2665

A 980 nm Yb-doped fiber MOPA source and its frequency doubling

D. B. S. Soh[1*], C. Codemard[1], S. Wang[2], J. Nilsson[1], J. K. Sahu[1], F. Laurell[2], V. Philippov[1], Y. Jeong[1], C. Alegria[1], and S. Baek[1,3]

1. Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

2. Department of Laser Physics and Quantum Optics, Royal Institute of Technology, Stockholm, Sweden

3. Permanent address: School of Electrical Engineering, Seoul National University, Seoul 151-742, Korea

* Corresponding author, Phone: +44 23 8059 3143, Fax: +44 23 8059 3142, e-mail: dbs@orc.soton.ac.uk

Abstract

A cw master oscillator – power amplifier (MOPA) fiber source, tunable around 978 nm, was frequency-doubled to 488.7 nm. Both the laser and the amplifier were made with cladding-pumped jacketed-air-clad Yb-doped fibers. The MOPA generated up to 2.7 W of power in an output beam with an M^2-value of 1.8. This was frequency-doubled in a periodically poled KTP crystal at room temperature, in a single-pass configuration. The generated blue light had a cw power of 18.1 mW, a nearly Gaussian spatial intensity profile, and an M^2-value of 1.7.

Keywords: Fiber Laser, MOPA, KTP, Frequency Doubling, Blue

1. Introduction

There are a number of important applications for blue laser light including high-density optical data storage, biological and medical diagnostics, and color displays. For reasons of efficiency, compactness, robustness, simplicity, and cost-effectiveness, a solid-state source at ~488 nm is an appealing replacement for argon lasers [1]. For example, a pulsed laser diode frequency doubled in KTP produced 2.2 mW of average power at this wavelength [2].

In this paper we report room-temperature frequency-doubling to 488.7 nm of a fiber MOPA (master oscillator - power amplifier) source in periodically poled KTP. We generated 18.1 mW of cw output power. The blue light showed good temporal and spectral behavior and nearly Gaussian-like spatial characteristics. The seed source of the MOPA was a tunable fiber laser made with a jacketed air-clad Yb-doped fiber (JAC YDF), as was the amplifier. The maximum output power of the MOPA was 2.7 W at ~978 nm. We believe this is the first report of a cladding-pumped fiber amplifier at this important wavelength.

2. Experimental Setup

For efficient frequency doubling, the infrared fundamental beam must satisfy several prerequisites, including narrow linewidth, single polarization, sufficient infrared power, and good beam quality with an appropriate focusing into the frequency-doubling crystal. Our experimental setup, shown in Fig. 1, is designed to fulfill these conditions. It consists of three sections, namely, a tunable laser, an amplifier, and a frequency doubler.

2.1 Tunable laser

In a MOPA system, only a small part of the total power is generated by the seed laser. Therefore, efficiency is not critical. Instead, it can be designed for narrow linewidth, single polarization, tunability, and stability. Here, we used a tunable fiber laser, made with a 35 cm long JAC YDF [3]. Figure 2 shows a cross-sectional image of the JAC fiber. It is designed with a small inner cladding (diameter 28 μm) and a high NA (~0.5) to overcome the challenges of cladding-pumping Yb-doped fiber lasers operating around 980 nm: The 980 nm transition is a two-level one, for which more than 50% of the ytterbium-ions must be excited to overcome the strong ground-state absorption and reach sufficient gain. In a cladding-pumped configuration this leads to a large pump threshold if the inner cladding is too large. In addition, gain on the quasi-four level transition at 1030 – 1060 nm appears at much lower levels of Yb-excitation, and emission in this wavelength range must be suppressed. A small inner cladding (diameter 28 μm for our JAC fiber) helps also here, by increasing the pump absorption so that shorter fibers with less 980 nm absorption can be used [4]. The inner cladding is surrounded by air holes, which provided a large refractive index difference (0.5 NA) enabling efficient end pumping. The fiber was pumped by a 915 nm multimode laser diode, with 1.5 W of power launched into the inner cladding. The cavity was formed by a 4% reflecting perpendicular flat cleave in the pump launch end of the fiber, and two diffraction gratings and a HR mirror at the other end. Thus, the laser field was diffracted four times off the grating surfaces per cavity roundtrip in order to realize a narrow linewidth (0.6 nm). The slope efficiency was 33% with respect to absorbed pump power. The laser was tunable between 975 and 982 nm. For frequency-doubling, the laser was tuned to 977.4 nm, where the maximum output power was 183 mW. The polarization characteristics of the output beam were investigated with a linear polarizer. A maximum transmission of 83% was obtained.

