Supercontinuum Generation in Photonics Crystal Fibers

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Introduction

Supercontinuum generation is the formation of broad continuous spectra by propagation of high power pulses through nonlinear media, and was first observed in 1970 by Alfano and Shapiro [1,2]. The term supercontinuum does not cover a specific phenomenon but rather a plethora of nonlinear effects, which, in combination, lead to extreme pulse broadening.

Provided enough power is available, supercontinuum generation can be observed in a drop of water, but the nonlinear effects involved in the spectral broadening are highly dependent on the dispersion of the media and clever dispersion design can significantly reduce power requirements. The widest spectra are obtained when the pump pulses are launched close to the zero-dispersion wavelength of the nonlinear media and the introduction of the nonlinear PCFs with zero-dispersion wavelengths in range of the Ti:Sapphire femtosecond laser systems, therefore, led to a boom in supercontinuum experiments.

Supercontinua combine high brightness with broad spectral coverage – a combination offered by no other technology (see Figure 1).

This application note discusses how to generate supercontinua at different wavelengths and gives suggestions for the equipment, sources and fibers needed.

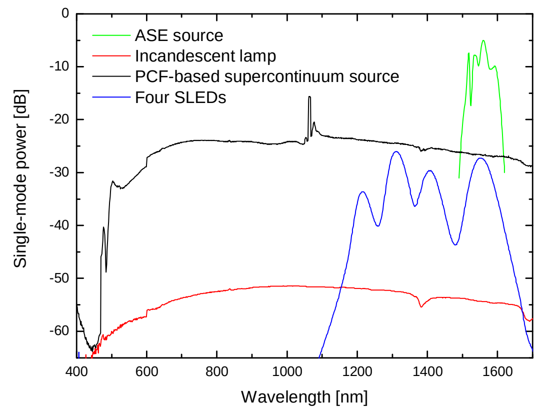

Figure 1 comparison between different broadband sources. The supercontinuum source shown is build from a NL-1040 PCF pumped by a nanosecond 1064 nm microchip laser.

Nonlinear Photonic Crystal Fibers

The term *photonic crystal fiber* is inspired by the unique cladding structure of this fiber class. Standard fibers guide light by total internal reflection between a core with a high refractive index (typically germanium doped silica), embedded in a cladding with a lower index (typical pure or fluorine-doped silica). The index differences in PCFs are obtained by forming a matrix of different material with high and low refractive index. In this way, a hybrid material is created with properties not obtainable in solid materials (e.g. very low index or novel dispersion). The hybrid material cladding can be constructed with a structure similar to that found in certain crystal, which is where the term photonic crystal fiber originates. The fibers are not fabricated in crystalline materials as the name might indicate.

There are two fundamental classes of PCFs: Index-guiding PCFs and fibers that confine light through a photonic bandgap (PBG).

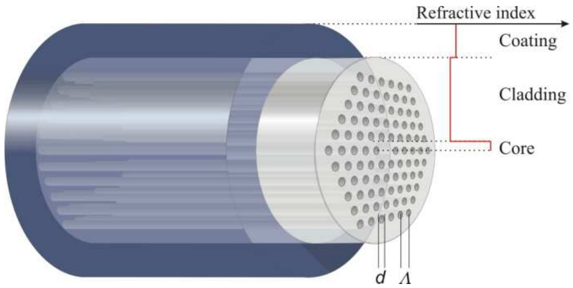

Figure 2 Schematic of the classical triangular cladding single-core photonic crystal fiber in which light is guided in a solid core embedded in a triangular lattice of air holes. The fiber structure is determined by the hole-size, *d*, and the hole-pitch, Λ. Like standard fibers, the PCF is coated with a high index polymer for protection and to strip off cladding-modes.

An index guiding PCF comprises a solid glass high-index core embedded in an air-filled cladding structure where a number of air holes are arranged in a pattern that runs along the length of the fiber, creating a hybrid air-silica material with a refractive index lower than the core. This air-silica matrix structure has given rise to several other names like microstructured and holey fibers, but despite the difference in terminology, they all refer to the same fiber type.

In Figure 2 is shown the principle of the classical triangular cladding single-core photonic crystal fiber, which has proven to be one of the most efficient and flexible designs, forming the basis of most PCFs today.

The fiber shown in Figure 2 is a large mode-area-type fiber. The outer diameter of the fibers are typically 125 µm and the pitch of the fiber in the figure is consequently 10-15 µm. Nonlinear fibers are typically designed with a pitch of approximately 1-3 µm, and therefore, the microstructured region of a nonlinear PCF only takes up the inner 20-50 % of the fiber cross section.

