Application Note:

Compact ultra-bright supercontinuum light source

Index

Introduction

This application note outlines how to integrate a specially designed photonic crystal fiber (PCF) with a new breed of passively Q-switched Nd^{3+}-microchip laser to form a compact and low-cost, ultra-bright supercontinuum source covering the spectral range of 550-1600 nm with a spectral “flatness” of better than 5 dB over the entire range.

What is a supercontinuum?

One of the unique features of lasers is that they are monochromatic – their output consists of just one wavelength. Another special property is that they are exceptionally bright when compared to thermal “white” light sources: a large amount of power is not only concentrated in a small spectral window but can also be focused tightly onto a small area. Despite their low brightness, however, white light sources have a wide range of applications, due to their broad and smooth spectrum and low temporal coherence.

Supercontinuum (SC) sources are a new type of light source that provide a combination of these desirable features: high output power, a broad, flat spectrum, and a high degree of spatial coherence that allows tight focusing. In applications such as the measurement of fiber or component attenuation, interferometry or spectroscopy, supercontinuum sources can often drastically improve the signal-to-noise ratio, reduce the measurement time or widen the spectral range over which measurements can be made.

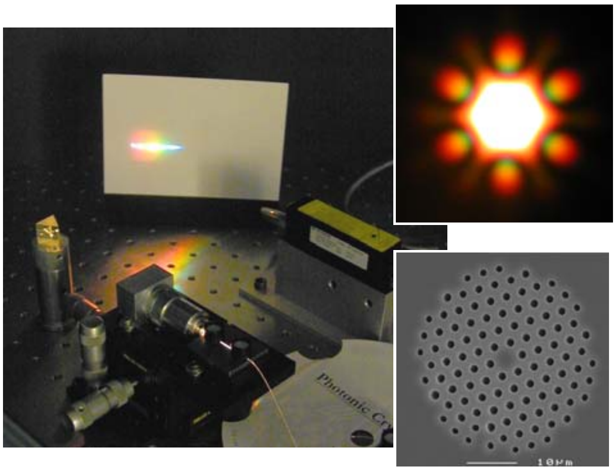

Fig. 1: Supercontinuum radiation viewed with a dispersing prism. Top right: Far field at the output of the photonic crystal fiber. Bottom right: Scanning Electron Micrograph

A supercontinuum source typically consists of a pulsed laser and a non-linear element, in which a combination of non-linear effects broadens the narrow-band laser radiation into a continuous spectrum without destroying the spatial coherence of the laser light. Photonic crystal fibers (PCFs) are uniquely suited as the non-linear medium for such sources, offering high non-linearity, suitable dispersion characteristics and ease of use.

Applications

Photonic device testing – Light source for measuring the optical properties of single-mode waveguide devices and fibers in the S, C and L bands and at 1310 nm. Possible uses include the measurement of fiber and waveguide attenuation, testing lasers and amplifiers at

915, 980 and 850nm wavelength, and characterising polymer waveguides in the visible part of the spectrum. Using a supercontinuum source for these measurements provides the brightness required to overcome a high level of attenuation.

Low-coherence "white light" interferometry – Broadband source for the highly accurate interferometric determination of the position of flaws in optical waveguides, for displacement measurements, or for the measurement of chromatic dispersion in fibers and planar waveguides. Since the spatial resolution achievable with low-coherence interferometry increases in proportion to the bandwidth of the source, supercontinuum sources offer significant advantages over other single mode light sources in this application.

Optical coherence tomography – Powerful, broadband, single mode source for achieving high spatial resolution and scan speed in transverse and longitudinal directions[1].

Spectroscopy – Fast data acquisition on small-volume samples in biology, chemistry, medicine, physics or environmental monitoring. Due to its high degree of spatial coherence, supercontinuum radiation can be focused to a small spot, or collimated to a narrow beam for long path length measurements in low absorbance analytes.

Broadband light sources compared

Fig. 2 compares the power spectral density of various fiber-coupled broadband sources:

With a spectral power density of -30 dBm/nm (0.6 µW/nm) in a single spatial mode, the supercontinuum source described in this note equals or exceeds the brightness of a typical fiber coupled SLED source, but offers greatly improved spectral flatness and bandwidth.

ASE sources based on Rare Earth doped fibers are comparable in total output power, but compared to the SC source described here, their output spectrum is narrower, and they are limited to wavelengths for which suitable dopant/host combinations are available.

