Pushing Technologies: ESO Fibre Laser Development for Laser Guide-Star Adaptive Optics

In the context of developments toward mature Adaptive Optics systems for large telescopes, we describe the present activities at ESO in the area of fibre lasers.

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The new technologies for astronomical Adaptive Optics are progressively becoming mature. Adaptive Optics in Astronomy allows the telescopes to deliver diffraction limited images, correcting the atmospheric turbulence effects: image motion and image blur. ESO already has three facility Adaptive Optics systems deployed on the VLT, with four more to be installed in the coming years.

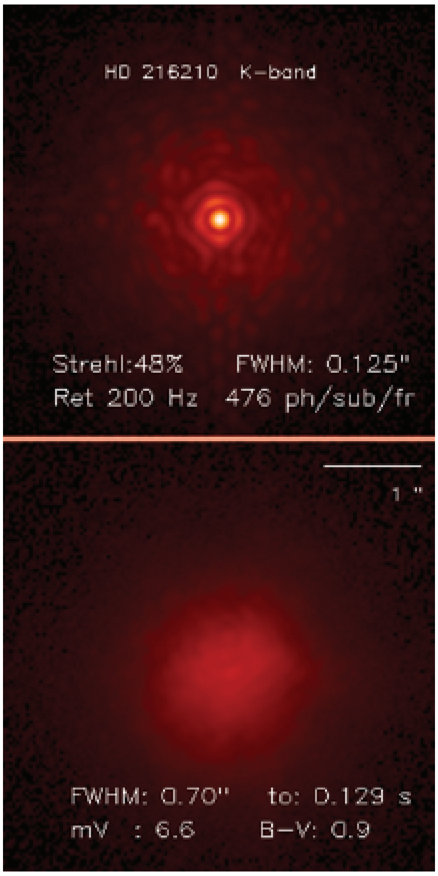

Figure 1: K band images obtained at the ESO La Silla 3.6m telescope with the Adonis system, in May 1997. The Adaptive Optics closed loop (top) and open loop (bottom) images show the difference between diffraction limits and seeing. The 5 second exposure image is in log scale to show the Point Spread Function details.

The Adaptive Optics servo control needs a bright reference source in order to perform the real-time correction at frequencies up to 1 kHz refresh rates. Besides, the optical wavefront correction is valid only within isoplanatic patch areas around the reference source, which at K-band (2.2 µm wavelength) at VLT sites have about 30″ radius in median seeing conditions.

Therefore the current two *limitations* of Adaptive Optics are the need of a bright reference point source, and the limited field of view. One would wish to extend the corrected field of view to one arcmin radius. Adaptive Optics has in recent years successfully demonstrated on the field its capabilities with single natural or laser reference sources (Takami et al., 2003; Wizinowich et al., 2003). ESO with its community has been one of the first players (Beuzit et al. 1997) with facility systems [Fig.1].

Adaptive Optics (AO) is still a young and rapidly evolving technology which in its maturity promises to overcome the current limitations. Toward this goal, useful for 8–10 m class telescopes, and vital for Extremely Large Telescopes of the future, strategic R&D work is being done at ESO as well as in other observatories around the world.

The stars are the natural reference sources for Adaptive Optics; however the brightness required limits to less than 1% the area of the sky which can effectively be used with Natural Guide Stars Adaptive Optics (NGS-AO) on 8–10 m class telescopes. Laser Guide Stars (LGS), i.e. artificial reference sources created by the backscattering of laser beams, allow the user to point almost anywhere in the sky, obtaining extremely large sky coverage. This opens the door to AO for extragalactic astrophysics, and allows overcoming the first of the two limitations.

Lick Observatory (USA), with a prototype system, has reported (Gavel et al., 2003) on the 3 m Shane telescope Strehl Ratios as high as 0.6 when imaging at wavelengths around 2.2 µm [Fig.2]. It is clear from their experience and from the European experience obtained with ALFA at the German Calar Alto observatory (Eckart et al., 2000), that an LGS-AO system requires multidisciplinary technologies, very well engineered systems and an overall tuning together with the science instrument, in order to perform as expected at a good astronomical site.

