Laser Development for Sodium Laser Guide Stars at ESO

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A breakthrough in the development of sodium laser guide star technology at ESO was made in 2009. The laser research and development programme has led to the implementation of a narrowband Raman fibre laser emitting at the wavelength of the sodium lines at 589 nm with demonstrated power beyond 50 W. Fibre lasers are rugged and reliable, making them promising candidates for use in the next generation of laser guide star systems, such as the Adaptive Optics Facility planned for installation on VLT UT4 in 2013.

Introduction

Laser guide stars (LGS) can be used as reference beacons for adaptive optics (AO) and significantly enlarge the sky coverage of AO on optical telescopes. Sodium LGS are obtained by illuminating the natural layer of atomic sodium in the mesosphere at 80–100 km altitude using a wavelength of 589 nm (the sodium D_2 lines) and causing it to fluoresce. In this way, an artificial "star" can be produced that is a useful alternative to a natural guide star where none exists at that sky location. AO uses the laser guide stars as reference sources to probe atmospheric turbulence and provide feedback to deformable mirrors in order to compensate image blur effects induced by this turbulence. Sodium LGS produce less focus anisoplanatism (cone effect) than Rayleigh LGS and they can probe the entire extent of the atmosphere (Ageorges & Dainty, 2000).

Several large telescopes are equipped with AO and LGS facilities, and future Extremely Large Telescopes will require LGS–AO for some operational modes. ESO installed its first laser guide star on the Very Large Telescope (VLT) Unit Telescope 4 (UT4; Yepun) for the NACO and SINFONI instruments (Bonaccini et al., 2003), and in 2013 the installation of a further four LGS is planned as part of the Adaptive Optics Facility (AOF; Arsenault et al., 2006) project. Future extremely large telescopes such as the European Extremely Large Telescope (E-ELT) will also require multiple laser guide stars (currently 6–8 are envisaged), and it is essential to provide reliable, compact, low-maintenance laser sources at a reasonable cost to meet the needs of these telescopes.

To produce sufficiently bright guide stars, lasers at 589 nm with powers of around 20 W Continuous Wave (CW) and extremely good beam quality are needed. The brightness of the guide star depends, amongst other things, on the detailed atomic physics of the sodium layer. As this has not been well modelled, extensive design simulations of the mesospheric sodium return flux have been undertaken (Milonni et al., 1998; Drummond et al., 2004; Holzlöhner et al., 2010). For the AOF multiple laser guide star facility, this has resulted in specific requirements on the optical characteristics of the laser, as summarised in Table 1.

Firstly, to facilitate efficient optical pumping and achieve small LGS sizes, the emitted laser-beam wavefront error has to be better than 70 nm root mean square (rms), with a goal of 25 nm rms. Secondly, a highly polarised output is needed to produce circular polarisation and perform optical pumping of the mesospheric sodium atoms, which further enhances the resonant backscatter signal. Circular polarisation is obtained by, for example, inserting a quarter-wave plate in the launch telescope system. Finally, re-pumping of the sodium atoms is extremely advantageous (Kibblewhite, 2008) for the LGS return flux and is achieved by emitting two identical laser lines at the centres of the D_{2a} and the D_{2b} sodium lines, with an intensity ratio of 10 : 1. These requirements on the laser and the launch equipment are stringent. For routine operation at astronomical observatories, the laser should also be rugged, turn-key, remotely operated from the control room, and require little maintenance. These laser characteristics have been specified for the AOF, but they are also relevant to the E-ELT baseline requirements. It must be mentioned that special formats of pulsed lasers may become useful in the coming years to reduce or eliminate the effects of spot elongation (Beckers, 1992; Beletic et al., 2005) in large aperture telescopes and to determine the rapidly varying sodium profile precisely, but have not yet been pursued.

Dye lasers provided the first generation of 589-nm lasers to the astronomical community. They were the only possible choice at the time when Keck and ESO decided to build their laser guide star facilities. One model of a 589-nm dye laser was built by the Lawrence Livermore National Laboratory for the Lick and Keck Observatories; a different dye laser model was made for ESO by the Max-Planck-Institut für extraterrestrische Physik in Garching (Rabien et al, 2003), as part of the LGSF project (Bonaccini et al., 2003). Although extremely useful for pioneering LGS–AO techniques and for conducting the first LGS–AO observations, this class of laser has the drawback that it requires high maintenance and preparation time before an observing night, which, at astronomical observatories, creates manpower loads with a considerable footprint on the observatory operation. These considerations make dye lasers possibly undesirable candidates for multiple laser guide star systems. Furthermore, dye lasers are limited to stable gravity vector installations.

When the first conceptual design of the AOF multiple laser guide star facility was conceived at the end of 2005, off-the-

Parameter	Value
Format	CW (continuous wave)
Wavelength	589 nm
Power (laser device/in air)	20 W/16 W
Linewidth	< 5 MHz
Polarisation	Linear, Pol. ratio > 100 : 1
Wavefront error (rms)	< 70 nm (< 25 nm goal)
Sodium D_{2b} re-pumping ratio[1]	12 %

Table 1. Laser optical characteristics specified for the VLT Adaptive Optics Facility.

[1] D_{2b} re-pumping denotes blue-shifting a fraction of the D_{2a} line laser power by 1.71 GHz in order to boost the sodium fluorescence efficiency.

shelf solid-state lasers at 589 nm, with the characteristics listed above, did not exist and ESO therefore launched an internal research and development (R&D) programme to support the goal of achieving second generation laser characteristics: turn-key, compact, solid-state CW lasers at 589 nm to be used routinely, requiring limited maintenance, and sufficiently ruggedised to be mounted next to the laser launch telescopes on the altitude structure of the telescope.