When compared to a thermal (incandescent) fiber coupled source, the SC source covers a comparable spectral range, but is thousands of times brighter, providing a signal-to-noise advantage of 30-40 dB in many applications.

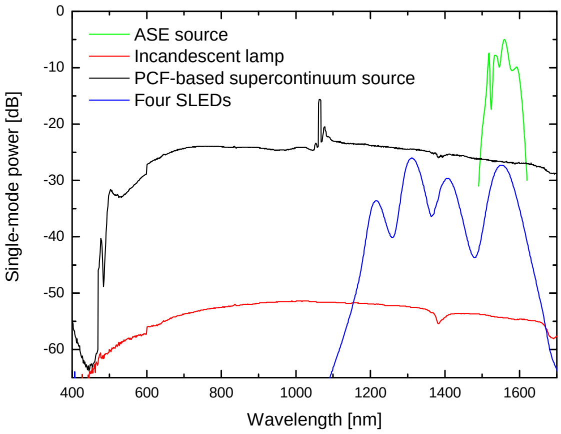

Fig. 2: Comparison of the power spectral density delivered into a single mode fiber for various broadband light sources. The SLED source contains four separate SLEDs with different centre wavelengths. The total integrated power for of these spectra are: ASE-source: 13 mW (+11 dBm), SLEDs: 160 µW (-8 dBm), Incandescent lamp: 3 µW (-25 dBm) and Supercontinuum source: 2 mW (+3 dBm)

Pulsed output

One important difference has to be pointed out: while ASE, SLED and incandescent sources can be operated continuous wave (CW), or are even limited to CW operation, the output of this SC source consists of pulses with a duration of ≈0.5-1 ns and a repetition rate of 6 kHz, resulting in a duty cycle of $\approx 10^{-5}$, and a peak power of up to ≈10 kW, determined by the Nd^{3+}-laser used as the pump. One added advantage is that the pulsed mode of operation makes the SC source highly insensitive to back-reflections.

In many applications, the detection systems used will provide sufficient temporal integration so that the SC source can be employed as a straightforward replacement for a CW source. In others however, the temporal response or the dynamic range of the detection system or of the process or component under investigation may be limiting, and the pulsed nature of the SC radiation should be taken into account. Furthermore, since the passive Q-switching process in the pump laser is free-

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[1] Higher pulse repetition rates than those available from the source described in this application note can be attained by using different types of pump lasers

running, it is not generally possible to synchronise these pulses to an external clock.

Experimental setup

Figures 3 and 4 show the laboratory breadboard setup of the PCF supercontinuum source, with which the results reported in this document have been generated. A JDS Uniphase Nanolase™ NP-10620-100 laser serves as the pump. Since the output of this laser is slightly divergent, an *f*=160mm lens is used to collimate the output beam. Two highly reflecting folding mirrors are used to adjust the horizontal and vertical position as well as the angle of the pump beam relative to the axis of the microscope objective that couples the pump light into the fiber. The setup occupies an area of approximately 250 × 550 mm.

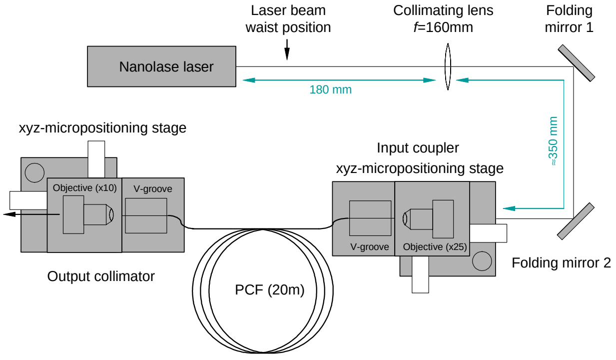

Fig. 3: Schematic of experimental setup

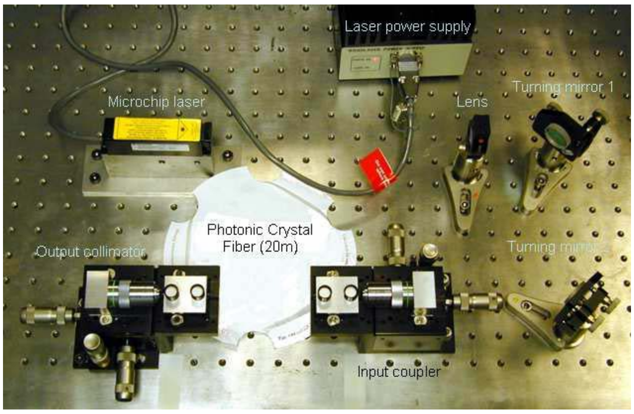

Fig. 4: Experimental setup, including Teem Photonics Nanolase™ microchip-laser, input and output coupling optics.

