Photonic Crystal Fiber
Built-in functionality: Fiber technology that does more than transmit light!

Reducing the complexity of optical systems emphasizes the need to increase the number of optical functions in as few modules as possible, making the system more compact and simple to operate. Optical functions such as light generation, frequency conversion, amplification, broadband transmission, wavelength filtering and interfacing to the outside environment typically needed separate, individual optical components to be chained together to comprise a system. However, with the advent of Photonic Crystal Fiber, many of these functions can be combined into multifunctional modules paving the way for simpler, turn-key systems.

Photonics is increasingly being employed as a tool for analysis, sensing, detection, processing and illumination in many commercial and academic applications. In the past, such techniques required complicated optical arrangements, which could only be operated by individuals experienced in handling optical equipment. However, the widespread penetration of photonics in many fields see the need for optical equipment to be operated by non-experts such as surgeons, production staff or military personnel to name a few. In this case, optical systems need to be built with ease of use as a priority allowing the user to operate the equipment simply by a touch of a button, without complicated startup procedures, beam alignment or wavelength filtering. This is were fiber based systems come into play.

Higher power fiber lasers made possible
Photonic crystal fibers, or PCFs, have been commercially available for a decade and in the labs for even longer. Many of the first results were centered on two special PCF types: The endlessly single mode LMA fiber (see also Info Box) and the dispersion engineered nonlinear fiber. Today, the nonlinear fibers are primarily used in supercontinuum lasers and the endlessly single mode fibers are used to transport the large bandwidth available from such system while keeping a pristine mode quality.

From the early focus on nonlinear and large mode area (LMA) transport fibers, much of the PCF development has moved to active double-clad fibers for oscillators and amplifiers. The need for increasing optical power levels, both in CW and pulsed fiber lasers are critical for applications in material processing and in defense, where a high power fiber laser with good beam quality is required. Traditional fiber technologies are rapidly reaching a ceiling on what can be offered. Standard, non-PCF double-cladding fibers utilize a low-index polymer coating to create the cladding for the pump core. The obtainable refractive index of the polymer limits the numerical aperture (NA) of the fibers (in praxis to below 0.48) which in turn limits the pump power absorption per fiber length and thereby how short a fiber laser can be made. This means a longer fiber laser is required to ensure enough pump is absorbed to generate the higher powers. Moreover, the polymer material itself can pose a challenge in high-power systems due to the risk of degradation at high pump powers and elevated temperatures.

The photonic crystal fiber equivalent to the double-clad fiber is the airclad LMA fiber. The fiber consists of an LMA structure with an active, doped core placed inside an airclad pump guide. Due to the large index contrast, the airclad can provide very large numerical apertures determined by the bridge width in the airclad (typical airclad fibers have NA of 0.6). The airclad has very low loss (a few dB/km) and the power density is only limited by the damage threshold of silica.

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Kim P. Hansen has been a research scientist and project manager at NKT Photonics (previously Crystal Fibre) since 2001, and has been responsible for developing the majority of the company’s nonlinear and active double-clad fiber products. Currently working as product manager for the fiber product line and managing several custom fiber development projects with focus on active double-clad fibers for high-power lasers and amplifiers. Kim P. Hansen studied applied physics and telecommunication and got his Ph.D in 2004 from the University of Denmark.

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When doping glass with rare earths, the index of refraction is increased and as a consequence also the V-parameter of the fiber increases. However, in PCFs the core is generally co-doped with fluorine to compensate for the refractive index increase, whereby the refractive index of the core material is closely matched to silica. The core material, therefore, does not contribute to the guiding properties of the fiber and the modal properties can be controlled by the photonic crystal structure surrounding the core and not by the index step due to the dopants. This allows the doped air-clad PCFs to benefit from the same properties as the passive PCFs and one can, therefore, obtain very large mode field diameters while keeping the fibers strictly single mode. So far we have manufactured up to 100 µm single mode cores, which should be compared to the standard step-index core technology, where the mode field diameter (MFD) limit for single mode fibers is currently below 15 µm (see Figure 1). This limit is mainly due to the limited index uniformity across the core and the challenges involved in achieving a sufficiently small index step to prevent higher order mode guidance. Larger cores can be made, but such fibers typically rely on tight coiling to obtain single-mode operation, which can cause instabilities and mode distortion.

