APPLICATION NOTE

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Supercontinuum Generation in SCG-800 Photonic Crystal Fiber

Technology and Applications Center
Newport Corporation

Spectra-Physics
A Division of Newport Corporation

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1. Introduction

Since the discovery of supercontinuum generation (white light produced by focusing an intense laser pulse onto a nonlinear medium), significant research was devoted to investigation of this phenomenon and many applications have been developed[1]. Early examples of supercontinuum based applications include the following: white light (supercontinuum) seeded Optical Parametric Amplifiers (www.newport.com/OPA), transient absorption spectrometers (www.newport.com/Helios) among others, all requiring amplified ultrafast systems.

In recent years, renewed interest in supercontinuum generation has been closely related to the remarkable progress in the development of photonic crystal fibers (PCF) as well as the development of robust, well-engineered single box ultrafast lasers (www.newport.com/MaiTai). Coupling an ultrafast laser pulse directly out of an oscillator into a few centimeters of PCF produces more than one octave broad supercontinuum. The fact that only an oscillator with a few nJ of energy is required to generate supercontinuum makes the PCF-based sources reliable, affordable and relatively simple to operate. To date, PCF generated supercontinuum has found applications in frequency comb spectroscopy, nonlinear spectroscopy, optical coherence tomography, CARS microscopy, metrology and the characterization of optical devices, to name a few.

By varying design parameters, the PCF can be fabricated to have zero dispersion at a given wavelength, thus enabling soliton formation and propagation in the PCF. Since the pump beam is confined to the 1-2 µm diameter core, the pulse interactions with the fiber are highly nonlinear over the entire length of the PCF. Raman scattering, four-wave mixing, self-phase modulation, as well as higher order nonlinear processes, all contribute to the supercontinuum generation[1]. As such, the output beam properties are highly sensitive to the pump laser pulse width, wavelength and energy. For detailed explanation of the PCF technology we refer readers to www.crystal-fibre.com.[2]

As a PCF based supercontinuum source, Newport offers SCG-800 (www.newport.com/SCG-800) shown in Figure 1.

Fig.1 Newport's SCG-800

1. R.R. Alfano, *The Supercontinuum Laser Source* (New York, Springer-Verlag, 1989)
2. *www.crystal-fibre.com*

It is a pre-assembled device consisting of a polarization maintaining PCF designed for zero dispersion at 750 nm in a hermetically sealed one inch diameter package. The ends of the PCF are sealed and spliced with regular fiber allowing for the facets of the device to be cleaned.

The purpose of this application note is to show in detail how to set-up and align the SCG-800. It describes a kit that, in combination with the Spectra-Physics line of ultrafast oscillators, offers a simple solution for a supercontinuum source covering spectral range 400 nm-2000 nm. Contained in this note are detailed characteristics, in the form of spectral "maps", of the supercontinuum generated while pumping the SCG-800 with the Spectra-Physics Mai Tai® femtosecond laser. These spectral "maps" allow users to choose the appropriate combination of wavelength and pump power to achieve the desired spectral profiles.

2. Experimental setup

Block diagram of the recommended experimental setup is shown in Figure.2.

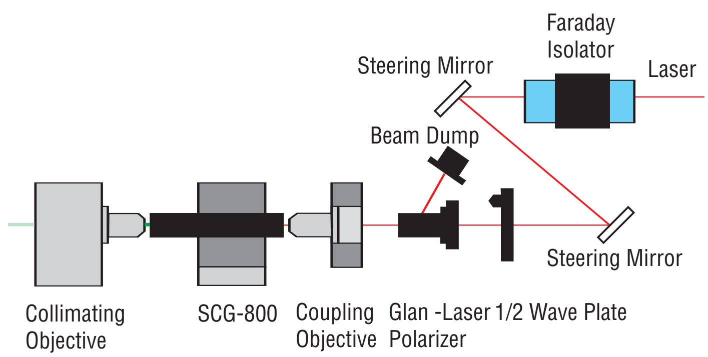

Fig. 2 Block diagram of the experimental setup

The output beam of the laser passes through the Faraday Isolator to eliminate coupling of the back reflected light into the laser. This is an important part of the setup and should not be overlooked. To achieve a high coupling efficiency, the pump beam must be positioned close to normal incidence with respect to the fiber. In addition, the high NA objective focuses the beam very close to the facet of the SCG-800, which has no anti-reflection coating. As a result, the back reflected beam will be collimated and sent back into the laser. Without the Faraday isolator this can lead to disruption of the mode-locking process and instability of the pump laser. Two steering mirrors are used for leveling the beam parallel to the optical table and to the axis of the SCG-800.

