Power adjustable visible supercontinuum generation using amplified nanosecond gain-switched laser diode

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Abstract: Supercontinuum (SC) light with a continuous spectrum covering 0.45-1.2 μm is scaled from 250-740 mW by varying the repetition rate of an amplified, frequency doubled, telecom laser diode. Efficient SC generation requires minimal non-linearity in the amplifier and anomalous dispersion pumping close to the fiber zero dispersion wavelength. Based on simulations, we present a 2-stage design that separates pulse break-up from spectral broadening to enhance the SC bandwidth for quasi-CW pumping.

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References and links

1. Introduction

We demonstrate supercontinuum (SC) extending between 0.45-1.2 microns with up to 0.74 W time averaged power by pumping a 1.5m photonic crystal fiber (PCF) with a frequency doubled, amplified, gain-switched, telecom laser diode. By controlling the non-linearity in the amplifier, the SC output is scalable in average power through an increase in the pulse repetition rate while maintaining a constant peak power. The continuum generation is initiated by modulation instability (MI), and we verify through simulations that the broadest spectrum is generated by pumping in the anomalous dispersion regime close to the PCF zero dispersion wavelength ($\lambda_0$). By leveraging mature telecom technology, the demonstrated SC source is economical, compact and robust. The broad spectrum and average power control make the SC source particularly useful for applications in optical coherence tomography and surface metrology.

Visible SC generation in PCF has been widely studied using a variety of pump sources [1]. Mode-locked Ti:sapphire femtosecond lasers around ~750 nm produce SC covering the visible, but these sources are expensive and have limited average power output. Higher SC average power outputs in excess of a watt have been obtained by pumping with mode locked picosecond pulses from a Yb fiber laser at 1060 nm [2,3]. Various techniques have been demonstrated to extend the SC spectrum towards the blue. Supercontinuum extending down to 400 nm was demonstrated using a microchip laser at 1064 nm to pump a PCF with modified group index in the infra red to efficiently phase match with deeper blue wavelengths [4]. Another method as demonstrated by Kudlinski et. al. was used to generate SC with a short wavelength edge of 400 nm and >2 mW/nm spectral density by using tapers with continuously decreasing dispersion [5]. Multi-wavelength pumping schemes involving a pump and its second harmonic [6] or four wave mixing pump conversion [7] have also been demonstrated to increase spectral coverage in the visible.

The techniques mentioned above using mode locked lasers suffer from one primary drawback – lack of average power scalability due to fixed repetition rate. The ability to vary the pulse repetition rate is inherent to many SC systems using microchip lasers [7,8] and master oscillator power amplifier type pumps. For example, Matos et. al. demonstrated a repetition rate tunable chirped pulse amplification erbium system which was frequency doubled to generate SC in PCF with 160 mW average power [9]. However, the control of the SC average power by varying the repetition rate while keeping the peak power constant has not been demonstrated earlier. In this paper, we demonstrate a simple nanosecond source based on frequency doubling amplified gain switched pulses from a standard 1.55 µm telecom laser diode. The pump source is a robust alternative to mode-locked laser based setups. The demonstrated system generates SC with a short wavelength edge down to 450 nm and has average power control through variation of the pulse repetition rate.

The paper has been divided into four sections. Section 2 describes details of the pump system and the experimental setup used to generate visible SC. The experimental results are shown in section 3. In particular, we describe the evolution of the visible SC with pump peak power and the average power control through variation of the pulse repetition rate. In section 4, we perform simulations of the non-linear Schrödinger equation to determine the SC generation mechanisms and understand the limits of the wavelength edge. Finally, we propose a new method to extend the short wavelength edge using a two stage SC generation process. The first stage uses MI to produce high peak power femtosecond pulses while the second stage uses a low dispersion but high non-linearity material to achieve large spectral broadening through self phase modulation.
2. Experimental setup

A block diagram of the all fiber integrated high power pump system at 1.55 μm is illustrated in Fig. 1. A 1553 nm DFB laser diode is gain-switched to produce 2 ns pulses at variable repetition rates. The nanosecond pulses are amplified by two stages – a single mode Er doped fiber amplifier (EDFA) pre-amp followed by a cladding pumped Er-Yb doped fiber amplifier (EYFA) power-amp. Since the noise performance of the system is determined by the high gain first stage amplifier, the pre-amp is designed to minimize the amplified spontaneous emission (ASE) to signal ratio. This is accomplished by splitting the gain in the pre-amp into two sections and by filtering the ASE between gain stages using a 100 GHz band pass filter. The pulses are further amplified in the power-amp which comprises a cladding pumped EYFA pumped by 2 multimode 976 nm laser diodes coupled into the gain fiber via a pump combiner. At the highest operating repetition rate of 1 MHz, the power-amp produced an output of 3.2W average power (1.6 kW peak power). The entire amplifier setup is fusion-spliced together.