The combinations of a very large MFD and high pump NA makes it further possible to create lasers and amplifiers with sub-meter fiber lengths (the so-called ROD fibers), drastically reducing the nonlinear effects. Nonlinear effects are the main limiting factor for the achievable power levels in a fiber amplifier or laser, and as the nonlinear effects are length dependent, it is critical to minimize the fiber length. Shorter fibers require higher pump light absorption per meter, which can be realized by reducing the ratio between the pump core area and the signal core area. Alternatively, one can increase the concentration of rare earths incorporated in the core, but higher concentration has a negative effect on fiber photo darkening and can lead to lower efficiency. Furthermore, extracting high levels of power from short lengths of fiber requires very good thermal conductivity for proper heat sinking. This challenge can be overcome by simply removing the protective coating of the all-glass airclad fiber and instead make the fiber so thick that it has enough mechanical stability in itself without the protective coating. Moreover, the large outer diameter (typically 1–2 mm) mitigates another issue: macro-bending loss. When the core size is expanded beyond 40–50 µm, the index step in a single-mode fiber is so small, that the bending radius needed for low loss operation becomes too large for practical systems, but the large diameter of the ROD fibers ensures the waveguide is not bent whereby low propagation loss is ensured. The pump absorption of the ROD fibers is so high (typically on the order of 30 dB/m at 976 nm) that the system can often be realized with 50–70 cm of fiber making setups build with straight fiber pieces feasible. Such fibers have been shown to sustain amplification of pulses to MW power levels and they are today deployed in various commercially deployed pulsed fiber laser systems with pulse lengths ranging from femtoseconds to nanoseconds such as the Boreas nanosecond lasers from Eolite Systems and the ultrafast Tangerine oscillators from Amplicity Systemes. The newest development is the DC-285/100-PM-Yb-ROD, which, to the best of our knowledge, is the largest polarization-maintaining (PM) single-mode fiber in the world (see Figure 2).

**INFO BOX**

**PCFs**

The term photonic crystal fiber is inspired by the unique cladding structure of this fiber class in which the index differences 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) and with a degree of index control unobtainable with standard doping techniques. 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. One of the novel features of PCFs is the possibility to design fibers, which exhibit no second-order mode cut-off, rendering them single-mode at any wavelength (also known as endlessly single-mode fibers).

**FIGURE 1:** The aeroLASE-PA100 amplifier engine is based on PCF airclad technology and allows high power performance with true single mode output.

**FIGURE 2:** PCF ROD technology allowing amplification to MW pulsed peak power levels with true single mode.
The fiber features a 100 µm 19-cell core surrounded by a PCF cladding with two imbedded boron-doped regions. The signal guiding structure is surrounded by a 285 µm pump cladding with an NA of 0.6. The fiber is single-mode with a mode field diameter of approximately 75 µm and an NA on the order of 0.02. This fiber was recently used by Fabio Di Teodoro from Northrop Grumman Aerospace Systems to create a MOPA system producing sub-ns pulses of >1.35MW peak power with > 100 kW cm⁻² Hz⁻¹ sr⁻¹ peak spectral brightness, which exceeds state-of-the-art fiber results by about an order magnitude. The results were reported on at this year’s Photonics West conference in San Francisco [1].

Nonlinear Fibers and supercontinuum generation

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 [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. The introduction of the nonlinear PCFs with zero-dispersion wavelengths in the range of commercially available pulsed lasers led to the rapid development of supercontinuum applications (see Figure 3).

Supercontinuum light combines the attractive properties of a laser and a lamp. The broadband spectrum of supercontinuum light brings many advantages to applications where a number of wavelengths are required. Lamps do have the broadband nature of supercontinuum, but lacks the brightness and only a small part of the light emitted by a lamp can be coupled into a single mode fiber. Lasers are inherently bright sources which lend themselves to routing by single-mode fibers but for users who need a number of different wavelengths, a combination of several lasers is required. This is not only complicated, but...
can be expensive with the drawback that not all wavelengths are available as laser sources. Moreover, alignment and multiplexing of lasers is problematic in industrial environments, where vibration and temperature changes can lead to the need for frequent realignment and maintenance. The supercontinuum source gives the user the flexibility of having high single mode power together with the access of any wavelength in the supercontinuum spectrum – all in an alignment free compact format.

The SuperK product range from NKT Photonics is an example of how the benefits of PCF technology have allowed the construction of a compact, turn-key supercontinuum source. The SuperK is a supercontinuum fiber laser, which contains a high power picosecond laser together with nonlinear fiber to generate high power supercontinuum. In this case, not only is the nonlinear fiber based on PCF technology, but the amplification of the picosecond fiber laser is based on PCF. The system truly epitomizes the multi-function aspect of PCF technology within the unit. The supercontinuum fiber laser has been integrated into the Leica Microsystems SP5x confocal microscope as the light engine (Figure 4).

Here, the advantage to obtain any wavelength at laser power levels in the visible compared to conventionally using 4-6 single wavelength lasers allows users to see cells stained with fluorescent dyes with increased sensitivity, typically important in areas of drug discovery or cancer detection.