2.2 Amplifier

Typically, the amplifier provides most of the power from a MOPA system, making amplifier efficiency a key parameter. Fiber amplifiers are attractive because they can combine high gain with high efficiency, and because they are simple and versatile. They can be relatively broadband, and readily amplify pulsed as well as cw light. The considerations for efficient cladding-pumping of a 980 nm Yb-doped fiber amplifier are largely the same as for a laser, and our amplifier used the same JAC YDF as the laser. The difference is the length (55 cm). The fiber was end-pumped by a 15 W 915 nm high brightness laser diode pump module (New Optics) , with 60% of the incident pump power launched into the inner cladding. The signal from the tunable laser was coupled into the amplifier with 40% efficiency. Both ends of the fiber were angle-cleaved to prevent laser oscillation. We also used a 1030 nm rejection filter between the laser and the amplifier because any emission around 1030 nm from the laser could seed 1030 nm amplification, in which case the 980 nm performances might be degraded.

Fig. 3 shows the amplifier performance. The difference in spectral power density between the amplified signal and the amplified spontaneous emission around the signal wavelength range was ~20 dB. The maximum output of the amplified 977 nm signal was measured to be 2.7 W. This compares favorably to our previous results: while we have previously reported a 3.5 W 977 nm fiber laser [5], this was pumped by two polarization-multiplexed similar laser diode sources, and a laser is normally more efficient than an amplifier. The output beam quality (M^2) was measured to 1.8, and 75% of the power would pass through a linear polarizer.

2.3 Frequency doubler

We used a periodically poled KTP crystal for single-pass (external) frequency doubling (Fig. 1). It was 9 mm long and had a cross-section of 1 mm ×4 mm. The acceptance bandwidth was 0.2 nm. The crystal operated with a controlled temperature of 25˚C. The optical conversion efficiency was measured to 1.5% W^{-1} cm^{-1} with a polarized Ti:Al_2O_3 laser, tuned for optimum conversion efficiency and with a linewidth much narrower than the acceptance bandwidth.

For frequency-doubling of the fiber MOPA system, the crystal operated with a controlled temperature of 25˚C. The optimized focusing waist size was 10 um e-2 intensity radius, determined experimentally. This is consistent with previously determined waist sizes for a 9 mm long sample [6, 7]. The beam was focused into the crystal by a single lens with a focal length of 18.5 mm. The beam size incident on the lens was measured to 2 mm (e^{-2} radius). The polarization of the light incident on the KTP crystal was adjusted with a half-wave plate. We note that this was insufficient to compensate for changes of the polarization state occurring in the amplifier. Nevertheless, the polarization was adjusted for optimum frequency doubling with our single waveplate. Lastly, we used a lens to collimate the blue light generated in the crystal, and optionally a filter to reject any infrared radiation transmitted through the KTP crystal.

3. Results and Discussions

The power and wavelength characteristics of the frequency doubling process are shown in Fig. 4. The maximum blue power was 18.1 mW at 488.7 nm. To assess the efficiency of the crystal, we first consider that actually only 2 W out of the total 2.7 W incident power is useful. The rest of the power was in the undesired polarization state. Hence, the optical conversion efficiency from useful infrared to visible light was 0.9 % at 18.1 mW blue light.