The holder for SCG-800 is an essential part of the setup. It plays a critical role in the stability and reproducibility of the continuum, given the fact that the core diameter of the SCG-800 is only 1.8 µm. We recommend Newport's 562-XYZ ULTRAlign™ precision crossed-roller bearing stage. Since this stage only provides XYZ translation, it is critical that the beam be aligned parallel to the axis of the PCF by adjusting the two steering mirrors.

The combination of the wave-plate and the polarizer serves as a variable attenuator for the incident pump laser power (see detailed description in Application Note 26). Reliable power control is important to avoid damaging the PCF.

The pump beam is focused into the fiber using a 20x or 40x objective. The 20x objective is used after the SCG-800 to collimate the output beam.

3. Alignment procedure

WARNING-Radiation emitted by laser devices can be dangerous to the eyes and appropriate precautions must be taken when they are in use. Only individuals who are adequately trained in proper laser use and safety procedures should operate the laser devices described herein.

1. Turn the Mai Tai laser on and set the wavelength at 800 nm.
2. Install the Faraday Isolator at the laser output as shown in Figure 3.
3. Use two steering mirrors to level the beam and direct it along the hole pattern of the optical table where the SCG-800 will be installed. The 562-XYZ stage SCG-800 holder doesn't have a tip/tilt adjustment, therefore it is important to have the laser beam parallel to the optical table and at the height of the optical axes of the SCG-800.
4. Install the variable attenuator assembly composed of a 1/2 wave-plate and the polarizer according to Applications Note 26 for horizontal polarization. Set laser power at 50 mW.
5. Install the focusing objective assembly. Remove the objective and position a target about 5 inches after the objective and mark the beam position. Install the 20x or 40x objective and use the XZ adjustments of the focusing objective to center the beam on the target. This insures the alignment of the focusing objective.
6. Block the beam and install the SCG-800 into the 562-XYZ stage and make sure that the line marking the polarization direction is aligned horizontally. The input facet of the SCG-800 should be at approximately 5 mm or 0.5 mm from the tip of the objective for 20x and 40x respectively.
7. Align the beam to pass through the fiber by observing the transmitted beam with an IR viewer on a screen positioned after the SCG-800 approximately 5 inches away. A small portion of the light will be reflected from the facet of the fiber. If the facet is at the exact focus of the objective, the reflected light will be collimated. Adjust the X on 562-XYZ holder to have the reflected light collimated by observing it at the exit aperture of the polarizer. Adjust the YZ (horizontal and vertical axis) on the 562-XYZ stage to achieve maximum coupling efficiency. Around the structured image of the beam, you will start seeing a larger and weaker image of the single mode beam as light starts coupling into the core of the fiber. It is very uniform and weak at first. By adjusting XYZ on the 562-XYZ stage, minimize the brightness of the central spot and maximize the zero mode brightness until the central spot completely diminishes.
8. Gradually increase the power until you observe red light at the output on a white sheet of paper. Adjust XYZ on the 562-XYZ stage to make the color of the beam more yellow and white. Attempting to perform major alignments of the SCG-800 at powers greater than 50 mW may result in damage to the fiber. When there is need to optimize the fiber alignment, always lower the power to less than 50 mW. Do not exceed 1.0 W at the input.
9. Install the collimating objective 20x, after the SCG-800 and adjust it to collimate the output beam.