Parts list

Supplier	Description	Part number	Qty
Crystal Fibre	Photonic Crystal Fiber	SC-5.0-1040	20 m
Teem Photonics	Nanolase laser	NP-10620-100	1
	Nanolase power supply[2]	PS-01402-100	1
Melles Griot	Microblock	17 AMB 003/D	1(1)
	Bracket	17 AMA 009	1(1)
	V-groove	17 HFV 001	1(1)
	Lens holder	17 HMO 001	1(1)
	×25 objective	04 OAS 014	1
	×10 objective	04 OAS 010	(1)
	singlet lens *f*=160 mm		1
New Focus	pedestal 2.0"	9954-M	3
	1" Valu-Mount	9773	2
	1" YAG mirror	5104	2
	Short holding fork	9916-M	3
	1" Lens holder	9834	1

Quantities in brackets () are optional items for the free-space output coupling stage.

When properly aligned, the total power at the endface of the supercontinuum fiber should be >50% of the power at the pump laser output. Alignment instructions are available separately. As an alternative to using the output collimator shown in Figs. 3 and 4, the supercontinuum radiation can be used directly from the fiber output or the supercontinuum fiber can be fusion spliced to a suitable output fiber. If a conventional solid fiber is used, the output will, however, not be spatially single mode for all wavelengths, due to the large bandwidth of the supercontinuum radiation. If single mode output at the end of the output extension fiber is required, endlessly single mode PCF should be used as the output fiber[3].

Optical properties

Average power at fiber end	>10	mW
	10	dBm
Peak power	1.5	kW
Spectral width	500-1750	nm

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[2] Options for computer controlled on/off, trigger pulse output and fixed frequency operation

[3] E.g. Crystal Fibre Endlessly Single Mode fiber ESM-12-01

Power spectral density	-30	dBm/nm
	0.5	µW/nm
Pulse repetition frequency*	≈ 6	kHz
Pulse duration	≈ 1	ns
Transverse mode shape	TEM_{∞}	
Stability (>15min)	±0.5	dB

Spectrum

A key advantage of the supercontinuum source is that its output is spectrally flat and smooth. The power spectral density varies by less than 6 dB over a bandwidth of more than 1000 nm, except in the direct vicinity of the pump at 1064 nm. Careful reduction of the water content of the fiber has made it possible to virtually eliminate a dip in the spectrum around the peak of OH^--absorption at 1380 nm wavelength [6].

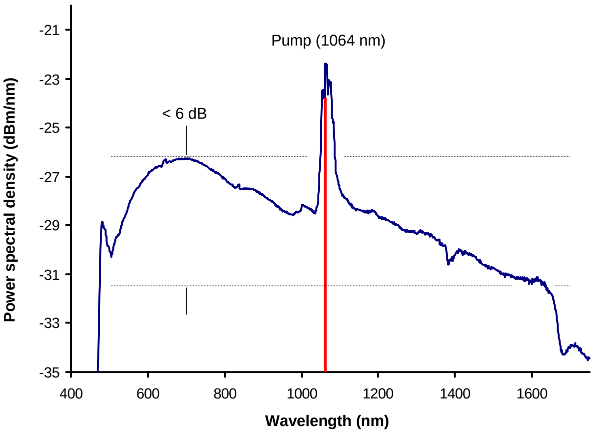

Fig. 5: Power spectral density at the end of 20m of SC photonic crystal fiber. (Pump power in the fiber: 10 mW, pulse width: 1 ns, repetition rate: ≈7 kHz. Spectrometer resolution: 5 nm)

Long term stability

For many applications the stability of the average and peak output power over time is critical, both over timescales of hours (drift) as well as from pulse to pulse. Since the stability of the pump laser, as well as that of the fiber properties and the launch optics, can contribute to changes in the output power, the level of long term stability achievable will depend on the engineering of the source. Fig. 6 gives an indication of what can be expected from a laboratory breadboard setup, as described above.

