

Power Amplifier for 1083 nm Using Ytterbium Doped Fibre

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Abstract

We have demonstrated a power amplifier for a single-frequency signal at 1083 nm as required in spectroscopic applications. It is based on a ytterbium doped silica fibre which was pumped by a MOPA semiconductor laser at 978 nm. In a preliminary experiment we achieved 14 dB gain and 60 mW of amplified signal. We discuss the design considerations, the possibility of significant improvements of output power and gain, and the relevance of the amplifier for high resolution spectroscopy.

Key words: fibre amplifier, spectroscopy

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The technology of semiconductor diode lasers has allowed considerable progress in the field of atomic and molecular spectroscopy as well as in other fields of applied research. Although these sources have many advantages over lasers which are more conventional in spectroscopy, like dye or Ti:sapphire, the available power is generally much lower when high spectral purity and a good spatial mode is required. Recently, DBR (Distributed Bragg Reflector) semiconductor diode lasers have been developed at a wavelength of 1083 nm, finding an immediate application in atomic and molecular spectroscopy^{1,2}. In particular, these sources have been used to study the $2^3S_1 \rightarrow 2^3P$ multiplet of the helium atom³ with the aim of improving measurement precision for the fine structure constant α , pushing the uncertainty down to the level of a few parts in 10^8 . One of the possible schemes proposed to reach such a level of accuracy includes frequency-doubling of a 1083 nm laser for locking to I_2 transitions in the green spectral region as already demonstrated for Nd:YAG lasers at 1064 nm⁴. For this purpose, high single-frequency power at 1083 nm is desirable for efficient

doubling, with the added convenience that a single pass scheme, making use of a quasi-phase matched nonlinear crystal⁵, may produce sufficient second-harmonic power. This would significantly simplify the experiment. Very recently, optical pumping of ^3He atoms has opened new possibilities to magnetic resonance imaging in medicine⁶. In this case, a powerful source of radiation at 1083 nm is required to polarize the ^3He atoms.

There are various ways to provide a single-frequency source around 1083 nm. LNA lasers can be tuned over a small range around the relevant helium transitions and can provide powers of a few hundred milliwatts^{7,8}. Semiconductor lasers around 1083 nm offer larger tuning ranges and operation on a single frequency with a linewidth of 100 kHz³. Their low cost is attractive, but the presently available powers are usually limited to below 100 mW. We therefore decided to investigate the approach of amplifying the output of a semiconductor DBR laser using an Yb doped fibre amplifier. With this approach one can combine the wide tuning range and the stability of the DBR laser with the higher powers that could be available from fibre amplifiers; by using a cladding-pumped Yb doped fibre⁹, several Watts at 1083 nm could be available in future.

Gain at around 1083 nm can also be produced by neodymium doped silica fibres. However, silica fibres can only accommodate a rather low Nd concentration, unless they are doped with phosphorus or aluminium; these dopants however shift the gain profile to shorter wavelengths¹⁰. A low neodymium concentration poses problems because the long fibre required would lead to high stimulated Brillouin gain pumped by the single-frequency signal.

Ytterbium doped germanosilicate fibres as used in various fibre lasers⁹ appear more suitable. The emission cross-section (see Fig. 1) shows a broad maximum centred at 1027 nm (as well as the narrow main maximum at 975 nm) and drops to roughly one third of the peak (1027 nm) value at 1083 nm. High ytterbium concentrations are possible (as discussed in Ref. 9) so that a length of at most a few meters is sufficient to produce large gain. Suitable high-power diode-laser pump sources at 975 nm are also available, and a high amplifier efficiency is obtainable.

The level structure of the ytterbium ion, Yb^{3+} , is very simple, with only the ground state manifold and one excited state manifold involved. The cross-sections for absorption and emission are shown in Fig. 1. Nearly complete inversion of the population is possible for a broad range of pump wavelengths around 910 nm, but under these conditions the amplifier would produce a very large gain on the 975 nm peak which would then lead to strong ASE (amplified spontaneous emission), thus limiting the gain obtainable at 1083 nm to ~ 4 dB only. This problem is avoided by pumping the amplifier at 975 nm. Absorption and emission cross-sections are essentially equal at this wavelength so that inversions approaching 50% are achieved for powers well above the pump saturation power, which is very low (0.37 mW in the case of the fibre we have used). The maximum gain then appears around the 1027 nm peak while at 1083 nm one has about one third of this peak gain. As the ASE around 1027 nm limits the peak gain to ~ 40 dB (if no scheme with ASE filtering is used), roughly 14 dB can be expected at 1083 nm.