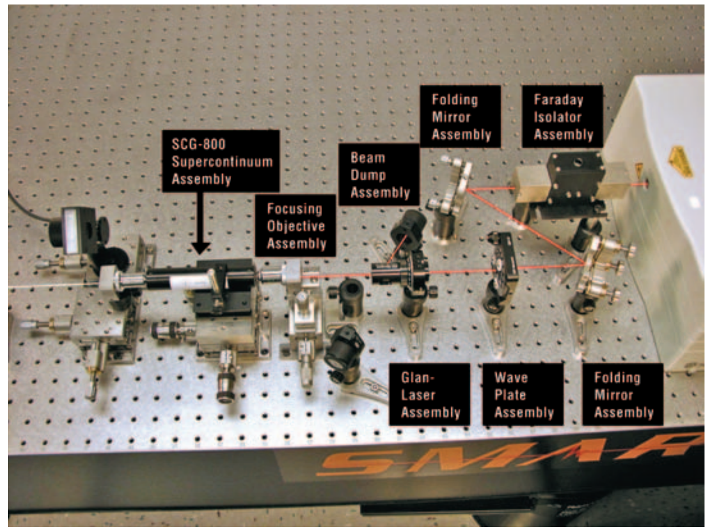

Fig. 3 Experimental setup for Supercontinuum generation in SCG-800

4. Coupling efficiency

We define coupling efficiency as the ratio of the power measured after the collimating objective and the laser power measured before the focusing objective. We also define coupled power as the power of the supercontinuum measured after the collimating objective. Coupling efficiency depends on the optics used to couple light into the fiber and proper filling of the objective aperture. In the configuration shown in Figure 2, we achieved 30% efficiency using Newport's M-20X and 60% efficiency when using M-40X. It must be noted that using a higher magnification objective makes the setup more sensitive to misalignment. At the same time we found that the properties of the generated white light are strictly defined by the amount of coupled power rather than efficiency of the coupling. Therefore, in those cases where the coupling efficiency is not an issue, we recommend using 20X objective.

Although in our experiments we never exceeded 150 mW in coupled power, higher powers can be achieved without damaging the fiber when proper care is taken to avoid misalignment and to ensure cleanliness of the facets.

5. Measurements

At high pump powers, the spectrum of the generated continuum extends from 400 nm to 2000 nm. Conducting calibrated measurement in such a broad spectral range is a challenge. Available spectrometers allow measurement only in a limited spectral range. After recording the spectra using several spectrometers, a cross calibration of the different measurements is required and reconstruction of the entire spectrum can prove complicated. To capture the entire spectrum of the white light in one measurement, we constructed a simple prism-based spectrometer. Using a grating as a dispersive element is not possible since the spectral components of the various diffraction orders overlap. Experimental setup for measuring the spectra of the white light is shown in Figure 4.

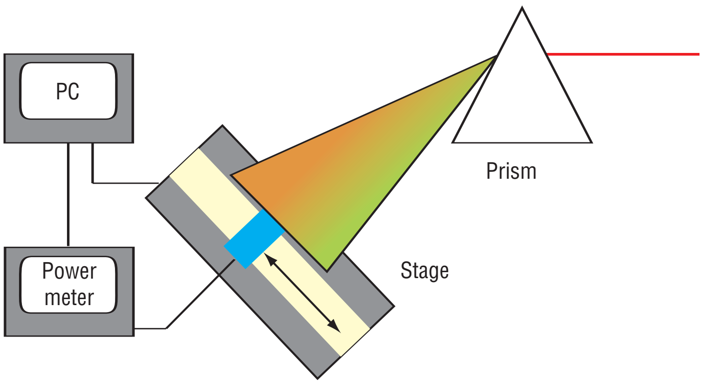

Fig. 4 Block diagram of the experimental setup for spectral measurements

It is based on a single LaKL21 prism. After passing through the prism, the white light is dispersed into a horizontal line. A detector, attached to the computer controlled motorized stage, is scanned along a line and the signal is recorded as a function of the detector position. For signal detection, we chose Newport's 2935-C power meter and 918-C detector. It has calibrated response in the 400 nm -1600 nm range, and consists of a specially designed integrating sphere with opposing Si and InGaAs diode. This detector can be directly plugged into a 2935 power meter. To calibrate the spectrometer, we used the different wavelength outputs of the Mai Tai, as well as band pass filters after the SCG-800. The accuracy of calibration of the spectrometer was +/-20 nm.

6. Experimental results

The white light spectrum out of SCG-800 for the different wavelengths is shown in Figure 5. For illustrative purposes, the contour plots are plotted on a logarithmic scale. The supercontinuum shown in Figure 5 is generated using a Spectra-Physics Mai Tai laser with 100 fs pulses width at a repetition rate of 80 MHz. These spectra strongly depend on pump power and wavelength.