![Fig. 1. All fiber integrated high power 1553nm pump system](image)

The 1553 nm pump system is then frequency doubled before coupling into the PCF. The corresponding experimental setup is shown in Fig. 2. A quarter wave plate and half wave plate at the output of the power-amp are used to adjust the polarization state of the light. The pulses then pass through an isolator before being coupled into a 10 mm long periodically poled lithium niobate (PPLN) crystal temperature stabilized at 160°C. The crystal temperature and the spot size of the focused beam within the PPLN are optimized for maximum second harmonic generation (SHG) efficiency. A thermal power meter and edge pass filters are used to determine the power in the fundamental and second harmonic wavelengths. The frequency doubled output from the PPLN at 776.5 nm acts as the pump source for continuum generation in the PCF. We couple the light into a 1.5m long PCF (core diameter=1.9 μm, λ_0=745 nm, dispersion slope at pump = 0.85 ps.nm^{-2}km^{-1}) using a 40X microscope objective and achieve ~50% coupling efficiency. The output spectrum is recorded using an optical spectrum analyzer with a 2nm resolution.

![Fig. 2. Experimental setup for visible SC generation](image)

3. Experimental results

The output spectrum from the PCF for a pump (776.5 nm) peak power of 420 W is shown in Fig. 3. We observe a continuum extending from 450-1200 nm with 0.74 W time averaged power. The spectrum is exceptionally smooth from 550-750 nm with better than 2dB flatness across this wavelength range. Apart from the peak at the pump wavelength, several addition peaks can be observed in the output spectrum. The peak at ~518 nm is due to third harmonic generation from the PPLN, while the peak at ~388 nm arises from phase matched four wave mixing. To calibrate the vertical axis of the spectrum, the area under the spectral curve was numerically computed and equated to the total SC power as determined by a thermal power meter.
Next, we study the SC spectral evolution as a function of input peak power (Fig. 4). Since we pump the fiber with nanosecond pulses in the anomalous dispersion region, we expect the SC growth to be initiated by MI [8,10]. In the time domain, this implies that the 2 ns pulse breaks up into a train of periodic femtosecond solitons. As the peak power is increased to 110W, we observe the characteristic MI spectral sidebands around the pump wavelength. The asymmetry in the spectral power density of the short and long wavelength regions arises due to the different continuum generation mechanisms responsible for each side. The long wavelength side of the spectrum experiences additional gain due to stimulated Raman scattering, which, transfers power from shorter to longer wavelengths. On the other hand, wavelengths below the pump are generated primarily by phase matched FWM [8,11]. The smooth nature of the continuum can be attributed to the ensemble average of spectra produced by multiple solitons within the 2ns pulse envelope [12].

We also show that the average power in the continuum can be scaled up through optimization of the pump source. Since the PPLN crystal has a limited doubling bandwidth of ~1 nm, spectral broadening in the amplifier reduces the SHG efficiency. To reduce the non-linearity, we first minimize the length of the power-amp lead fiber (SMF-28) to ~0.5 m. Next, we vary the input peak power to obtain maximum SHG efficiency ~70% at 1 kW (Fig. 5(a)). The theoretical efficiency for a lossless crystal at the given peak power is ~99%. But, we measure the transmission loss through the crystal at low power to be ~30%, and thus achieve the maximum conversion efficiency possible experimentally. With a further increase in peak power, the efficiency starts to drop as the amplifier output spectrum broadens and more power shifts outside the 1nm conversion bandwidth of the crystal.

Since the nonlinear phenomena responsible for SC generation are dependent on peak power, the average power in the continuum is scaled up by increasing the repetition rate of the laser diode while keeping the peak power (and hence, the spectral shape) constant around 1kW [13]. Figure 5(b) shows the linear increase in SC average power from 250mW to 740
mW with an increase in repetition rate from 300 kHz to 1 MHz. The average power could be further increased by using a larger core gain fiber (to reduce amplifier non-linearity) and increasing the pumping power by additional 976nm pump diodes.