Supercontinuum generation is not limited to stand-alone fiber sources, but can also be realized as an extension to existing laser sources. E.g., a commercial Ti:Sapphire fs laser can be used to pump a PCF module to generate a supercontinuum between 500nm-1700nm. The zero-dispersion wavelength is optimized to be close to the 800nm pulsed output of Ti:sapphire lasers (see Figure 5).

One application is CARS microscopy. CARS (Coherent Anti-Stokes Raman Spectroscopy) requires two beams (Stokes and Anti-Stokes) to tune into the vibrational resonances of cells. Here, each wavelength needs to be tunable (i.e. a continuous spectrum is needed). Usually, expensive picosecond lasers pumping optical parametric oscillators are required to produce the two tunable beams. However, with the use of Ti:Sapphire lasers already employed in multi-photon excitation microscopes, an additional PCF module with two zero dispersion wavelengths can be integrated to provide the additional ability to perform CARS microscopy (Figure 6) [4].

Fibers with filters
As described above, photonic crystal fibers can be used for both amplification and generation of new wavelengths, but they can also include filtering functions. Fibers that rely on the photonic band gap (PBG) effect for confinement has the unique property, that they only guide in a specific wavelength range outside of which, the attenuation is hundreds of dB/m. PBG fiber designs are not limited to hollow core fibers, but can also be realized in all-solid designs, where the air-holes are substituted with high index glass-regions, whereby one can create PBG fibers with solid cores, that can be doped with rare earths like conventional PCFs. Combining a doped PBG core with an airclad, this very strong filtering effect can be used in a variety of applications, among which the two major ones are traditional out-of-band amplified spontaneous emission (ASE) filtering in low signal-level amplifiers and gain shaping for long wavelength amplifiers.

Traditional ASE filtering is important in multi stage amplifier chains, where ASE from the first stages is amplified in subsequent stages. By introducing a strong filter in the fiber, one can suppress the ASE allowing the gain in each stage to be increased, thereby reducing the number of amplifier stages needed. Fewer stages leads to lower cost and a more compact and efficient system.

Gain shaping is relevant for long wavelength systems that operate at the tail of the gain bandwidth. One notable example is Ytterbium fiber amplifiers running at 1178 nm that can be frequency doubled to 589 nm.

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NKT Photonics A/S uses its PCF platform to design and manufacture industrial fiber solutions within high-power fiber amplifiers, supercontinuum lasers and ultra precise DFB fiber lasers under the brand names CrYSTAL FIBRE, aeroLASE™, SuperK™ and KoHERAS™. These systems are commercially deployed in material processing, bio-photonics, metrology, optical sensors, coherent communications, test and measurement, spectroscopy and LIDAR markets. NKT Photonics A/S is wholly owned by the Danish industrial conglomerate NKT Holding A/S.

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589 nm – a wavelength of interest for medical and astronomical application. At 1178nm, the gain is extremely low in Ytterbium, and in a free running system, an Ytterbium amplifier seeded at this wavelength will be completely dominated by the strong ASE at 1030nm causing the system to lase in this wavelength region instead of providing amplification for the 1178nm seed. If the fiber contains a strong PBG filter, that filters below 1178 nm, one can create a system where the gain peaks at 1178nm, leading to amplification at this wavelength without any extra components. Such a system was recently demonstrated running at a record high power of 167 W [5].

PBG fibers are only one way to create a distributed filtering effect in a PCF. Another is to use spatially confined resonant structures whereby one can selectively couple different modes and wavelength regions out of the core. Resonant designs are attractive as they offer a high degree of flexibility in designing both the width and center wavelength of the transmission passband [6]. Moreover, where the PBG fibers have a tight design relation between the core size and the operation wavelength, fibers with resonant couplers, can be designed with an arbitrary core size for any given wavelength region. Thus, such fibers are especially interesting for amplifier fibers with very large cores where one needs filter functionality – such as narrow linewidth 1178nm lasers for frequency conversion.

Conclusion

Intelligent design of PCF technology to control optical fiber parameters allows the realization of extra functionality within the fiber. High power, true single mode amplification, broadband supercontinuum generation and efficient filtering are just some of the unique features that can be embedded within the fiber. NKT Photonics continuously pushes the technology to enable new functionality which can be available as bare fiber, self-contained modules or fully integrated systems. New PCF technologies are being developed for example with hollow core technology, which is a unique breed of fiber with specific properties and PCF technology that extends into the IR. With the optical industry always looking for methods of increasing functionality together with reducing complexity, PCF technology is already providing realistic solutions. The immense efforts being devoted to PCF research around the world will ensure that there will not be a shortage of applications that will be untouched by this technology.

References