REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
29-03-2006	Final Report	10 September 2004 - 10-May-05

4. TITLE AND SUBTITLE Fiber-Based 589 nm Laser for Sodium Guide Star	**5a. CONTRACT NUMBER** FA8655-04-1-3065
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Dr. Lars J Nilsson	**5d. PROJECT NUMBER**
	5d. TASK NUMBER
	5e. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Southampton Highfield Southampton SO17 1BJ United Kingdom	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 821 BOX 14 FPO AE 09421-0014	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) Grant 04-3065

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking University of Southampton as follows: The work will entail the construction of the required sub-assemblies, their integration into the laser source, and the exploration and adjustment of parameters in order to obtain adequate performance. We have reasonable versions of several of the needed fibers, and though we are likely to have to fabricate new fiber, this requirement is assumed to be modest. The 1060 nm pulsed diode-based seed source is based on our previous work in the field. A simple low-power pre-amplifier (YDFA) with high gain efficiency will be built with all-fiber technology and core-pumping. The 1178 nm Raman fiber seed source requires appropriate highly nonlinear fiber to be acquired or fabricated and, more challenging, narrow-linewidth FBGs to be written. A cladding-pumped Yb-doped fiber laser with a few watts of output power will be assembled, to be used as a pump source for the Raman seed source. Fiber for the high-power amplifier and Raman converter will be fabricated as necessary. We hope to be able to use modest-size, strictly single-mode cores, as this will simplify system integration (splicing in particular). We plan to use a pre-configured frequency-doubler which requires minimum effort on our part. Besides fabrication and assembly of the source, most effort will go into characterization and evaluation of components, sub-assemblies, and the system as a whole. This is important to identify the right operating point, which is relatively narrow in a pulsed system based on nonlinear conversion. It will also enable us to assess the power-scaling potential and overall potential of the approach

15. SUBJECT TERMS

EOARD, Lasers, Adaptive Optics, Astronomy, Fibre Lasers

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			DONALD J SMITH
UNCLAS	UNCLAS	UNCLAS	UL	21	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)20 7514 4953

AQ F07-06-06639

Fiber-Based 589 nm Laser for Sodium Guide Star

Final report

Grant Number: FA8655-04-1-3065

Date: February 2006

Principal Investigator: Dr. Johan Nilsson

Co-investigators: Dr. Yoonchan Jeong, Mr. Pascal Dupriez

Address: Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

List of abbreviations and acronyms

CRFL	Cascaded Raman fiber laser
Cw	Continuous wave
DBR	Distributed Bragg reflector
DFB	Distributed feedback
DM	Dichroic mirror
DSF	Dispersion shifted fiber
FBG	Fiber Bragg grating
FWHM	Full width at half maximum
FWM	Four wave mixing
GTWave	GTWave is a multi-fiber platform for cladding pumping. GTWave is a trademark of SPI Lasers, LLC.
HR	High reflectivity
HT	High transmittance
IR	Infrared
LBO	Lithium triborate (LiB_3O_5)
MOPA	Maser oscillator – power amplifier
NA	Numerical aperture
OC	Output coupler
SHG	Second harmonic generation
SMF	Single mode fiber
SPM	Self phase modulation
SRS	Stimulated Raman scattering
WDM	Wavelength division multiplexing
XPM	Cross phase modulation
Yb	Ytterbium
YDF	Ytterbium-doped fiber
YDFA	Ytterbium-doped fiber amplifier
YDFL	Ytterbium-doped fiber laser

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

1. Background

This final report describes the work carried out by Optoelectronics Research Centre at the University of Southampton on a fiber-based 589 nm laser for sodium guide star applications under grant no. SPC FA8655-04-1-3065. Contract period October 1 2004 – September 30 2005.

2. Approach and objectives

The objective has been to realize a 589 nm laser source suitable for a laser guide star based on an all-fiber source at 1178 nm, which is then frequency-doubled to 589 nm in a crystal a simple single-pass configuration.

The 1178 nm fiber laser source is a based on second-order cascaded Raman amplifier, pumped by pulses at 1060 nm from a master oscillator – power amplifier (MOPA) source. The 1060 nm MOPA is based on an injection-seeded gain-switched diode laser which is amplified by a cascade of Yb-doped fiber amplifiers. The 1178 nm Raman amplifier is in turn seeded by a cw 1178 nm cascaded Raman laser.

The work has entailed the construction of sub-assemblies, their integration into the laser source, and the exploration and adjustment of parameters for best performance. The project has targeted an average power of 1 W at 589 nm. However, we have targeted a source that would be scalable to the 100 W level. An essential requirement, which however has not meant to be fully addresses within this work, is a narrow linewidth. This is dictated by the ~3 GHz absorption linewidth of sodium.

The use of rugged, robust, and highly efficient fiber sub-systems, is key to the feasibility of a laser that is as complex and sophisticated as this, with good overall efficiency.

3. Results, findings, accomplishments

Key outcomes

The key outcomes of the project are:

- A 1060 nm ps – ns fiber MOPA source with up to 321 W of output power was realized in an effort including several projects, of which this was one. We believe this was the highest-power pulsed fiber source ever reported. It points to the tremendous capability of the diode-seeded fiber MOPA technology in terms of power and versatility, which promises to open up for many important applications.
- A 1178 nm Raman-shifted MOPA source with 24 W of average power and 7.5 kW of peak power was realized.
- A 1 W average power 589 nm light source was realized.
- The linewidth of the light was much too large. Raman amplification is associated with very significant linewidth broadening in the regime we were working in. Our approach would only be able to generate narrow linewidths in another regime, with much longer pulses. The linewidth of the 1178 nm seed laser would also have to be reduced.
- Although the system is quite complex and is made from a large number of sub-assemblies, it still worked quite reliably, although with inadequate performance. This demonstrates that complex fiber systems, as commonly used in telecom systems, can be assembled also in the high-power regime.
- We believe that if the linewidth can be narrowed, our approach has excellent power scaling potential. Then, it should be possible to frequency-double the 25 W of 1178 nm radiation already obtained to 15 W of power at 589 nm. Further power-scaling would also be possible, by increasing the diode pump power.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

The latter part of the project focused on the linewidth, but progress was modest. However in particular with longer pulse duration and rectangular pulses it should be possible to reach the required linewidth of 3 GHz, at least if a 1st-order Raman amplifier rather than a 2nd order one is used.

System layout

Several layouts were tried, primarily aiming at reducing the linewidth. These to a large degree used the same sub-assemblies. Figure 1 shows our baseline system, which was described in the proposal.

The system is composed of a continuous-wave (cw) cascaded Raman fiber laser emitting at 1178 nm and a pulsed fiber MOPA source producing picosecond pulses at 1060 nm. In the baseline configuration shown in Fig. 1, the 1060 and 1178 nm beams are combined in a 980/1060 nm WDM coupler and free-space launched through an isolator designed for 1060 nm into a 23 m long Yb doped fiber. This fiber, pumped by a laser diode stack emitting at 975 nm, constitutes the final stage of amplification of the Yb based fiber MOPA. It both amplifies the 1060 nm pulses through stimulated emission from the Yb-ions and the 1178 nm signal through cascaded Raman conversion via an intermediate wavelength of 1119 nm. Hence, the last-stage amplifier is both an Yb-doped fiber amplifier and a Raman fiber amplifier. The cw Raman seed laser generates light at 1119 nm as well as at 1178 nm, and so seeds both the Raman conversion steps. Since the 1060 nm pulses are co-propagating (in the same direction) with the 1119 – 1178 nm seed light, also the seeds become pulsed through the instantaneous Raman amplification process.

The resulting high-power pulsed 1178 nm beam is then launched into a type-I non-critically phase-matched lithium triborate (LBO) crystal for frequency doubling to 589 nm. Highly selective dichroic mirrors (DM) are employed at the input and output of the crystal to filter out unwanted beams, at 975 – 1114 nm before the LBO crystal, and any IR light after the crystal.

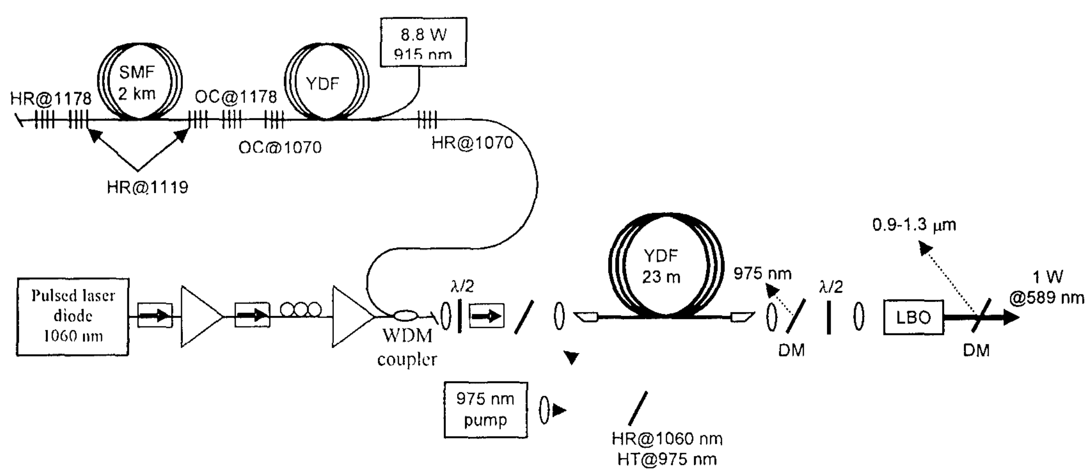

Figure 1: Experimental set-up of the 1 W pulsed fiber based source at 589 nm. HR: high reflection, HT: high transmission, OC: output coupler, DM: dichroic mirror.