This R&D programme, which reached a successful conclusion at the end of 2009, has resulted in the demonstration of progressively increased laser output power in the last two years, reaching up to 50.9 W CW output at 589 nm and a measured linewidth of 2.3 MHz. During the course of this development, we have capitalised on a significant industry trend towards increasing use of high power fibre lasers in multiple industry segments, while developing a unique and innovative narrowband Raman fibre amplifier technology as a solution to those laser problems that are specific to guide stars and therefore could not readily be solved by recourse to the commercial sector. In the final year of the programme, we have made this technology available to industry and an industrial consortium has been able to independently demonstrate a 20 W class 589-nm laser based on the ESO narrowband Raman amplifier technology.

Courtesy of S. Seip

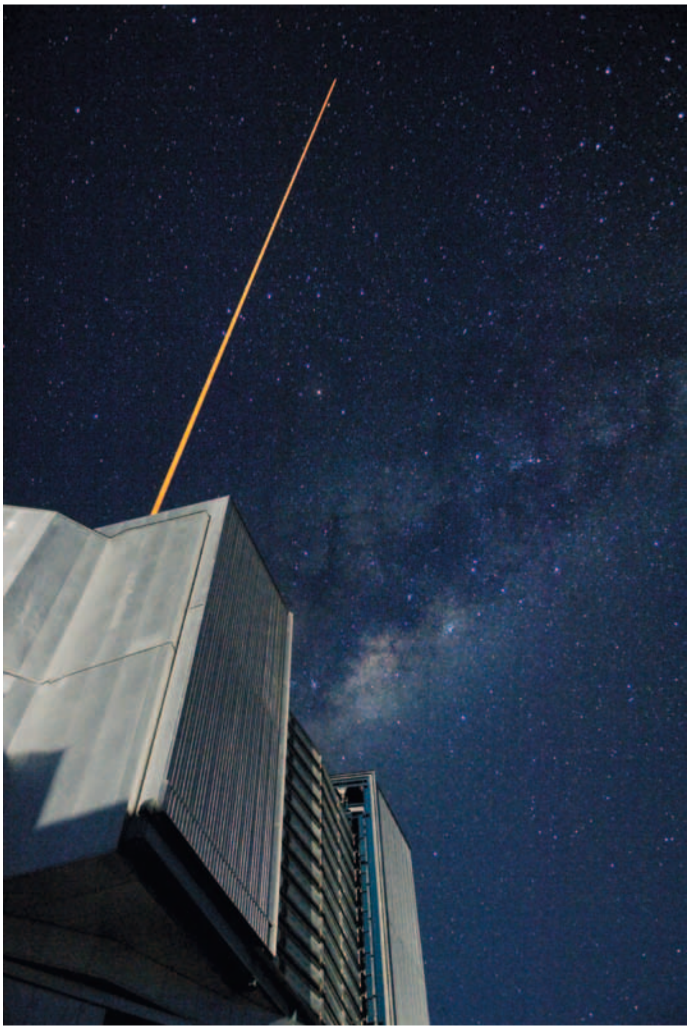


Figure 1. VLT UT4 (Yepun) shown with the LGSF laser beam propagated at Paranal. The Galactic Centre is visible over the dome. The photograph, taken in 2007, is a 5-s exposure during full Moon.

Laser technology background

With the operation and experience of the ESO LGSF, it has become clear that new laser sources had to be developed for the next generation instruments or telescopes, that meet stringent requirements concerning reliability, compactness, and turn-key operation at astronomical sites. When we started the R&D activity, sum-frequency solid-state lasers combining 1064-nm and 1319-nm lasers were being pursued independently by the US Air Force and by the Gemini project together with Coherent Technologies as the industrial partner. In both cases these are solid-state lasers with free-space optics and bulk optical tables full of components that must remain aligned during telescope operation. A broad exploration of the technology readiness levels of different laser technologies was performed at the beginning of the R&D phase, visiting different institutes and several laser companies in Europe and in the US, and studying the vast laser literature.

We decided to explore the technology of lasers at 1178 nm, to be frequency doubled to 589 nm in nonlinear crystals using Second Harmonic Generation (SHG), shown schematically in Figure 2. We studied ytterbium fibre lasers care-

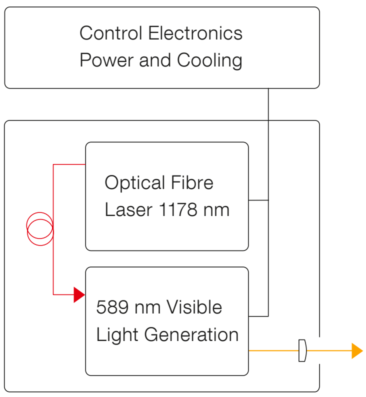


Figure 2. The laser scheme is shown. A fibre laser at 1178 nm feeds a compact second harmonic generation unit based on nonlinear crystals, which converts two photons at 1178 nm into one photon at 589 nm.

fully, but it seemed at that time very unlikely that they can ever lase directly at 1178 nm, while suppressing the amplified spontaneous emission at shorter wavelengths, in particular to 1064 nm. VECSELs (Vertical External Cavity Surface Emitting Laser, also called Optically Pumped Semiconductor Lasers) were considered and discussed with Coherent Inc. in Santa Clara, but their technology readiness was low for our application. We therefore further explored the booming fibre laser technology for the following reasons:

- fibre lasers are alignment-free, being long waveguides with the photons confined to the fibre core;
- their output optical beam quality is diffraction-limited in single mode fibres at the powers of interest to us;
- the heat is distributed along the fibre volume, hence there are no overheating locations in the fibre laser creating strain, lifetime, or beam optical quality issues at the powers of interest to us, contrary to other known solid-state lasers such as VECSELs or waveguide amplifiers;
- there is a robust industrial base for fibre lasers, and they are commercially available (at other wavelengths than 1178 nm) with powers even higher than required;
- fibre lasers can be rack-mounted and located further away from the compact 589-nm SHG unit using the fibre laser output as relay. Thus it is possible to create compact laser heads, where the 589-nm light is produced, that are mounted directly on board the laser launch telescope;
- fibre lasers are simple and contain very few components, hence are generally more reliable and also intrinsically cheaper than other lasers.

Fibre laser technology has made very fast progress in recent years, with Raman fibre lasers used in the telecom industry, and ytterbium lasers used in the material processing and the car industry, among others. This development has led to the availability of in-fibre components such as fibre Bragg gratings (FBG, equivalent to free-space mirrors placed inside the fibre), fibre couplers (equivalent to free-space beam splitters), and wavelength division multiplexers (WDM, equivalent to free-space dichroics). In the broad technological class of fibre lasers, we further narrowed down the technology to Raman fibre lasers, because existing rare-earth doped fibre lasers have low gain at 1178 nm. In contrast to rare-earth doped fibre amplifiers, such as the well-known EDFAs (erbium-doped fibre amplifiers), Raman fibre amplifiers take advantage of a nonlinear conversion process in the fibre which converts "pump energy" from the laser at short wavelengths to the signal wavelength via optical phonons, rather than via atomic transitions. As shown below, however, we had initially to overcome several technological problems.

Broadband Raman fibre amplifiers (RFA) are extensively used in the telecommunications market. Our challenge was to achieve narrowband fibre Raman amplification with powers of about 40 W CW at 1178 nm. As an illustration, the power density in a 5-micron core fibre at 40 W exceeds 2×10^8 W/cm^2, giving rise to nonlinear effects due to the interaction of the electromagnetic radiation with the glass. Today, other laser technologies such as the photonic crystal ytterbium lasers/amplifiers, VECSELs, and bismuth-doped fibre lasers have risen in technology readiness level to become potential laser sources at 1178 nm, both CW or pulsed. Furthermore, new fibre lasers/amplifiers allow novel sum-frequency photon combinations to reach 589 nm, using fibre lasers with rare earth dopants such as thulium or neodymium; however, these developments have yet to be fully demonstrated.

Nonlinear optical effects in optical fibres

Sufficient optical intensities can momentarily modify the optical properties of a medium so that its behaviour depends nonlinearly on light power. This circumstance can be expressed mathematically by expanding the susceptibility χ, which describes the dependence of the optical polarisation of a medium on the electric field, in a Taylor series. The second-order term $\chi^{(2)}$ is responsible for second harmonic generation and sum-frequency generation (SFG) that are used for frequency conversion in materials such as lithium tri-borate (LBO). However, the silica glass, of which optical fibres are made, obeys a structural centre symmetry, implying that $\chi^{(2)}$ vanishes, and thus $\chi^{(3)}$ is the first non-zero nonlinear expansion term ($\chi^{(3)}$ is a complex third-order tensor; Boyd, 2003). In the particle picture, $\chi^{(3)}$ effects describe the interaction of four different photons.

Nonlinear effects due to $\chi^{(3)}$ can be conceptually divided into parametric effects, including the Kerr nonlinearity (index variation of the glass due to high electric fields that can induce self-focusing and self-phase modulation), four-wave mixing (FWM) and non-parametric processes in which light energy is exchanged with the glass, such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). While we exploit SRS in Raman amplification, SBS and FWM are unwanted effects. Brief explanations of these effects, important for the LGS development, are presented.

SRS

Stimulated Raman scattering is the nonlinear effect at the core of our RFA technology, producing a frequency shift, in this case of the 1120-nm photons of the pump fibre laser to 1178 nm. SRS is a combination of the Raman inelastic scattering process with stimulated emission, which amplifies the optical signal with low noise and distributed amplification along the fibre. The pump photons undergo inelastic scattering with the glass molecules of the fibre core, exciting vibration states and creating "optical phonons", which divert part of the photon energy so that the pump photons at 1120 nm are shifted to longer wavelengths, known as the Stokes shift. The extent of the wavelength shift and the efficiency of the Raman process at a given light intensity are related to the material composition and the index profile of the fibre core.

SBS

Stimulated Brillouin scattering limits the output power of the RFA, depending on its emitted linewidth. It arises from the interaction of photons with acoustic phonons generated in the fibre core. In a simplified model of SBS via the electrostrictive effect, a travelling acoustic wave is created that carries forward a periodic variation of refractive index in the fibre core, producing, in effect, a long optical grating that reflects part of the signal back towards the seed laser (see Figure 3). The grating modulation is amplified progressively together with the Raman signal. The onset of SBS with increasing power is very sudden, and its threshold depends on the fibre length and core material, the fibre acoustic waveguiding properties, the laser wavelength, the optical power and, importantly, the bandwidth of the radiation. Linewidths less than a few tens of MHz lead to low SBS thresholds: a standard RFA at 1178 nm is limited to output powers of only 2–4 W! Valuable experience was gained with mitigation of SBS during the LGSF project, where SBS can occur in the 27.5-metre fibre relay to transfer the Parsec dye-laser beam from the optical bench to the launch telescope, and we developed special photonics crystal fibres to suppress SBS (Hackenberg et al., 1999). In the RFAs described in this article, we employ novel ESO-proprietary SBS suppression techniques that push up the SBS threshold by more than an order of magnitude.