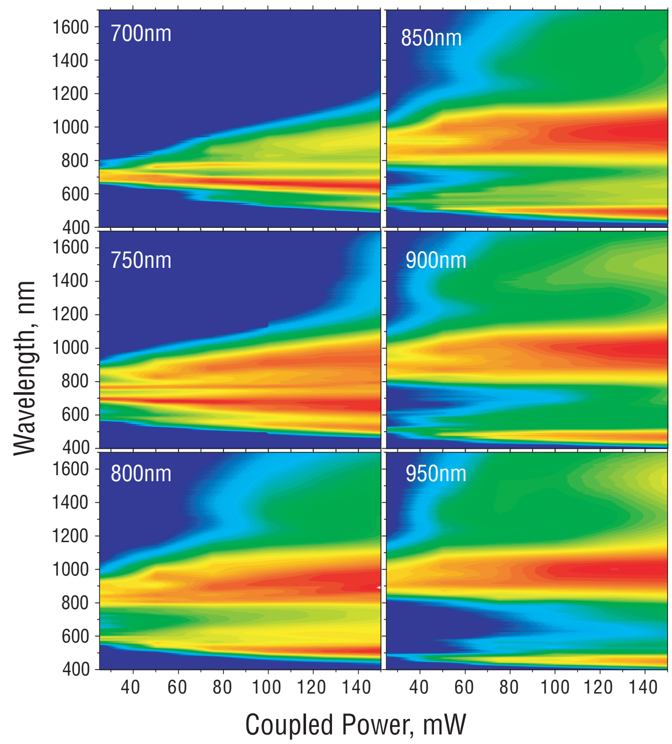

Fig. 5 Contour plots of pump dependence for different wavelengths

6. 1 Pump power dependence

As mentioned earlier, the white light spectrum depends only on coupled power. Figure 6(a-f) depicts the power dependence of the white light spectra for the different wavelengths produced by the Spectra-Physics Mai Tai laser.