Sub-modules and their performance

Several different configurations were investigated. We will describe the performance of the different sub-modules in a baseline experiment with the baseline configuration. Some of the sub-modules have been described in further detail, in similar and different operating regimes, in publications [1], [2], [3], [4]. They were constructed for this project, or were modified from existing setups to fit to the needs of this project.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

1060 nm pulsed diode-based seed source and intermediate-power amplification stages

The 1060 nm pulsed diode laser (master oscillator) was based on an injection-seeded gain-switched Fabry-Perot laser diode. See publications [1], [2], [3] for further details. It was operated at different repetition rates and pulse durations, in different experiments. In our baseline experiment, it was operated at 32 MHz to produce pulses with 140 ps duration (FWHM) as presented in Fig. 2.

These pulses, with 0.2 mW average power, were then amplified by a core-pumped YDFA and a cladding-pumped YDFA separated by isolators to avoid any back reflections, raising the average power to 250 mW average power. These were constructed in-house. The core-pumped amplifier used a conventional WDM coupler for the pump launch. The cladding-pumped fiber was based on a GTWave™ fiber from Southampton Photonics (i.e., SPI Lasers LLC, previously SPI Optics, Inc.).

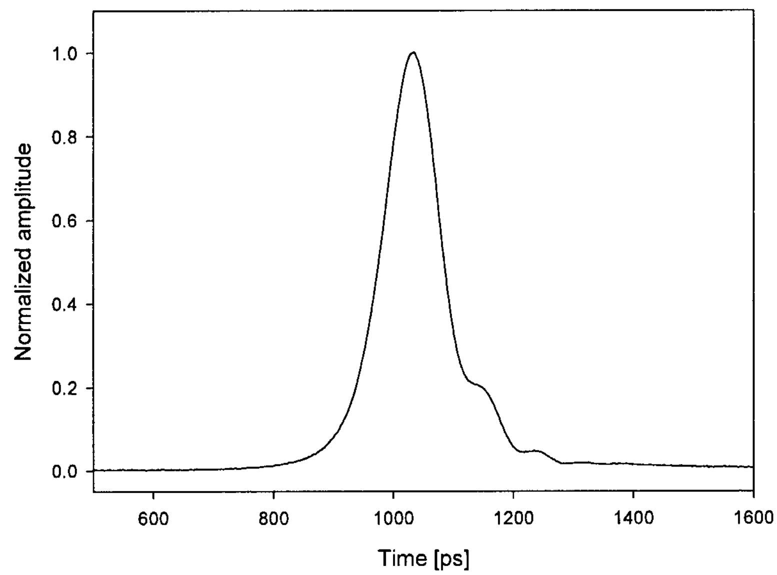

Figure 2: Pulse shape from the pulsed laser diode, pulse width (FWHM) ~ 140 ps.

In our view the diode seed source was adequate for this work, for the sub-ns pulse regime that we targeted. It would probably have been better to use longer pulses (~ 1 ns). We believe that the diode and driver would have been able to operate in that regime, with preferred rectangular-shaped pulses.

The performance of the two intermediate amplifiers were not thoroughly characterized, e.g., in terms of pulse shape and linewidth broadening. However we believe that the system performed adequately up to the output of the second amplifier.

1178 nm Raman fiber seed source

A cascaded Raman fiber laser (CRFL) was designed and built to realize the continuous-wave seed source for the fiber based system. The Raman oscillator was composed of a 2 km long dispersion shifted fiber from Pirelli, which was single-mode at 1.5 μm. The fiber was spliced to two pairs of fiber Bragg gratings (FBGs) with reflectivity peaking at 1119 nm and 1178 nm, and bandwidth of 2 and 0.1 – 0.2 nm respectively. These were fabricated in-house for this project.

The CRFL was pumped in a counter-propagating scheme by a cladding pumped YDFL with 3.8 W of output power in the baseline experiment. This was assembled within the project, using GTWave™ fiber from Southampton Photonics. With this pump source, the CRFL generated 690 mW of total Raman-scattered output power. The first Raman Stokes at 1119 nm was not totally depleted in the

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

oscillator as depicted in the spectrum in Fig. 3. The powers produced in the 1119 nm first Stokes and 1178 nm second Stokes beam were estimated to be 156 mW and 534 mW, respectively.

Although FBGs were designed with a narrow bandwidth, lasing is observed outside the grating and the signal linewidth broadens severely to 0.6 nm as shown in Fig. 3 (resolution 0.05 nm). The central dip in the spectrum reveals the linewidth of the grating. It is approximately 0.18 nm, or 39 GHz, on the outcoupling end of the cavity. The grating in the other, HR, end of the cavity had a broader linewidth of 2 nm, as is typical of HR gratings. Their reflectivities were 40% and 90%, respectively.

Unfortunately this source is inadequate for a sodium guide star laser. The spectral width of the source is much larger than the sodium absorption linewidth, and this is a major concern. One problem is that the combination of long fiber length and four-wave mixing (FWM) between longitudinal modes in the Raman resonator broadens the linewidth [5], outside the linewidth of the outcoupling gratings.

One possibility to reduce the linewidth of the laser is to reduce the linewidth of the grating in the HR end of the cavity. This reduces its reflectivity as well, but acceptable efficiency would still be achievable. A shorter Raman gain fiber would reduce the linewidth, too, [5] but at the expense of efficiency. With very narrow FBGs, the threshold might even reduce with a shorter fiber as the linewidth broadening reduces. However we have no clear view of how narrow linewidth might be achievable. Although the linewidth of the laser may well be a more important factor than the power, our optimization of the fiber length focused on power rather than linewidth.

It is also possible to couple out the power reflected by the FBG, rather than the power transmitted through it, in a ring cavity with a circulator (a so-called sigma configuration with the grating attached to the circulator). This will give a narrow linewidth of the laser, comparable to the linewidth of the FBG, or possibly even narrower. However, the efficiency will be degraded by the large amounts of power outside the grating bandwidth. Furthermore, gratings with a linewidth of 1 GHz are very challenging, even more so as the side band suppression should be sufficient to suppress the FWM side bands. Still, sub-GHz gratings have been fabricated. At very low powers the conventional line-narrowing effects of a laser would dominate, but at higher powers parametric amplification of sidebands (through FWM) would broaden the linewidth. Again, a shorter fiber would reduce the linewidth broadening and might even decrease the threshold.

More conventional technology would be preferred for a narrow-line seed source on the (sub) 1 GHz level, or ideally a single-line source such as a DFB laser. These are also likely to be temporally more stable. Any temporal instabilities lead to self-phase modulation and cross-phase modulation in the Raman amplifier, which significantly broadens the line.

Simplest would be a DFB laser diode at 1178 nm, but these are not available. Maybe they will become available in the future. Alternatively, a holmium-doped fiber laser (e.g., a DFB fiber laser or otherwise a DBR fiber laser) originating on the $^5I_6$ level could be used for 1178 nm, but unfortunately this level is quenched in silica glass. It may work in germanate glass, or otherwise in tellurite, which has a significantly lower phonon energy than silica.

Final-stage high-power amplifier and Raman converter

In the baseline experiment, about 120 mW of Raman signal is launched into the high-power final stage amplifier via the WDM coupler and a free-space single-polarization isolator (optimized for 1060 nm) and a dichroic mirror between a pair of lenses. The final-stage amplifier comprised a 23 m long YDF with a core diameter of 8 μm and a D-shaped inner cladding of 400 μm diameter. It was end-pumped by a diode stack emitting at 975 nm from the signal launch end of the YDF.

The final focusing lens has to launch the diode pump beam as well as the 1060 nm and 1178 nm beams (and the 1119 nm beam) into the final-stage YDF. The lens alignment is a compromise between the slightly different optimum positions for the different wavelengths. Somewhat better performance would be possible with an optical arrangement that would allow for independent optimization of the focusing of the different beams. It would be preferable to use an all-fiber path, which would be possible with a pig-tailed isolator and a tapered fiber bundle to launch the pump

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

beam. One could also use a counter-propagating pump, although that tends to destabilize the output beam somewhat through thermally induced shifts in the fiber position.