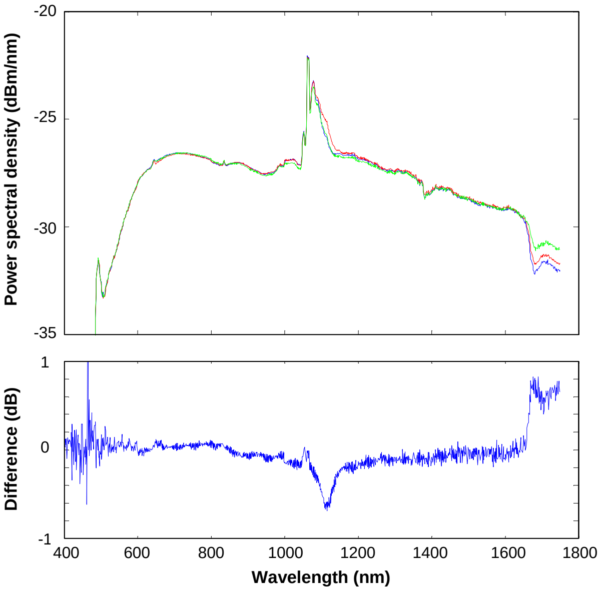

Fig. 6: Long term stability of the PCF supercontinuum. Top: power spectral density immediately after powering up the source laser (blue), after 15 minutes (red) and after 1 hour (green). Bottom: Change in the power spectral density from the end of the 15 minute warm period to the steady state (1 hour).

Pulse-to-pulse stability

Small variations in pump power resulting from the passive Q-switching process in the pump laser can translate into fluctuations of the supercontinuum power. Due to the multistage non-linear processes involved in formation of the supercontinuum, this effect becomes more pronounced with increasing distance in wavelength from the pump. These fluctuations are uncorrelated from pulse to pulse, and can result in detector noise with spectral components around the repetition frequency of the laser.

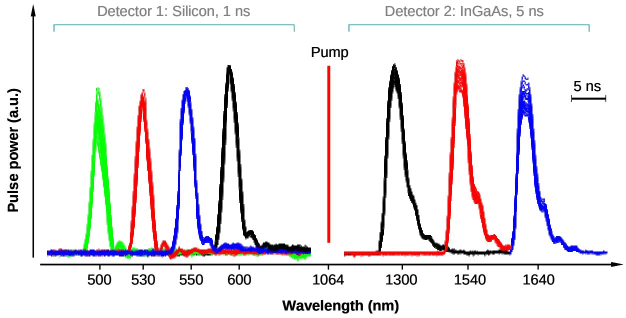

Fig. 7: Pulse-to-pulse stability. Superimposed images of 30 non-consecutive pulses for each wavelength shown. Spectral components closest to the pump exhibit the smallest amount of pulse-to-pulse energy

variation. (Note that different detectors were used for wavelengths >1064 nm and <1064 nm, respectively, explaining an apparent difference in pulse width.)

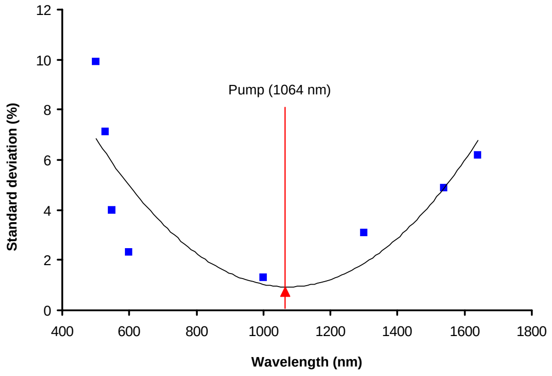

Fig. 8: Standard deviation of pulse energy as a function of wavelength, derived from the measurements shown in Fig. 7 (square: supercontinuum radiation, triangle: pump at input fiber).