Figure 5 shows the spatial and temporal characteristics of the blue beam. The spatial intensity profile was nearly Gaussian, with a beam quality (M^2) of 1.7 (Fig. 5a). The temporal behavior at 488.7 nm is shown in Fig. 5 (b). The power fluctuation was 6% at 15 mW blue power and 3% at 6 mW in a 1 MHz measurement bandwidth. There were no rapid power fluctuations up to a 500 MHz measurement bandwidth. It is also noted that the output power does not show any degradation or roll-over in the high power regime in Fig. 4 (a), suggesting that higher blue power, and higher conversion efficiency, would be possible if we could better control the polarization, reduce the linewidth of the seed source, and / or increase the power at the fundamental wavelength. We did not saturate the amplifier, so a more powerful seed source should result in more blue light. One attractive alternative is to use a diode laser seed source. These are widely available at powers up to ~0.5 W (pig-tailed) in compact butterfly mounts. They operate on a single polarization and on a single-mode spatial mode. They can be fitted with external fiber gratings for wavelength-stabilized narrow linewidth operation and can be tuned by stretching the fiber grating. They can be readily pulsed to reach higher amplified peak powers and thus more efficient conversion in the KTP crystal. One can also use a Q-switched fiber seed laser [8]. Indeed, one of the appeals of our 980 nm source is its flexibility.

4. Conclusions

We demonstrated blue light generation at 488.7 nm via frequency doubling in a periodically poled KTP crystal pumped by a JAC YDF MOPA system. The generated power was 18 mW. The blue light shows stable behavior and has a beam quality factor (M^2) of 1.7. We believe that this is the highest power reported from a frequency-doubled fiber source at this wavelength, and also that this is the first description of a cladding-pumped 980 nm fiber amplifier.

References

[1] Datasheet, Coherent Sapphire 488-200 (2002), Available: http://www.coherentinc.com

[2] D. J. L. Birkin, E. U. Rafailov, W. Sibbett, and P. Battle, "Efficient direct frequency conversion of a non-resonant injection-seeded laser diode using a periodically-poled KTP waveguide crystal", in *Tech. Dig. CLEO/QELS 2001*, 2001, pp. 546 – 547

[3] J. K. Sahu, C. C. Renaud, K. Furusawa, R. Selvas, J. A. Alvarez-Chavez, D. J. Richardson, and J. Nilsson, "Jacketed air-clad cladding pumped ytterbium-doped fibre laser with wide tuning range", *Electron. Lett.*, vol. 37, no.18, pp. 1116-1117, Aug. 2001.

[4] J. Nilsson, J. D. Minelly, R. Paschotta, A. C. Tropper, and D. C. Hanna, "Ring-doped cladding-pumped single-mode three-level fiber laser", *Opt. Lett.*, vol. 23, no. 5, pp. 355-357, Mar. 1998.

[5] K. H. Ylä-Jarkko, R. Selvas, D. B. S. Soh, J. K. Sahu, C. Codemard, J. Nilsson, S.-U. Alam, and A. B. Grudinin, "A 3.5 W 977 nm cladding pumped jacketed-air-clad ytterbium-doped fiber laser", in *Proc. 18th Advanced Solid-State Photonics (Optical Society of America), Topical Meeting of*, San Antonio, Feb. 2003, postdeadline paper PDP 2

[6] G. D. Boyd and D. A. Kleinman, "Parametric interaction of focused Gaussian light beams", *J. Appl. Phys.* vol. 39, pp. 3597-3639, 1968.

[7] P. L. Ramazza, S. Ducci, A. Zavatta, M. Bellini, F. T. Arecchi, "Second-harmonic generation from a picosecond Ti:Sa laser in LBO: conversion efficiency and spatial properties", *App. Phys. B. Lasers and Optics*, vol. 75, no. 1, pp. 53-58, 2002.

[8] R. Selvas, J. K. Sahu, and J. Nilsson, "Q-switched 980 nm Yb-doped fiber laser", in *Tech. Dig. CLEO/QELS 2002,* 2002, pp. 565 – 566

Figure captions :

Fig. 1. Blue light generation experimental setup. There are three sections, i.e., tunable laser, amplifier, frequency doubler with focusing optics.

Fig. 2. Cross-sectional view of our JAC YDF.