Compared to the well-known standard fiber, one of the most novel features of the triangular PCFs is the possibility to design fibers, which exhibit no second-order mode cut-off, rendering them single-mode at any wavelength. This fiber type is known as *endlessly single-mode fibers,* and can be realized by choosing sufficiently small holes in the cladding [3,13].

Nonlinear PCFs comes in two basic flavors: 1) multimode fibers with extremely small core and cobweb like microstructure, and 2) single-mode fibers with slightly larger cores, smaller holes and engineered zero-dispersion wavelength (see Figure 3 for the difference in microstructure for the two types).

The single-mode version has several advantages compared to multimode nonlinear fibers with large air-holes:

- The fibers are easier to splice to solid standard fiber due to the lower air-filling fraction
- Easier free-space coupling as light focused on the cladding region will not be guided, unlike in high-air-filling faction fibers, where light can be guided in the silica "islands" between the large holes
- Strict single-mode operation.

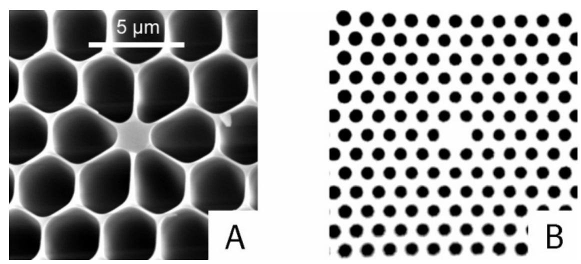

Figure 3 (A) SEM picture of a multimode fiber with zero dispersion at visible wavelengths. **(B)** Optical microscope picture of a single-mode fiber with zero dispersion at wavelengths around 800 nm. The relative hole-sizes are ~0.9 and 0.5, respectively. The pictures are shown on same scale.

Stripping and Cleaving of Nonlinear PCFs

The nonlinear fibers supplied by Crystal Fibre are all equipped with a standard acrylate coating, which can be removed with conventional stripping tools used for telecommunication fiber. Some fibers have a non-standard outer diameter, and for this type of fiber, we recommend an adjustable stripper. Both mechanical and thermal strippers can be used. Stripping with solvents or other liquids should be avoided as capillary forces might cause the liquid to enter the microstructure of the fiber, resulting in unpredictable performance and possible damage of the fiber. Furthermore, we do not recommend burning of the coating, as the high temperatures can make the fiber fragile and can cause fiber breaks.

When working with bare nonlinear fibers in a non-clean-room environment, dust and other contamination might deteriorate the performance over time as the fiber facets are contaminated. As the fiber facets cannot be cleaned with e.g. ethanol, recleaving the fiber is necessary. All fibers can be cleaved with conventional high precision cleavers (e.g. Fujikuras ct04b1 cleaver). The fibers can also be cleaved using e.g. a diamond scriber, but cleaving by hand might yield a high cleaving angle and bad cleave quality, reducing the coupling efficiency.

Recleaving can be avoided by choosing a connectorized fiber with sealed, cleanable end facets (see more information about connectors and end-sealing in the section on "Fiber Termination Solutions").

Coupling into Small Core Fibers

When coupling light from a femtosecond laser into a PCF, a number of issues regarding pulse distortion must be addressed to achieve the optimum performance. In this section we discuss the precautions taken to couple light from a femtosecond Ti:Sapphire laser (such as the Coherent Mira 900) into a small-core PCF. However, the considerations are applicable to most free-space setups. Figure 4 shows a schematic overview of a typical setup.

The first issue to be addressed is the 4 % reflection from the fiber surface, which can lead to a distortion of the pulse train and, in severe cases, stop the laser from modelocking. Back reflections can be minimized by cleaving the fiber at an angle. However, we recommend that the problem is avoided by the use of a Faraday isolator (supplied by e.g. Optics for Research). Coupling out a small portion of the beam and directing it to an autocorrelator allows for online monitoring of the pulse quality.

The femtosecond pulses are easily coupled into the fiber through standard microscope objectives. Magnifications of x40 (e.g. the Thorlabs RMS40X) and x60 provide good results. Aspheric ball lenses can also be used but as these are not achromatic, they should not be used with short femtosecond pulses due to the broad spectral range of these pulses. The dispersion in the microscope objective should be compensated using a precompensating prism or grating compressor in order to launch the shortest possible (i.e. highest intensity) pulse into the fiber (See [18] for a discussion of dispersion in microscope objectives). The diameter of the laser beam should match the aperture of the microscope objective. This can be achieved with a standard telescope.