To extend the field of view, the Multi-conjugate AO technique has been proposed (Beckers, 1988) and is being actively pursued worldwide. Multiple guide stars of sufficient brightness and correct separation are necessary for this technique. Again this may be obtained with groups of bright Natural Guide Stars

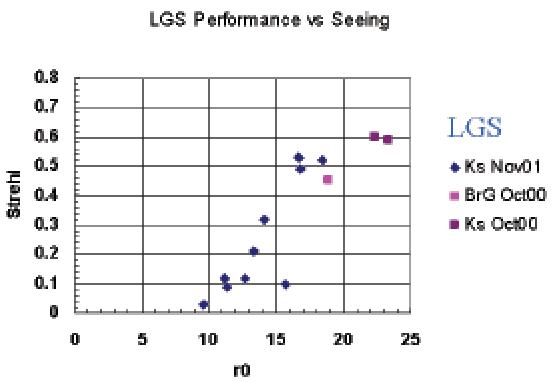

Figure 2: Lick Observatory 3 m telescope results with their experimental LGS-AO. The K-band Strehl ratio vs Fried parameter size, r_o, is shown. A Fried parameter of 15 cm at 0.5 µm wavelength corresponds to a seeing of 0.7 arcsec (Courtesy of Don Gavel, Lick Obs.).

which happen to be of the right magnitude and angular separation, the so-called "asterisms", or with multiple Laser Guide Stars (Ellerbroek et al., 2003). The latter give a preciously uniform Point Spread Function across the field of view in closed loop.

Around the world there are at the moment more than 13 telescopes being equipped with single or multiple LGS-AO systems.

ESO is integrating a Laser Guide Star Facility (LGSF) on the VLT [see *Messenger* No. 100], which will serve the NACO and SINFONI instruments equipped with AO. We are building the LGSF with provision for up to 5 LGS to be projected and diagnosed by the system [Fig 3], in order to be ready for an upgrade toward Multi-conjugate Laser Guide Star Adaptive Optics.

Although much research is still in progress, looking at the past trend it is likely that in the timeframe of 10 years LGS-MCAO will become a mature, advanced, deployable technology enabling AO to overcome or make negligible, the current limitations of guide star brightness and field of view. By the use of single or multiple *laser guide stars* current and future adaptive optics (AO) systems will provide imaging at the diffraction limit of resolution over a wider field of view and at shorter wavelengths than currently possible. This is because laser guide stars (LGSs) can be virtually projected anywhere in the sky and made bright enough to fulfil the utmost flux requirements for real-time compensation of the atmospheric turbulence.

The ESO group working on the Laser Guide Star Facility project, aimed at LGS Adaptive Optics, is following this strategic view. For this reason it is pushing R&D for two different technologies crucial to LGS-AO systems for astronomy: the fibre lasers and the high power laser beam relays based on Photonic Crystal Fibres.

We report briefly in this article on the fibre laser program at ESO, which has provided so far two Patents for our organisation. We will report on the fibre relays in a coming article.

ESO has carried out internally, and then double checked with consulting companies, the fibre laser design and its numerical simulations. We are now in the breadboarding phase of a prototype fibre laser to be transferred later to European industry for commercialization.

Which Lasers

Laser guide stars created in the mesospheric sodium layer at an altitude of about 90 km (and a wavelength of 589 nm) play a major role, since they are generated at the greatest possible distance in the earth's atmosphere, making them most star-like and minimizing focus anisoplanatism effects.

The requirements for a sodium-guide star laser for multiple-guide-star AO systems are stringent: it needs to be an efficient, highly reliable and turn-key system. The output wavelength needs to be precisely centred on the mesospheric, 3 GHz wide sodium D_2 line at 589 nm. The format may be Continuous Wave (CW) or pulsed (800 Hz repetition rate, 200 microsec duration pulses) to exploit techniques which reduce or eliminate the perspective elongation effects. The equivalent power to be emitted is 10 W (15 W goal) per LGS. A polarised output is desirable for optical pumping of the mesospheric sodium atoms in order to enhance the resonant backscatter signal. For multiple sodium guide-star adaptive optics at least four laser guide stars will be required on an 8 m class telescope.

The laser beam quality when emitted at the launch telescope has to have a wavefront variance equal or comparable with the variance introduced by the atmospheric turbulence in the uplink beam (from telescope to Mesosphere). Therefore the high power laser beam quality has to be also quite good (better than 1.3 times the diffraction limit beam Full Width Half Maximum, $M^2 = 1.3$).

On the other end, the different LGS beams do not have to be coherent and may be generated separately or the lasers distributed at different locations. Other requirements apply specifically to the telescope environments. The laser should be efficient in term of power conversion (i.e., less energy to dissipate per watt emitted). It should be rugged, turn-key and ideally require little or no maintenance.