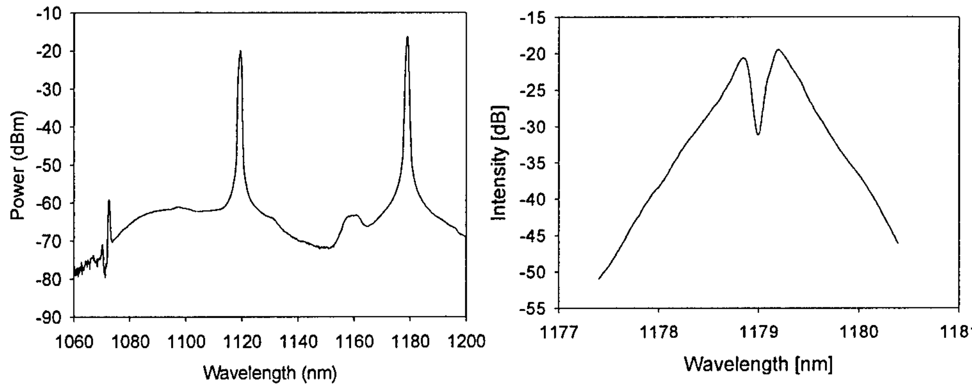

Figure 3: Output spectra of the cascaded Raman fiber seed laser. (a) Spectrum of first and second Raman Stokes signals at 0.69 W total output power (0.5 nm resolution). (b) High resolution spectrum of the 1178 nm output beam at 534 mW output power, linewidth (FWHM) ~ 0.6 nm (0.05 nm resolution).

The final stage YDFA was capable of producing 45 W of average output power as shown in Fig. 4. The slope efficiency of the last-stage amplifier was 48% with respect to the launched diode pump power. The 1060 nm seed pulses had a duration of 140 ps and a pulse repetition frequency of 32 MHz. The Raman conversion was not seeded, i.e., the Raman seed laser was not operating. Still, at 45 W of output power, two spontaneous Raman peaks appeared at around 1119 nm and 1178 nm.

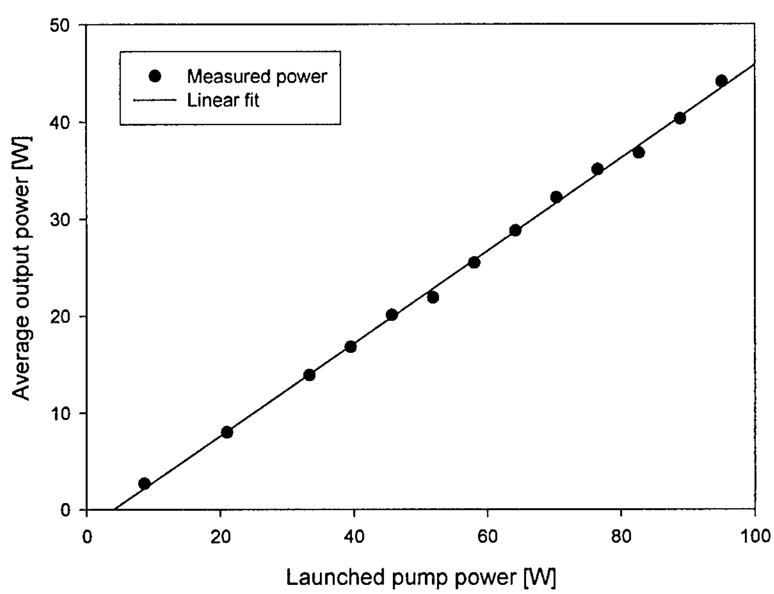

Figure 4: Output power characteristics at output of the 23 m Yb doped fiber (final stage YDFA) when seeded by 140 ps pulses at 1060 nm (average power ~ 250 mW), but not by the cw Raman seed laser.

The total output power at maximum pump power remains at 45 W also when the Raman conversion is seeded. That power is divided between 1060 nm, 1119 nm, and 1178 nm. The output power is limited by the appearance of the third Stokes order for higher pump powers. It is possible to suppress the third

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

Stokes, e.g., by using a shorter fiber or by using a waveguide spectral filter [6]. Alternatively, the repetition rate could be increased, for a higher average power within a constant peak power. Any of these options should open up for significant further power scaling, beyond the 100 W level. Figure 5 shows the evolution of the output spectrum as a function of average power as the pump power changes. An on-off gain of the average power of about 23 dB was reached at 1178 nm. The fraction of the average output power in the second Stokes order is 53%. Figure 6 shows the temporal pulse shapes at the different wavelengths. The duty cycle of the 1178 nm output pulses was ~0.3%, which indicates that the pulse gain was 48 dB to ~ 7.5 kW of peak power.

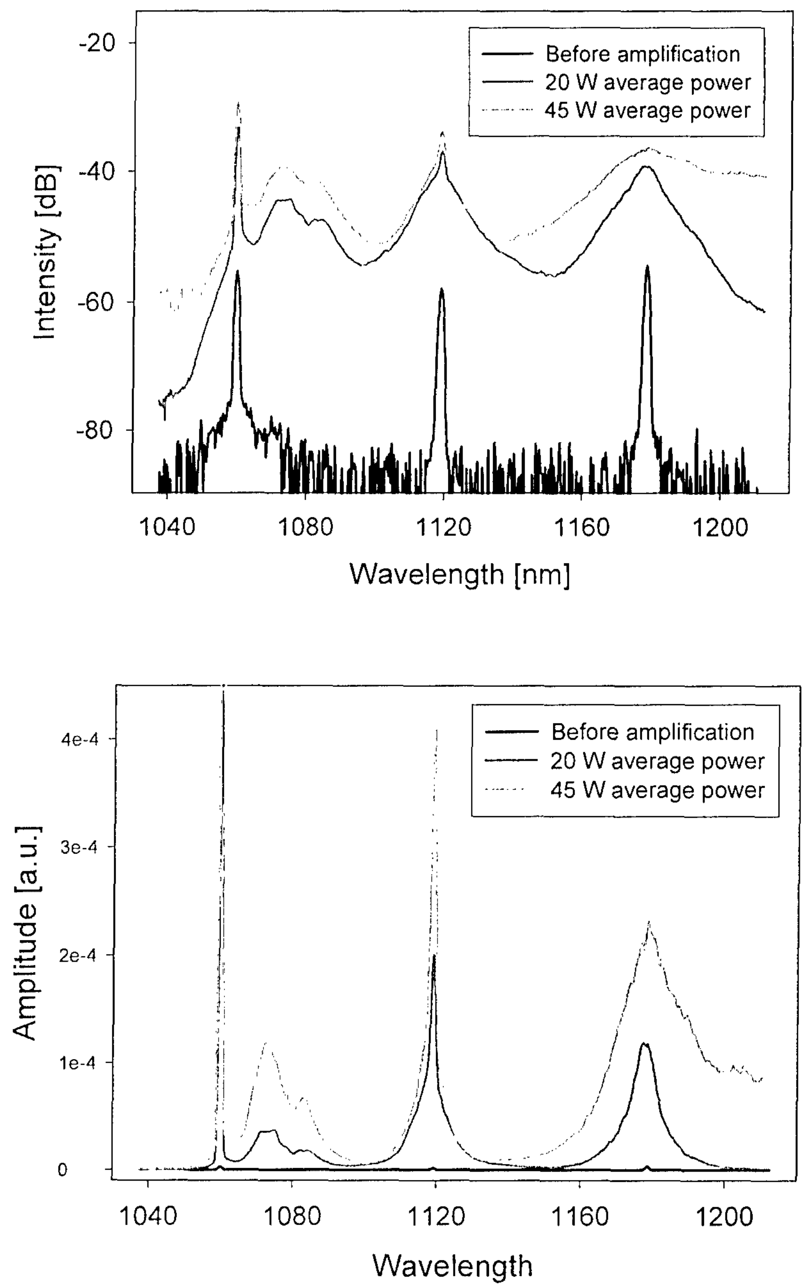

Figure 5: Output spectra from the last-stage amplifier at various total average output power levels in logarithmic scale (top) and linear scale (bottom). Color plot.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

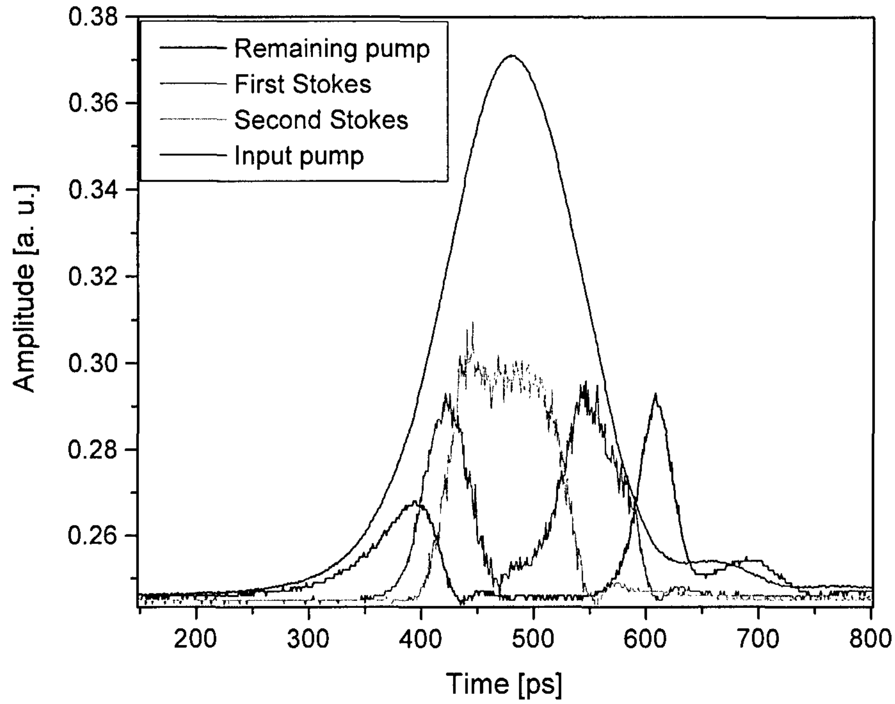

Figure 6: Pulse shapes at the output of the last-stage amplifier at 25 W of total average output power. Pulse width (FWHM) at 1178 nm ~ 100 ps. Color plot.