Behind Supercontinuum Generation

Supercontinuum generation is the conversion of a single wavelength – in this case the output of a 1064 nm microchip laser – into a broad spectrum through a complex combination of non-linear effects in an optically non-linear medium. What is simple in practice hides an intricate physical picture. The Q-switched laser pulses are sufficiently long that they may be considered continuous wave (CW). In this case the dominant nonlinear process is phase-matched four-wave mixing (FWM), generating sidebands spaced at equal frequency intervals from the pump [1-4, 6]. Conditions for phase matching and conservation of energy give the equations [5]:

$$2k_{pump} = k_{signal} + k_{idler} + 2\gamma P \qquad (1)$$

$$2\omega_{pump} = \omega_{signal} + \omega_{idler} \qquad (2)$$

where k_j are the wavevectors (propagation constants), and ω_j the frequencies of the pump, signal and idler waves, respectively; P is the pump power (in the quasi-CW case the peak pump power is several tens of kilowatts); and γ is the nonlinear coefficient of the fiber:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \qquad (3)$$

where A_{eff} is the effective mode area of the fiber and λ is the pump wavelength. Phasematching and energy conservation determine the wavelength at which the gain of the non-linear conversion process peaks, and this wavelength depends on the chromatic dispersion of the fiber. It is in achieving the appropriate amount and spectral dependence of chromatic dispersion where PCF technology has unique advantages, offering the possibility to design single mode fibers with a zero dispersion wavelength shorter than the pump wavelength of 1064 nm. This is not possible in conventional silica fibers. With a PCF the dispersion at the pump wavelength can be anomalous, and the phase matched sidebands (solutions of equation (1)) are broad and quite close to the pump. As light propagates along the fiber, these sidebands grow in intensity, and then act as the pump for further FWM, in a cascade process eventually generating a broad flat continuum spanning the visible and near infrared part of the spectrum [6].

Even though the intrinsic material non-linearity of silica is not large (non-linear refractive index of silica: $n_2 = 2\times10^{-20}$ m^2/W), the total amount of non-linearity can be significant owing to the substantial length and small effective area of the fiber waveguide. It therefore becomes possible to create a practical supercontinuum source with modest pump powers. For the photonic crystal fiber used here, a peak pump power of a few kilowatts, corresponding to a few tens of milliwatts of average power, is sufficient to achieve complete conversion of the pump power to a broad supercontinuum in 20 m of fiber.

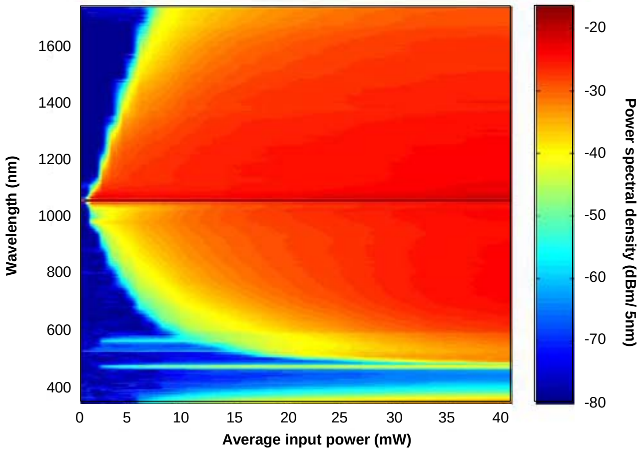

Fig. 9.: Power spectral density at the end of 20m of PCF as a function of average pump power in the fiber (Pulse width 600 ps, repetition rate ≈7 kHz) [6]

The Photonic Crystal Fiber

Photonic crystal fibers are a new type of glass optical fiber in which the cladding contains a regular array of microscopic air-holes running along the entire length of the fiber. The size and position of these holes determine the optical behaviour of the fiber and it is possible to create fibers with highly unusual optical properties not attainable with conventional fiber technology. Light can, for example, be guided in a hollow core, or, as in the case of the supercontinuum fiber, it is possible to create fibers with a zero dispersion wavelength shorter than 1270 nm, the zero dispersion wavelength of bulk silica. Photonic crystal fibers can be divided into two fundamental classes, solid-core and hollow-core:

Solid-core PCFs: Solid-core PCFs can guide light using a similar mechanism to that in conventional fibers: Total Internal Reflection (TIR) from a lower-index cladding material. The supercontinuum fiber falls into this class. In conventional fibers the required index difference between core and cladding is created by doping either the core or the cladding glass. In a PCF, the presence of holes in the cladding causes the weighted average index "seen" by the field to be lower than that of the all-solid core. By altering the arrangement of holes or the shape of the core, optical properties such as mode shape, nonlinearity, dispersion, and birefringence can be varied over a wide range. Furthermore, the fibers can be made from a single solid material without the need for dopants. Additionally, solid core PCFs can be designed to be single mode at all wavelengths by choosing an appropriate combination of hole size and hole spacing, something that is not possible with conventional fiber technology. This feature is exploited in the supercontinuum fiber to ensure that the supercontinuum radiation remains guided in the fundamental mode, despite its very large bandwidth.

