measured supercontinuum generated from 13.5cm of Fiber A (a) and 12.5cm of fiber N (b), for different average input powers. Zero-dispersion wavelengths (the pump) are marked by vertical solid (dash-dotted) lines.
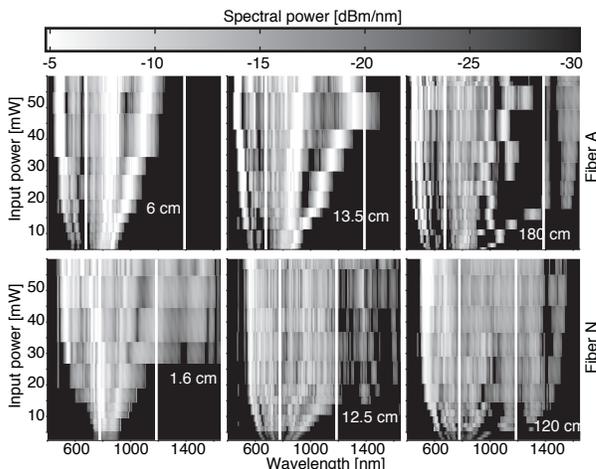

Fig. 3. Grey scale contour plot of the average input power versus output spectrum of fibers A (top) and N (bottom), for different fiber lengths indicated on the figure. Zero-dispersion wavelengths are marked with white lines.

must pump with more than 55mW for a soliton to reach λ_{Z2}, while a longer length of 180 cm allows more solitons to reach λ_{Z2}, the first one arriving above 15mW and the second above 40mW. It appears as if the first recoiled soliton looses most of its power before the second soliton arrives at λ_{Z2}, — this will be quantified in the next figure. For fiber N Fig.3 confirms again that the anomalous dispersion regime is so narrow and the effective nonlinearity so strong, that the solitons that are generated are spectrally too close to be clearly distinguished. For fiber A dispersive waves are generated around 1500nm and for

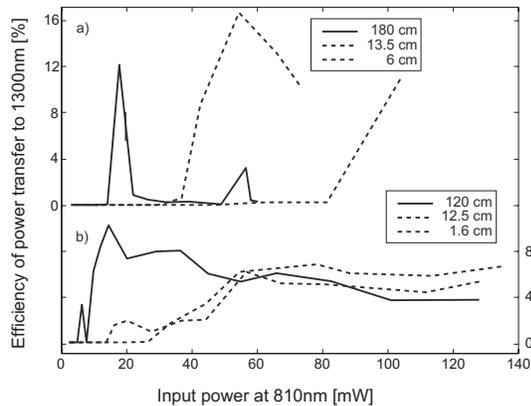fiber N they are generated around 1300nm, as expected.

Fig. 4. Efficiency of generation of power in the 1250-1350nm regime, calculated by filtering the output spectrum with a 100nm FWHM Gaussian filter centered at 1300nm and dividing the resulting filtered power with the total input power. a) Fiber A. b) Fiber N.

The power transfer for the two schemes may be quantified through the efficiency, calculated by numerically applying a 100nm FWHM Gaussian filter centered at 1300nm to the output spectrum and dividing by the input power. The efficiency is depicted in Fig.4 versus the input power for the three lengths of fiber. Naturally the efficiency will never be high due to the initial significant loss of power to blueshifted dispersive waves below λ_{Z1}.

For fiber A (the soliton scheme) the measurement for 180cm shows that unfortunately there is no accumulating effect for this fiber design. The recoiled soliton looses its power to redshifted dispersive waves before the next soliton arrives at λ_{Z2}. Note that the power in the next soliton at around 55mW is much less than the first soliton, in accordance with soliton fission theory.[2] For the shorter fiber lengths a higher input power is necessary for the first soliton to experience enough redshift to arrive at λ_{Z2}. Since the power predominantly goes into the first soliton, this means that the efficiency is higher. The largest efficiency for the soliton scheme is about 16%, which is obtained for the 13.5cm fiber.

For fiber N the scenario is much different. Clearly the dynamics is that of SCG and not single solitons arriving at λ_{Z2}. The efficiency increases initially with input power, but above a certain saturation power, which depends on the fiber length, the supercontinuum has been generated completely, and there is no advantage in increasing the input power further. The saturation power is about 55mW for fiber lengths of 1.6cm and 12.5cm and about 15mW for 120cm. Thus, above 55mW, there is no point in increasing the fiber length. The maximum efficiency for this scheme is about 10%.

In conclusion, we have experimentally investigated PCFs with two zero-dispersion wavelengths, λ_{Z1} and λ_{Z2}, pumped at 810nm in the anomalous regime with a fs laser. By using two PCFs with λ_{Z2}=1400nm and 1200nm, we have been able to compare the efficiency of transfer of power from 810nm to 1300nm for two schemes based on accumulating recoiled solitons and redshifted dispersive waves, respectively. We have shown that the rate of power transfer from solitons to dispersive waves is too high for an accumulating effect to take place in the soliton scheme. The coupling efficiency to dispersive waves could possibly be reduced by appropriate dispersion design, which we leave for future work. We have also shown that in the dispersive wave scheme, because we pump closer to λ_{Z1}, the SCG process is too strong to observe isolated solitons arriving at λ_{Z2}. In this case the second zero-dispersion wavelength acts as a limiter for the strong SCG process. The two schemes have comparable efficiencies.

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