The high absorption cross-section at 975 nm leads to very efficient pump absorption. The inversion is held at essentially 50% from the input of the fibre to the point where the pump power falls below the saturation power; beyond this point the residual pump power reduces quickly. A potential problem caused by the high absorption cross-section is the strong sensitivity to absorption by small amounts of quenched ytterbium ions in the fibre

as we discovered recently in a number of fibres¹¹; for this experiment, however, a fibre was available which exhibited quenching of only $\sim 1\%$ of the Yb ions.

The numerical aperture and cut-off wavelength of this fibre are 0.21 and 927 nm, respectively. The ytterbium concentration is ~ 2300 ppm, based on lasing experiments and cross-sections corresponding to values measured for a similar fibre. The background loss for pump and signal is estimated to be 0.3 dB/m. For these parameters we calculated a maximum gain of 6.5 dB/m for strong 975 nm pumping. Some overlength of fibre does not degrade the performance because the signal reabsorption at 1083 nm in unpumped fibre is very weak (estimated at 0.4 dB/m, including background loss).

Fig. 2 shows the experimental set-up. A pump power of up to 500 mW at 978 nm was generated by a fibre-coupled semiconductor MOPA laser (SDL, model 5762). The 1083 nm signal was produced by a semiconductor DBR laser (SDL 6702-H1) with external cavity (as in Ref. 3), having a 40% transmitting mirror as output coupler. This cavity is about 4 cm long, and the laser temperature is stabilized to within 1 mK. The laser linewidth, with this feedback arrangement, is a few hundred kHz (FWHM). The output beam from the laser cavity passes through a pair of anamorphic prisms for beam-shaping and two Faraday isolators. The maximum power available after the isolators was 16 mW.

We first tried to combine pump and signal using a fibre coupler. The available coupler however had a high loss for the signal wave. Thus, while we actually measured 18 dB gain in a 3 m long fibre, close to the predicted value, we could only launch ~ 0.1 mW of signal power via the coupler, so that the amplified signal power for this arrangement was only 6.6 mW.

To increase the amplified signal we used instead a dichroic mirror (which had 40% loss for the signal) to combine the pump and signal beams and then launched both into the 3 m long Yb-doped fibre using a microscope objective. The input fibre end was polished to an angle of 12 degrees in order to suppress back-reflection while the output end of the amplifier was fusion spliced to an undoped fibre with an angled cleave on its other end. With this arrangement the signal power at the objective was up to 11.3 mW; 3 mW (27%) could be launched into the single-mode fibre (the diode laser mode profile had some imperfection). The launched pump power was difficult to determine because of the presence of Yb absorption but it was probably somewhat higher than 27% as the pump beam showed a better mode profile. The splice loss between the doped and undoped fibre was later determined to be 23% (1.1 dB).

Fig. 3 shows the output signal power as a function of pump power for maximum input signal power (3 mW launched into the fibre). A monochromator was used to filter out residual pump and ASE. For pump powers above approximately 300 mW the gain saturated. This was due to ASE around 1027 nm which extracts significant power if the gain around 1027 nm reaches about 40 dB; this was verified using the monochromator.

Fig. 4 shows the output signal power as a function of signal input power (incident on the microscope objective). Obviously the available input signal power was not enough to saturate the gain which was limited by ASE. Thus, more signal output could be generated for the given pump power if more signal input were available. The maximum signal power obtained was 60 mW; taking into account the (avoidable) splice loss we calculate 78 mW produced at the end of the doped fibre. With a better beam combiner, avoiding the 40% loss of input signal power, more than 100 mW output would be expected. The saturated gain within the fibre was about 14 dB which is significantly less than the 18 dB achieved

earlier using the fibre coupler. Examination of the ASE spectrum for full pump power revealed structure with a number of peaks between 1020 nm and 1040 nm, indicating the occurrence of lasing caused probably by weak residual reflection from the fibre's input end, whose surface may not have been perfectly polished.

We have estimated the Brillouin gain generated in the fibre by the signal wave, based on Brillouin data from Ref. 12. The predicted Brillouin gain is 11.5 dB/m per Watt of signal power. Note that the Brillouin gain is generated in a wavelength region where there is also laser gain and fluorescence so that significant power could be extracted by a backward propagating wave even if the overall Brillouin gain reaches only a few tens of dB. For our experimental conditions the Brillouin gain is not large enough to cause any problem, but the estimate shows that for amplification to high powers the fibre length will need to be limited and thus too low dopant concentration should be avoided.