Hollow core fibers: Hollow core fibers employ a fundamentally different guiding mechanism: the photonic bandgap (PBG). PBGs can be created in a "photonic crystal" material by forming a periodic array of holes with the correct sizes and spacing. Properly designed, a photonic crystal cladding surrounding the core of a fiber acts as a perfect, loss-free mirror, confining light of certain wavelengths to the core. The choice of index for the core material is not fundamentally constrained, so that it is possible to create optical fibers with gas-filled or even evacuated cores, with very little interaction between the light and the fiber material. This can result in unusually *low* optical non-linearity, making these fibers suitable, for example, for the delivery of powerful, ultra-short optical pulses.

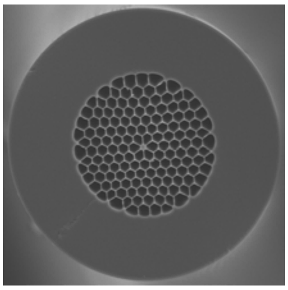

Fig.10 (a): Solid core PCF. This example shows a fiber designed to provide high non-linearity by strongly confining the light in the small central core. Such fibers can be used to create supercontinuum radiation from the femtosecond output of a Ti:Sapphire laser at 800 nm wavelength.

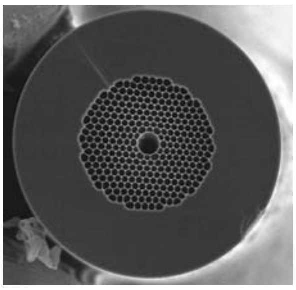

Fig.10 (b): Hollow core PCF. An empty core is embedded in a photonic crystal cladding, formed by large air holes in silica (fraction of hole area to total cladding area >91%). Up to 95% of the light is travelling in the hollow core and the holes in the cladding, and not in the glass.

The most widely-used method for fabricating photonic crystal fibers is to stack silica capillary tubes by hand to form a preform. A core is embedded by omitting several capillaries from the centre of the stack and inserting a rod of glass or a hollow tube in their place. Typically, several hundred capillaries are stacked in a close-packed array and inserted into a jacketing tube to form a fiber preform. A second jacketing tube is added before the final draw. Draw lengths of a few kilometres are typical, but there are no known limits to drawing much longer fiber.

Fig. 11 shows an electron micrograph of the cross section of the supercontinuum fiber. Despite the hexagonal structure of the cladding, the mode field is very similar to that of the fundamental mode of a conventional fiber, with a form overlap in excess of 95%, facilitating the coupling of the supercontinuum radiation into standard fibers.

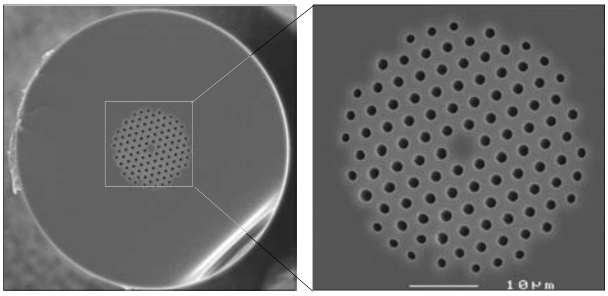

Fig. 11: Supercontinuum photonic crystal fiber. Scanning Electron Micrograph of the fiber cross section and an enlarged view of the central “holey” cladding

The fibers have an outer diameter of 125 µm, a core diameter of 5 µm and are protected by a single layer acrylate coating. They can be stripped and cleaved like conventional solid fibers, and PCFs can be spliced to other PCFs or to standard fiber.

The Nd^{3+}-microchip pump laser

The pump laser for the supercontinuum fiber belongs to a new breed of compact, solid state, passively Q-switched Nd:YAG lasers, available now from several manufacturers in stand-alone and OEM versions. The smallest OEM versions occupy just a few cubic centimetres and require less than 5W of electrical power to operate.