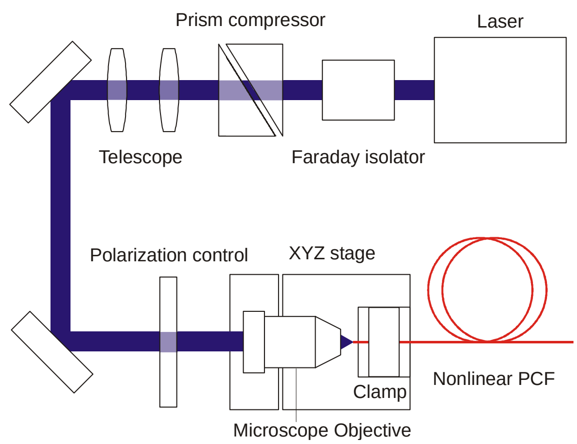

Figure 4 Schematic drawing of a typical setup for supercontinuum generation using a Ti:Sapphire femtosecond laser and a short piece of highly nonlinear photonic crystal fiber.

To obtain maximum coupling efficiency, it is essential that the laser beam travels along the optical axis of the microscope objective. Using two mirrors, the laser beam is aligned with the optical axis.

Nonlinear effects are inherently very sensitive to variations in the input power, thus a very stable mounting platform is needed. The small core size requires critical alignment, which is difficult to maintain over an extended period of time due to thermal, acoustic and other unwanted effects. To help minimize these effects, the fiber should be mounted as close to the end as possible. Further stability can be achieved by gluing the fiber to the mount. Recommended stages include the Thorlabs Nano Max stages with Stepper Actuators (DRV001).

Long-term stability can be improved by using a fiber auto-alignment system (like the Thorlabs APT NanoTrak Auto-alignment with NanoMax stages) that monitors the output power from the fiber and dynamically adjusting the fiber input alignment. Good results have been demonstrated with such systems, maintaining very good supercontinuum generation for many hours in extremely harsh operating conditions.

To further enhance the coupling stability, the fiber may be spliced to a larger core standard fiber. The standard fiber length can be made very short (few mm's) to reduce added dispersion and the splicing can be housed inside a standard connector. At the output end, a slightly different solution is typically chosen: To avoid splicing loss and to enhance the high pulse energy handling capabilities (output UV light might be worse than the input pump light), the output fiber end can be collapsed resulting in effective beam expansion towards the end facet.

Due to the birefringence of most crystal fibers, the polarization axis of the linearly polarized femtosecond pulses should coincide with one of the principal axis in the fiber. The relative orientation of the axes can be controlled either by a $\lambda/2$ plate or by rotating the fiber. To find the principal axes one can measure the polarization state of the output and rotate the $\lambda/2$ plate/fiber until the output is linearly polarized.

Using the above described alignment procedure coupling efficiencies well above 40-50 % are routinely achieved with most nonlinear PCFs.

Fiber Termination Solutions

Our nonlinear fibers are not only available as bare fibers, but can be delivered with a range of termination solutions. We currently offer the following termination options:

- Hermetically sealed ends for trouble-free operation in dusty environments.
- Termination with standard connectors (FC-PC, FC-APC, SMA).
- Beam expansion at fiber end to reduce intensity and damage risk at free space coupling.
- Splicing to standard step-index fiber to facilitate easy coupling and splicing into devices or setups.

Supercontinuum Examples

The determining factors for generation of supercontinua are the dispersion of the fiber relative to the pumping wavelength, the pulse length and the peak power. The dispersion, and especially the sign of the dispersion, is determining for the type of nonlinear effects participating in the formation of the continuum, and ultimately for the nature of the spectrum in terms of spectral shape and stability.

When pumping with femtosecond pulses in the normal dispersion regime, self-phase modulation dominates with Raman scattering broadening to the long wavelength side. A typical output is shown in **Figure 5**, where a 12.5 cm fiber is pumped at 800 nm. The pulse duration is 25 fs and the average coupled power is 53 mW. The fiber has normal dispersion at the pumping wavelength and zero dispersion at 875 nm. The output spectrum is smooth and stable, and well suited for pulse compression or optical coherence tomography, OCT.