Significant improvement of the amplified signal power could be achieved in various ways. More signal power could be launched by improving the launch efficiency for the input signal and by using a better dielectric mirror or ideally an optimized fibre coupler with lower loss for the signal. A fibre coupler would at the same time allow essentially the full power of the fibre-coupled pump laser to be available for pumping the doped fibre. The amplifier gain would also be increased somewhat with improved fibre ends (weaker reflections). For further increases of gain a double-pass configuration could be used: the signal power would be reflected back at the end of the doped fibre, and the signal output would then be extracted at the Faraday isolator. The fibre would then need to be long enough to ensure that no significant pump power is reflected back into the pump laser (if no Faraday isolator for the pump is used). The end mirror should have high reflection for the signal and high transmission for the ASE (between 1010 nm and 1060 nm). In this way a gain well in excess of 20 dB at 1083 nm should be possible. The use of cladding-pumped amplifying fibre should allow the generation of a few Watts of amplified power if sufficient pump power (not necessarily in a single spatial mode) and input signal power are available.

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FIGURES

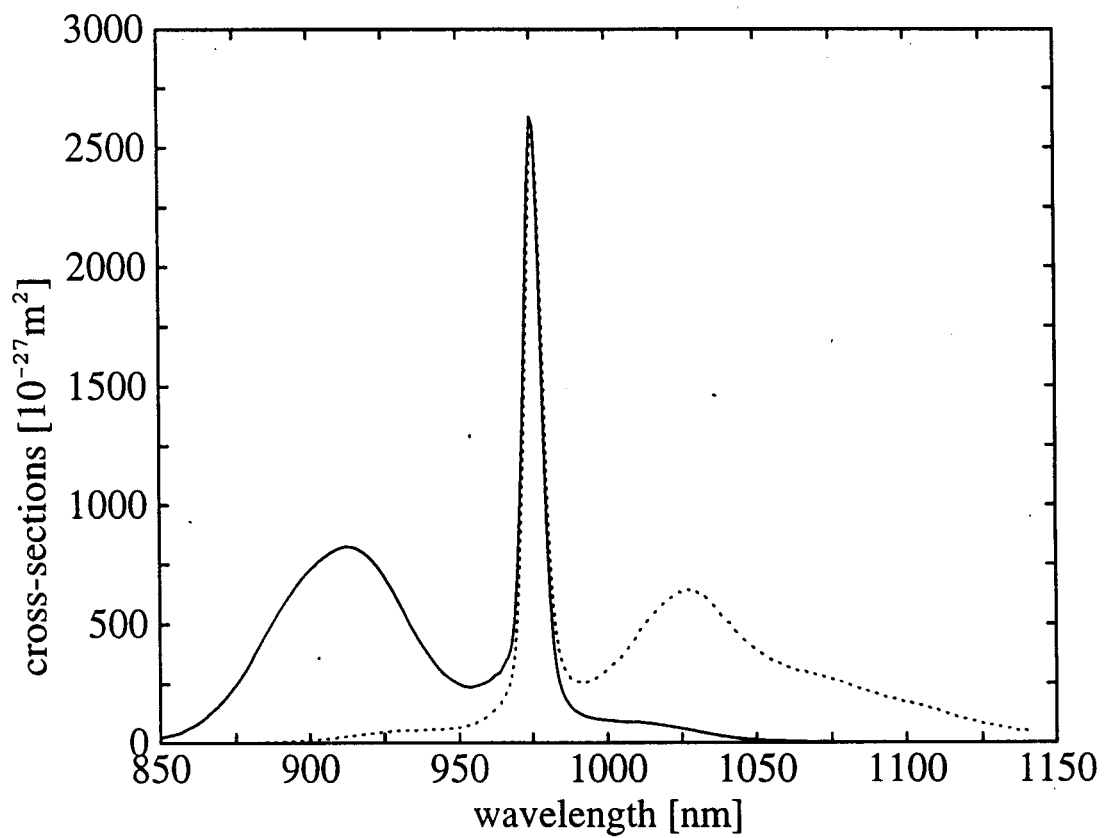


Fig. 1. Absorption (solid) and emission (dotted) cross-sections of Yb in germanosilicate glass.