At the heart of these microchip lasers is a laser diode, coupled to a slab of Nd:YAG laser crystal, which in turn is bonded to a thin slab of Cr:YAG that acts as the saturable absorber. Light from the diode laser continuously pumps the Nd:YAG crystal. During this pumping phase, the saturable absorber inside the cavity prevents the laser from oscillating. The population inversion in the laser crystal builds up gradually until the optical gain has increased sufficiently to overcome the losses in the absorber. At this point, oscillation sets in, the absorber becomes rapidly more transparent, and the energy stored in the laser crystal is released in a single Q-switch pulse of typically ≈1ns duration, and up to several tens of kilowatts of peak power in a single spatial mode at 1064 nm wavelength. After the inversion is depleted, a new cycle starts, causing the laser to emit a continuous quasi-periodic train of pulses with a repetition rate of typically 5-10 kHz.

The pump laser used to generate the results reported in this note is the Nanolase™ laser manufactured by Teem Photonics, see Fig 12. The laser head itself occupies just 20×30×100 mm, and a compact external power supply module is available, that also contains the circuitry required to control the laser temperature.

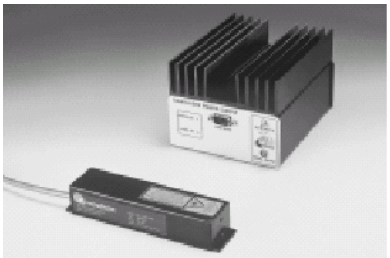

Fig. 12. Teem Photonics Nanolase™ Nd3+-microchip laser head and power supply module.

▪ ey specifications[4]:

Wavelength	1064	nm
Pulse energy	>6	nJ
Pulse width	<1	ns
Repetition rate	5-9	kHz
Average power	≈ 40	mW
Power stability (6 hours)	0.03	
Beam diameter	0.2	mm
Beam divergence	±1	mrad
Beam ellipticity	<1÷1.1	

One drawback of passively Q-switched lasers is that the output pulses are not strictly periodic and that it is not generally possible to synchronise the pulses to an external source[5]. While these micro-chip lasers are convenient to create a compact low-cost supercontinuum source, it is of course possible to employ other, more complex pump lasers with comparable peak power, to pump the supercontinuum photonic crystal fiber.

Fiber preparation and handling

Like standard single-mode telecommunication fibers, the supercontinuum PCF has an outer diameter of 125 µm and is protected by an acrylate polymer coating

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[4] ©Teem Photonics

[5] The Teem Photonics Nanolase™ laser is available with a “fixed frequency” option, which allows the laser to be run at a reduced (<1 kHz), but exactly known, factory-set repetition rate. Since the pulse energy remains unchanged, the average power reduces proportional to the ratio of the fixed and free-running frequency.

of 250 µm diameter. Despite the "holey" region in the centre, the fibers are mechanically no more sensitive than conventional fibers, and general fiber tools and procedures are adequate for preparing the fiber end faces:

Stripping: With a little practice, the coating can be removed mechanically using a blade, or, more easily, by using a hot air gun set to 390˚C.

Cleaving: Specialist cleaving tools (York, Fujikura) generally give the best results, but a diamond scribe or ceramic tile for cleaving will produce perfectly acceptable results with practice. The quality of the cleaved surfaces should be checked under an optical microscope. An important difference from conventional fibers is that the fiber cannot be cleaned with solvents after cleaving due to the danger of ingress of solvent into the cladding holes.

Splicing: The supercontinuum PCFs can be fusion spliced to conventional fibers, but splicing recipes need to be optimised to avoid the collapse of the cladding holes. Splicing instructions are available on request.

The supercontinuum fiber is also available with stripped and cleaved endfaces on request.

Tight bends in the fiber should be avoided and it is recommended to keep the minimum bend radius to at least 20 mm over most of the fiber length. Even short (¼-turn) tight bends can cause significant loss of light, especially at the long wavelength end of the spectrum.

Eye safety

The pump source employed here is a class 3B (class IIIB) laser. Suitable laser safety precautions should be taken and protective eyewear must be worn.

After conversion to a supercontinuum, the beam is still pulsed, and it can still be focused by the eye onto the retina as tightly as a laser beam. Since the output consists of a broad spectrum, protective eyewear that filters out only certain distinct wavelengths is not suitable.

Treat as laser class 4 (class IV)

Operator **training** required

Danger from exposure to direct or scattered beam

References

[1] W.H. Reeves, D.V. Skryabin, F. Biancalana, J.C. Knight, P.St.J. Russell, F. Ominetto, A. Efimov, and A.J. Taylor, "Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibres", Nature 424:511-515, 31st July (2003).

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