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Tunable spectral enhancement of fiber supercontinuum

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We demonstrate tunable spectral enhancement of the supercontinuum generated in a microstructured fiber with a fiber long-period grating. The long-period grating leads to phase distortion and loss that, with subsequent high-intensity propagation in uniform fiber, evolves into an enhancement around the grating's resonant wavelengths. Wavelength tunability is achieved by varying the temperature or the ambient refractive index, and the spectral peak can be extinguished by immersing the grating in index-matching oil. © 2007 Optical Society of America

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The generation of large spectral broadening of short laser pulses, leading to a supercontinuum, has been revolutionized by the development of microstructured photonic crystal fibers (PCFs) [1,2]. This is because PCFs have a very strongly confined core mode, and because their zero dispersion point can be shifted to visible or near-infrared wavelengths. Supercontinuum generation in PCF consists of a number of well-understood processes associated with the formation and evolution of temporal optical solitons in the fiber [3,4]. The large spectral broadening, often spanning more than an octave, has led to applications in optical frequency metrology [5,6], optical imaging [7], and wavelength division multiplexing [8].

It has been shown that the use of a fiber Bragg grating (FBG) written in the PCF can considerably enhance supercontinuum in the spectral region around the Bragg wavelength [9,10], an effect associated with a change in the dispersion relation [9–12]. A significant application of the effect was demonstrated by Kim *et al.* [13], who showed an improvement of the signal-to-noise ratio in a frequency metrology experiment by writing a FBG into the highly nonlinear fiber, which generated a supercontinuum frequency comb. Using a free-space geometry, Präkelt *et al.* [14] showed that a narrow loss feature in the spectrum of an ultrafast pulse also evolves into a spectral enhancement during self-phase modulation.

Here we demonstrate spectral enhancement of supercontinuum created in highly nonlinear fiber using a long-period grating (LPG) [15]. An LPG is a filter that, like an FBG, induces phase and loss features near its resonant frequencies, but which generally exhibits a number of such resonances created by coupling of the fiber core mode to one of several cladding modes. The key advantage of LPGs is that since these resonant frequencies are associated with modes of the fiber cladding, they are sensitive to the fiber's environment and so they can be widely tuned or even be

extinguished by external means [16]. In this way, we generate a spectrally tunable narrowband enhancement in the supercontinuum. We demonstrate up to 7.5 dB enhancement, and show that this notch can be temporarily removed by fluid immersion. Our experimental results agree well with simulations.

The principle of our method is schematically shown in Fig. 1. It uses three different fiber types, because PCFs, in which the supercontinuum generation is strongest, lack the germanium doping necessary for writing gratings. Having introduced the three different fibers, we can select each to optimize the device performance, as discussed below. In the first stage, an ultrafast laser pulse propagates through the highly nonlinear PCF1. The initially transform-limited pulse is converted into a broadband supercontinuum by self-phase modulation, soliton fission, and Raman self-frequency shift [4], such that the broadened spectrum is wide enough to cover the range of the chosen resonant wavelengths of the LPG in the

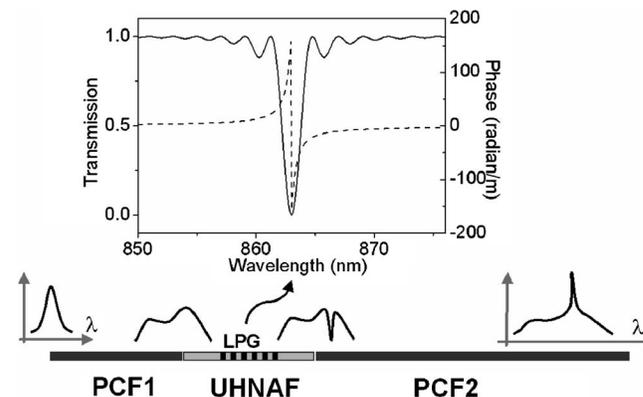


Fig. 1. Schematic of the device, as described in the text. Sketches above each section show the spectral profile of the laser pulse at the end of each section. The inset shows the typical amplitude loss and phase feature of an LPG near resonance.

second stage. The output of PCF1 is then coupled into an ultra-high-numerical-aperture fiber (UHNAF) selected for mode matching to the initial PCF and in which an LPG has been written. In this second fiber, the phase velocity of the propagating light is modified near the resonant coupling wavelengths of the LPG [17], which leads to a different phase development around the resonances. The magnitude of the phase feature is comparable with that in an FBG: after propagating through a length L of grating with a coupling strength κ , the maximum phase variation near the resonance is $\pm\kappa L$ in both LPG and FBG. In further propagation through PCF2 after the LPG, the light that was coupled into the cladding modes by the LPG is lost by absorption in the fiber jacket, resulting in sharp spectral loss features at low intensities. The inset in Fig. 1 shows a calculation of the phase variation and amplitude loss of the light near a resonance after propagation through an LPG with $\kappa L = \pi/2$, roughly corresponding to the one used.