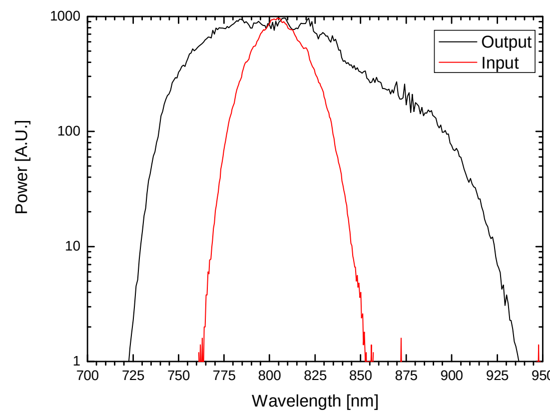

Figure 5 In- and output spectrum measured on 12.5 cm fiber pumped at 800 nm with 25 fs pulses (average power 53 mW and repetition rate 76 Mhz). The fiber has normal dispersion and zero dispersion at 875 nm.

The output from the normal dispersion pumping changes dramatically, when the pump is moved closer to the zero-dispersion wavelength, and other nonlinear effects start to participate. **Figure 6** shows supercontinua for four different pumping wavelengths - all at a coupled average pumping power of 50 mW. The pumped fiber is a highly nonlinear 2.5 µm core fiber. It has –50 ps/(km·nm) dispersion at 800 nm and zero dispersion around 900 nm. The fiber is very similar but not identical to the one used in Figure 5. The fiber is pumped with a mode-locked Ti:Sapphire laser producing 20 nm broad 100 fs pulses with a repetition rate of 76 MHz. Note that the absolute power levels of the spectra are not directly comparable due to differences in output coupling.

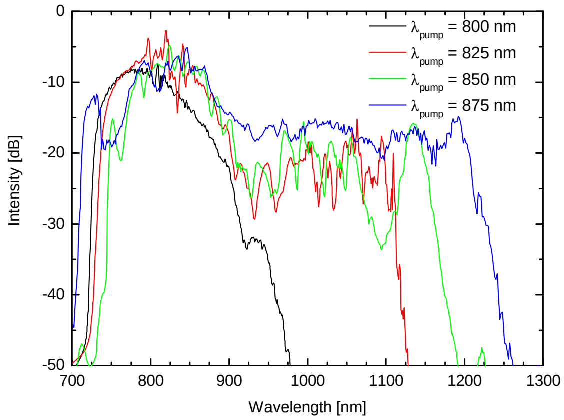

Figure 6 Supercontinuum formed with pumping at different wavelengths in a fiber with zero dispersion at approximately 900 nm. The fiber is pumped by 100 fs pulses with a repetition rate of 76 MHz. [5]

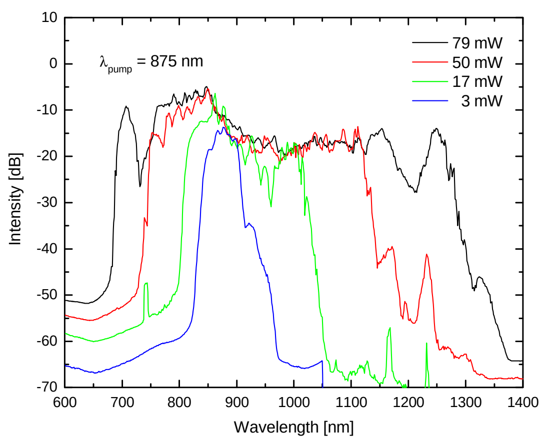

Figure 7 Supercontinuum formation with pumping at 875 nm at four different average pumping power levels. The fiber is pumped by 100 fs pulses with a repetition rate of 76 MHz. [5]

Pumping at 800 nm leads to broadening as described in the previous section but the zero-dispersion wavelength is now closer to the pumping wavelength and SPM and Raman scattering broadens the spectrum into the anomalous regime. Consequently, a soliton is formed around 940 nm and it self-frequency shifts to longer wavelengths, as the pumping power is increased [14].

To maximize the broadening at a given pumping power, it is advantageous to choose a polarization maintaining (PM) nonlinear fiber. Pumping a PM fiber with the pump source polarization aligned to one of the principle axes in the fiber yields a power advantage close to a factor of two compared to a non-PM fiber. Moreover, the output from the fiber is also polarized, increasing the usability of the generated light. In Figure 8 is shown the output from a 1m long NL-PM-750 fiber pumped at 800 nm with 67mW average power and a pulse length of 50 fs.