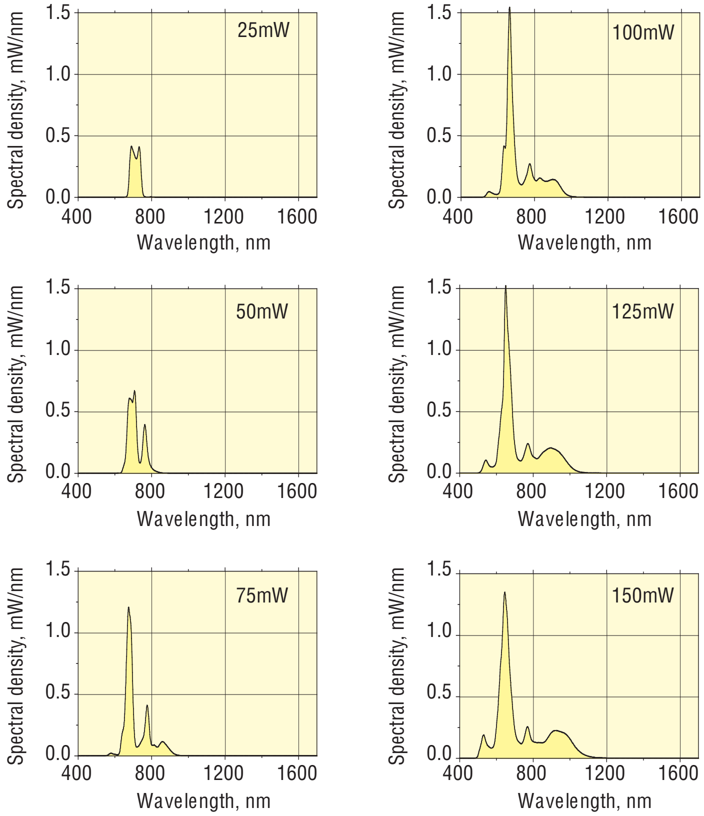

Fig. 6a *Dependence on coupled power at 700 nm pump power*

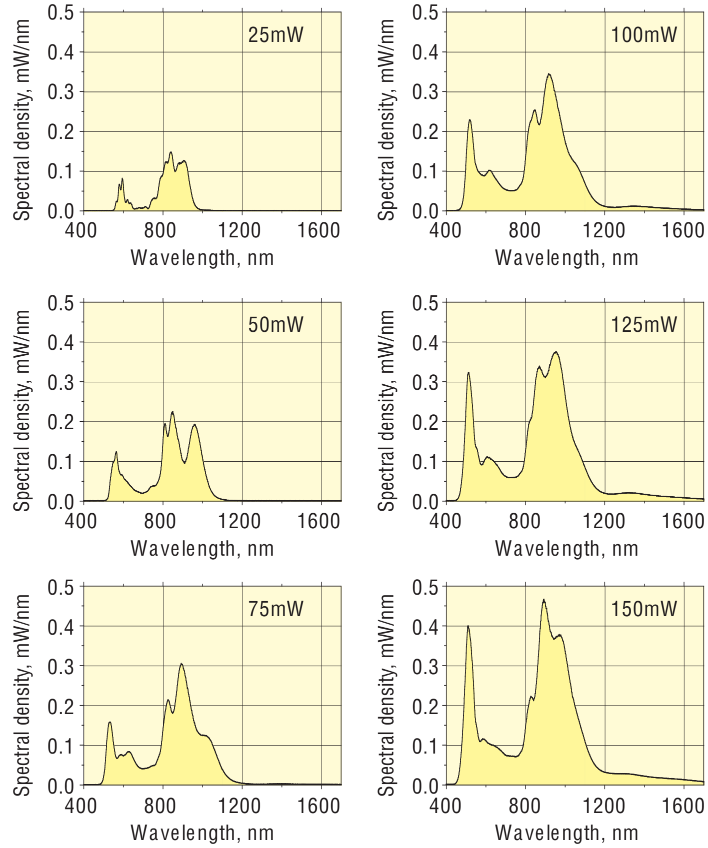

Fig. 6c *Dependence on coupled power at 800 nm pump power*

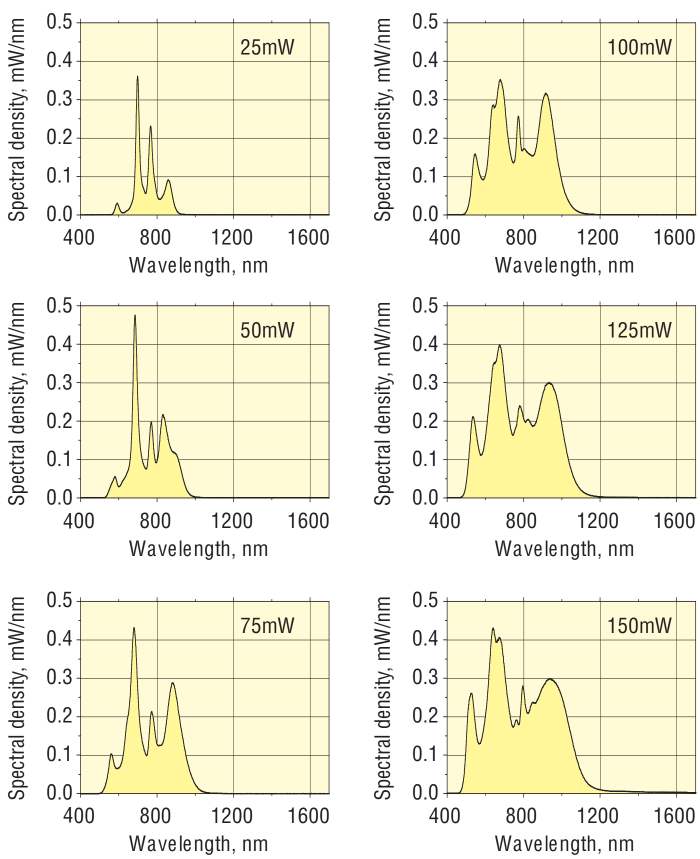

Fig. 6b *Dependence on coupled power at 750 nm pump power*

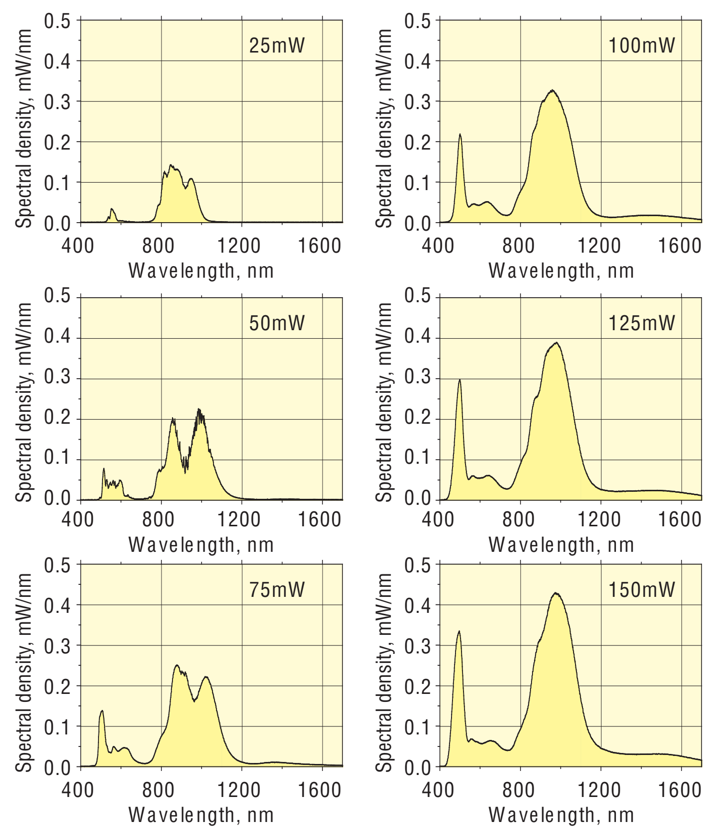

Fig. 6d *Dependence on coupled power at 850 nm pump power*

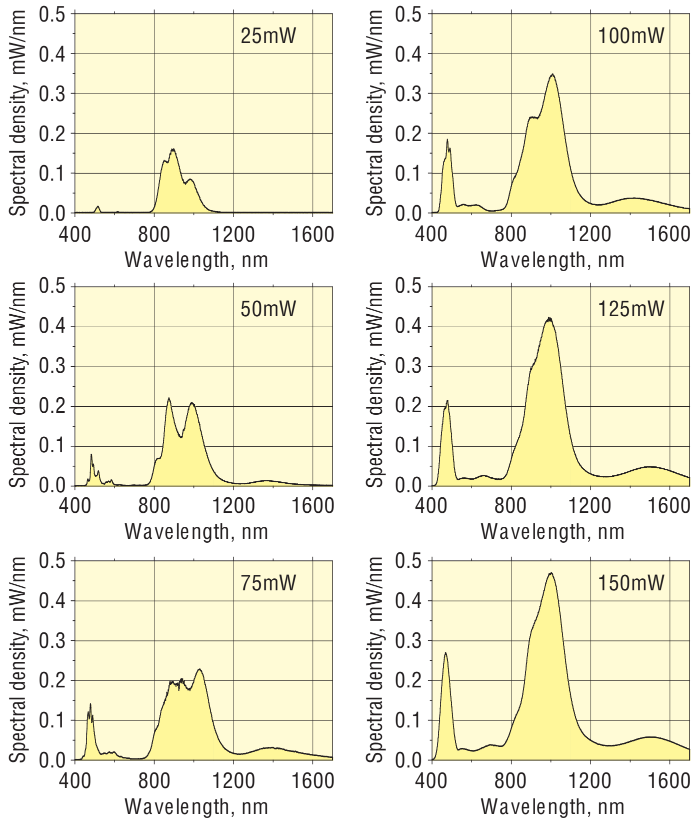

Fig. 6e Dependence on coupled power at 900 nm pump wavelength

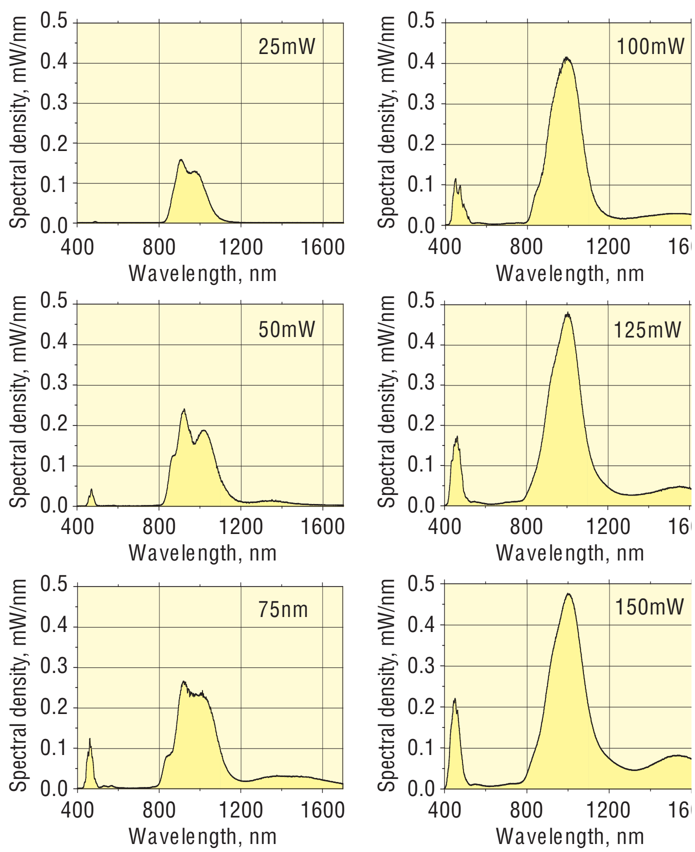

Fig. 6f Dependence on coupled power at 950 nm pump power

It is important to note that the area under the curve is equal to the coupled power. Thus, the Y scale on the graphs is in absolute units of mW/nm, and represents spectral density. To determine the total power in a given spectral interval, one has to simply multiply the width of the spectral region of interest, in nm, by the amplitude of the spectrum in the same region. The strong dependence of the white light spectra on coupled