**Fig. 5(a). SHG efficiency versus peak pump power**  
**Fig. 5(b). SC average power versus pulse repetition rate**

### 4. Numerical simulations

To determine the wavelength limits of the generated SC and identify the generation mechanisms, we performed numerical simulations of the generalized non-linear Schrodinger equation using the adaptive split-step Fourier method. This section is divided into three parts. First, we describe the equations used in the simulator and underlying assumptions. We confirm the validity of our simulator by comparing the simulator result with a corresponding experimental data set. Next, we perform simulations with different fiber zero dispersion wavelengths and confirm the role of MI in initiating the SC generation process. Finally, we propose a two stage model to enhance the SC generation process and extend the short wavelength edge of the continuum.

#### 4.1 Simulation methodology

The complex envelope \( \hat{A}(z, \tau) \) of a pulse, under the slowly varying approximation satisfies the generalized NLSE given by,

\[
\frac{\partial \hat{A}}{\partial z} = (\hat{D} + \hat{N}) \hat{A}
\]

\[
\hat{D} = -\frac{i}{2} \beta_2 \frac{\partial^2 \hat{A}}{\partial \tau^2} + \frac{1}{6} \beta_3 \frac{\partial^3 \hat{A}}{\partial \tau^3} + \frac{i}{24} \beta_4 \frac{\partial^4 \hat{A}}{\partial \tau^4} - \frac{\alpha}{2}
\]

\[
\hat{N} = i \gamma (1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}) \int_{-\infty}^{+\infty} \left[ (1 - f_R) \delta(t) + f_R h_R(t) \right] |A(z, t-t')|^2 dt'
\]

where the pulse moves along \( z \) in the retarded time frame \( \tau = t-z/v_s \) with the center angular frequency of \( \omega_0 \). The linear terms in the differential operator \( \hat{D} \) account for the second \((\beta_2)\), third \((\beta_3)\) and fourth order \((\beta_4)\) dispersion as well as the loss \((\alpha)\) of the fiber. The terms in the operator \( \hat{N} \) result from nonlinear interactions, which describe self-phase modulation, self-steepening and stimulated Raman scattering effects. In particular, the effective nonlinearity is defined as \( \gamma = n_2 \alpha_0 / c A_{\text{eff}} \), where \( n_2 \) and \( A_{\text{eff}} \) are the nonlinear refractive index and effective mode area of the fiber respectively. In addition, \( h_R(t) \) represents the Raman response function, and \( f_R \) is the fractional contribution of the Raman response to the nonlinear polarization. To reduce computation time, we assume a 20 ps super-Gaussian pulse at 776.5 nm as the input to our simulator. Simulations with broader pulse widths (up to 200 ps) were also performed and showed no significant difference in the spectrum obtained.
Figure 6 shows comparison between experiment and simulation results for 1.5m of PCF with $\gamma = 65$ W$^{-1}$km$^{-1}$. The pump wavelength is 776.5 nm and the peak power is 420 W. There is reasonable agreement between the 2 curves on the short wavelength side while on the long wavelength side, simulation results show higher power than the experimentally obtained spectrum. The simulator assumes a constant mode field diameter (MFD) across the entire wavelength range but the MFD actually increases for long wavelengths as the guiding properties of the fiber become weaker. Thus, the effective non-linearity at long wavelengths is smaller in the experiment compared to the simulations.

**4.2 Supercontinuum generation mechanism**

To confirm that the SC generation is initiated by MI, we performed simulations with fibers having different zero dispersion wavelengths but the same dispersion slope 0.85 ps.nm$^{-2}$km$^{-1}$. In each case, we assumed a pump wavelength $\lambda_p = 776.5$ nm, peak power $P = 420$ W and non-linear coefficient $\gamma = 65$ W$^{-1}$km$^{-1}$. Figure 7(a) shows the output spectrum after propagation through 0.3m of fibers with $\lambda_0$ ranging from 745 nm to 775 nm. We observe symmetrical side bands around the pump wavelength and obtain maximum broadening for the fiber with $\lambda_0=775$ nm. This is consistent with MI, since MI phase matches only when the pump is in the anomalous dispersion region and the gain bandwidth is inversely proportional to the separation of the pump wavelength from the fiber $\lambda_0$. The theoretical MI gain coefficient is given by,

$$g = \sqrt{(\gamma P)^2 - \left[\frac{\Delta k}{2}\right]^2 + \gamma P}, \Delta k = -\frac{\lambda^2}{2\pi c} \left[\frac{dD}{d\lambda}\right]_0 \left(\lambda_p - \lambda_0\right) \left(\omega_p - \omega_i\right)^2$$