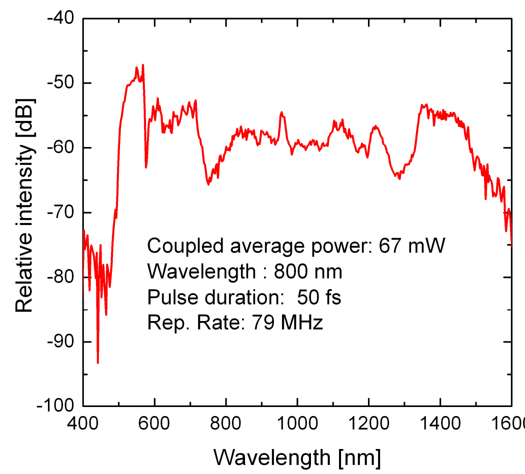

Figure 8 Octave-spanning supercontinuum generated in 1 m NL-PM-750 fiber.

The examples given above are valid for fibers where the two zero-dispersion wavelengths are spaced with several hundred nanometers. However, it is possible to fabricate nonlinear PCFs where the two zero-dispersion wavelengths are very close. Such fibers open up completely new possibilities for supercontinuum generation.

The following example is from the NL-1.4-775-945 fiber which has zero-dispersion at 775 and 945 nm. When this fiber is pumped around 800 nm, the resulting continuum is very different from the spectra shown in the previous sections. All power in the area between the two zero-dispersion wavelengths are converted to two peaks at each side in the normal dispersion region. The depletion of the pump is so effective, that more than 99% of the light is converted to the two side peaks (see Figure 9).

The two side peaks are very flat, and what is even more interesting; they are virtually insensitive to fluctuations in wavelength, pulse energy and chirp of the pump pulses, resulting in highly stable spectra.

When the pump wavelength is tuned, the ratio between the two peaks varies while the center wavelengths remain unchanged. Consequently, one can pump the fiber anywhere between the two zero-dispersion wavelengths and generate light in the same two wavelength regions. The centers of the peaks are determined by the zero-dispersion wavelengths, and one can therefore directly design the output spectrum by changing the zero-dispersion wavelength, creating a fiber that generates light in any part of the visible and near-infrared spectrum. The phase of the pulses is smooth and the spectra are suitable for subsequent compression, or they can be used as-is for e.g. optical coherence tomography or other applications requiring low noise and stable smooth spectra.

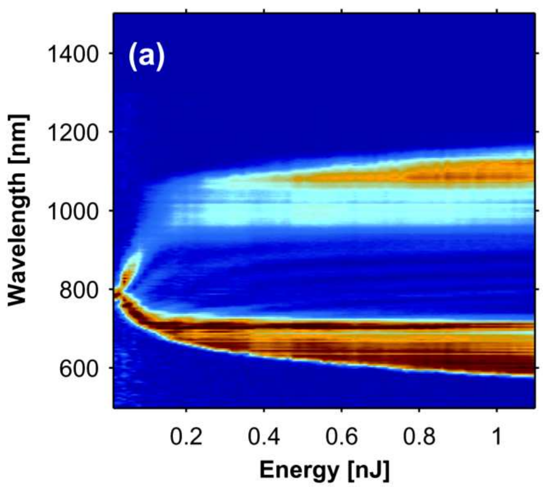

Figure 9 Supercontinuum from a NL-1.4-775-945 fiber at different pulse energies. Experimental results on continuum created by 790 nm pumping in 5 cm fiber (40 fs pulses). From reference [7]

The dominant nonlinear processes behind the double-peak spectra are four-wave mixing and self-phase modulation. The SPM process initially broadens the pump pulse after which the phase matching conditions are fulfilled and the two peaks are generated. The simple process facilitates easy design of fibers optimized to generate light in a selected wavelength range.

More detailed descriptions of the experiments and the nonlinear processes involved can be found in reference [8].

Supercontinuum does not necessarily require large expensive femtosecond systems, but can also be realized with more cost-effective telecommunication sources and fiber amplifiers.

When pumping with slow pulses around 1060 nm, the broadening is typically dominated by Raman scattering, and it is difficult to reach the short wavelength below 1 µm, but by combining pumping at 1064 nm with its second harmonic component at 532 nm, it is possible to reach wavelengths on the short side of both pump sources. Figure 10 shows the output from simultaneously pumping with 1064 and 532 nm in a NL-2.0-740 fiber spliced between two pieces of standard fibers. The pulses have a peak power of ~3 kW at a repetition rate of 5 kHz. The spectral coverage is at least two octaves, with the measurement range limited by the optical spectrum analyzer, spanning from 430 to 1750 nm.