Fig. 3. MOPA output spectra with measurement resolution 0.05 nm (a) and output power characteristics at 977.4 nm (b). The source is tunable between 975 nm and 982 nm. The maximum output power was 2.7 W.

Fig. 4. 488.7 nm output power vs. fundamental 977.4 nm power (a) and spectrum (b) (measurement resolution 0.05 nm). The maximum blue output is 18.1 mW.

Fig. 5. 488.7 nm spatial intensity profile (a) and output temporal behavior (b). The output power fluctuation was 6% at 15 mW. The spatial intensity profile is nearly Gaussian.

Figures:

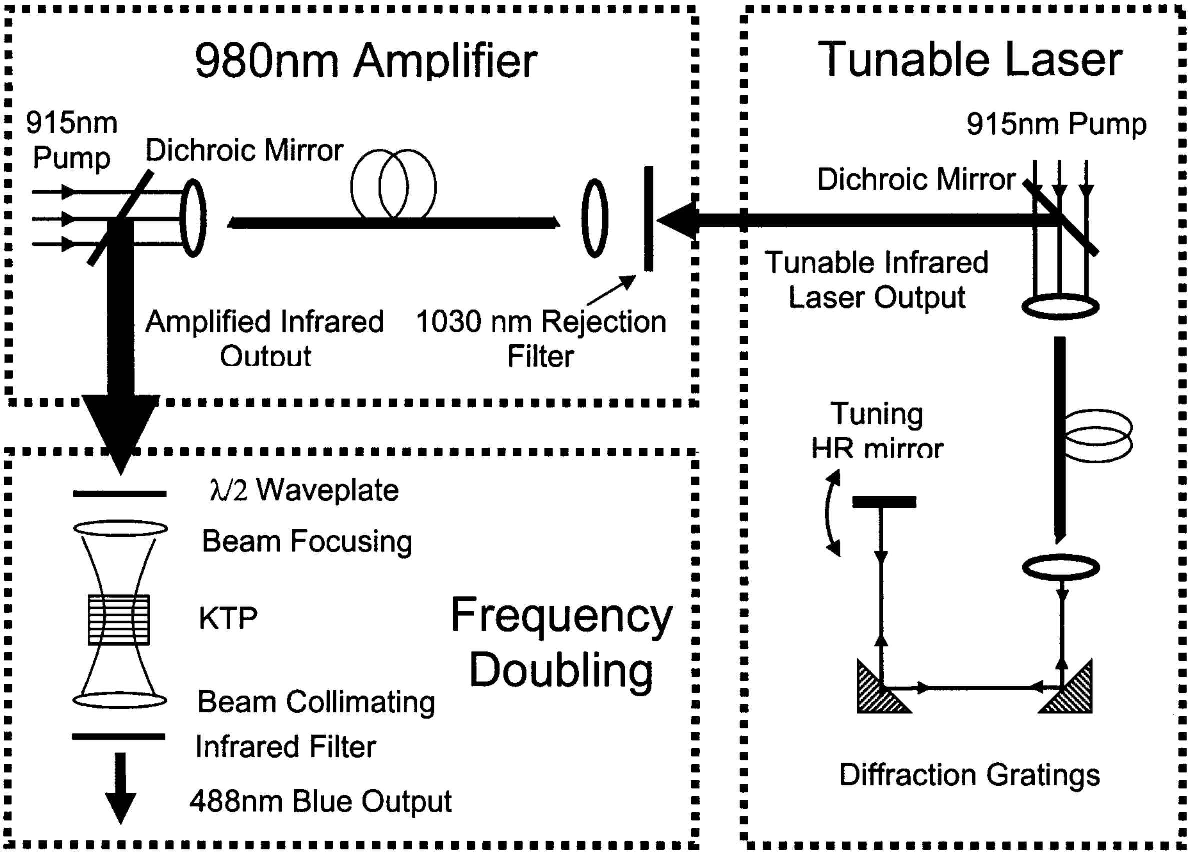

Fig. 1.

