High brightness picosecond all-fiber generation in 525-1800nm range with picosecond Yb pumping

A. B. Rulkov, M. Y. Vyatkin

NTO IRE-Polus, Fryazino, Russia

S. V. Popov, J. R. Taylor

Femtosecond Optics Group, Imperial College, London SW7 2BW, England
s.popov@ic.ac.uk

V. P. Gapontsev

IPG Photonics Corp., Oxford, MA, USA

Abstract: Pumping of highly-nonlinear microstructured fibers with zero-dispersion around the pump wavelength of a 50kW peak-power picosecond Yb-fiber laser allowed extensive polychromatic picosecond operation down to 525nm in all-fibre format. Spectral power densities over 1mW/nm and potential of further pulse compression to femtoseconds is demonstrated.

OCIS codes: (060.4370) Nonlinear optics, fibers; (190.2620) Frequency conversion.

References and links

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High brightness visible laser sources with extensive wavelength tunability or simultaneous polychromatic operation, particularly extending into the green and blue, are required for numerous applications including fluorescence life-time and multi-photon imaging, the characterization of optical properties of nano-materials and for example, dispersion measurement in fiber optics. Traditional bulk-format sources, such as solid state or dye lasers, provide a limited choice of wavelengths. Their recent use for extending the wavelength coverage via SPM or modulation instability initiated super-continuum generation in photonic crystal fibres (PCF) inherits the limitations of bulk to fiber coupling and also generally suffers from insufficient spectral power densities impeding applications where continuous versatility of the wavelength together with high peak power is required [1,2]. Recent development in high power single mode all-fiber sources showed the possibility of ultra-short pulse operation with durations of a few picoseconds [3] in all-

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fiber format and the potential for femtosecond operation [3,4]. Not only would this approach allow the achievement of record high peak powers of tens of kilo-Watts within the Yb, Er or Nd gain windows, but a significant wavelength extension of all-fibre operation into the visible and infrared can be achieved. This can be undertaken while maintaining high average power levels and employing an appropriate peak and average power budget sources directly integrated with highly nonlinear microstructured photonic crystal fibres (PCF). The spectral extent of the supercontinuum generated is limited only by fundamental loss mechanisms of the optical fibres, namely the Rayleigh losses in the visible and material and waveguiding losses above 2 microns wavelength.

Here for the first time to the best of our knowledge we propose and demonstrate an all-fibre platform, where picosecond pulse amplification in a short-length, large-mode area active fibre results in peak powers approaching hundreds of kilo-Watts, and in association with an integrated highly nonlinear PCF allowed generation of a picosecond Watt-average power supercontinuum extending over the entire fundamental mode transmission window of the PCF, from 525 to over 1800nm. The high, up to 1mW/nm, spectral power density and spectral selection allowed the generation of tunable picosecond pulses through out this wavelength range.

We designed an all-fiber setup comprising a passively-modelocked seed fiber ring laser amplified in a specially-designed Yb doped fiber amplifier. The seed fiber source (Fig. 1) employed an all-isotropic-fibre integrated, loop, passive-modelocking configuration [3,5,6].

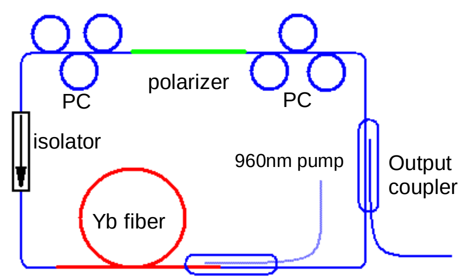

Fig. 1. Configuration of the all-fiber, ps seed laser source. PC – polarization controller.

The short, normally dispersive fibre cavity length of ~3 m allowed stable self-starting modelocked operation without the need for additional intra-cavity dispersion compensation. The seed laser produced stable single, round-trip repetition rate pulses with a duration of 3 to 15 ps depending on the output power and length of the active Yb-doped fiber in the cavity. Due to the normal-dispersion operation and SPM, the resulting strongly chirped pulses from the seed source had up to 20 nm bandwidth (Fig. 2(a)). With further amplification in mind and to minimize the total effect of dispersion broadening, we spectrally filtered the output of the seed source with a tunable fiber-pigtailed optical filter of 1nm bandwidth set to a central wavelength of 1061nm. Due to largely linear chirp compared to the 1nm bandwidth the filtered pulses were nearly transform-limited with a Lorenzian spectral shape (Fig. 2).