FWM

Four-wave mixing, or self-modulation, is induced by the Kerr effect in the interaction between the photons at different frequencies and the medium. Repeated beating effects between the generated photons at different frequencies create strong line broadening. In optical amplifiers, this effect leads to a mixing of the signal with optical noise and hence broadens the laser line. Counter-propagating the pump laser limits FWM effects in the RFA, and that is the solution adopted. FWM is a phase-sensitive process and can be effectively suppressed by a phase mismatch between the photons at different wavelengths (Boyd, 2003).

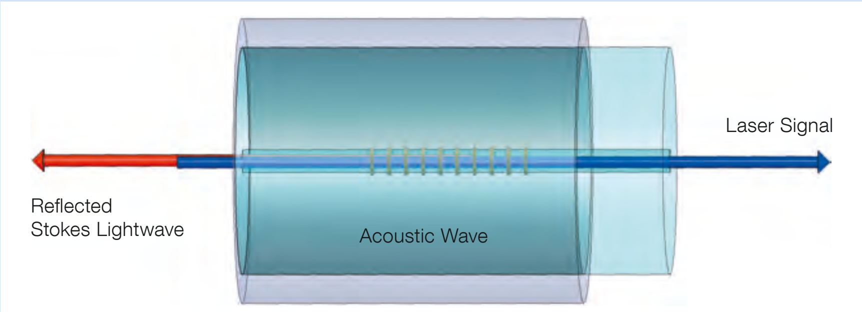


Figure 3. Schematic illustration of the SBS effect is shown. In the fibre core, the forward signal is amplified via SRS. The travelling acoustic wave created by the interaction of the photons with the acoustic phonons creates a periodic refractive index pattern, which extracts energy from the forward signal photons to create phonons, sending back and amplifying a fraction of the lower energy SBS “Stokes” photons, shifted in wavelength to the red. The SBS at high powers can be very effective and send back > 99 % of the forward signal.

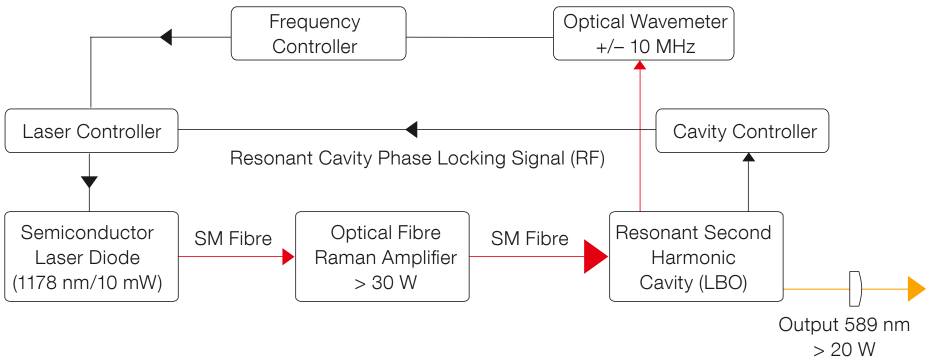


Figure 4. A schematic of the 589-nm fibre laser and its control is shown.

Technical approach

We have pursued 1178-nm narrowband Raman fibre amplifier technology (Bonaccini et al., 2006; Feng et al., 2008). The RFA output radiation is frequency doubled in a commercially available, compact resonant cavity producing a 589-nm beam. Second harmonic generation (SHG), or frequency doubling, is a parametric nonlinear process by which, using suitable nonlinear crystals, two photons are combined into one with twice the energy, or half the wavelength, of each of the fundamental frequency photons. A schematic of the 589-nm laser is shown in Figure 4. All subsystems of the lasers except the RFA are commercially available off-the-shelf. A commercially available 1178-nm seed, frequency stabilised by a wavemeter with an absolute error of less than 10 MHz, feeds, via a single-mode fibre, an 1178-nm high power RFA, whose output is frequency doubled in a compact SHG resonant cavity containing an LBO nonlinear crystal. The 1178-nm narrowband RFA source has been the core of our research.

Nonlinear effects such as Stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) (see insert) were limiting the laser linewidth to tens of GHz for the powers of interest, while we aimed at a few MHz laser linewidth. The invention achieved at ESO, and being patented, uses SBS suppression methods, pushing the SBS threshold power up by an order of magnitude. The FWM is limited by the properties of the fibres and by counter-propagating pump and radiation signals. As a consequence, very little line broadening is observed in the optical amplifier, even at full power.

