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Submitted to
Optics Comm. [illegible]

High-power single-frequency operation, at 1064nm and 1061.4nm of a Nd:YAG ring laser end-pumped by a beam-shaped diode bar.

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Abstract

A Nd:YAG laser having a ring configuration, with a Faraday rotator to provide unidirectional operation has been end-pumped by a single 20W diode bar equipped with a beam-shaper. A single-frequency TEM_{00} output of 5.4W is achieved at 1064nm. Using a thin intracavity etalon for wavelength selection, a single-frequency output of 4.2W is obtained on the 1061.4nm transition.

Laser diode bars offer simple and cost-effective sources of light for pumping many solid-state lasers. With the provision of appropriate beam-shaping, as, for example, recently described by Clarkson and Hanna [1], the diode-bar source provides an intense, collimated beam ideally suited for use in end-pumping of lasers. In this way efficient TEM_{00} mode operation has been demonstrated for a Nd:YAG laser with a simple standing-wave cavity, both for the 1064nm transition [2] and the 946nm transition [3]. Here we describe a diode-bar-pumped Nd:YAG laser operated in a ring cavity configuration, with unidirectional travelling-wave oscillation enforced by the insertion of a Faraday rotator. This laser then operates in a single-frequency with an output power essentially the same as the power available in multi-frequency operation. Using a thin etalon, we have been able to select the 1061.4nm transition, achieving 4.2W of single-frequency output. With suitable-wavelength selecting etalons it should be possible, with this same basic arrangement, to obtain single-frequency operation at multi-watt levels on a number of other Nd transitions.

The beam-shaper device has been described in detail elsewhere [1]. For these experiments we used a diode bar pump, beam-shaped to have the following parameters at the Nd:YAG laser rod: spot-size ($1/e^2$ intensity diameter), 590μm (in both the x direction, i.e. horizontal plane and the y direction, vertical), with M^2 values, $M^2_x = 60$, $M^2_y = 64$. As a result of its long confocal parameter (~10mm) this remained essentially collimated over the length of the laser rod. The output wavelength of the bar was ~809nm, and a total power of 14.4W was incident at the laser rod when the bar itself was operated at a nominal 20W output. The anti-reflection coated Nd:YAG rod was 10mm long and 2mm in diameter, and contacted via indium foil to a water cooled heat sink, and placed close to one of the plane mirrors of the bow-tie resonator (see fig.1), through which the pump light entered. The choice of a 'bow-tie' resonator was based on the requirement, for a separate experiment, of a tightly focused region, between the concave mirrors (100mm radius of curvature) where a nonlinear crystal could be located for efficient intracavity second-harmonic generation (SHG). The results of these experiments leading to a 3W output at 532nm are reported elsewhere [4]. In principle a rather simpler three mirror resonator would have been suitable for the experiment described here, although the bow-tie configuration did in fact provide a convenient means (by changing the spacing of the concave mirrors) to match the lasing mode spot-size in the rod to the pump spot-size. The other cavity components include a 1mm thick Brewster angled plate, to act as a polariser, a Faraday rotator (TGG) and a half-wave plate, which were required to enforce unidirectional operation. An alternative, and very effective means of providing enough loss difference between counter propagating waves to enforce unidirectional operation, is via an intracavity acousto-optic modulator (see [5] for a detailed discussion of this technique). Our use of a Faraday rotator here was again based on the requirements of a separate experiment, namely efficient intracavity SHG, for which one needs the larger loss difference that a Faraday rotator can provide, to ensure that the loss difference is not reversed by the action of efficient SHG.

The Faraday rotator used here had a rotation of 7.5° for 1064nm light. The half-wave plate was oriented so as to give a compensating opposite rotation of the same amount for one direction of propagation. For the counter direction the rotations do not cancel out and the calculated value of the extra loss thus experienced at the Brewster plate is 0.6%, which is more than sufficient for robust unidirectional operation. Inserting a second half-wave plate would increase the loss difference to 16% [4], but this was unnecessary for this laser, and would only result in extra cavity loss due to the insertion loss of this second half-wave plate.