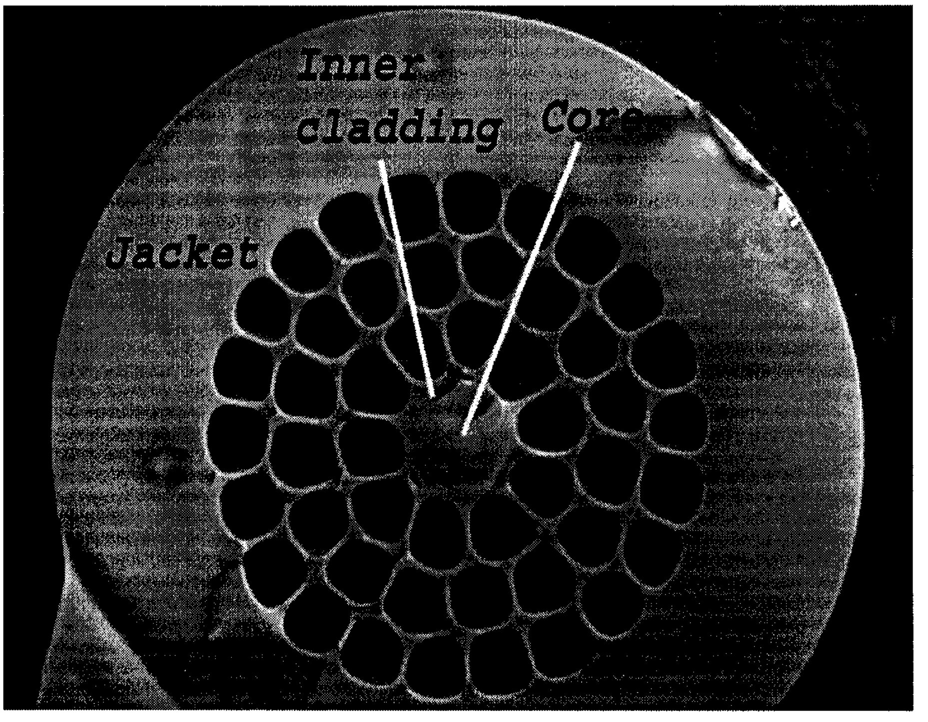

Fig. 2

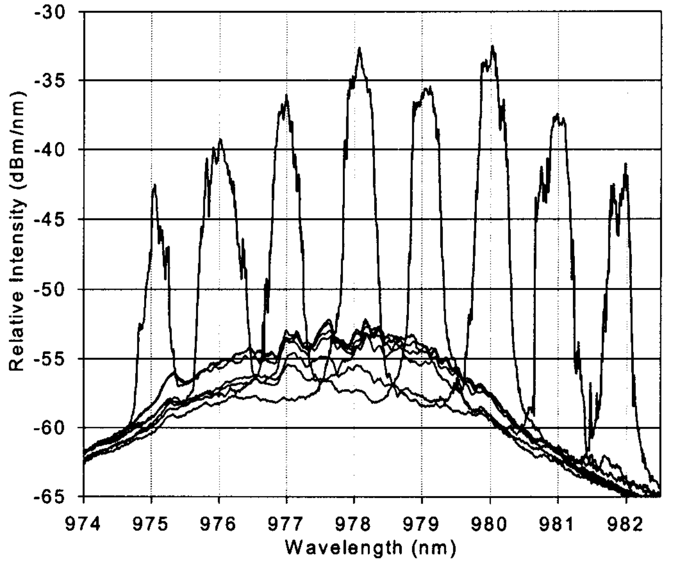
-30
-35
-40
-45
-50
-55
-60
-65
Relative Intensity (dBm/nm)
974
975
976
977
978
979
980
981
982
Wavelength (nm)

Fig. 3 (a).