The MOPA suffers as it comes to the linewidth and the distribution of power between the different Stokes orders (and the pump). Figure 6 shows that it is possible to get good conversion to the second Stokes beam, however only in the center of the pulses. At the leading and trailing edges, both the fundamental 1060 nm beam and the intermediate 1st order Stokes wave contain significant power. A longer fiber could be used to deplete the short-wavelength beams throughout the duration of the pulse, but that could lead to the generation of the 3rd Stokes order and in any case leads to further spectral broadening. A better solution is to use rectangular rather than Gaussian-like pulses. Our current system was not able to generate rectangular pulses with this short duration. However, with longer pulse durations it becomes easier to generate nearly rectangular pulses. That would allow us to increase the fraction of the output power in the 2nd Stokes beam at ~1178 nm to nearly 100%. However our simulations show that there is still a trade-off between linewidth and conversion efficiency.

Most important though is the dramatic spectral broadening of the 1178 nm beam, to 8 nm. In a high-gain Raman amplifier pumped by short pulses, several factors will broaden the linewidth. Temporal intensity variations will induce a chirp through self-phase modulation (SPM) and cross-phase modulation (XPM). This will broaden the pulses. The 1178 nm Stokes beam suffers from XPM and SPM induced by the 1060 nm, 1119 nm and 1178 nm pulses. The amount of broadening depends on the detailed temporal shape of the pulses. While Fig. 6 shows that the shape of the pump beam is relatively benign (within the temporal resolution of the detection system), even at the output of the MOPA, the 1st and 2nd Stokes beams are more jagged, with sharp features evident down to the resolution limit of the detector and in all likelihood beyond.

The nonlinear phase shift induced by XPM and SPM, in radians, is greater than the Raman gain, in nepers. SPM and XPM with parallel polarizations are greater than the Raman gain by roughly a factor

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

two and four, respectively, [7] although for XPM some averaging occurs because of the walk-off between the 1060 nm pulses and the Stokes pulses. For orthogonal polarizations the factor is larger. With cascaded Raman conversion, XPM is operating throughout the fiber while Raman amplification of the final (2^{nd}) Stokes order only occurs in the latter part of the amplifier. In total we roughly estimate that the nonlinear phase shift is larger than the Raman gain by a factor ten. The Raman gain is ~ 10 Np so the nonlinear phase shift is roughly 100 rad. The induced frequency shift depends on the rate of change of the nonlinear phase shift. From Fig. 6, we can estimate it to being roughly equal to the rate of change of the envelope of input pump pulses (at 1060 nm). Hence, we estimate the induced frequency shift $\Delta f = \Delta\omega / 2\pi = (1/2\pi)\, \Delta\phi_{NL} / \Delta t = (1/2\pi)$ 50 rad / 70 ps = 114 GHz or 0.5 nm. This is double-sided, so the corresponding linewidth broadening may be twice as large or 1 nm. This is nearly two orders of magnitude too large for sodium excitation. It follows that according to this analysis, the maximum rate of change of the intensity, relative to the peak power, that allows for a 3 GHz linewidth, is approximately 2×10^{-4} ps^{-1} with two-step cascaded Raman conversion in a germanosilicate fiber.

The observed linewidth broadening is actually larger still. One reason for the discrepancy may be that the temporal variations of the jagged 1^{st} and 2^{nd} order Stokes pulses are actually faster than the smooth variations of the pump seed pulses. Another reason may be that the polarization state may vary rapidly. This broadens the linewidth, but variations in polarization are not detected by the detector. In addition, intensity noise in the input pump or seed beams would also contribute to the broadening through SPM and XPM.

There is also parametric gain, induced by four-wave mixing even in the absence of temporal variations. Parametric amplification requires phase-matching, and will therefore not occur, for example, between the different Stokes beams with the dispersion characteristics of our fiber. However, in any fiber, parametric amplification will remain phase-matched over a long distance for wavelengths close to the pump beam. This leads to line broadening [5, 7], as discussed previously in conjunction with the cascaded Raman seed laser. In our case the 1178 nm beam would be the "pump" of interest. We have not looked closely into how FWM affects the linewidth of an already relatively broad line like ours. However, with the narrow lines that we would ultimately have to target, FWM broadening can be small if the initial side mode suppression is good.

We repeat that the broad linewidth is the main limitation of our source and the latter part of the project was focused on reducing it, but with limited success. We expect that the linewidth will be reduced if we maintain the same linear polarization for all beams, with polarization-maintaining fibers. The Raman gain almost vanishes for orthogonal polarizations whereas XPM remains significant. Hence, to maximize the Raman gain relatively to the XPM, the polarizations should be co-linear. Single-polarization operation would also eliminate polarization beating effects. We believe however that reducing the temporal variations, by having longer, rectangular, pulses is the most promising route to increased efficiency (the Raman conversion efficiency as well as the SHG efficiency would increase) and most importantly, to reduced linewidth broadening in the amplifier.

2.4. Frequency doubling to 589 nm

For frequency-doubling, we used a temperature-controlled 15 mm long LBO crystal in a conventional type-I non-critically phase-matched configuration. The advantage with LBO is its reliable operation. A disadvantage is that it requires kW-level peak powers for efficient operation. However we believe that fiber systems can generate the required peak power with the required narrow linewidth. Note here that the large linewidth obtained is primarily a consequence of the need to generate sufficient Raman gain in the system, rather than of the requirement to reach sufficient peak power. Therefore, a reduction in the peak power does not by default reduce the nonlinear linewidth broadening by a significant amount.

The amplified pulsed 1178 nm Raman signal was launched into the LBO crystal through a combination of lenses. The crystal temperature was optimized for second harmonic generation at 589 nm and set to 36°C. The state of polarization was not carefully monitored and controlled; a half-wave

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

plate was used to rotate the polarization for best doubling efficiency. Figure 7 shows the 2nd Stokes power at 1178 nm and the 589 nm power as a function of total output power from the MOPA. With a maximum power of 25 W at 1178 nm, the frequency doubled power reached 1.01 W.

The poor conversion efficiency is mainly due to the broad spectral linewidth (FWHM) of 8 nm of the fundamental beam at 1178 nm. The output spectrum of the frequency doubled beam at various power levels is shown in Fig. 8. The spectral linewidth (FWHM) was 3.7 nm or 3.2 THz at maximum output power.

The linewidth is much too broad for the sodium guide star application. However this is a result of the linewidth of the fundamental beam, and is not really related to the frequency doubling process. The other shortcoming of our frequency doubler, the poor efficiency, would require that the fundamental linewidth be reduced. Typical SHG acceptance bandwidths are around 1 nm. The linewidth requirements set by the sodium absorption bandwidth are much tighter than that. We therefore believe that the doubling unit *per se* is fully adequate, and can reach conversion efficiencies of over 50%, provided that we pump it with a fundamental beam of sufficiently narrow linewidth for the guide star application. This is emphasized by our recent result of 80 W of frequency-doubled power obtained with this crystal at 530 nm, when the crystal was temperature-tuned for that wavelength and pumped directly by a high-power 1060 nm pulsed MOPA [1]. The conversion efficiency was 46%.

