

High Power Fibre Lasers and Nonlinear Optics for Wavelength Diversity

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Integration of MOPFA (Master Oscillator Power Fibre Amplifier) technology with photonic crystal fibre has led to a family of compact, versatile, broad band (500nm-2000nm) sources with pumps operating from CW to femtosecond. High spectral power density ($\sim 20\text{mW/nm}$) is achieved in the continua and scaling points to 100mW/nm being readily possible with single mode delivery. Through the introduction of air-core photonic bandgap fibres, further pulse compression and high peak power is achievable in all-fibre chirp pulse amplifier configurations.

Introduction

Over the past five years there has been quite remarkable progress made in the operational power levels of multi-clad rare earth single mode doped fibre lasers [1] and these devices are beginning to replace conventional and diode-pumped solid state lasers in many application areas. Interest has primarily been directed towards Yb-based schemes, broadly operating around $1.06\ \mu\text{m}$ and although highly efficient wavelength conversion has been demonstrated, using for example frequency doubling and parametric generation using external nonlinear crystals, nonlinear generation in optical fibre remains an attractive alternative, not least because the all fibre format can be maintained, allowing a hands-free approach and simplification of any developed instrumentation. Parallel development in photonic crystal fibre [2] has allowed families of fibres to be produced with designer controlled parameters applicable to the optimization or even elimination of nonlinearity. These have allowed versatile, yet simple, all fibre configurations to be developed for non linear generation. Here we describe some of these approaches to produce spectrally bright (10's mW/nm), high power supercontinuum generation, with average powers of tens of Watts using various fibre laser pump formats from cw to picosecond as well as femtosecond chirped pulse amplifier schemes.

High Power CW pumped Supercontinuum

Traditionally, pulsed formats have been the preferred fundamental pump source for the vast majority of non linear generation investigations, simply because of the peak power dependence of the processes. However, with the exceeding long interaction lengths allowable with low loss fibres and micron sized cores, the generation of most nonlinear process is possible in optical fibres at readily achievable cw pump powers.

Using nanosecond pumping from gain switched DBR diodes at $1064\ \text{nm}$ in a Yb-seeded MOPFA configuration has allowed peak powers of up to 150W , in $3.5\ \text{ns}$ pulses at variable repetition rate $5\text{-}50\text{MHz}$ and average powers up to 15W . These pulses launched into an integrated photonic crystal fibre, approximately $10\ \text{m}$ long with a core diameter of $2.6\ \mu\text{m}$ and a zero dispersion around $900\ \text{nm}$ allowed the generation of a supercontinuum extending from the pump wavelength to approximately $1.38\ \mu\text{m}$. Considering the power-length factor of approximately 1kW.m indicated that with a

100m long fibre and 10W average power, a rather modest requirement from a Yb fibre source, would be adequate to generate a similar supercontinuum [3].

Figure 1 shows a representative continuum spectrum obtained at 9.4W cw pump power. Both laser pumping and ASE seeded amplifier pumping were investigated at equivalent cw power levels. The 100m long holey fiber had a core diameter of 2.3 μm and an estimated 1.06- μm dispersion of ~ 30 ps/(nm km). In the 1.0-1.2- μm range the attenuation of the holey fiber was nearly constant with a ~ 15 dB/km value, while attenuation peaks of ~ 38 dB/km and 1070 dB/km were present at 1.25 μm and 1.38 μm respectively. The characteristics of the continuum were investigated by employing spectral slicing with further autocorrelation (soliton structure analysis), optical spectrum analyzer (OSA), scanning Mach-Zehnder interferometer (coherence-length measurements), and a fast 50GHz detector with RF spectrum analyser (noise measurements). The flatness of the 5.5W total power continuum was better than 10dB (peak-to-peak) in the 1.09-1.37 μm range and was under 3dB in the 1.12-1.33 μm range. The roll-off of the continuum at 1380nm is related to the water-peak absorption losses. In the 1.09-1.37 μm range, continuum power was 2.3W which correspond to a spectral power density of 8.2mW/nm.

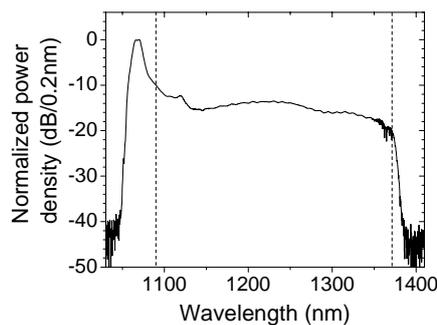


Figure 1 CW ASE seeded Yb-amplifier supercontinuum generated in 100m of PCF.

Our measurements have revealed that the supercontinuum generation process is initiated via modulational instability of the pump in the anomalous dispersion region around the dispersion zero. Soliton pulse formation is enhanced by Raman amplification leading to rapid pulse narrowing and consequently Raman self interaction (or the soliton self frequency shift) of the large numbers of solitons that emerge from the noise structure leads to a continuous long wavelength shift. As a result of the high loss associated with water at the air hole-glass interface, the generated continuum does not extend beyond 1.38 μm . One notable feature of such supercontinua is the flatness of the spectrum which is a result of the large number of soliton-like structures contributing to the spectrum and their random distribution.

Developments and optimization of PCF in manufacture has meant that the attenuation due to OH⁻ absorption has been reduced by more than an order of magnitude to ~ 70 dB/km and has permitted cw pumped supercontinua to readily extend beyond the 1.38 μm barrier, achieving bandwidths of nearly 1000nm and permitting watts level average powers as well as sub micron coherence lengths- making these simple compact and inexpensive sources attractive to application in optical coherence tomography.