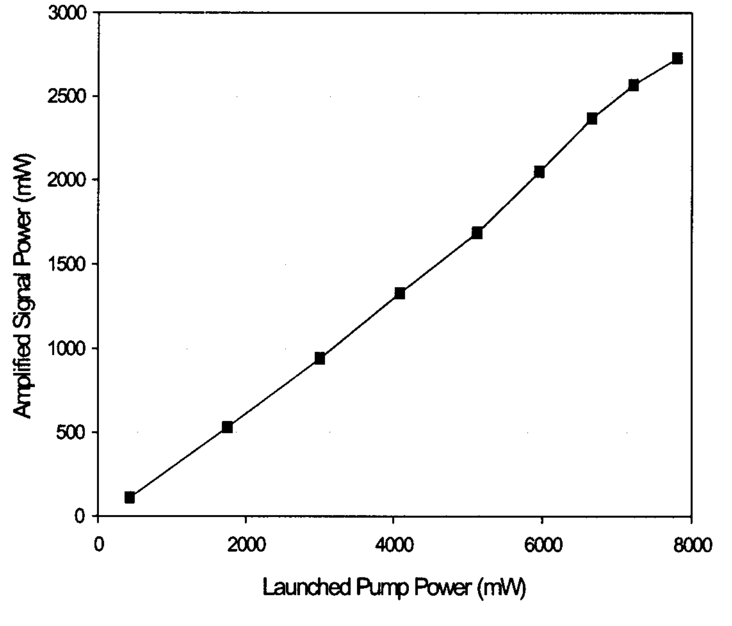
3000
2500
2000
1500
1000
500
0
Amplified Signal Power (mW)
0
2000
4000
6000
8000
Launched Pump Power (mW)

Fig. 3 (b).

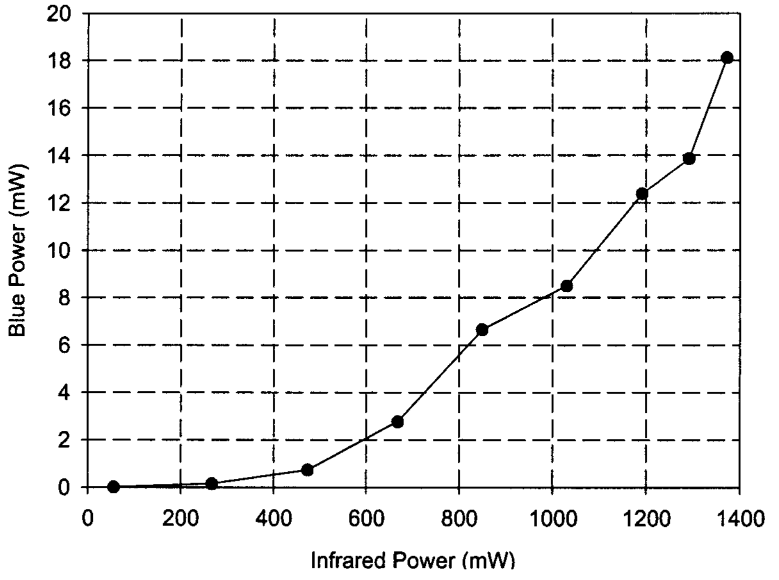
Blue Power (mW)
20
18
16
14
12
10
8
6
4
2
0
0
200
400
600
800
1000
1200
1400
Infrared Power (mW)

Fig. 4 (a)

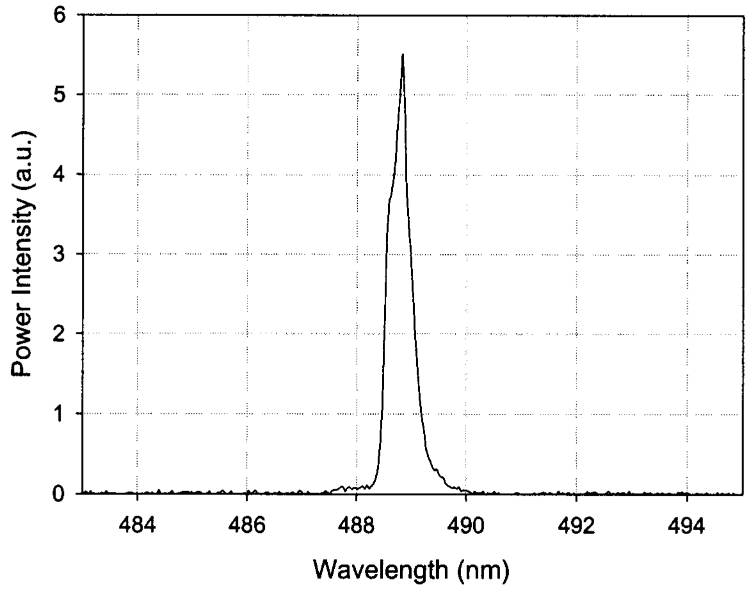
Power Intensity (a.u.)
6
5
4
3
2
1
0
484
486
488
490
492
494
Wavelength (nm)