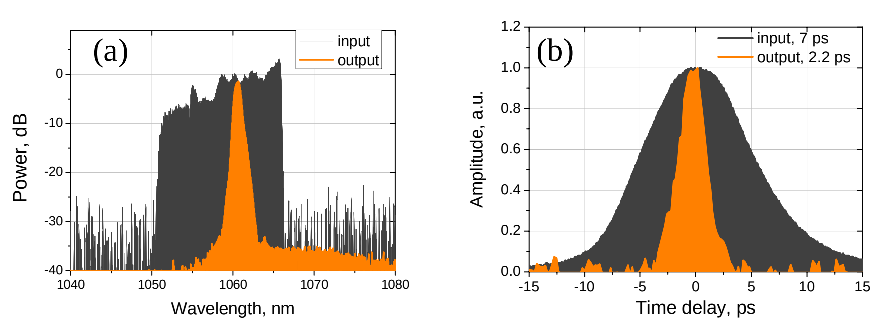

Fig. 2. The effect of the pulse bandwidth restriction (a) on pulse duration (b).

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This also allowed the implementation of straightforward control of the output pulse duration by varying the filter's bandwidth. The filter could also be directly included into the cavity of the seed laser, however the decrease of the modelocked pulse duration in this case led to subsequent decrease of the average power, so the output power was effectively the same as with external use, of the order of 1mW, in both configurations. In the intra-cavity case, the additional losses and spurious reflections the filter assembly introduced pointed in favor of the external filtering configuration. The output pulses of 2.2 ps duration and 40 MHz repetition rate had 11W peak power and were amplified in a 1m long preamplifier stage followed by a 1.5 m long large mode area cladding-pumped Ytterbium-doped fiber amplifier. The single-mode output W-index profile fiber with 12µ mode-field diameter ensured perfect beam quality and provided a possibility of low-loss fibre splicing to the output.

Despite the low nonlinearity of the active fiber of about 1.2 $(W\ km)^{-1}$ the amplified pulses experienced strong spectral broadening due to the SPM. This led to temporal broadening due to the fiber dispersion. We estimated an average dispersion of the whole setup as -19 ps $(nm\ km)^{-1}$ by taking into account evolution of the output bandwidth with the increase of the average output and peak power (Fig. 3), The direct measurements of the output pulse

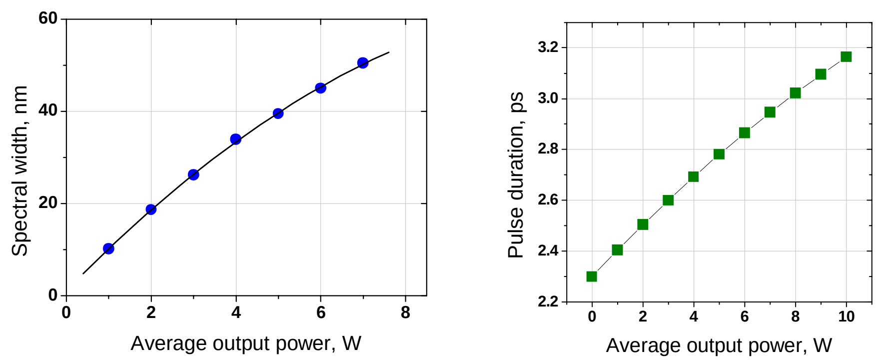

Fig. 3. Evolution of the output bandwidth (-10 dB level) and calculated output pulse duration (dispersion of the fiber amplifier of -19 ps/(nm km) assumed) for the ps pulses.

second-harmonic autocorrelation function were difficult due to both the large spectral bandwidth and the inhomogeneous polarization state across the temporal profile of the amplified pulse. Notwithstanding, by assuming the estimated dispersion value, the output pulse duration was maintained within 3.3 ps across the whole amplification range (Fig 4.).