Off the shelf solid state lasers at 589 nm with these characteristics do not yet exist.

The suitable 589 nm lasers available today are only of the dye type. One model has been built by Lawrence Livermore National Laboratory for Lick Observatory and Keck, a different model is built by the Max Planck Institut für Extraterrestrische Physik in Garching as part of the ESO-LGSF collaborative project.

Very recently the US Air Force has demonstrated a sum frequency laser able to produce 20 W, which will be scaled up to 50 W CW. Development programs for discrete solid-state lasers are in place at GEMINI Observatory and the University of Chicago.

For the next-generation laser guide star and multiple guide-star adaptive optics systems ESO's strategy is to develop 10 W fibre lasers at 589 nm, together with industry. This strategy has created a collaboration agreement with the Lawrence Livermore National Laboratory (LLNL) in the U.S to develop a sum-frequency fibre laser and an internal effort on a less complex fibre Raman laser. The decision for fibre lasers was based on a number of advantages which are hard to overestimate. Moreover they have been very recently demonstrated with powers up to 500 W at visible wavelengths, both in CW and pulsed formats.

- Due to their waveguide structure, there are no bulk optical cavities to be kept precisely aligned and thermostatized.
- There are no hot temperature spots, astigmatisms of optical components, vibration-induced instabilities.
- Beam splitters, reflectors and dichroics are today all integrated in the fibre itself giving very high efficiencies.
- Fibre lasers are very compact and efficient, and rugged
- They are alignment-free (simplifying turn-key operation)
- They are power scalable up to the power of interest
- They provide in-built fibre delivery with diffraction-limited output.
- They have also a potential for low

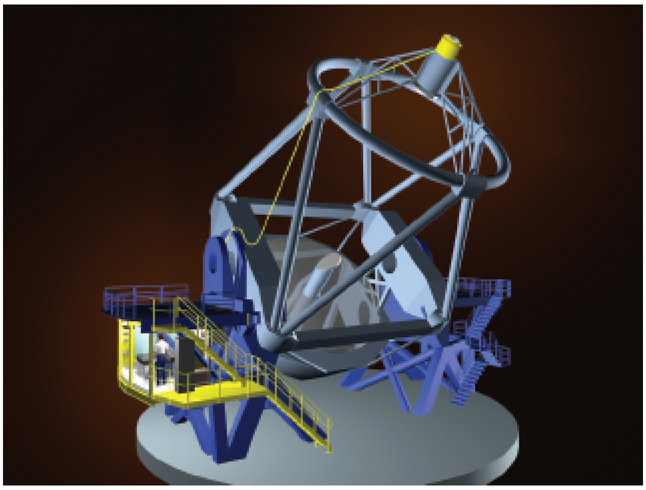

Figure 3: The ESO LGSF projects the laser beam from behind the M2 hub, where a 500 mm Launch Telescope is installed. The 589 nm laser is mounted on the laser clean room installed under the Nasmyth A platform. A single mode Photonic Crystal Fibre relays the laser power for 30 meters, from the laser location to the focal plane of Launch Telescope System behind M2. The LGSF has provision for 5 such fibres to be installed, producing up to five Laser Guide Stars.