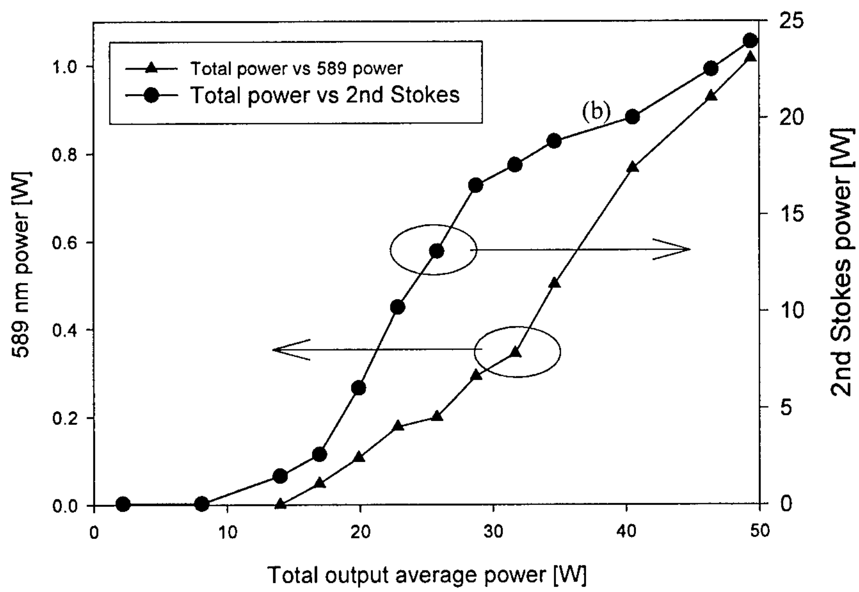

Figure 7: Second harmonic generation at 589 nm. Average output at 1178 nm and 589 nm versus total average output power from the MOPA.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

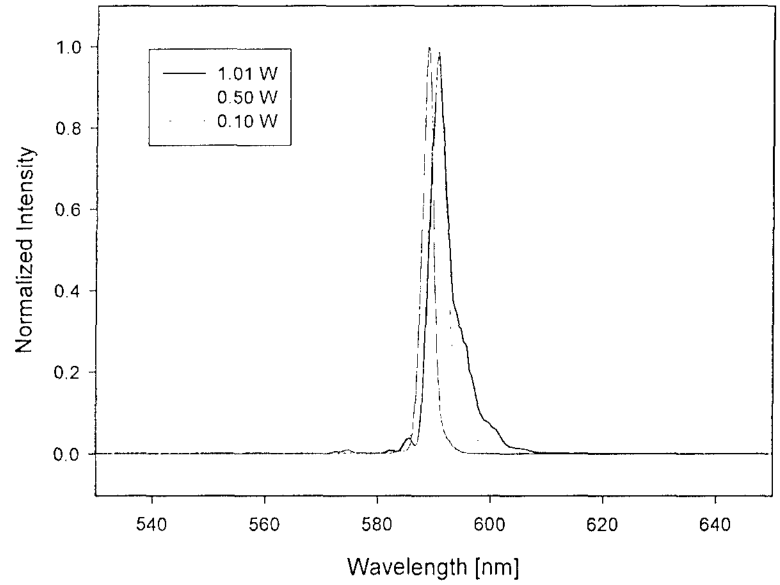

Figure 8: Output spectrum of the frequency doubled pulsed signal at different second harmonic power levels. Linewidth (FWHM) at 1 W ~ 3.7 nm. Color plot.

Alternative configurations

After the large linewidth had been identified as the major issue, methods of reducing this were investigated.

We investigated a number of alternative systems layouts, utilizing, e.g., Raman conversion in an external fiber, counter-pumping, different fiber lengths, polarization control, and pulse shaping. However success was limited. We do consider pulse shaping to be quite promising. Although our set-up with a MOPA in principle is very versatile and does allow for pulse shaping, our work focused on the sub-ns regime. However the nanosecond regime now appears more promising.

In the previously described fiber laser system, Raman amplification at 1178 nm was realized directly in the YDFA. Although this configuration is very suitable for power scaling, it restricted the optimization to a specific fiber with given dispersion, length, and other physical parameters. These were not necessarily ideal for the Raman conversion. An alternative scheme was exploited wherein Raman fiber amplification was realized in a passive single-mode fiber. The Raman conversion is obtained by free-space launching 150 – 200 ps pulses at 32 MHz at 1060 nm into 40 m of dispersion-shifted fiber (DSF, Pirelli Freelight) that was used as a Raman converter. To improve the efficiency and stability in light-coupling between the YDF and the DSF, a forward-pumping configuration was used. It allowed for a stable launch efficiency at over 50% (e.g., 8.6 W out of 17 W launched). When the DSF Raman fiber was pumped with 8.6 W, 160 ps, 32 MHz pulses at 1060 nm and seeded with 150 mW (cw) at 1178 nm, it produced 3.9 W of output power in the second Stokes at 1178 nm. The resultant linewidth was ~ 6 nm. Thus, although some improvement was obtained, the linewidth was still too large. The broad linewidth was due to the cross-phase modulations among the pump, first Stokes, and second Stokes pulses. This situation was typical also for other investigated configurations and parameter ranges.

Simulations

Numerical simulations of a Raman amplifier were carried out to, firstly, assess the linewidth broadening and, secondly, investigate possible improvements of the output linewidth at 1178 nm after pulsed Raman amplification. A commercial software, VPI Transmission Maker, was employed to model the interaction of pump and signals. While nonlinear effects in a passive single-mode fiber (SRS, SPM, XPM, FWM) can be assessed with this software, a similar analysis in a rare-earth doped

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

fiber amplifiers is not possible. Therefore our analysis was restricted to passive single-mode fibers. Although propagation properties in a passive fiber differ from that in a rare-earth doped fiber, this analysis helped to study the impact of XPM induced spectral broadening in such a fiber laser system.

Linewidth broadening in a picosecond pulsed Raman amplifier

In this section, nonlinear effects in a pulsed Raman amplifier were investigated. The fiber was 40 m long with an effective area of 60 μm^2 and a dispersion of -30 ps nm^{-1} km^{-1}. The pump beam had a peak power of 2 kW with pulse durations of 140 ps at 32 MHz. The powers of the seeds at 1119 nm and 1178 nm were both fixed to 100 mW.

The optical spectra after Raman amplification of signals with different input linewidths in the 40 m long fiber are shown in figure 9. Although the initial considered linewidths are very narrow, 1 GHz and 50 GHz, simulations show a dramatic increase of linewidth to 3.5 nm and 7 nm, respectively. The impact of XPM on the output pulses was also investigated and the simulated pulse shapes for the various pump and Raman beams are shown in figure 10. Although the simulated output pulse shapes at 1178 nm matched the experimentally measured pulses reported in Fig. 6, large intensity distortions induced by strong XPM between the co-propagating beams are revealed.

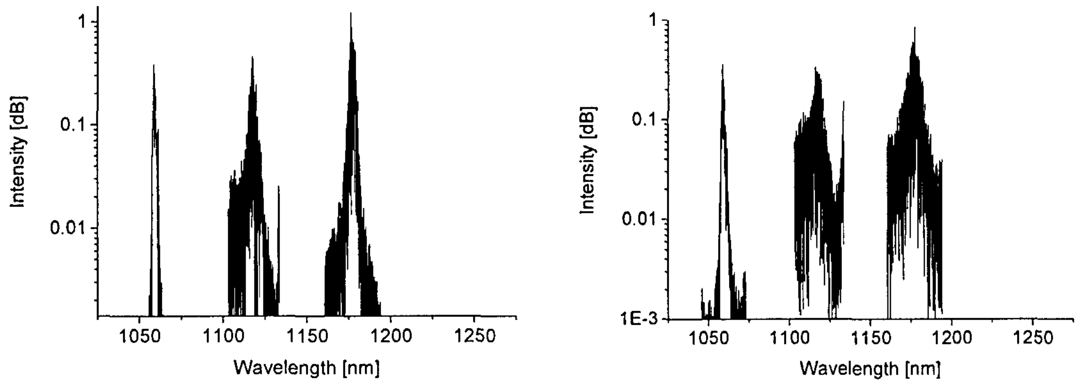

Figure 9: Simulated optical spectra after pulsed Raman amplification in a 40 m-long single-mode fiber for two input signal linewidths. Left: 1 GHz; right: 50 GHz at 1119 and 1178 nm.

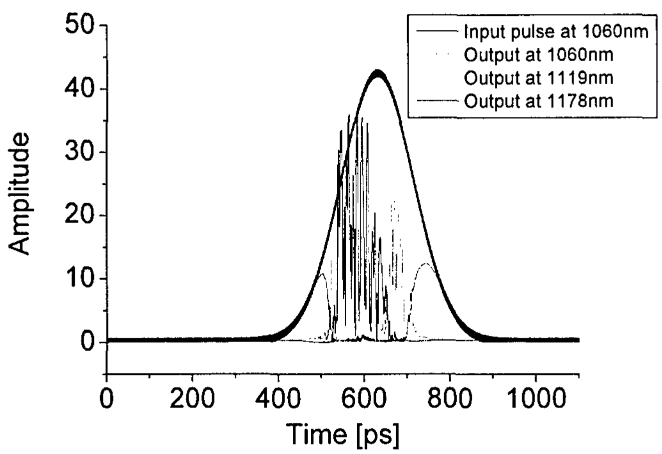

Figure 10: Simulated pulse shape for the pump and Raman beam after co-propagating in a 40 m-long single-mode fiber. Color plot.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

Reduction of linewidth broadening in a pulsed Raman amplifier

Self-phase and cross-phase modulation can be suppressed by a employing flattened (e.g., rectangular) pump pulses [8]. However the generation of such pulses in a practical and simple way is possible only in the nanosecond regime where "standard" high-speed electronics can be utilized. In our simulations we compared the interaction of the pulsed pump beam with various shapes with the signal beams. The pulse width was set to 1 ns and two pulse shapes were considered: Gaussian and super-Gaussian of order 8 (rise and fall times of about 100 ps). Seed linewidths were set to be 3 GHz. With a fiber length of 40 m, 600 W of pump peak power enabled amplification of the second order Stokes to more than 100 W of peak power. Figure 11 shows the optical spectra after amplification of the seed. While visible spectral broadening occurs with Gaussian pulses, the super-Gaussian pulse does not induce dramatic linewidth degradation and although part of the power is converted outside the 3 GHz linewidth, this is a clear improvement from the previously described scheme. Figure 12 depicts the corresponding pulse shapes obtained in the different configurations.