The high-power fibre components needed for the RFA at 1178 nm had to be progressively developed with the laser industry, such as in-line wavelength division multiplexers, free-space isolators, in-fibre isolators, couplers and high-power 1120-nm polarisation-maintaining (PM) pumps. To minimise the R&D risk, we have furthermore followed two paths in parallel: an in-house development of RFA based on fibres that do not maintain optical polarisation (non-PM); and, in parallel, via contracts with industry, the development of RFA based on PM fibres. Both amplifier

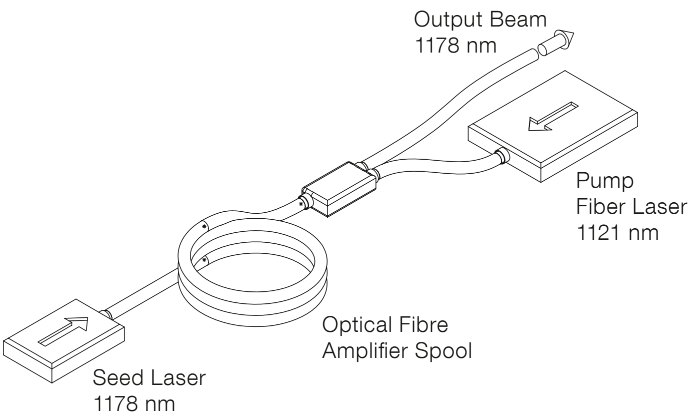


Figure 5. The layout of the Raman fibre amplifier is shown. The output from a high power pump fibre laser at 1121 nm is coupled via a fused glass optical fibre coupler into a fibre spool, where it amplifies the output of a low power seed laser at 1178 nm by the nonlinear optical process of Stimulated Raman Scattering.

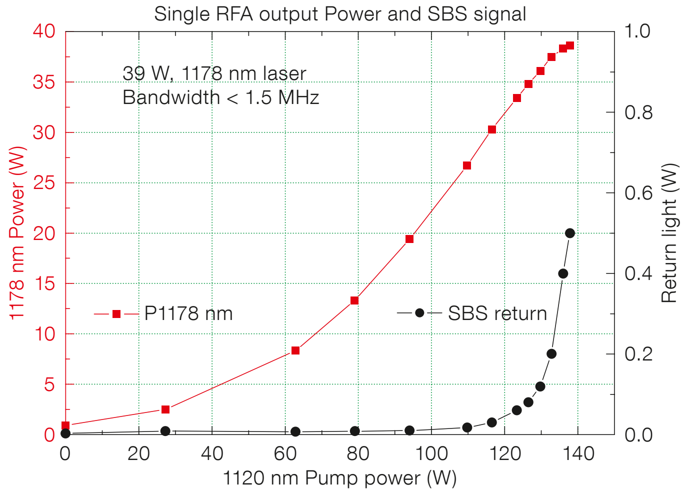


Figure 6. The 1178-nm RFA output power as a function of the pump power at 1120 nm is shown. The maximum value obtained is 39 W. The onset of SBS (black curve, right axis) is seen as return light going back toward the optically isolated seed source. The RFA optical conversion efficiency is 28 % and its wall-plug efficiency 5 %.

technologies have different pros and cons for the RFA and pose different risks. Today we can say that both approaches have been highly successful, meeting and exceeding their goal targets. PM RFA solutions are to be preferred because they are simpler to implement and are thus becoming commercially available.

Besides developing the RFA and integrating them in the laser system at our labs, we have explored the scalability of power, successfully developing coherent beam combination (CBC) schemes. In the following sections we report the results obtained with the single RFA and with coherent beam combination.

Raman amplifier results

We have progressively increased the achieved RFA power once the right methods to overcome SBS were found, following the progressive availability of the necessary fibre components. From 4 W output power at 1178 nm in November 2007, we moved to 39 W in August 2009, maintaining a linewidth below 1.5 MHz and an all-fibre system. In August 2009 we had reached 39 W CW with a single non-PM RFA system developed in-house, together with a novel 150-W fibre laser pump at 1120 nm (Feng et al., 2009); see Figure 6. Using an adaptation of the technology developed at ESO, MPBC Inc. in Canada had produced 44 W with a single PM RFA by the end of 2009. These RFAs give ample margin to reach 20 W at 589 nm — the laser power specification for the AOF with four LGS and the E-ELT LGS system — with adequate linewidth. These results represent both record power and intensity output from a narrowband RFA at spectral power densities well in excess of those normally tolerable in non-SBS-suppressed systems.

The spectral properties of the RFA output are shown in Figure 7, which indicates a very clean spectrum with more than 45 dB emission above amplified spontaneous emission and a linewidth of below 1.5 MHz, measured at 39 W.
The 1178-nm laser beam is collimated and mode-matched to a compact resonant cavity (Figure 8). Frequency doubling