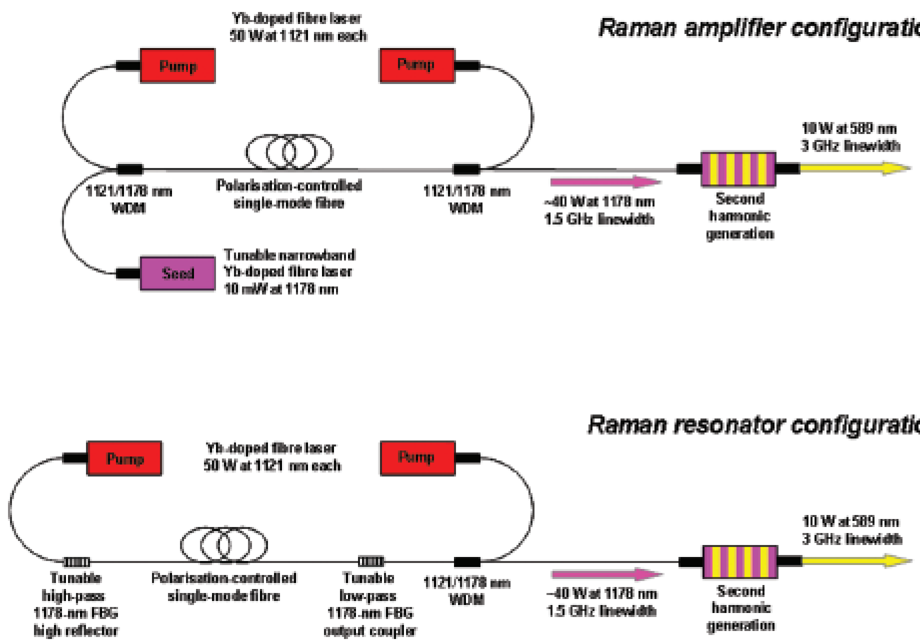

Figure 4: *The fibre Raman laser at 589 nm is obtained by frequency doubling a laser at 1178 nm via a second harmonic generation crystal. The 1178 nm wavelength is obtained as the first Stokes of a Stimulated Raman Scattering process. The two configurations of amplifier (upper drawing) and resonator (lower drawing) are being breadboarded.*

cost, whereby current 10 W CW Raman lasers cost ~40 kEUR.

Moreover, the fibre laser single mode output ensures diffraction limited beam qualities, with M^2 values ≅ 1.1 (confirmed at high power in our laboratory). The fibre output allows the laser beam to be relayed around the telescope with diffraction limited beam quality deployed directly in the Launch Telescope Systems area. This is in most LGSF systems a major engineering effort, coping with laser beam degradation and fast jitter. With fibre lasers this effort is removed from the LGS telescope facility cost and complexity.

Which Fibre Lasers

Since there are no optical materials known that are directly lasing at 589 nm, nonlinear optical frequency conversion processes have to be exploited in the fibre laser design.

Our approach (Hackenberg et al, 2003) is optical frequency-shifting of infrared light by stimulated Raman scattering (SRS) to exactly twice the sodium wavelength (or 1178 nm) in combination with subsequent frequency doubling. This is a Raman fibre laser which we have designed and is being breadboarded at the ESO laser laboratory.

We are also collaborating with LLNL, which has proposed a sum-frequency mixing (SFM) from two suitable fibre lasers at infrared wavelengths, 1583 nm and 938 nm. Common to both approaches is the use of periodically poled crystals for the nonlinear optical frequency conversion of infrared light to the wavelength of 589 nm. Both fibre laser concepts will be described in more detail in the following.

Fibre Raman Laser

The Raman laser approach is the simplest, more robust fibre laser configuration and it is directly scalable up to 20 W CW. It uses the inelastic scattering of photons by the molecules of the fibre. The input or pump laser photons excite the molecules to a higher vibration state and are thus downshifted in frequency by an amount equal to the energy difference between the final and initial state of the molecule. This so-called Stokes shift of course depends on the material composition and is, e.g., 17 THz in silica.

In our fibre Raman laser a germanosilicate single-mode fibre is used as the Raman scattering medium (see Figure 4). The fibre is pumped by a 40 W CW commercial ytterbium-doped fibre laser (YDFL) operating at 1121 nm. By this the incident pump photons experience a frequency shift to exactly 1178 nm or twice the sodium D_2 wavelength. The efficiency of this process, on the first Raman Stokes, is known to reach 80–90% levels in single mode fibres. YDFLs are commercially available at very high output powers (up to 100 W CW), which make them the ideal pump source for our application. In a final frequency conversion step (see Figure 4) the 1178 nm output of the Raman fibre is frequency-doubled in a nonlinear crystal to produce light at 589 nm (the second harmonic). Ideally the frequency doubling happens in a single-pass through a periodically poled crystal (see below). Alternatively, second harmonic generation by a bulk crystal in a small resonant cavity can be used, a concept that is used in commercial frequen-