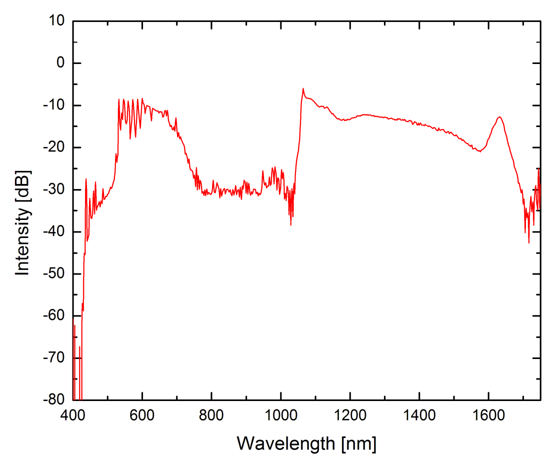

Figure 10 Supercontinuum generated in a nonlinear fiber with zero dispersion at 740 nm by simultaneous pumping with nanosecond pulses at 1064 and 532 nm. Measurements by Scott C. Buchter, Optical Fibre Group, Helsinki University of Technology [4].

A close up of the 400-600 nm region is shown in Figure 11. When pumping solely with 532 nm, only stimulated Raman scattering is observed. However, when the 1064 nm pulses are launched in the fiber simultaneously, new components are created on the low wavelength side of the 532 nm peak. This 100 nm flat plateau is created by FWM between the two pump pulses.

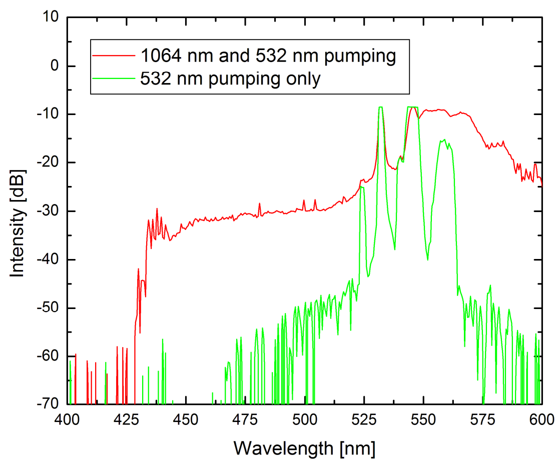

Figure 11 Generation of short wavelengths by dual pumping with 532 and 1064 nm in a NL-2.0-740 fiber. Measurements by Scott C. Buchter, Optical Fibre Group, Helsinki University of Technology.

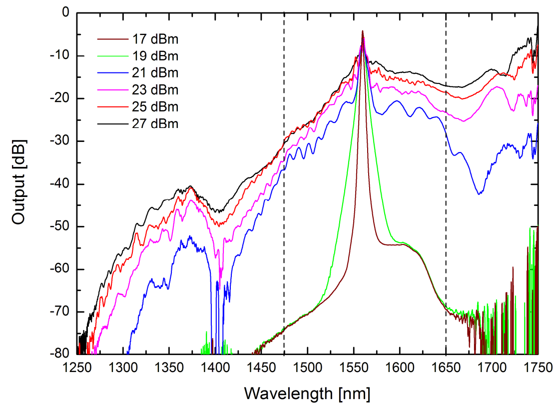

Figure 12 Supercontinuum spectra from a NL-1550-POS-1 fiber pumped with a 2 ps 1555 nm source at six different pumping powers. The shown power levels are average coupled pumping power. Dashed lines indicate the two zero-dispersion wavelengths of the fiber.

Two closely spaced zero-dispersion wavelengths are not only available at 800 nm, but can also be realized at telecom wavelengths in the NL-1550-POS-1 fiber which features zero-dispersion wavelengths close to 1475 and 1650 nm. Pumping between the zero-dispersion wavelengths can therefore be realized with readily available telecommunication sources operating at 1555 nm. Figure 12 shows the resulting supercontinuum from pumping 100 m fiber with a 2 ps source at 1555 nm running at a repetition rate of 10 GHz.