The losses (single-pass) of these various components were approximately 0.4% for the Faraday rotator, 0.2% for the half-wave plate, 0.2% for the laser rod, and 0.1% for each of the mirrors. The laser rod also introduces a degree of depolarisation via thermally induced birefringence [6] resulting in a reflection from the Brewster angle plate, the measured value of loss per round trip via this depolarisation at full pump power being 0.24%. Thus the total excess loss (i.e. other than the transmission of the output mirror) was ≈1.3%.

The performance of this laser at 1064nm is shown in fig.2, where it is seen that power increases linearly with pump-power over the whole range, showing no significant roll-off at high-powers. The maximum output power obtained using a 10% transmission output coupler was 5.4W. With output couplers of 5% and 2% transmission, the output powers were 4.9W and 4.1W respectively. A comparison of slope efficiencies for these various couplers confirms an excess loss value of ~1.3%. Single frequency operation, confirmed using a Fabry Perot interferometer (see fig.3), was found to be very stable and robust. Beam quality measurements gave M^2 values of $M_x^2 = 1.05$, $M_y^2 = 1.13$ confirming the excellent quality indicated by visual assessment.

By inserting a thin uncoated fused quartz etalon in the resonator we have been able to enforce oscillation on the 1061.4nm transition with efficient single-frequency operation. The insertion loss (due to walk off) of such an etalon is given simply by reference [7] as

$$l = \frac{4\theta R d}{n D} \qquad (1)$$

For a thin etalon (d≈100μm) made of fused silica (refractive index n=1.45, reflectivity R=0.034) placed in the collimated arm of the laser beam (beam diameter D=600μm), and a relatively large angle of incidence (θ=0.1 Rad), the loss is only 0.2%, and therefore will have no significant effect on the lasers performance. Ideally the etalon should be chosen to have a free spectral range twice that of the spacing between the transitions, so that the 1064nm line can be at the minimum transmission (a loss of 12.6% for fused silica) while the 1061.4nm line has maximum transmission. The most suitable etalon available, was approximately ≈100μm thick (calculated from the angular separation of the reflected fringes from a helium neon laser) hence with a free spectral range of 34.2 cm^{-1} compared to the transition spacing of 23cm^{-1}. The transmission of the etalon, derived from an expression given in reference [7] is given by

$$T = \left[1 + (2F/\pi)^2 \sin^2\left(\frac{2\pi n d \cos(\theta/n)}{\lambda_0^2}\Delta\lambda\right)\right]^{-1} \tag{2}$$

Where F is the finesse, which is 0.60 for an uncoated fused silica etalon, λ_0 is a wavelength for which the etalon gives maximum transmission, and $\Delta\lambda$ is a small offset from this wavelength. For the above etalon, aligned for 1061.4nm, the extra loss at 1064nm is 9.5% (compared to 12.6% for an etalon of optimum thickness). Unfortunately, the value for relative gain of the 1061.4nm compared to the 1064nm gain is not clear. From reference [8] an emission cross section of 0.76 times of the highest gain, transition at 1064nm, but reference [9] gives a value of the ratio of 0.52. With the etalon tilted for maximum transmission at 1061.4 and using a T = 10% output coupler the frequency discrimination was not quite sufficient to prevent 1064nm oscillation. To achieve maximum suppression of 1064nm the etalon had to be tilted such that it no longer had optimum transmission at 1061.4nm. Tilting the etalon, to give an extra loss of 0.8% at 1061.4nm, can increase the discrimination between the two wavelengths from 9.5% to 10.8%. As a result, the output power of 3.6W at 1061.4nm, under these conditions, was significantly reduced from the available 1064nm power. This indicates that the gain of the 1061.4 transition is in fact close to half that of the gain at 1064nm supporting reference [9]. However with a T = 5% output coupler, suppression of 1064nm was achieved with the etalon tuned for maximum 1061.4nm transmission and 4.2W was obtained at 1061.4nm. With the same output coupler transmission and the etalon tilted for optimum 1064nm transmission an output of 4.9W was obtained, i.e. the same as without the etalon, implying that the etalon had no detectable contribution to the excess loss. Fig. 4 shows, for comparison, the output power characteristics for the 1064nm and 1061.4nm transitions with a T=5% output coupler and the etalon in place, optimally oriented in each case. The high-power output, 4.2W, in a single frequency, in the TEM_{00} , linearly polarised, at 1061.4nm, suggests that with appropriate, optimally chosen etalons, efficient multi-watt single-frequency operation should be possible for a number of Nd transitions.