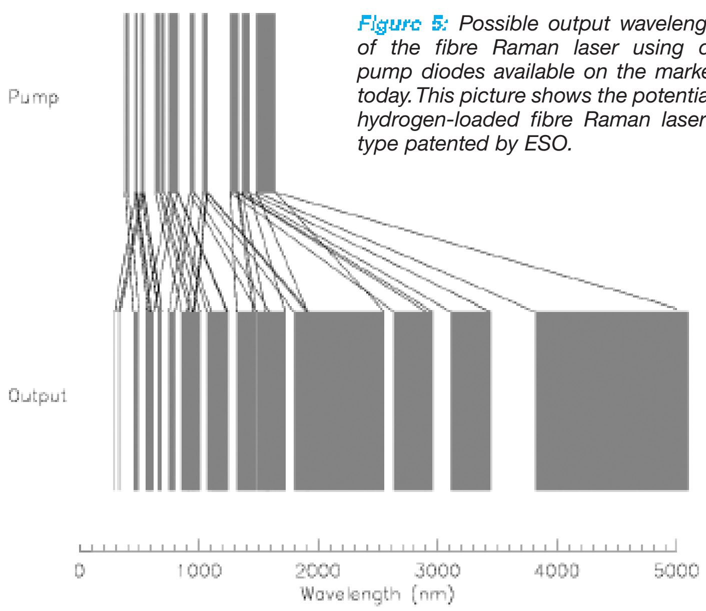

Figure 5: *Possible output wavelengths out of the fibre Raman laser using different pump diodes available on the market as of today. This picture shows the potentiality of a hydrogen-loaded fibre Raman laser of the type patented by ESO.*

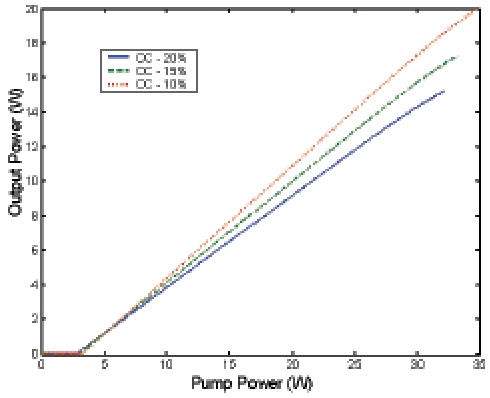

Figure 6: Numerical Simulations results for the fibre Raman laser. The 1178 nm output power obtained vs. pump power is shown, for different output couplers. A 10% output coupler will give the best performance of the fibre laser. 1121 nm pump powers up to 100W are now commercially available.

cy-doubled laser.

The fine tuning of the output wavelength and bandwidth to exactly the sodium D_2 line wavelength can be obtained in two ways (see Figure 4), in an amplifier or a resonator configuration.

Raman amplifier configuration

The Raman fibre is seeded with light from a tunable narrowband laser operating at exactly twice the sodium D_2-line wavelength. The output is the seed light amplified by the SRS process in a single pass. This possibility has now become very attractive due to the recent commercial introduction of low-power tunable and narrowband 1178 nm laser. Parasitic nonlinear optical effects like stimulated Brillouin scattering (SBS) are suppressed by the use of a sufficiently short Raman fibre.

Raman resonator configuration

A narrow-band resonator is created within a single mode fibre, using a pair of dedicated fibre Bragg gratings tuned to 1178 nm wavelength. The Bragg gratings for the Raman-shifted light are designed such that they only reflect 1178 nm and not wavelengths that might be created by parasitic nonlinear processes such as Stimulated Brillouin Scattering. Thus, only the 1178 nm (Raman Stokes I) light will be enhanced in the laser cavity by multiple pass reflections from the Bragg gratings, whereas any parasitic nonlinear light will leave the resonator in a single pass without additional reflections, thus preventing the stimulated SBS emission. Again, having the fibre made sufficiently short, SBS will not build up in a single pass.

This configuration allows building narrow band Fibre Raman Lasers at many other wavelengths than 589 nm, and also multiple wavelength lasers. It has therefore the potential for many applications besides astronomical LGS-AO. This is shown in Fig. 5, for hydrogen loaded fibres. It is likely the most attractive configuration for industry, as high power *narrow-band* Raman fibre laser do not exist on the market yet. ESO is patenting the invention and is applying for technology transfer funds together with interested industries. Our goal is to have compact and turn-key commercially available fibre lasers for LGS-AO within three years.

In Figure 6 the predicted narrowband (0.5 GHz) output power at 1178 nm is shown as a function of pump power. At each pump power the optimal fibre length maximising the output power has been assumed. This length is less than 100 m at the highest pump powers shown here. With commercially available YDFL as pump sources output powers in excess of 40 W at 1178 nm are feasible. This sets an upper limit to the conversion efficiency needed in the subsequent second harmonic generation.

Sum-Frequency Fibre Laser

The sum-frequency fibre laser is developed at LLNL, with collaboration from ESO. It is based on two rare-earth doped fibre amplifiers (Fig.7).