Despite similarities in dispersion, the output of the dispersion-flattened fiber is significantly different from the results obtained at 800 nm. The two FWM-side-peaks are still generated, but the area between the zero-dispersion wavelengths is not depleted. This is due to the lower pulse energy (0.05 nJ) and the nonlinear coefficient of the fiber, which is only 1/10 of the value for the 800 nm fiber. Consequently, the SPM process is drastically reduced, which then reduces the FWM efficiency. The resulting spectrum features a large peak created by residual pumping light and a long-wavelength part dominated by Raman scattering. Pumping with faster pulses will increase the SPM process and thereby decrease the amount of residual pump light in the spectrum but it is unlikely to result in massive pump depletion as possible at short wavelengths.

Pumping the dispersion flattened NL-1550 series fibers with a femtosecond source yields a more flat and wide spectrum compared to picosecond pumping. **Figure 13** shows the output from 10m NL-1550-ZERO-1 pumped by an IMRA Femtolight B-60 fiberlaser (50mW, 1nJ, 110fs) at an average coupled power of 22 mW.

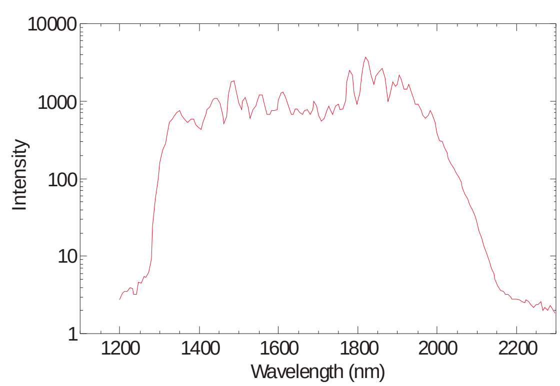

Figure 13 10m NL-1550-ZERO-1 pumped by an IMRA Femtolight B-60 (50mW, 1nJ, 110fs) at an average power of 22 mW. Measurements by Akira Shirakawa, Institute for Laser Science, University of Electro-Communications, Japan.

Supercontinuum Applications

The most straight-forward application for supercontinuum sources is a replacement for the common, and often tungsten-based, white-light sources used in many characterizations setups like interferometer-based dispersion measurements, broadband attenuation characterization and numerous spectroscopy and microscopy setups. The major disadvantage to all incandescent sources is the low brightness, which is determined by the filament temperature (black body radiation). Sources with higher output power utilize larger filaments with same brightness and the power that can be coupled to a single-mode fiber is therefore the same. Moreover, the efficiency of light coupling from the filament to the fiber is generally low, resulting in only a small fraction of the light being available in the fiber. The supercontinuum source solves both the brightness and coupling issue and it is possible to create sources with the spectral width of a tungsten lamp and the intensity of a laser.

The big issue in incandescent-light replacement-sources based on supercontinuum generation is the pump source. A white-light source can, in its simplest form, be build for a few hundred dollars and takes up very little of the precious laboratory space. In the extreme case, a supercontinuum source re-quires a large femtosecond laser system worth hundreds of thousands of dollars, and it is therefore crucial to develop more compact and cost-effective supercontinuum schemes. In this development, the long pulsed nano- and picosecond-sources around 1060 nm seem promising and especially the dual-wavelength pumping scheme shown in section 4.4 is expected to yield both cost-effective, compact and portable devices.

Most supercontinuum experiments yield output in the mW-range, but systems with high average power have also been realized. As an example, a 900 nm broad supercontinuum source with an aver-age output power of 2.4 W was recently demonstrated [17]. The output was generated by pumping a 1 m long PCF with zero-dispersion wavelength at 975 nm. The fiber was pumped by a mode-locked Nd:YVO4 laser with a pulse length of 10 ps, repetition rate of 85 MHz and an average power of 5 W. The complete system is simple and compact (500x250x100 mm3) and potentially cost-effective.

Broadband sources are also needed for the low-coherence-based imaging-technique *optical coherence tomography* (OCT) [12]. OCT has been used extensively in a large wavelength range for both bio-logical and non-biological applications. However, for biological applications, wavelengths in the 1.3-1.5 micrometer wavelength range are highly attractive as they provide high penetration depth in the biological tissue. This is unfortunately contradictive to the aim for high resolution, as the longitudinal resolution of OCT is inversely proportional to the width of the source and proportional to the square of the center wavelength

Consequently, long wavelength has resulted in poor resolution, as the spectral width of the source has not been sufficiently large. Typical sources for OCT are super luminescent diodes and sources based on amplified spontaneous-emission, ASE, from doped fibers or semiconductors. Common for all these sources are limited spectral bandwidth and restrictions to wavelength range.