Fig. 4 (b)

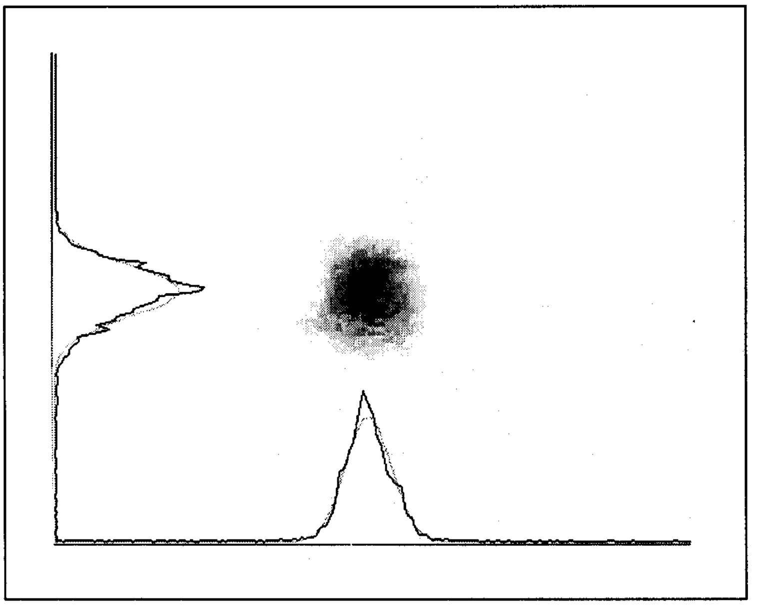

Fig. 5 (a)

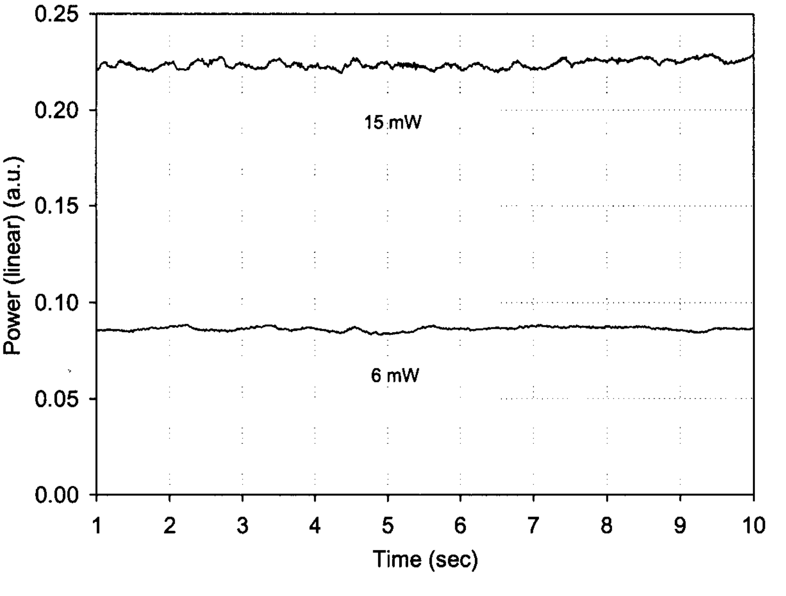
Power (linear) (a.u.)
0.25
0.20
0.15
0.10
0.05
0.00
15 mW
6 mW
1
2
3
4
5
6
7
8
9
10
Time (sec)

Fig. 5 (b)