power is an indication that the process is highly nonlinear. Interpretation of the spectral feature is beyond the scope of this note. Newport's Technology and Applications Center has capability of conducting similar measurements and can provide a customer this type of data for a specified PCF.

6. 2 Wavelength dependence

The SCG800 is designed for zero dispersion at 750 nm. One should expect very different behavior with the pump wavelength being either shorter or longer relative to the zero dispersion point, which defines the spectral regions of normal and anomalous dispersion. In the region of normal dispersion, rapid pulse broadening occurs within a few centimeters of the fiber, thus limiting the peak power and spectral broadening. In the region of anomalous dispersion, soliton formation is possible resulting in the pulse propagating without broadening. Therefore, efficient conversion of energy into the continuum will be expected. The output spectra for different wavelengths at coupled powers of 150 mW are depicted in Figure 7. Indeed, at 700 nm (normal dispersion), the white light spectrum is relatively narrow and most of the energy is concentrated around the pump wavelength. At 750 nm (zero dispersion) the spectrum is relatively flat, and could be a good choice for applications where the white light is used as a probe source or tunable source. At 900 nm (anomalous dispersion) the broadest spectrum can be obtained with most of the intensity concentrated around 1100 nm.

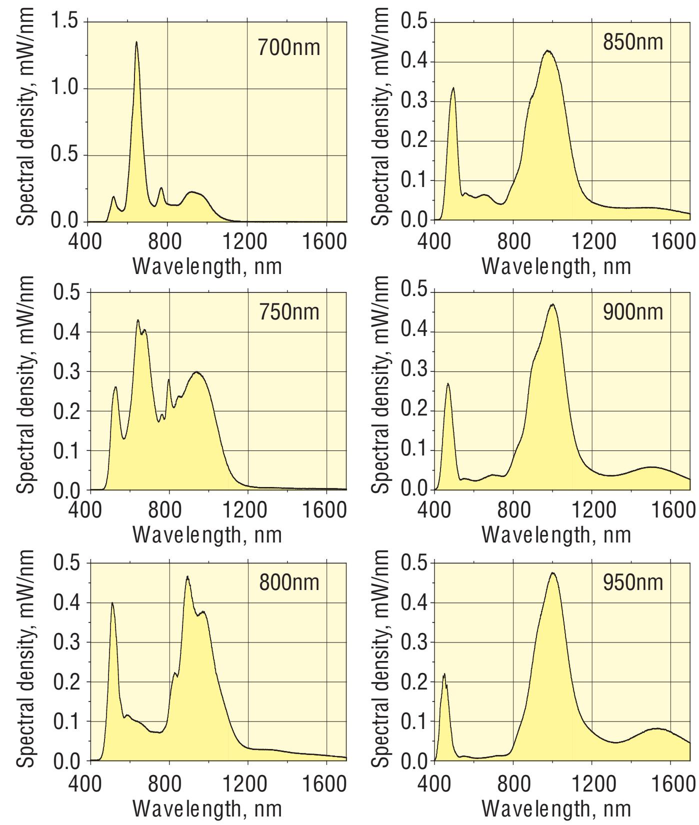

Fig. 7 Dependence on wavelength at 150mW coupled power

6. 3 Chirp/group delay

For pump-probe experiments or multicolor nonlinear spectroscopy experiments (CARS for example), when using different spectral regions in the supercontinuum, it is important to know temporal properties of the generated white light. In particular, the distribution of colors in time or chirp is strictly defined by dispersive properties of the PCF and pump parameters. We measured the white light chirp using the experimental setup shown in Figure 8 (a and b).