These issues have been solved by using supercontinuum sources, where the enormous band-width has resulted in unprecedented resolution. In this way, a longitudinal resolution of only 2.5 µm has been achieved by using a 1210 nm broad supercontinuum ranging from 390 to 1600 nm, generated by using 2 nJ 100 fs pulses from a Ti:Sapphire mode-locked laser [6].

1060 nm pumped systems are expected to be very useful, as the slow pulses create a large flat continuum generated mostly by Raman scattering, which is very stable. The large continuum can then be filtered to select the desired wavelength range – filtering which is easily obtained in e.g. bandgap guiding fibers, which guide light in only a limited wavelength range.

The massive spectral broadening achievable in the fibers can also be used to create extremely precise frequency standards. The output from a mode-locked femtosecond-oscillator consists of a range of equidistant modes with a spacing given by the repetition rate of the laser (also known as a frequency comb). The frequency of the n'th mode, ν_n, of the laser is given by

$$\nu_n = n \cdot \nu_{rep} + \nu_0$$

in which ν_0 is the offset frequency, which cannot be measured directly with high precision. If the out-put from the laser is broadened such that the output spans more than one octave, one now has access to both ν_n and the frequency doubled component $2 \cdot \nu_n$. If these two components are mixed, a beat signal occurs, yielding the offset frequency directly:

$$2\left(n \cdot \nu_{rep} + \nu_0\right) - \left(2n \cdot \nu_{rep} + \nu_0\right) = \nu_0$$

The frequency of all modes are now known with same precision as the repetition rate, which can easily be measured with a fast photodiode as it is typically on the order of 50 MHz to a few GHz. The technique is very effective, and frequency standards based on supercontinuum generation were one of the first applications of supercontinuum generation to be commercialized.

More details can be found in reference [16] describing the fundamental principle, and in reference [9-11,15] where the technique is expanded by the use of supercontinuum generation.

Fiber Selection Guide

The choice of fiber for supercontinuum generation naturally depends on the wavelength range in which one whishes to generate light, and on the available pumping sources. In the following paragraphs we go through the most important choices one must make when selecting a nonlinear fiber for supercontinuum generation.

Choosing zero-dispersion wavelength

As a rule of thumb, the source should be in the lower half of the desired wavelength range, and the fiber should have a zero-dispersion wavelength close to the pumping source center frequency.
Depending on the available pump sources, we recommend to start with one or more of the following fibers:

800 nm femtosecond sources:
NL-PM-750 (broad polarized spectra)
NL-1.4-775-945 (smooth double peak spectra)

1060 nm pico- or nanosecond sources:
NL-4.8-1040
NL-5.0-1065
SC-5.0-1040 (see also separate application note on this fiber)

1550 nm femto- or picosecond sources:
NL-1550-POS-1
NL-1550-ZERO-1
NL-1550-NEG-1 (if solitons are to be avoided)

The listed fibers are standard products, and only represent a small fraction of our nonlinear fiber program. Contact us for a complete list of available fibers.

Choosing single-mode cut-off wavelength

Whether cut-off is important or not is determined by the pump source. In general, pumping with a single-mode source yields a single-mode continuum output, even in the range where the nonlinear fiber is multi-mode. If the fiber is also multimode at the pumping wavelength, it requires careful coupling to achieve single-mode operation.

If strict single-mode operation is to be guaranteed or if the pump source is not single-mode, the fiber chosen should be single-mode at the pumping wavelength and ideally over the entire region in which one wises to generate light.

Choosing length

The required length depends on the pulse length of the pump source – faster pulses, shorter fibers.
For femtosecond pumping 1m or less is generally sufficient. Pico- and nanosecond pumping at 1060 nm require 10-20 m of fiber.

Choosing termination

While it is perfectly possible to couple to and from bare cleaved fiber, we generally do not recommend this solution for several reasons. The bare fibers are more sensitive to contamination and cannot be cleaned. Moreover, the facets are easily damaged, making re-cleaving necessary.

For free-space coupled systems, fibers with collapsed and cleaved end facets or fibers with connectors are preferred. For fiber-coupled systems, connectorized fibers are a must. If the dispersion is critical for the application, and one wishes to minimize disturbance from other fiber types, we recommend to chose a directly connectorized fiber. If mode-field matching to other larger fiber types is needed, one should chose a nonlinear fiber spliced to standard fibers.

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- Research Center COM, Technical University of Denmark.
- Optical Fiber Group, Helsinki University of Technology
- Institute for Laser Science, University of Electro-Communications, Japan

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