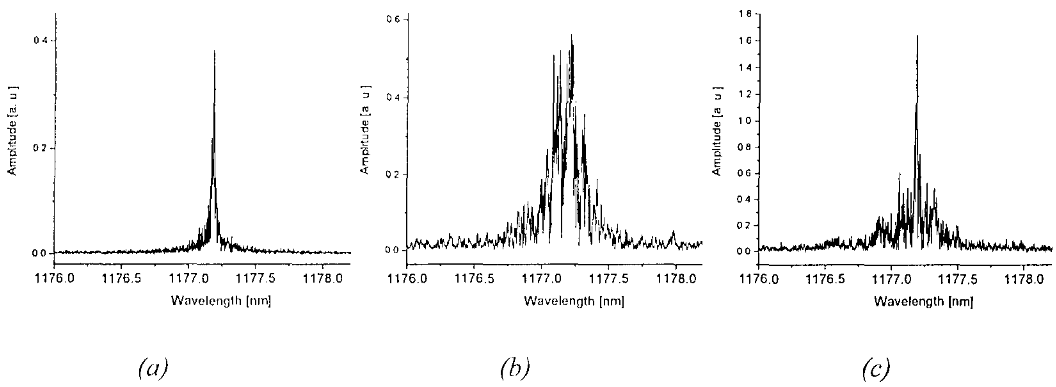

Figure 11: Simulated optical spectra at the second Raman Stokes after pulsed Raman amplification in a 40 m long single-mode fiber for various pulse shapes: (a) CW seed; (b) Gaussian pulse; (c) super-Gaussian pulse order 8.

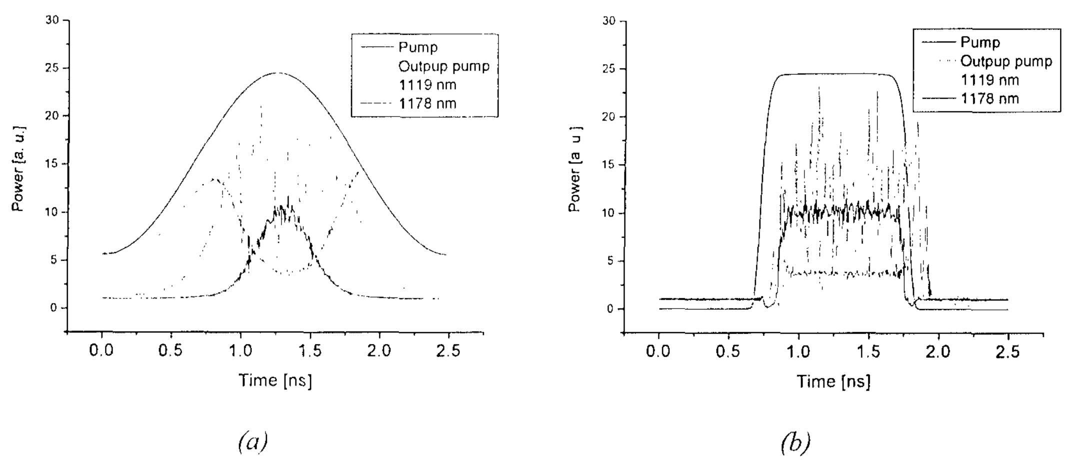

Figure 12: Simulated pulse shapes for pump and Raman beams after co-propagating in a 40 m-long single-mode fiber for (a) Gaussian pump pulses and (b) super-Gaussian pulses. Color plot.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

4. Conclusions, discussion, and possible future work

We reached the targeted 1 W of 589 nm radiation and we believe that our approach can be scaled to significantly higher powers with modest modifications of the system. However the linewidth was much too large and that is the most critical issue. We next discuss the scope for reducing the linewidth down to the required 3 GHz, using simple, analytical, approximations.

With two-stage Raman amplification with ~ 40 dB gain in both conversion steps, the nonlinear phase shift by necessity becomes ~ 100 rad in a germanosilicate fiber. According to Agrawal [7], with transform-limited gaussian pulses, a nonlinear phase shift ϕ_{NL} leads to an increase of the linewidth by a factor 0.85 ϕ_{NL}, or by roughly 100 times. We here assume that Agrawal's formula for SPM also applies to linewidth broadening through XPM. In order to reach a linewidth of 3 GHz at 1178 nm we would need a pulse duration of 10 ns. At high peak powers, the pulse energy would be significant in such long pulses.

There are several reasons to keep the pulse energy down. With 10 ns pulses, a peak power of 10 kW (as desired for efficient SHG) leads to a pulse energy of 0.1 mJ, so a repetition rate of 0.1 MHz for 10 W of average output power and 1 MHz for 100 W of average output power. These repetition rates are perhaps on the low side. Furthermore, high energy extraction leads to pulse distortion through gain saturation in the Yb-doped fiber amplifier.

The repetition rate can be increased through lowering the peak power and the pulse duration. As it comes to the pulse duration, the simulations have shown that it is possible to reduce this, within a given linewidth, if rectangular (super-Gaussian) rather than Gaussian pulses are used, since SPM and XPM do not broaden the linewidth for constant power in the normal dispersion regime. SPM and XPM will have an effect in the edges of the pulses, and broaden the linewidth there, but if these are sharp then the pulse energy affected by the line broadening will be small. The effective sharpness of the edges is set by the modulator (can be sub-100 ps) but also by fiber dispersion. We will here assume that we use a separate Raman fiber converter, rather than the final-stage YDFA, for Raman conversion. If we target 2 ns long pulses then the maximum peak power (limited by damage) is ~ 300 W/μm^2. We may operate at 100 W/μm^2, or with a 50 μm^2 core area if we target 5 kW of peak power (repetition rate 1 MHz for 10 W average power). The Raman gain at 100 W/μm^2 intensity becomes 43 dB/m (10 Np/m). Hence, a 3 m long Raman fiber converter or shorter may be appropriate. The dispersion in our wavelength range is ~ 20 ps/nm/km, or 2.4 ns/km with a 120 nm wavelength difference between pump and second Stokes beams. A 3 m long fiber leads to a walk-off of less than 10 ps, which would be acceptable. Indeed, it would be possible to operate with core areas perhaps ten times as large (so ten times longer fibers), or ~ 10 times lower power (as in the simulations) before dispersion becomes prohibitive with 5 kW, 2 ns long pulses. Thus, as it comes to linewidth broadening of the edges, although large, the energy affected by this broadening is relatively small (~10%) while 90% of the energy can remain unbroadend by SPM and XPM according to this simple analysis.

This still assumes that the intensity stays constant during the central part of the pulse, which will not be completely true. Intensity noise would cause both XPM and SPM, although the walk-off would low-pass filter XPM, and reject variations beyond 100 GHz for a 10 ps walk-off. The allowable rate of change of the intensity, relative to the peak intensity, that allows for a 3 GHz linewidth, is approximately 2×10^{-4} ps^{-1}. Insofar as temporal variations at 1060 nm and the two Stokes orders are uncorrelated, somewhat larger variations would be allowable.

In the high peak power pulsed regime, the gain of the YDFA changes with within the pulse. The rate of change of the gain, in Np/s is given by P / E_{IS}, where P is the instantaneous power and E_{IS} is the intrinsic saturation energy of the YDFA. A 40% monotonic change would be allowable over 2 ns, if a 3 GHz linewidth is to be maintained. If the input pulses, at 1060 nm, into the YDFA are undistorted, then a gain variation of 0.5 Np (~ 2.2 dB) would give a 40% change of gain and hence instantaneous power within the pulse. More directly, the maximum allowable value of P / E_{IS} is simply given by 2×10^{-4} ps^{-1}. With P = 5 kW, E_{IS} needs to be 25 μJ. The saturation energy fluence of an YDFA at ~

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

1060 nm is ~ 0.3 μJ/μm^2, so a core size of 100 μm^2 would suffice, although 300 μm^2 appears preferable. At such a core size, SRS in the YDFA can be kept at a low value, although this may not be important.