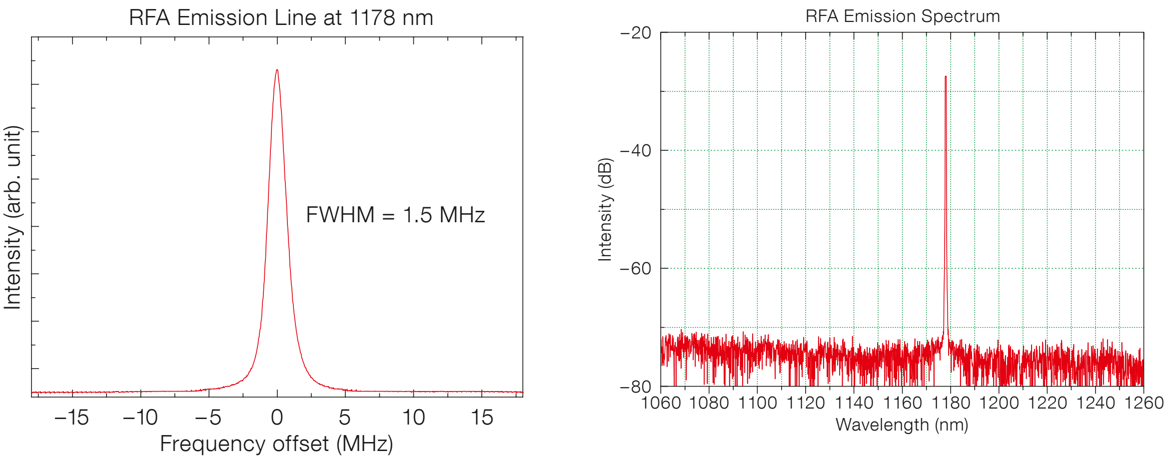


Figure 7. RFA emission linewidth, measured with a scanning Fabry Perot (left, linear plot), and an Ando spectrum analyser (right, log plot) are displayed. The right plot shows that there is a single laser emission line, no residual pump signal at 1120 nm present and no second order SRS Stokes.

is performed by slightly modifying a commercially available SHG unit. The SHG is a very compact bow-tie cavity configuration with a 30-mm long LBO nonlinear crystal (see Figure 10) and a control system based on the Pound–Drever–Hall technique. LBO is well known to be able to handle very high laser powers without lifetime issues. Optical conversion efficiencies up to 86 % have been achieved (Taylor et al., 2009), thanks both to the diffraction-limited beam quality of the single mode RFA (ensuring a good mode-matching capability) and the RFA low intensity/phase noise behaviour. 28 W CW at 589 nm have been obtained (Feng et al., 2009) with a single RFA and SHG in September 2009 (Figure 9 and 10), with excellent beam wavefront quality.

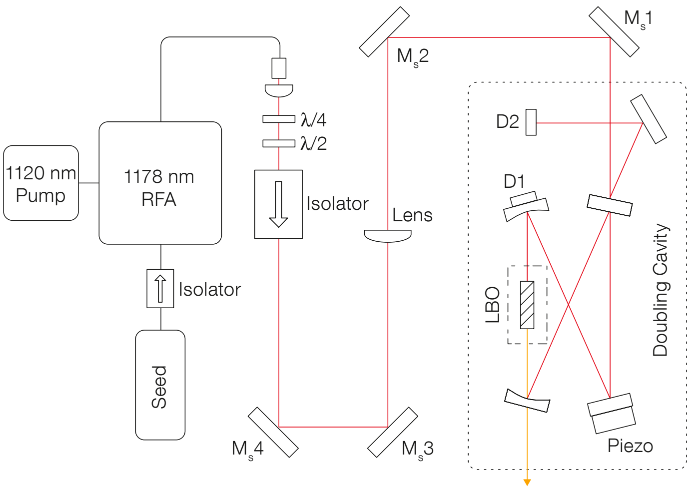


Figure 8. Layout of the RFA and the 589-nm SHG resonant cavity is shown.

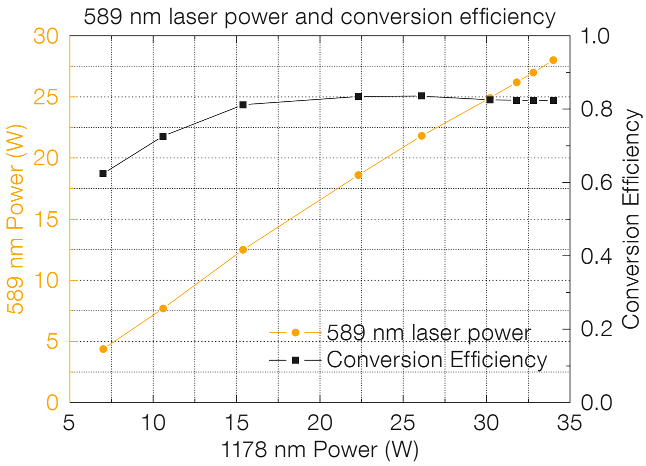


Figure 9. Plots of laser output power at 589 nm (yellow curve, left axis) and SHG efficiency (black curve, right axis) are shown as a function of the 1178-nm power entering the SHG cavity, obtained with the single RFA.

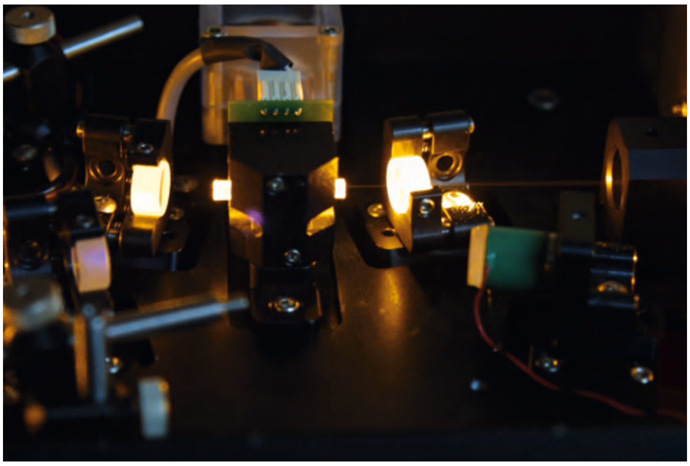
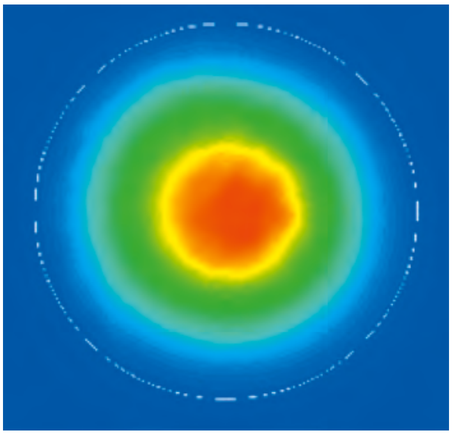


Figure 10. Photograph of the compact bow-tie SHG cavity with the 30-mm LBO crystal mounted in its temperature controlled oven (centre). The 1178-nm laser beam enters from the left side into the crystal; the generated thin yellow beam is visible to the right, exiting the crystal.