High Brightness Picosecond Source 500 nm-1800nm

For many clinical based biological applications, modest average power picosecond, wavelength tunable pulses are required. The short pulse capabilities of fibre lasers is well established and the integration of these with high power fibre amplifiers and nonlinear generation in PCF integrated to the output of MOPFA configurations allows simultaneous generation of all wavelengths from 500nm-2000 nm (practically limited by the transmission window of the single mode fibre) at spectral power densities of 10mW/nm and above, permitting enormous versatility of the simple integrated, fibre delivered pulse source.

We have developed picosecond and femtosecond mode locked Yb-doped fibre oscillators, using passive techniques based either on polarization rotation or semiconductor saturable absorbers. In the former case, pulses as short as 2.2 ps have been generated at 40 MHz repetition rate, at peak powers of ~11W. These were amplified in a 1m long Yb pre-amplifier and a 1.5m long, large mode area (12 μm MFD) Yb amplifier, to an average power of 8W and peak powers up to 100kW. At such peak powers, spectral broadening as a result of nonlinear process in the output leads of the amplifier is observed, however, for sequential supercontinuum generation, in a few meters of integrated PCF this is not problematic. Figure 2 shows the supercontinuum generated in 30m of PCF with an average output power of 1.25 W

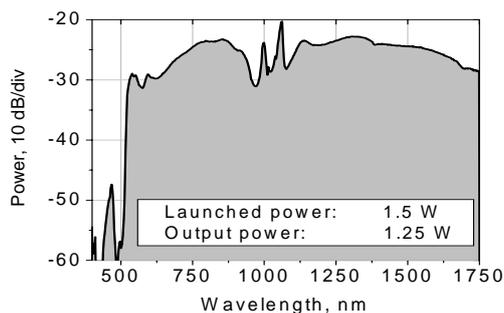


Figure 2. Picosecond pulse pumped supercontinuum in 30m long PCF

The dominant mechanisms contributing to the spectrum include, high order soliton fragmentation, Raman amplification, self Raman interaction, self phase modulation and for visible generation, four wave mixing. Picosecond pulse functionality was maintained throughout the complete spectrum. For example, around 700nm, selection of a 20 nm bandwidth, exhibited a 15 ps autocorrelation, broadened primarily by dispersion, while peak powers were in the range of several 10's W.

We will report on currently developed fully integrated similar picosecond supercontinua with average powers of up to 20 W corresponding to a spectral power density of ~ 15mW/nm, as well as techniques used to enhance and extend the short wavelength operation range of the supercontinuum. The primary process for visible generation is through four wave mixing. Through management of the dispersion zero of the fibre in which the interaction takes place, the four wave mixing process can be enhanced as the pump and corresponding long wavelength component develop on propagation through the non linear fibre.

All fibre chirp pulse amplifiers

In the recently introduced air core photonic bandgap fibres more than 95% of the transmitted radiation is guided in the air core, resulting in thresholds for non linear generation being increased by up to three orders of magnitude. In addition, the strong waveguide dispersion associated with the photonic bandgap gives rise to an overall fibre dispersion that exhibits anomalous behaviour to the long wavelength side of the bandgap, that consequently allows pulse compression of positively chirped pulses and soliton-like behaviour. We have demonstrated pulse compression of picosecond duration radiation selected from the supercontinuum to 250fs using air core photonic bandgap fibre, although higher order dispersion in the bandgap can lead to incomplete compression and ghost pulses, as shown in figure 3.

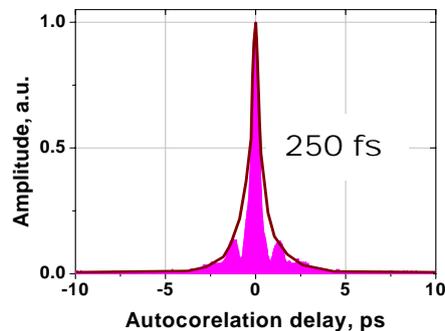


Figure 3. Compression in 1m of integrated, air-core photonic band gap fibre of spectral component selected from picosecond supercontinuum

We have also demonstrated the principle of all fibre integrated chirped pulse amplification in Yb, Yb-Er and in Raman based fibre amplifiers, illustrating the wavelength versatility of the technique. From these systems that exhibit no bulk optical elements, peak powers of up to 50kW have been obtained, although substantially higher peak powers can be achieved either through the use of bulk elements or by employing large core area amplifiers.

A medium power CPA based upon a 30 dBm Yb:Er amplifier has been constructed using 35 ps pulses generated at 50 MHz by direct intensity modulation of a semiconductor laser, stretched in 3.5 km of dispersion shifted fibre and subsequently amplified and compressed in 110 m of air core fibre. The compressed, 1 ps, 20kW pulses were further frequency doubled in a 3mm long PPKTP crystal generating up to 400 mW of 770 nm radiation in 700 fs pulses in a simple compact system that could replace a Ti:Sapphire laser. The frequency doubled output was then converted to a 200 mW average power supercontinuum covering the spectral range 400nm-1400 nm, adding to the versatility of this unique and compact assembly.

References

- [1] V. Gapontsev and W. Krupke, "Fiber lasers grow in power", *Laser Focus World*, vol 38 (8), pp 83-87, 2002
- [2] P. Russell, "Photonic Crystal Fibers", *Science*, vol. 299, pp358-362, 2003
- [3] P.A. Champert, S.V. Popov and J.R. Taylor, "Multi-watt broadband continua generation in holey fiber", *Optics Letters*, vol 27, pp 122-124, 2002