An erbium-doped fibre amplifier (EDFA) operates at 1583 nm, and a neodymium-doped fibre amplifier (NDFA) works at 938 nm. Both fibre amplifier outputs are mixed in a nonlinear crystal to generate light at the sum frequency corresponding to 589 nm. The fibre amplifiers are double-clad pumped by high-power diode laser. The seed lasers needed for output frequency control are low-power tunable and narrowband diode laser.

The EDFA is constructed entirely of commercially available components. The NDFA requires development to bring it to realisation. This will be discussed in the next Section.

ESO contributions are for design issues on the 938 nm arm, some basic components and joint work on the non-linear crystals.

Fibre Laser Development Status

Raman Laser

We have done at ESO, and in parallel contracted out to Directed Energy Solutions, full numerical simulations for the Amplifier and Resonator Raman laser configurations. Both indicate feasibility of the laser system and sufficient suppression of the SBS.

We have procured all discrete components, and assembled the amplifier configuration with discrete components. Thanks to the work of Daniela Werner, a student who has done her master thesis with us, we have obtained practical experience with the fibre amplifier and Raman emissions up to 4 W CW.

We are now procuring and assembling the all-fibre configurations from industry, which will give a better Raman conversion efficiency. We have prepared the test set-up and the doubling crystal to first get ~1 W CW of yellow light, and will then scale it up. We have sufficient pump power and all components are specified to perform 10 W CW tests in our labs.

The breadboard tests are mandatory for the technology transfer to have the fibre laser engineered by industry.

Sum Frequency

The sum frequency laser has produced the first yellow light (50 mW) from fibre laser obtained in November 2002, and it is close to the 1 W level today.

The 938 nm laser (Dawson et al., 2003) is the technological challenge. It is getting close to specifications. Problems to be resolved are the amplified mode selection with the large core NDFA fibre, and polarization control. Currently we have achieved 4.5 W CW useful output at 938 nm. We have achieved 5 W CW at 938 nm and 6 W CW at 1583 nm, polarized, which at the time of this writing are being combined into the sum-frequency crystal.

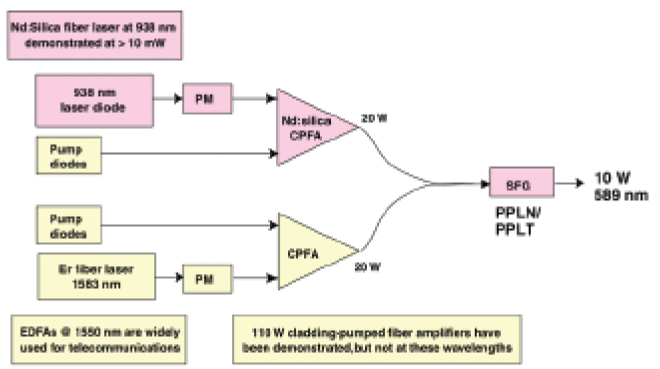

Figure 7: Scheme of the sum-frequency fibre laser pursued at LLNL. The sum of 1583 nm and 938 nm photons energies creates photons at 589 nm in a Periodically Poled SFG crystal.

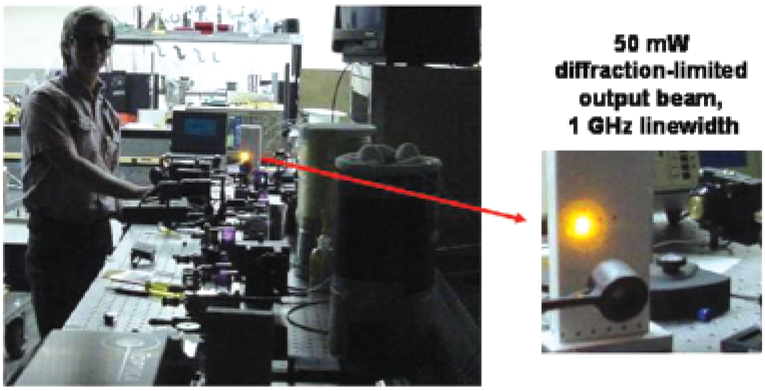

Figure 8: Alex at LLNL tuning up the laser to get the maximum output at the time (Nov 6, 2002). This is the first yellow light from a fibre laser, produced at 589 nm with 1 GHz bandwidth, 50 mW.