In conclusion we have shown that for an end-pumped Nd:YAG ring laser, using a beam-shaped diode bar as pump, it is possible to obtain single-frequency TEM_{00} mode operation at power levels which are essentially the same as those available in multi-frequency operation. Furthermore with the use of a single etalon of negligible insertion loss this efficient multi-watt single-frequency performance can be achieved on other, lower gain Nd transitions.

This work has been supported by the Engineering and Physical Science Research Council. Kevin Martin acknowledges EPSRC and Lumonics for the provision of a CASE research studentship.

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Figure Captions

Figure 1 Diagram of the single frequency ring laser, shown with the etalon that was used to select the 1061.4nm transition. The intracavity components are 1) Nd:YAG laser rod, 2) Brewster angled plate, 3) TGG Faraday rotator, 4) 100μm etalon, 5) Half wave plate, 6) Output coupler (2,5 or 10%).

Figure 2 A graph of single frequency output power versus pump power for the 1064nm single frequency laser, with the 10% output coupler.

Figure 3 Typical scanning Fabry-Perot trace, confirming single-frequency operation.

Figure 4 A graph of output at 1064nm and 1061.4nm, both with the 5% output coupler and the 100μm thick uncoated intracavity etalon.

Fig 1

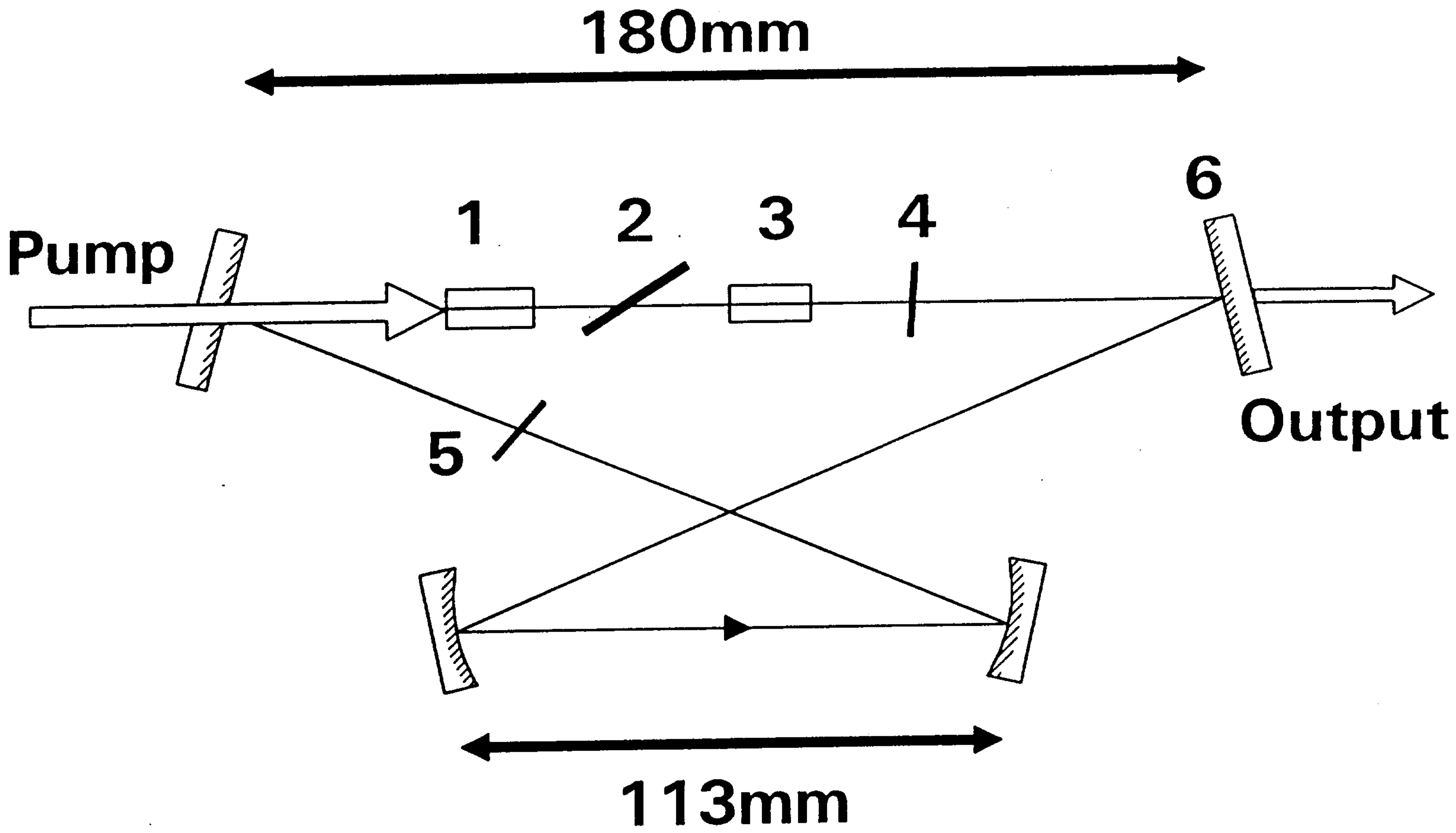


Fig 2:

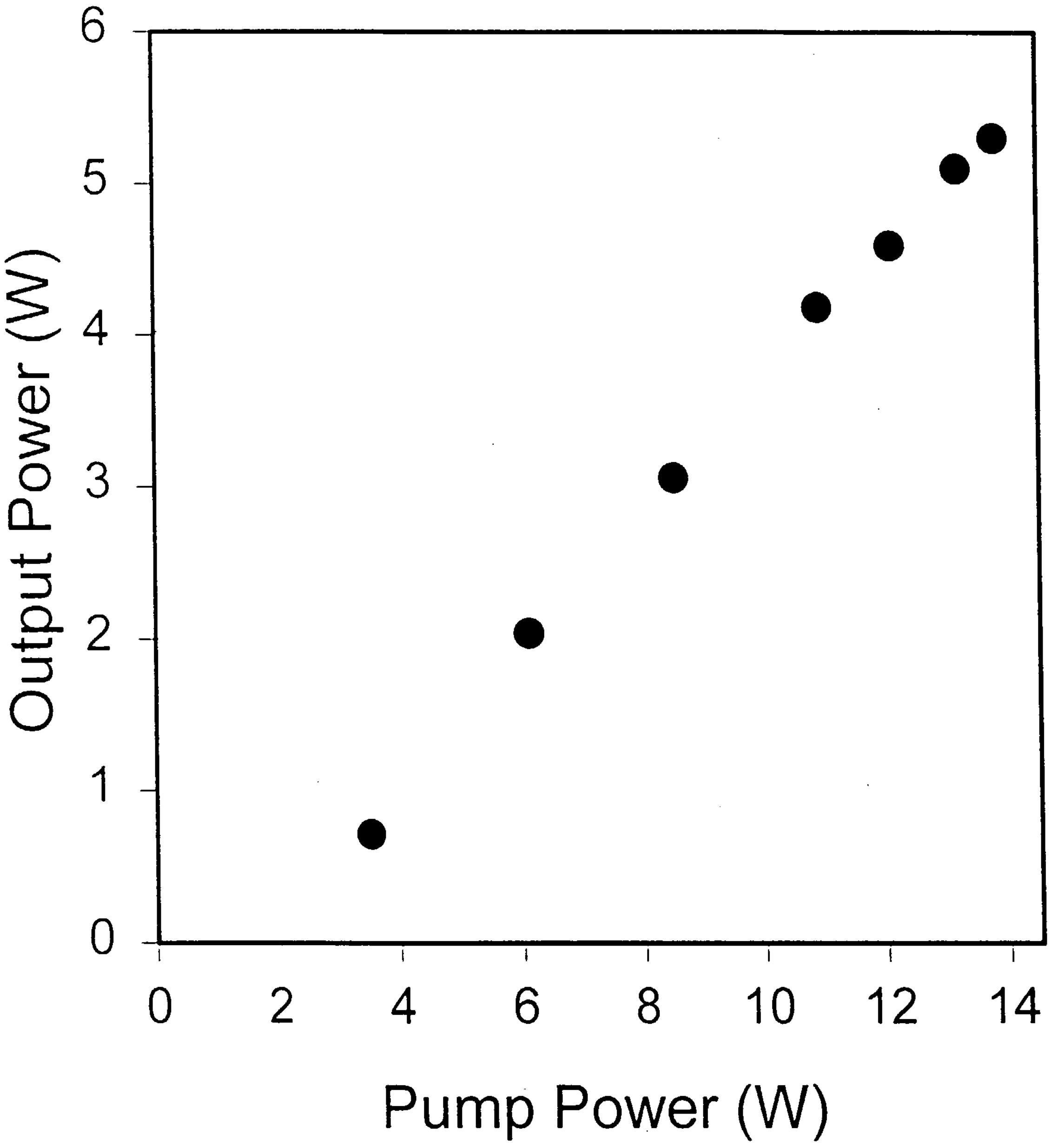


fig 3

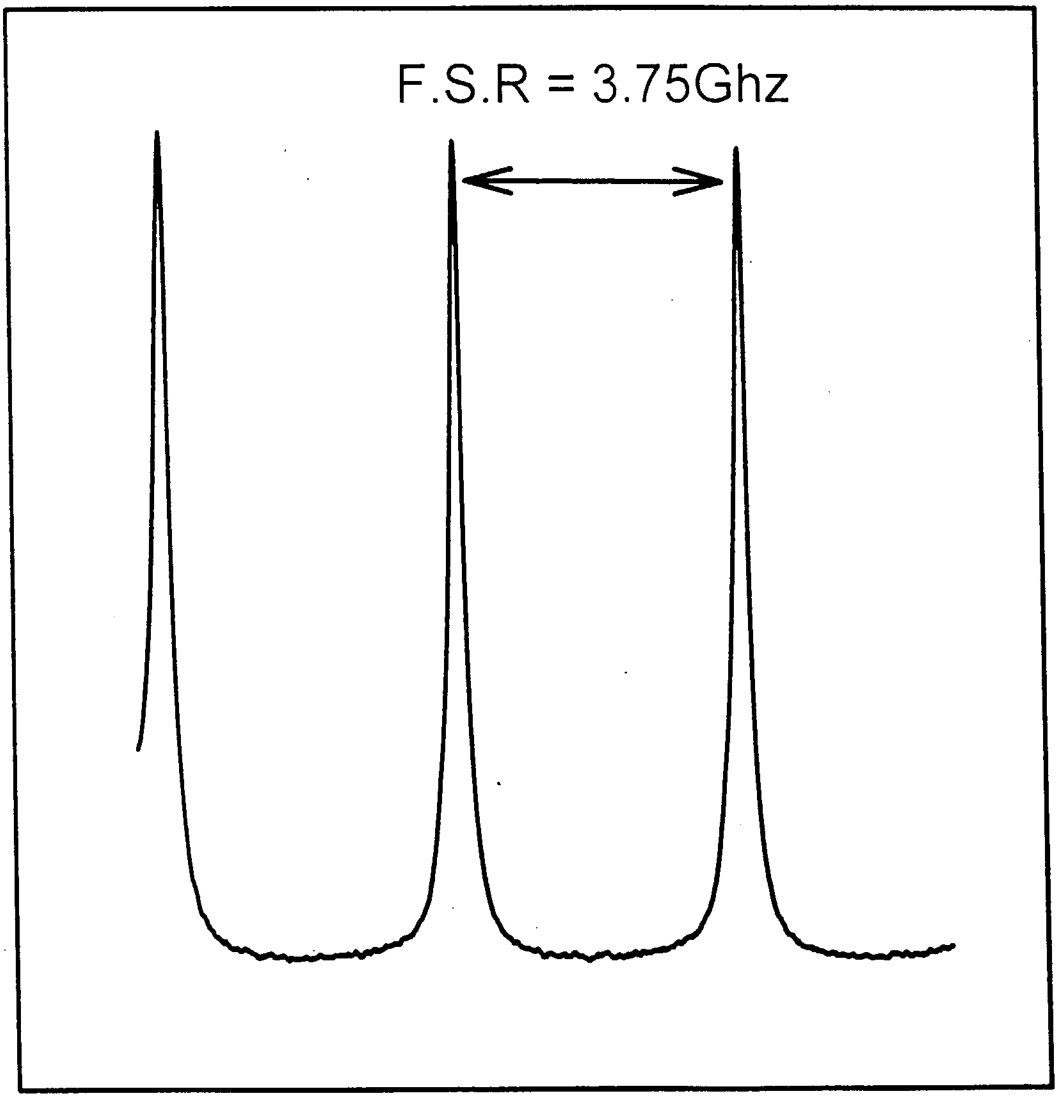