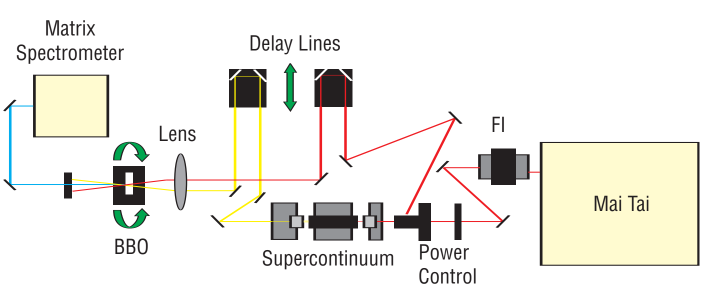

Fig. 8a Block diagram of the experimental setup for chirp measurement

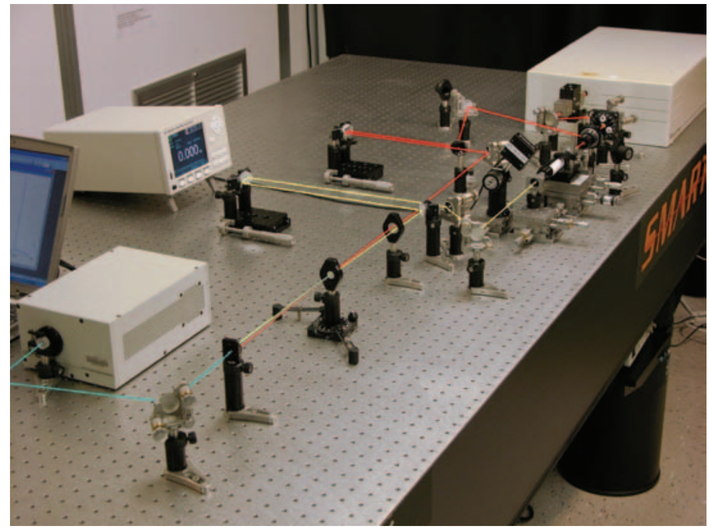

Fig. 8b Experimental setup for measuring the group delay of different spectral components

The output of the laser is split by the polarizer into a pump and a reference beam. The pump beam is launched into the PCF in order to generate the white light. After passing through the delay lines both the white light and the reference beam are recombined inside a nonlinear crystal (BBO, Type I, 0.2 mm) in order to generate a sum frequency signal. The spectrum of the sum frequency signal is recorded for each orientation of the crystal (phase matching angle) and the delay line position is optimized to maximize the sum frequency signal. The results are shown in Figure 9 for an 800 nm pump and 150 mW of coupled power. The different spectral components are generated in different parts of the fiber and additional time delays are acquired during the propagation through the fiber. The group delay between the blue and red components of the white light reaches 2.0 ps.

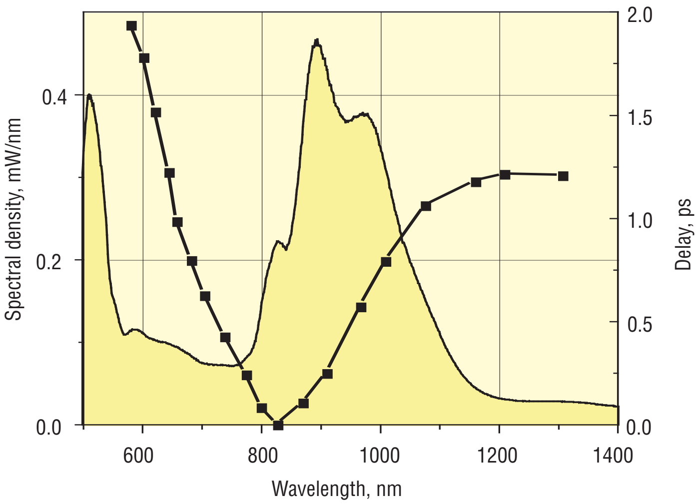

Fig. 9 Group delay for different spectral components at 800 nm pump and 150 mW power

It is interesting to note that under certain conditions, two different colors can be generated at the same time delay.

7. Conclusions

We demonstrated that the SCG-800 pumped by the Spectra-Physics Mai Tai laser is a powerful source of coherent white light covering the spectral interval from 400 to 2000 nm. Detailed calibrated spectra are provided allowing users to obtain desired spectral profiles by varying the pump laser parameters.

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