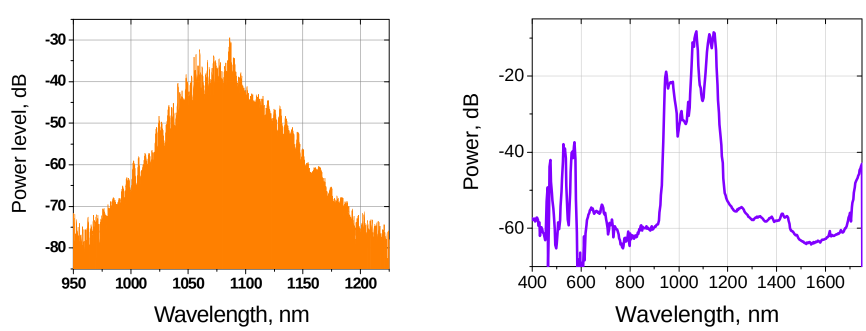

Fig. 4. (a) The spectrum of the 8W average power 3.2ps pulses. (b) Output spectrum after 30m long PCF in low-pump-power regime (6 mW average, 68W peak-power pumping)

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The above all-fiber integrated setup allowed us to generate an average power of 8 W with a corresponding 60kW peak power level. Further power scaling was restricted due to the Raman process and consequent power transfer to the generated Stokes orders. The output spectrum at the highest power level is shown in Fig. 4(a).

The 60kW peak - 8W average-power all-fiber picosecond single-mode picosecond source was applied to broadband picosecond generation (Fig. 5) in a highly nonlinear microstructured PCF with a zero dispersion around the pump wavelength (Blaze-Photonics). The silica based

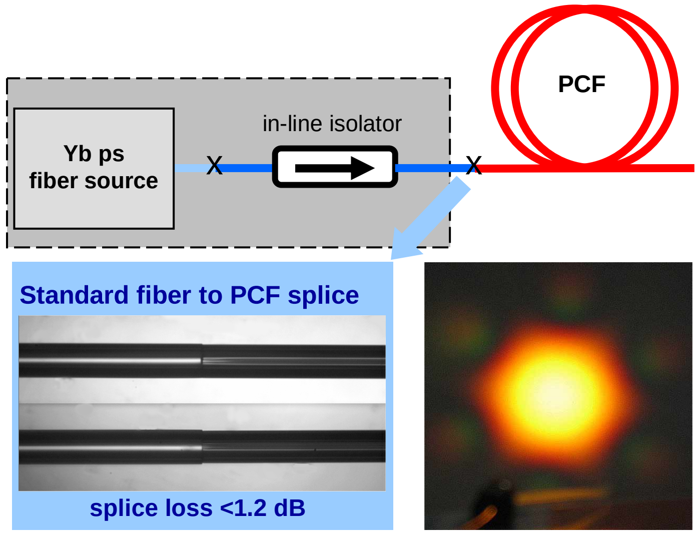

Fig. 5. Diagram of the picosecond polychromatic fiber integrated source with up to 1mW/nm spectral power density in 525-1800nm range .

PCF had zero dispersion at 1040nm and a dispersion slope of +0.2ps $(nm^2\,km)^{-1}$, mode field diameter of 3.2μm and attenuation of less than 2dB/km at the pump wavelength. The holey fiber was directly spliced to a standard 6.6μm MFD single mode fiber. The controlled spicing with a filament fusion splicer allowed to restrict the extensive collapse of the holes in the splice area and resulted in a splice losses of 1.2dB, which is lower than the expected mode-field mismatch loss of 2.2dB. To avoid possible back-reflection in the Yb amplifier, we used a fiber-integrated, polarization insensitive optical isolator which capped the maximum average output power we could use in this configuration. The relatively high nonlinearity of 4 $(W\,km)^{-1}$ of the standard pigtail fiber contributed to an additional increase of the spectral bandwidth of the ps pulses to 100 nm. This however did not affect the supercontinuum spectrum at the output of the PCF due to relatively high pulse peak power of 4kW in the PCF core and this was also verified through a cut-back of the standard fiber.