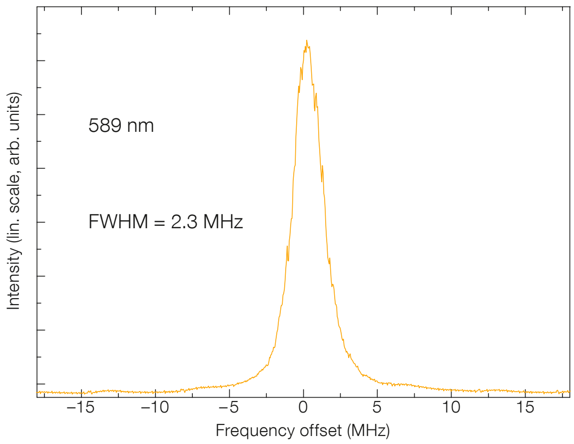


Figure 11. Left: The output laser beam intensity profile taken at 589 nm in high power operation is shown. The wavefront error measured with an interferometer is 11 nm rms. Right: line profile at high power, measured with the optical spectrum analyser.

The output beam quality has been measured at high power using a Phasics SID4 interferometer. The wavefront error measured over the $1/e^2$ diameter was below 0.018 waves, or 11 nm rms (Figure 11), well below the 70 nm rms specification.

Power scaling

During the development there was the risk that a single RFA would not reach sufficient power levels. In order to mitigate this risk, we developed coherent beam combination (CBC) of 1178-nm laser beams. By coherently combining the output beams of different RFAs, the power can be scaled. We have demonstrated that two or more RFAs of equal power can be coherently combined at near-unity combination efficiency, in free space using bulk optics (see Figure 12) via the colinear interference technique, or directly in-fibre without free-space laser beams. We employed a phase control loop acting on a fibre stretcher on one of the RFAs and a 50/50 beam splitter. The loop controls the piston term of the wavefront phase in the fibres at a bandwidth of several tens of kHz. A woofer/tweeter technique was used, cascading two different fibre stretchers, to combine ample phase range to cope with the large phase changes during the laser warm-up with high bandwidth.

CBC has been demonstrated in-house both with bulk optics and, via research contracts with industry, in-fibre (in-line), using 50/50 fibre splitter components (couplers). It has thus been demonstrated for the first time that CBC with narrowband RFAs is possible and indeed extremely efficient. We note that this result is very encouraging and applicable to a wide realm of laser light combination.

We have used CBC with stable output power and efficiencies from 93 % to > 97 % with both PM and non-PM RFAs and with two and three CBC channels. CBC with PM RFA uses in-fibre 50/50 couplers (in-fibre beam splitter). Since the power scaling is done all in-fibre, the setup is extremely compact and there are no optics to align. With two-channel CBC systems we have consistently demonstrated more than 30 W CW at 1178 nm, optically isolated and polarised. In August 2009 we demonstrated more than 60 W at 1178 nm, optically isolated and polarised, from a three-arm free-space cascaded CBC system based on non-PM RFAs (see Figure 13). This is the maximum narrowband power at 1178 nm produced so far via CBC.

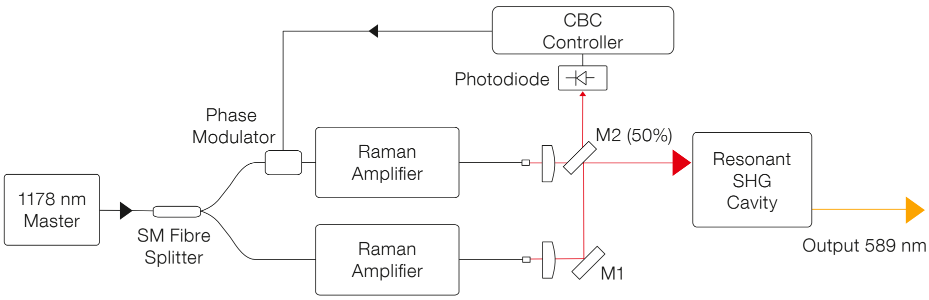


Figure 12. Schematic layout of the power-scaling using free-space coherent beam combination based on non-polarising maintaining RFA is shown. A servo loop controlling the phase of one RFA arm of the CBC allows constructive interference to be kept in the 50/50 splitter M2, in the direction of the SHG cavity.