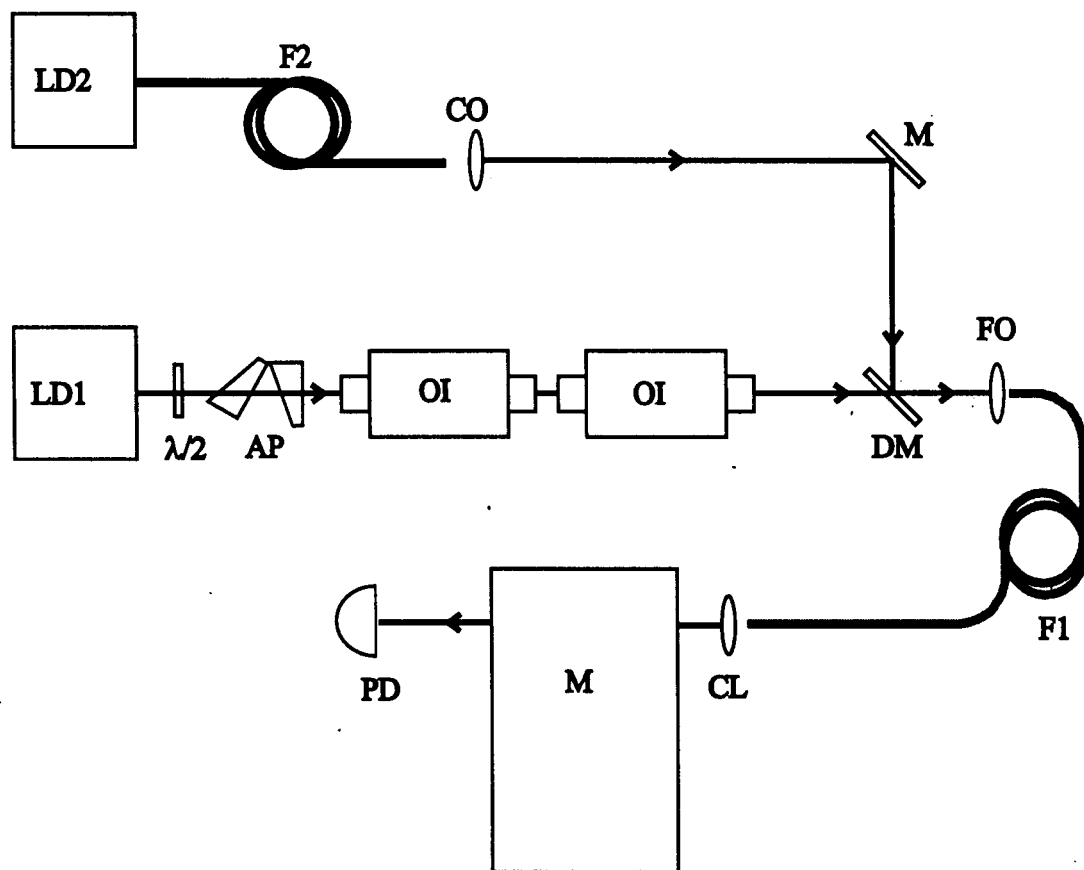


Fig. 2. The experimental set-up. LD1 = 1083 nm laser diode, AP = anamorphic prisms, OI = optical isolator, DM = dichroic mirror, FO = 20x microscope objective, LD2 = 978 nm pump laser (fibre coupled), F1 = Yb doped fibre, CO, CL = collimating lenses, M = monochromator, PD = photodetector.