The results of the picosecond supercontinua generation with different lengths of the PCF are shown in Fig. 6(a). With the increase of the PCF length to 20m and above, the visible part of the continuum stops developing to shorter wavelengths after reaching 525nm. The influence of the typical water peak loss at 1380nm is negligible in this case due to the short nonlinear interaction lengths and high peak power of the pump radiation. Estimates of the characteristic dispersion and non linear lengths for the 8ps pump pulses with 80 nm bandwidth and 4 kW peak power were 10m and 0.02m respectively. It is worth noting that in the first meter of the PCF nonlinear effects such as SPM, FWM and Raman scattering dominate over the dispersive effects. The Raman threshold length and the characteristic soliton length for the pump pulses were also estimated as 0.7m and 16m respectively. The relative depletion of the spectral components in the wavelength range from 900 to 1100nm is a result of the FWM

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process. From the output spectrum at 6 mW pump (Fig. 4(b)) one can see second harmonic generation in PCF in the earlier stages of nonlinear interaction. However the sample fiber has strong waveguiding losses at wavelengths below 500 nm, setting also short wavelength limits on the continua spectra.

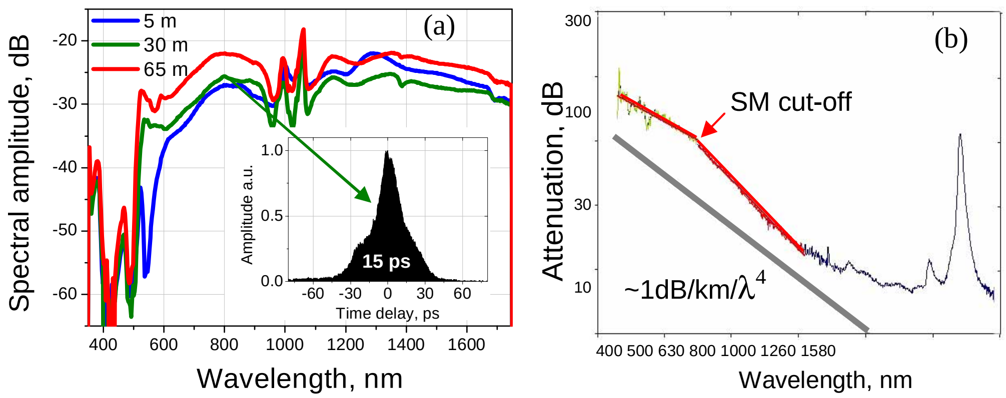

Fig. 6. (a) Output spectrum of different lengths of the PCF at 1.5 W average- (16kW peak-) pump level; inset- autocorrelation trace of the 15ps pulse at 780nm. (b) The loss profile of the 1040 ZDW PCF.

With the optimal PCF length of 30 m, at an average pump power level 1.5 W, a supercontinuum width of 1275 nm (10 dB level) with 1.6 mW/nm average spectrum power density and better than 12 dB peak-to-peak natural flatness was obtained. The picosecond nature of the polychromatic operation of the source was confirmed by obtaining autocorrelation traces of spectrally sliced pulses. A 20 nm bandwidth autocorrelation trace of 15ps pulse at 780 nm is shown in the inset of Fig. 6(a). The corresponding peak power of the sliced pulses was estimated to be in the range of several tens of Watts.

The extension of the all-fiber generation further towards the blue in the 1040nm zero dispersion wavelength PCF was generally restricted due to Rayleigh scattering loss (Fig. 6(b)) and also due to the cut-off of the single-mode guiding below ~600nm which can bee seen as a change of the slope of the loss profile in Fig. 6(b). Because of the high fundamental losses in the silica fibres in the visible, the way to extend the generation to the blue in all-fibre format is to reduce the dispersion and enhance the nonlinearity of the PCF, so the effective nonlinear length can be further reduced enhancing generation of new visible components. This, for example, can be undertaken through cascading and integrating dispersion zero shifted PCFs.

In conclusion we demonstrated an approach that has the potential to produce picosecond wavelength tunable pulses throughout the complete visible and near infrared. The operable power levels can be increased simply by utilizing the available power budget of the fundamental all-fibre Yb source. An additional unique feature of this source is its compact, and robust entirely fibre integrated platform.

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