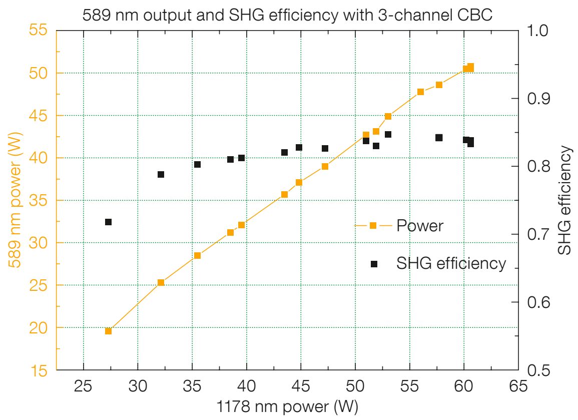


Figure 13. Power-scaling of RFAs using two cascaded coherent beam combinations is shown. In this setup three non-PM RFAs have been combined in sequence via free-space colinear CBC, obtaining, after the optical isolator, power of more than 60 W at 1178 nm, with 93 % CBC efficiency. The CBC output at 1178 nm is used to feed the SHG cavity. The 589 nm power obtained is shown by the yellow curve, related to the left axis. The corresponding SHG conversion efficiency is shown by the black squares, given by the right axis.

Thus we have demonstrated that reliable RFA power-scaling is possible and can be efficiently achieved with CBC, even with cascaded CBC systems. The CBC loop controller electronics and the in-fibre phase actuators are commercially available as off-the-shelf components. With the three-way CBC at 1178 nm via SHG, we have reached 50.9 W CW at 589 nm (Taylor et al., 2010), with more than 85 % peak conversion efficiency and a laser linewidth below 2.3 MHz (see Figure 14). We have observed very stable performance of this system.

Outlook

The 589-nm laser research and development programme at ESO has made great progress to support the goal of implementing a second generation of laser technology for multiple laser guide star AO systems. We have designed, built, and demonstrated novel narrowband, CW high-power Raman fibre amplifiers (RFAs) feeding compact 589-nm laser heads, attacking and solving some fairly fundamental laser technology issues. There has been steady progress in terms of laser output power in the past two years for both 1178-nm RFAs and lasers at 589 nm. It has been demonstrated that 589-nm lasers based on a novel RFA, that suppresses stimulated Brillouin scattering, can deliver the required power and spectral formats to meet the needs of the next generation multiple laser guide

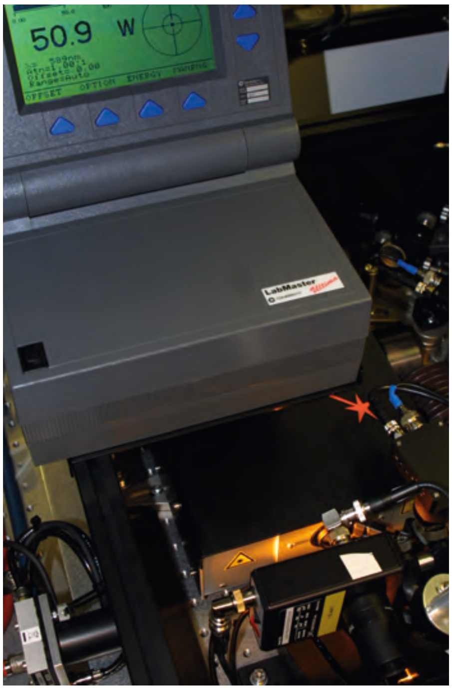


Figure 14. 50.9 W CW at 589 nm obtained from the three-way free-space CBC, as shown by the display.

star facility. Moreover, the ESO Laser Systems Department of the ESO Technology Division has achieved a world record in terms of power output of narrowband RFAs, inventing novel techniques to overcome the undesired nonlinear effects in the RFA.

We have further demonstrated laser power scalability via coherent beam combination, using RFAs with PM and non-PM fibre setups, in different configurations. The demonstrations have been done both in-fibre and with colinear beams in free space, obtaining CBC efficiencies up to 97 %. The three-beam, free-space, cascaded CBC produced a laser beam close to 60 W CW at 1178 nm. This laser beam has been mode-matched to the SHG cavity, and we have demonstrated more than 85 % peak conversion efficiency and laser powers up to 50.9 W at 589 nm. This is the highest laser power published so far for narrowband CW fibre lasers at 589 nm. From a laser research perspective, a natural continuation of the team activities would be to investigate the feasibility of the pulsed laser format for "LGS spot-tracking", to cover potential long-term advantages for adaptive optics systems.

In the final year of the programme we have made, and continue to make, these developments available to the laser industry, and an industrial consortium has independently demonstrated a 20 W class 589-nm laser based on narrowband RFA technology. Thanks to the inherent wavelength flexibility of the Raman effect, high-power lasers may also become available at wavelengths inaccessible today, for different applications in astronomy and elsewhere, for example in the life and geophysical sciences. The lasers demonstrate power levels and beam parameters that meet or exceed the AOF requirements and are relevant to the E-ELT baseline laser needs. The research and development programme has given ESO and the astronomical community much more attractive options for the supply and deployment of reliable, compact, next generation lasers for LGS–AO, suited for operation at astronomical observatories.

Acknowledgements

We sincerely acknowledge Guy Monnet, who as Division head very much encouraged and supported the start of the laser development, as well as Roberto Gilmozzi, Martin Cullum and Roberto Tamai, all of whom fostered our continuing work. We also acknowledge the technical contributions to the laser laboratory activities by Ivan Guidolin, Bernard Buzzoni and Jean-Paul Kirchbauer.

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An example of adaptive optics in action is shown, but using natural guide stars. This near-infrared image of the dust-obscured Galactic Bulge globular cluster Terzan 5 was formed from *J* and *K* images obtained with the Multi-conjugate Adaptive Optics Demonstrator (MAD) instrument on the VLT. The field of view is 40 arcseconds. See ESO Press Release eso0945 for more details.