After propagation through a length L of the fiber, the power gain experienced by the Stokes signal is given by, $G = \frac{P(L)}{P_{10}} = 1 + \left(\gamma P L\right)^2 \frac{\sinh^2 \left(\frac{gL}{g}\right)}{\left(\frac{g}{gL}\right)^2}$. Figure 7(b) plots $G$ after L=0.3m for fibers with different $\lambda_0$ and the results are in excellent agreement with Fig. 7(a). This confirms that modulation instability is the dominant non-linear effect in the initial propagation through the PCF. Initially, anomalous dispersion plays an important role in breaking up the quasi-CW pulse into ultra short pulses required for SC generation. Thus, while MI seeds the SC generation process, MI alone cannot account for the final continuum bandwidth obtained. The resulting ultra short pulses further broaden the spectrum as they propagate down the fiber through an interplay of self phase modulation, stimulated Raman scattering and phase matched four wave mixing. But, as the continuum evolves towards the

Fig. 6. Comparison of experimental and simulation spectra for 1.5m PCF at 420W peak power
blue wavelength region, the large normal dispersion prevents efficient four wave mixing. In other words, the short wavelength edge of the continuum is limited by phase mismatch caused by the fiber dispersion.

4.3 Two stage model

In this section, we propose a 2 stage model to optimize the SC generation process. In order to extend the blue continuum generation, we separate the pulse break-up and spectral broadening stages. In the first stage, we use a short length of PCF in the anomalous dispersion regime to break-up the nanosecond pulse into a train of ultra short femtosecond pulses through MI. For the 2nd stage, we choose a material with high Kerr non-linearity (large non linear refractive index n2) and minimal dispersion to maximize spectral broadening. Simulation results for the 2 stage model are presented below. Figure 8 shows the temporal output after propagating through 0.5m of PCF with $\lambda_p=745$ nm and $\lambda_0 = 776.5$ nm. The initial 20 ps super-Gaussian pulse is broken up into ~20 fs wide pulses with ~3x the original intensity. The separation between pulses is ~74 fs and is in excellent agreement with the theoretical separation given by $T = 2\pi / \sqrt{2\gamma P_0 / |\beta_2|} = 73$ fs, where $P_0=420$ W, $\gamma=65$ W$^{-1}$km$^{-1}$ and $\beta_2=-7.39e-3$ ps$^2$/m.

The narrow pulses from the 1st stage PCF are then launched into an ideal 2nd stage dispersion less material with non-linearity comparable to the PCF. The output spectra for different lengths of the 2nd stage material are shown in Fig. 9. We observe symmetric and smooth broadening around the pump wavelength indicative of SPM as the primary broadening mechanism. On the other hand, Fig. 10 shows the results for the same propagation length in a single stage PCF. The corresponding spectra are asymmetric and much narrower as further
spectral broadening is ultimately limited by fiber dispersion. The 20 dB SC bandwidth after just 4 cm of stage 2 material is ~425 nm compared to ~230 nm for the single stage, an enhancement of almost 2x. The choice of the 2nd stage material is based on the relative values of the dispersion length ($L_D$) and non-linear length ($L_{NL}$). The dispersion length is given by $L_D = \tau_0^2 / |\beta_2|$ and the nonlinear length is $L_{NL} = 1/(\gamma P)$, where $\tau_0$ is the FWHM of the soliton from the 1st stage and $P$ is the peak power. While it is essential for the 1st stage PCF to be pumped in the anomalous regime, the 2nd stage can be normally dispersive provided $L_{NL} \ll L_D$. This ensures that significant SPM broadening takes place before the pulses are reduced in intensity due to the normal dispersion. As an example, PCF filled with liquid carbon disulfide [14] not only exhibits large non-linearity ~ 6W$^{-1}$m$^{-1}$ at 775 nm, but can also be tailored to minimize dispersion at the pump wavelength.

![Fig. 9. Spectra from two stage model: 0.5m 745 nm $\lambda_0$ PCF followed by different lengths of ideal $n_2$ material](image)

![Fig. 10. Spectra from single stage model: 0.50-0.70m of 745 nm $\lambda_0$ PCF](image)

5. Summary

In summary, we generate a 750 nm wide visible SC with 0.74 W average power pumped using a telecom laser diode and EDFAs. We also show that average SC power can be scaled up through an increase in the pulse repetition rate, but the maximum power is limited by the non-linearity in the EDFA. Numerical simulations confirm that the broadest SC spectrum requires pumping in the anomalous dispersion regime close to the PCF $\lambda_0$. Further enhancement of the continuum bandwidth is possible through a two step SC generation process – MI induced pulse breakup in a short length of anomalous dispersion PCF followed by SPM broadening in an ideal dispersion less high non-linearity material.

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