The supercontinuum, modified by the LPG, is now coupled into PCF2, chosen for high nonlinearity and low dispersion. Previous work on nonlinear propagation of pulses filtered within a narrow spectral band [12,14] showed that the phase and loss features generated by the filter alter the phase relationship between the modified narrowband part of the field and the overall broadband pulse. After nonlinear propagation, this results in a spectral enhancement near the LPG resonance. The spectral enhancement can be tuned in wavelength and magnitude either by heating or by changing the refractive index of the medium around the LPG.

Figure 2 shows simulated results of the spectral intensity after low- and high-intensity propagation through the system obtained by solving the generalized nonlinear Schrödinger equation, [4], augmented by terms describing the effect of the LPG. We included only a single LPG resonance near 887 nm for simplicity. All simulation parameters, such as fiber length, nonlinearity, dispersion, and grating strength are chosen to match the experiment (see below). As

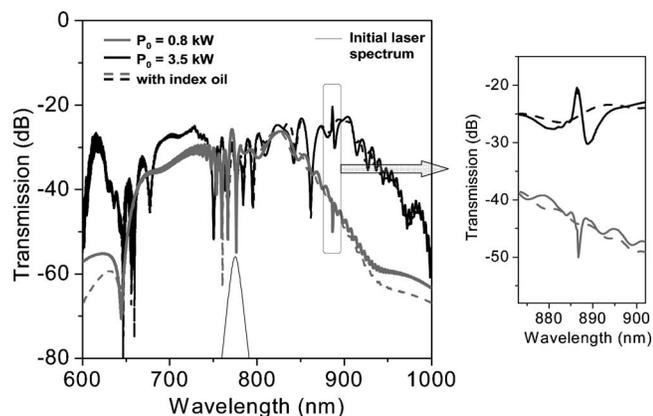


Fig. 2. Left: Modeling results showing propagation through the device at a peak power P_0 of 0.8 kW (gray curves) and 3.5 kW (black curves). The diagrams on the right show expanded views of the spectrum near the LPG resonance at the (top) high power and (bottom) lower power. Dashed curves are the corresponding spectra in the absence of the grating.

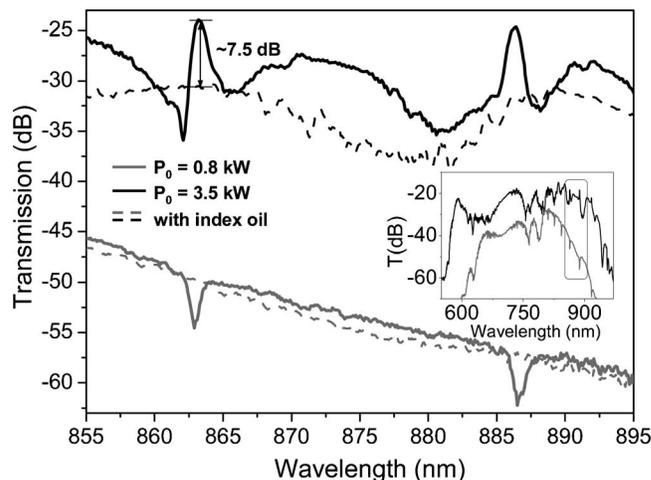


Fig. 3. Measured output spectra at peak power levels of 0.8 kW (gray curves) and 3.5 kW (black curves) showing two LPG resonances. The two dashed curves show corresponding spectra when the LPG is removed by immersing the grating in index-matching oil. Inset shows the entire supercontinuum spectrum at both power levels.

the expanded diagrams on the right-hand side of Fig. 2 show, the supercontinuum spectrum at low powers contains a narrow, deep loss feature as expected. At high powers, this loss transforms into a sharp spectral enhancement of ~ 7.5 dB compared with the level in absence of LPG (dashed curve).

In our experiments PCF1 (Fig. 1) is a 50 mm long PCF with a mode field diameter of $1.4 \mu\text{m}$, numerical aperture of 0.42, a nonlinear coefficient $\gamma = 0.104 \text{ W}^{-1} \text{ m}^{-1}$, and a dispersion zero at 749 nm. The input pulses, generated by a mode-locked Ti:sapphire laser emitting 75 fs FWHM pulses at 777 nm are significantly broadened in this fiber. The LPG is written in the second fiber, a short 50 mm length of hydrogen-loaded Nufern UHNAF. This fiber has second mode cutoff at 900 nm, a numerical aperture of 0.35, and a mode-field diameter of $\sim 2 \mu\text{m}$. The LPG, inscribed by UV exposure, has a length $L = 20$ mm, while the absorption notch depth is 8 dB, which leads to an estimated $\kappa L \sim 1.2$. The LPG has a period of $25 \mu\text{m}$, much shorter than the period of $100\text{--}1000 \mu\text{m}$ that is typical for fibers with lower numerical aperture. The first two fibers are spliced together with a loss of 1.5 dB. PCF2 is a 700 mm long length of a different PCF, spliced with a 1 dB loss onto the UHNAF. This second PCF has a dispersion zero at 868 nm and a nonlinear coefficient of $\gamma = 0.049 \text{ W}^{-1} \text{ m}^{-1}$, and can generate strong self-phase modulation of the perturbed supercontinuum pulse.