According to the simulations however, the broadening is not negligible, even with super-Gaussian pulses (Fig. 11). The simulations show a rapid temporal variation in the second Stokes, that would explain the linewidth broadening. The temporal variations may be a result of conversion of a SPM and XPM induced frequency-modulation into an amplitude-modulation. A shorter fiber would lead to less FM → AM conversion, induced, e.g., by dispersion in the fiber. It is very important to not propagate the pulses longer than necessary, i.e., not having a fiber longer than necessary, as the nonlinear effects accumulate quite quickly, and FM → AM conversion caused by fiber dispersion also accumulates with length. It may well be necessary to make the fiber too short for complete Raman conversion, but rather operate with, say, 20% of power left in the intermediate Stokes beam. This corresponds to a nonlinear (Raman anti-Stokes) absorption of 7 dB of the first Stokes beam, induced by the second Stokes beam.

FWM-induced linewidth broadening could be a concern, as well. However, if the Raman anti-Stokes absorption induced by the second Stokes is only 7 dB, it implies that also the Raman gain induced by the second Stokes is 7 dB. The parametric gain induced by FWM can be as much as twice the Raman gain, i.e., 14 dB. However, imperfect phase-matching induced, for example, by SPM and XPM, may reduce this gain. If we assume a parametric gain of 10 dB, it implies that the side bands in the vicinity of the 1178 nm beam will see a 10 dB higher gain than the central part of the 1178 nm beam. This may be manageable, although it would help to explain the growth of the sidebands seen in Fig. 11. A fiber with non-constant parameters (dispersion), and in particular a high dispersion, may help to suppress FWM for long fibers.

The precise control of the Raman conversion fiber that is required implies that the Raman conversion should be done in a separate fiber, rather than directly in the Yb-doped fiber. We note also that RE-doped amplifier fibers tend to have a higher nonlinear coefficient, related to the change in population inversion. Some SRS may still take place in the YDFA. If the YDFA reaches a peak power of 5 kW in a 300 μm^2, the Raman gain becomes 7 dB/m. Spontaneous Raman scattering should be modest at this level, if the effective length is, say, 2 m. If the 1119 and 1178 nm seed beams propagate through the YDFA they may still experience some amplification, which may be associated with excess linewidth broadening. If so, those beams should be combined with the 1060 nm pump pulses at the output of the YDFA.

We believe that if intensity noise can be kept sufficiently low and the Raman conversion fiber is somewhat under-length, it may be possible to keep the linewidth within 3 GHz with simple rectangular pulses, even without additional pulse shaping. We note further that the first Stokes wavelength suffers considerably less from temporal spiking than the 2nd Stokes wavelength does (Fig. 12). Thus, at least with a first-order Raman amplifier, it should be possible to reach the required 3 GHz. A first-order Raman amplifier in germanosilicate would require a pulsed pump laser at ~1114 nm, which is challenging but possible to with an Yb-doped fiber amplifier system.

Guide star lasers have additional requirements related to the system architecture, e.g., to generate pulses of a few μs duration, or pulse bursts of that duration. Another issue is possible saturation of the sodium absorption. The saturation energy fluence of sodium is ~ 0.4 mJ/m^2. The laser spot size is typically 1 m^2, so a pulse energy of at least 0.1 mJ is acceptable. Even with 10 kW of instantaneous pulse power, this allows for pulse durations of 10 ns from a sodium saturation point of view.

In our analysis of the fiber amplifier the (minimum) pulse duration is primarily set by the walk-off considerations. The maximum pulse duration was limited by saturation in the YDFA and the reduced Raman and frequency doubling conversion efficiency at lower instantaneous power. The pulse power variation should be kept, say, below 20%, in which case a 300 μm^2 core size allows for a duration of ~ 5 ns. Thus, the maximum pulse duration of 10 ns set by the sodium saturation does not represent a restriction.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

A pulse duration of 5 ns corresponds to a pulse length of 1 m. The Raman fiber is typically longer than this. This has some benefits: if the pump pulse fills the fiber and generates high gain at 1178 nm, multiple reflections can occur that can degrade the output through spurious lasing, for example. That would make it very difficult to generate the 40 – 60 dB instantaneous gain, and the narrow linewidths, that we may require. This is not a concern if the pump pulses are shorter than the fiber, which will be the case for us. Thus, we should be able to reach quite high gain.

Brillouin gain can be a problem at narrow lines, but a 3 GHz linewidth should be sufficiently large to suppress SBS. SBS is known to be relatively small for ns-scale pulses, but we may have to keep the nonlinear fiber converter longer than, say, five times the pulse length to completely suppress the SBS.

We only recently learnt that pulses with energies exceeding 0.1 mJ were acceptable, and therefore that nanosecond-class pulses could be used. This is the reason why they were not studied experimentally within the project, even though they do look good.

Thus, it seems that the amplifier can work, with careful optimization of the Yb gain fiber and the Raman gain fiber, use of under length fiber, and rectangular pulses. It also looks advantageous to use a 1st-order Raman amplifier rather than a 2nd-order amplifier.

In addition, polarization-maintaining fibers should be used in an improved system.

We also need to consider the 1178 nm seed source. Indeed, the relative intensity noise of the seed sources (1178 and 1060 nm) appears to be the biggest uncertainty of an improved system. Some options for this were discussed briefly in the section on the 1178 nm seed source.

References

1. P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, M. Ibsen, Y. Jeong, L. M. B. Hickey, M. N. Zervas, J. Nilsson, and D. J. Richardson, "321 W average power 1 GHz 20 ps 1060 nm pulsed fiber MOPA source", in *Proc. Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, Anaheim, CA, USA, March 6 - 11 2005, post-deadline paper PDP3

2. A. Malinowski, A. Piper, J. H. V. Price, F. He, M. Ibsen, J. Nilsson, and D. J. Richardson, "Short pulse high power fiber laser systems", in *CLEO/IQEC Technical Digest on CDROM* (The Optical Society of America, Washington, DC, 2005), paper CThG3 (invited)

3. P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, Y. Jeong, J. Nilsson, D. J. Richardson, L. M. B. Hickey, and M. N. Zervas, "High average power and picosecond pulses from a fiber amplified diode laser at 1060 nm", Proc. Conference on lasers and electro-optics – Europe (CLEO-E) 2005, Munich, Germany, June 12 - 17 2005, paper CJ3-1-MON

4. Y. Jeong, J. Nilsson, J. K. Sahu, D. B. Soh, C. Alegria, P. Dupriez, C. A. Codemard, D. N. Payne, R. Horley, L. M. B. Hickey, L. Wanzcyk, J. Chryssou, J. A. Alvarez-Chavez, and P. W. Turner, "Single-frequency single-mode plane-polarized ytterbium-doped fiber master-oscillator power amplifier source with 264 W output power", Opt. Lett. **30**, 459-461 (2005)

5. J.-C. Bouteiller, "Spectral modeling of Raman fiber lasers", IEEE Photonics Technol. Lett. **15**, 1698-1700 (2003)

6. J. K. Sahu, P. Dupriez, J. Kim, C. Codemard, J. Nilsson, and D. N. Payne, "Suppression of stimulated Raman scattering in a high peak-power pulsed 1060 nm fiber MOPA source with purely single-mode output using W-type fiber", in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference on CD-ROM* (Optical Society of America, Washington, DC, 2006), paper OWD5

7. G. P. Agrawal, *Nonlinear fiber optics, 2nd ed.* Academic Press (1995)

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

8. Toshiya Sato, Tsuneo Horiguchi, Mitsuhiro Tateda, Yahei Koyamada, and Hisashi Izumita, "Spectral-linewidth broadening in synchronous Raman fiber amplification caused by cross-phase modulation effects and its suppression", Opt. Lett. **22**, 880-882 (1997)

5. Personnel Supported

Staff Employed

Principal Investigator: Dr. J. Nilsson

Research Staff: Dr. Y. Jeong

Facility Technician: Mr. T. McIntyre

Doctoral Student

Mr. P. Dupriez (not directly supported by the grant)

6. Publications

P. Dupriez, A. Piper, C. Farrell, A. Malinowski, J. K. Sahu, Y. Jeong, B. C. Thomsen, J. Nilsson, D. J. Richardson, L. M. B. Hickey, M. N. Zervas, "High average power picosecond pulses from a fiber amplified diode laser at 1060 nm", CLEO/Europe-EQEC 2005, Munich 12-17 Jun 2005, paper CJ3-1-MON.

P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, M. Ibsen, Y. Jeong, L. M. B. Hickey, M. N. Zervas, J. Nilsson, and D. J. Richardson, "321 W average power 1 GHz 20 ps 1060 nm pulsed fiber MOPA source, Optical Fiber Communication Conference (OFC) 2005, Anaheim, 6-11, Mar., 2005 PDP3 (Postdeadline).

A. Malinowski, A. Piper, J. H. V. Price, F. He, M. Ibsen, J. Nilsson, and D. J. Richardson, "Short pulse high power fiber laser systems", CLEO 2005, paper CThG3 (invited). (Paper contains some material related to this project).