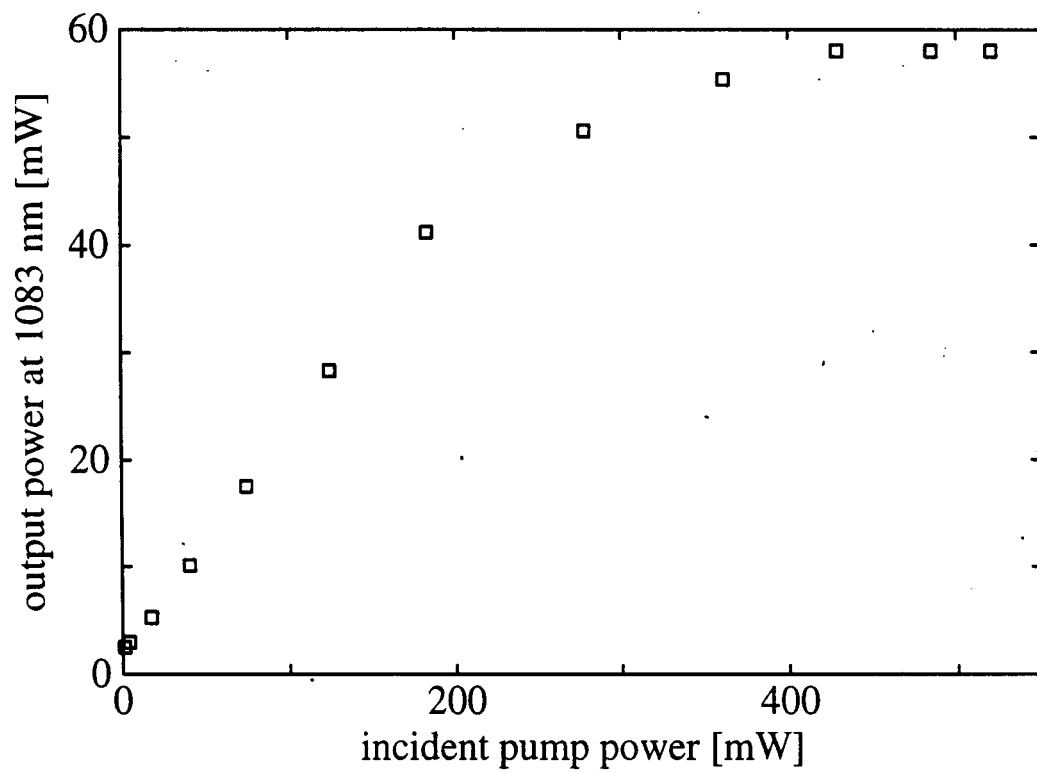


Fig. 3. 1083 nm output power versus pump power (incident on the objective) for maximum signal input power (3 mW launched).

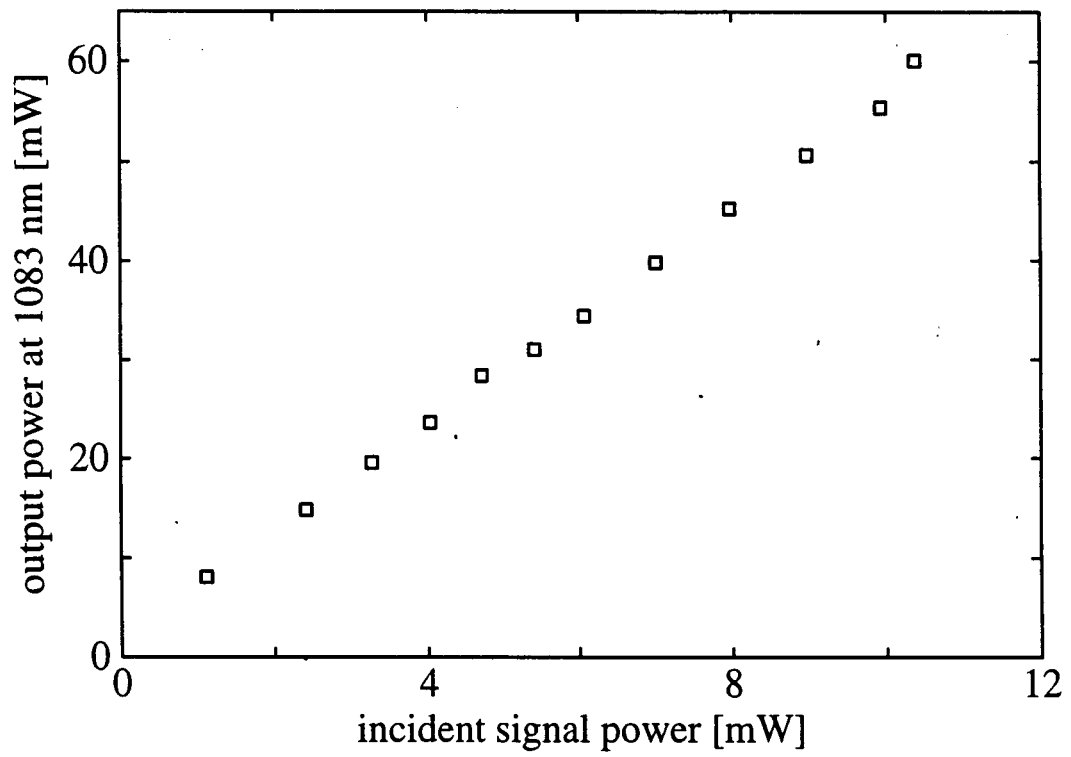


Fig. 4. . 1083 nm output power versus incident signal input power (at the microscope objective) for maximum pump power.