Figure 3 shows the measured output spectrum. At low power (0.8 kW, gray curve), the final fiber, PCF2, does not act nonlinearly and the supercontinuum excites linear core-to-cladding coupling resonances, leading to the sharp dips in the spectrum observed at 863 and 887 nm. By contrast, at the higher power (3.5 kW, black curve) more energy is transferred into the spectral region around these resonances. The core-to-cladding loss resonance is transformed by the self-phase modulation in PCF2 into a dramatic 7.5 dB narrowband spectral enhancement, in close

agreement with modeling results. The dashed curves in Fig. 3 show the corresponding spectra acquired when the fiber with the LPG is immersed in a fluid of refractive index 1.45, matching that of the fiber cladding. At low powers (gray dashed curve) the loss resulting from coupling to the cladding mode has vanished. At the higher power (black dashed curve), when the enhancement mechanism is active, the presence of the fluid causes the enhancement feature to disappear.

Figure 4 demonstrates the thermal tunability of the enhancement. Two resonances initially at 845 and 864 nm (labeled L_1 and L_2 , respectively, in the figure) are monitored as the temperature of the sample is increased. The main diagram shows how the position of each of the enhancement peaks shifts linearly as a function of temperature by ~ 0.054 nm/ $^{\circ}$ C. The inset contains spectra acquired at several temperatures, showing that the spectral enhancement peaks can be tuned, in combination, over a bandwidth of 35 nm.

Having shown that the enhancement of the supercontinuum can be tuned using LPGs, let us compare our spectra with those reported earlier using FBGs. Taking the results of Li *et al.* [10], we note first that the spectrum shown in Fig. 3 is affected by the LPG over tens of nanometers, whereas the effect of FBGs is restricted to a much narrower spectral range. This is not surprising since the spectral features of LPGs are generally much wider than those of FBGs [15]. While the enhancements of Li *et al.* [10] are 10–15 dB, those observed here are somewhat lower (~ 7.5 dB). This is primarily due to splice losses in our system, which amount to 2.5 dB. Indeed, simulations show that without these losses, the enhancement is substantially higher. It is true that higher enhancements with FBGs were reported [13], but in this work, the authors use a sharp edge in the supercontinuum spectrum to increase the enhancement fur-

ther, making a direct comparison with our work inappropriate. We finally note that though the observed wavelength dependence of the enhancement of 2–3 dB (inset of Fig. 4) is consistent with simulations, a good understanding of the wavelength dependence is still lacking.

The manipulation of the spectral power density by nonlinear optical processes and external control represents a novel approach in waveguide-based nonlinear optics. The nonlinear interaction between the pulse and the fiber can be modified in real time without the need to couple light out of the fiber and back into it. The method could be used to increase the flexibility of optical frequency chains for frequency metrology, or, in telecommunications, permit tunable power transfer in spectrally sliced wavelength division multiplexing [8].

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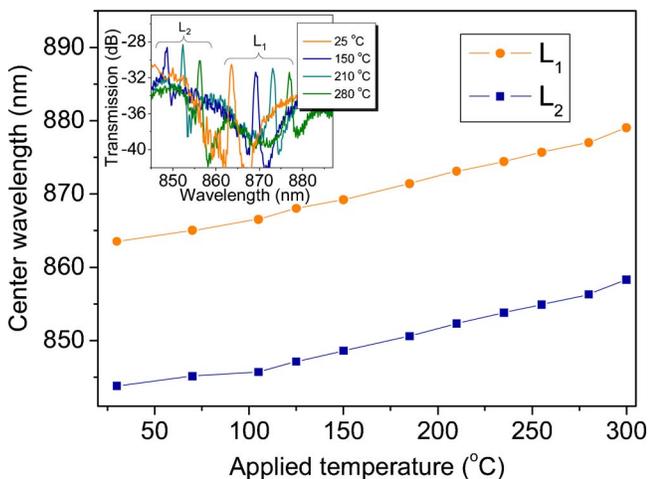


Fig. 4. (Color online) Tunability with increasing temperature of the enhancement at the two resonances. Inset shows examples of spectra measured at several temperatures.