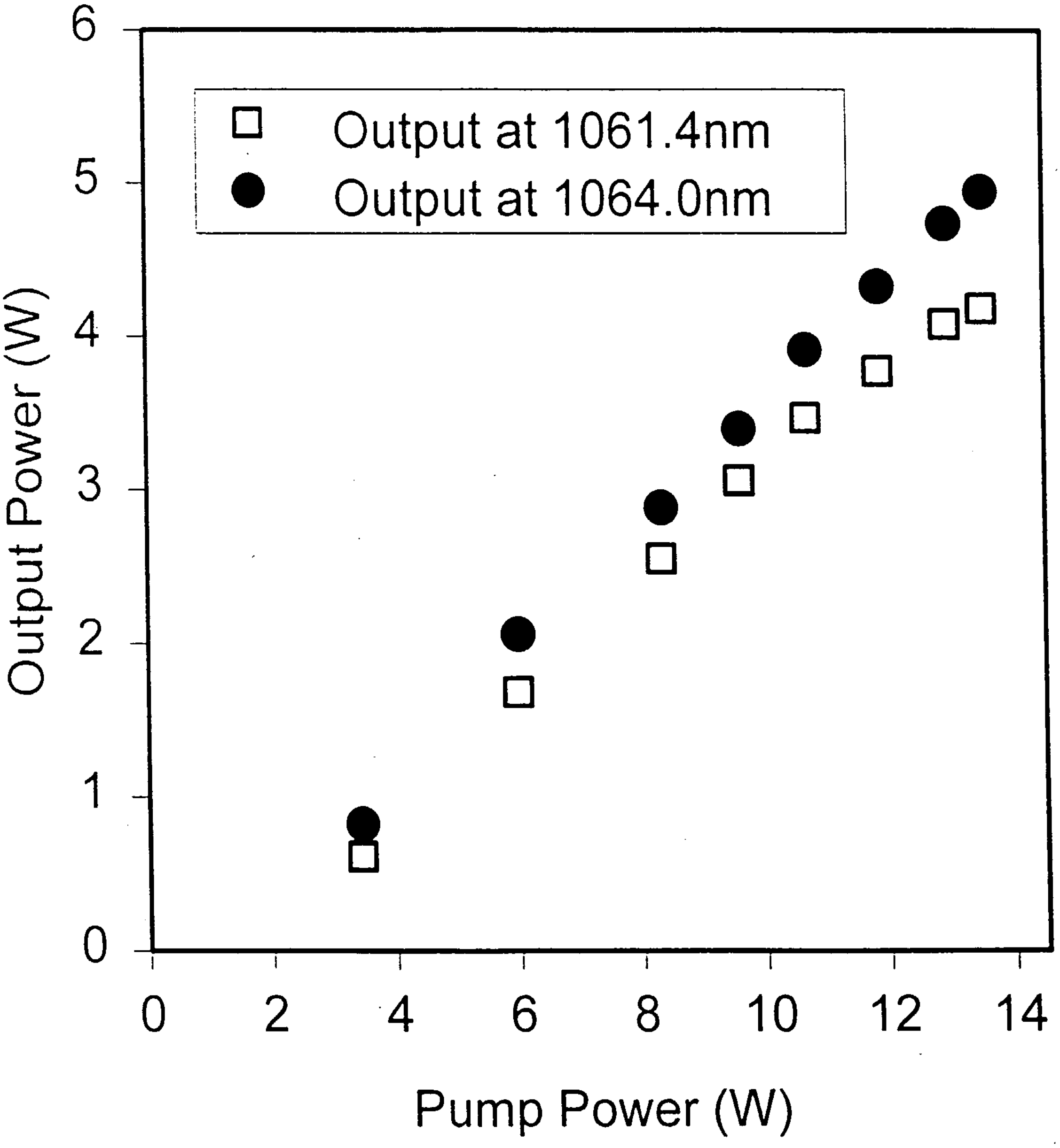


Fig. 4



Output at 1061.4nm
Output at 1064.0nm
Output Power (W)
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
Pump Power (W)