Technologies Related

In pursuing the fibre laser we are pushing some technologies which are related to it, together with industry. These are described in the following.

Narrow band high power Raman lasers

Although high power Raman lasers are commercially available at 1178 nm with powers up to 15 W CW, their linewidth is of the order of 1 nm. We are pushing the linewidth to 1 pm, the main challenge in doing this is to suppress the Stimulated Brillouin Scattering. For this we have a viable path supported by design, numerical simulations and soon by experiments.

High power fibre couplers

Beam splitters and dichroics are fully integrated in the fibre laser, in the form of TAP couplers and WDM. Recently high power (20 W CW) couplers have been developed and are commercially available. Couplers and dichroics for polarisation preserving fibres are still under development by the industry. Although not mandatory, they will be an asset for the fibre Raman laser.

Periodically-poled nonlinear crystal

Periodically-poled crystals have the advantage of a very high nonlinear coefficient. They can be inserted directly in the laser beam and give efficient conversions. Such a crystal consists of a sequence of permanent ferroelectric domains of alternating polarity perpendicular to the optical axis (see Figure 9). By this the sign of the nonlinear coefficient is reversed every period, and quasi-phase matching is achieved for the three interacting waves in the crystal. Without poling the fundamental and second harmonic waves would quickly run out of phase due to chromatic dispersion.

The periodically poled crystals commercially available are sensitive to the so-called photorefractive damage. Together with LLNL we are investigating several methods to avoid this type of damage. This include elliptical beam formatting to keep the power density low and improved (i.e., stochiometric) crystal growth and poling techniques. For this purpose a crystal test facility has been set up at LLNL to investigate conversion efficiency and long-term reliability. European laser industries have expressed strong interest in this technology. We are investigating PPSLN and PPSLT materials.

Fibre Bragg Gratings

Fibre Bragg Gratings (FBG) are reflective optical elements or filters created by periodic modulation of the refractive index in the fibre core. They are written permanently into the glass of the fibre by exposing it once to a suitable ultraviolet light interference pattern.

Apodized Fibre Bragg gratings of the required extinction and shape for the Raman fibre laser are feasible, although our specifications have been considered by industry as high-end, low-yield FBGs.

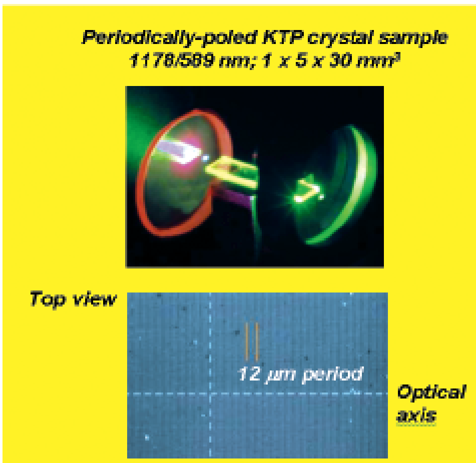

Figure 9: Periodically poled cristals allow to obtain sum frequency or frequency doubling effects, without the need of a resonant cavity. They are an emerging laser technology.

938 nm Neodimyum Doped Fibre Amplifier

In the NDFA design the main technical challenge is the suppression of amplified spontaneous emission (ASE). To force the amplifier to operate at 938 nm and to suppress the ASE at longer wavelengths we are using in parallel several methods: seeding at high power, introducing bend losses to the longer wavelengths which is especially effective in fibres of low numerical apertures and finally long-period Bragg gratings for frequency-selective feedback in the amplifier fibre. These methods have different efficiencies, but more or less independent from each other. We have designed and developed a special fibre to use for the 938 nm laser, together with the Institut für Physikalische Hoch Technologie in Jena (Germany)

What are we going to do next on the fibre Raman laser

For the ESO Raman fibre laser we will receive the all-fibre lasers breadboard around mid 2004, and perform the tests in the summer in our laboratory. The periodically poled crystals activities shared at LLNL will help us to choose the appropriate crystal for the Second Harmonic Generation required by the Raman laser.

We will in the meantime apply for European funds for technology transfer of these new laser types to industry. We are forming a consortium of companies with member state countries and preparing the funding application for the beginning of 2004. The deliverable will be fibre lasers at 589 nm, to be field tested at our LGSF facility. An option for pulsed formats fibre lasers will be opened.

The first part of the program will last two years leading to a tested, well engineered preproduction unit. The second part will call for a field test final unit, to be delivered in the subsequent year.

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