P. Dupriez, C. Farrell, M. Ibsen, J. K. Sahu, J. Kim, C. Codemard, Y. Jeong, D. J. Richardson, and J. Nilsson, "1 W average power at 589 nm from a frequency doubled pulsed Raman fiber MOPA system", in *Fiber lasers III: technology, systems, and applications*, A. J. W. Brown, D. Harter, J. Nilsson, A. Tünnermann, Eds., Proc. SPIE vol. 6102 (in press)

7. Interactions and Transitions

a. Participation/presentations at meetings, conferences, seminars, etc.

b. Consultative and advisory functions to other laboratories and agencies

c. Transitions

European Symposium on Optics and Photonics for Defense and Security

Although not directly related to this project, Dr. Nilsson participated in the SPIE European Symposium on Optics and Photonics for Defense and Security, London, England, October 25 – 28, 2004. There, he presented the following paper:

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

Y. Jeong, P. Dupriez, J. K. Sahu, J. Nilsson, D. Shen, W. A. Clarkson, and S. D. Jackson, "Thulium-ytterbium co-doped fiber laser with 75 W of output power at 2 μm", Solid state laser technologies and femtosecond phenomena, [Proc. SPIE 5620-04]

There were short discussions on this project with Dr. Sandy Smith.

Photonics West

Although not directly related to this project, Dr. Nilsson took part in Photonics West in San Jose, California, January 23-27 2005. He was a co-chair of the conference "Fiber Lasers II: Technology, Systems, and Application" (within Photonics West) and also gave a short course "Fiber Lasers and Amplifiers" (SC228).

At Photonics West, there were short discussions on this project with Dr. Rick Berdine and Dr. Craig Denman, both of the Air Force Research Lab in Albuquerque.

Advanced Solid State Photonics

Although not directly related to this project, Dr. Nilsson took part in the Topical meeting on Advanced Solid State Photonics (ASSP), Vienna, Austria, February 7-9 2005. The meeting was organized by the Optical Society of America, and Dr. Nilsson was a member of the technical program committee.

At ASSP, there were short discussions on this project with Dr. Gerold Moore and Dr. Craig Denman, both of the Air Force Research Lab in Albuquerque, as well as with Dr. Sandy Smith.

Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference

Dr. Nilsson took part in the Optical Fiber Communications conference (OFC), Anaheim, California, March 7-11 2005. He was a member of the sub committee B, Amplifiers and lasers: fiber or waveguide. He presented two papers, of which one is related to this project:

J. Nilsson, J. K. Sahu, Y. Jeong, V. N. Philippov, D. B. S. Soh, C. A. Codemard, P. Dupriez, J. Kim, D. J. Richardson, A. Malinowski, A. N. Piper, J. H. V. Price, K. Furusawa, W. A. Clarkson, and D. N. Payne, "High power fiber lasers" in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference on CD-ROM* (Optical Society of America, Washington, DC, 2005), paper OTuF1 (invited)

P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, M. Ibsen, Y. Jeong, L. M. B. Hickey, M. N. Zervas, J. Nilsson, and D. J. Richardson, "321 W average power 1 GHz 20 ps 1060 nm pulsed fiber MOPA source", in *Proc. Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, Anaheim, CA, USA, March 6 - 11 2005, post-deadline paper PDP3

Conference on lasers and electro-optics – Europe

Mr. Dupriez took part in the Conference on lasers and electro-optics – Europe (CLEO-E) 2005, Munich, Germany, June 12 - 17 2005. There, he presented the following paper, related to the project:

P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, Y. Jeong, J. Nilsson, D. J. Richardson, L. M. B. Hickey, and M. N. Zervas, "High average power and picosecond pulses from a fiber amplified diode laser at 1060 nm", Proc. Conference on lasers and electro-optics – Europe (CLEO-E) 2005, Munich, Germany, June 12 - 17 2005, paper CJ3-1-MON

Optoelectronics and Communications Conference

Although not directly related to this project, Dr. Jeong took part in the Optoelectronics and Communications Conference (OECC) 2005, Seoul, Korea, July 4-8 2005. There, he presented the following invited paper:

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

Y. Jeong, J. Nilsson, J. K. Sahu, D. B. S. Soh, P. Dupriez, C. A. Codemard, C. Farrell, J. Kim, D. J. Richardson, and D. N. Payne, "Beyond 1 kW, the rising power of fibre lasers" Proc. Optoelectronics and Communications Conference (OECC) 2005, Seoul, Korea, July 4-8 2005, paper 8D1-1

Conference on Lasers and Electro-optics – Pacific Rim

Although not directly related to this project, Dr. Jeong took part in the Conference on Lasers and Electro-optics – Pacific Rim, Tokyo, Japan, July 11-15 2005. There, he presented the following invited paper:

Y. Jeong, J. Nilsson, J. K. Sahu, P. Dupriez, C. A. Codemard, D. B. S. Soh, C. Farrell, J. Kim, D. J. Richardson, and D. N. Payne, "High power fiber lasers", Proc. Conference on Lasers and Electro-Optics - Pacific Rim, Tokyo July 11-15 2005, paper CWI4-1-INV

International Laser Physics Workshop

Although not directly related to this project, Dr. Nilsson took part in the 14th International Laser Physics Workshop, Kyoto, Japan, July 4-8, 2005. There, he presented the following plenary paper:

J. Nilsson, Y. Jeong, D. B. S. Soh, C. A. Codemard, P. Dupriez, C. Farrell, J. K. Sahu, J. Kim, S. Yoo, and D. N. Payne, "High-power fiber lasers: progress and opportunities", Proc. 14th International Laser Physics Workshop 2005 (LPHYS 2005), Kyoto, Japan, July 4-8, 2005, paper PS5

He also presented the following invited paper:

J. Nilsson, "High-power fiber sources: fundamental properties", Proc. 14th International Laser Physics Workshop 2005 (LPHYS 2005), Kyoto, Japan, July 4-8, 2005, paper 4.5.3

Optical Amplifiers and Their Applications

Although not directly related to this project, Mr. Dupriez took part in the Topical Meeting on Optical Amplifiers and Their Applications, Budapest, Hungary, July 7-10 2005. There, he presented the following invited paper:

P. Dupriez, J. Nilsson, Y. Jeong, J. K. Sahu, C. Codemard, D. B. S. Soh, C. Farrell, J. Kim, A. Piper, A. Malinowski, and D. J. Richardson, "Current progress in high-power fiber lasers and amplifiers", in Optical Amplifiers and Their Applications Topical Meeting on CD-ROM (The Optical Society of America, Washington, DC, 2005), paper TuD1 (invited)

Stanford Photonics Research Center Annual Symposium

Although not directly related to this project, Dr. Nilsson took part in the Stanford Photonics Research Center Annual Symposium, Stanford, California, Sept. 19 - 21, 2005. There, he presented the following invited paper:

J. Nilsson, "High-power fiber lasers: Surge to power", Stanford Photonics Research Center Annual Symposium, Stanford University, USA, Sept. 19-21 2005 (invited)

At Stanford, there was a short discussions on this project with Dr. Gerold Moore of the Air Force Research Lab in Albuquerque.

Windows of Science visit, Air Force Research Lab in Albuquerque

Dr. Nilsson visited the Air Force Research Lab in Albuquerque, NM, on Sept. 23 2005. He was hosted by Dr. Shay of the AFRL, and gave the following talk:

J. Nilsson, "High-power and narrow-linewidth fiber sources", Windows on Science seminar, Kirtland Air Force Base, Albuquerque, USA, Sept. 23 2005.

He also visited Dr. Craig Denman and others at the Starfire Optical Range. There, this project was discussed in some detail, and Dr. Denman presented AFRL's sodium guide star source based on sum frequency generation.

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk
www.orc.soton.ac.uk
Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173

Photonics West, 2006

Although outside the time frame of this contract, Dr. Nilsson took part in Photonics West in San Jose, California, January 22-26 2006. He was joint chair of the conference "Fiber Lasers III: Technology, Systems, and Application" (within Photonics West) and also gave a short course "High power fiber sources" (SC748). He also presented one talk on the results of this project:

P. Dupriez, C. Farrell, M. Ibsen, J. K. Sahu, J. Kim, C. Codemard, Y. Jeong, D. J. Richardson, and J. Nilsson, "1 W average power at 589 nm from a frequency doubled pulsed Raman fiber MOPA system", in *Fiber lasers III: technology, systems, and applications*, A. J. W. Brown, D. Harter, J. Nilsson, A. Tünnermann, Eds., Proc. SPIE vol. 6102 (in press)

There were also brief but very useful discussions with staff from Lawrence Livermore National Labs on the requirements on lasers for sodium guide star applications.

8. New discoveries, inventions, or patent disclosures (if none, report none.)

None.

9. Honors and awards

None

Johan Nilsson, Yoonchan Jeong, Pascal Dupriez
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England

jn@orc.soton.ac.uk
www.orc.soton.ac.uk

Phone +44 23 8059 3101
Fax +44 23 8059 3142
Mobile +44 77 5298 4173