3W of single-frequency output at 532nm via intracavity frequency doubling of a diode-bar-pumped Nd:YAG ring laser

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ABSTRACT

A beam-shaped 20W diode-bar has longitudinally pumped a Nd:YAG laser in a ring configuration. Unidirectional single-frequency operation is enforced by a Faraday rotator. Intracavity frequency doubling, using a KTP crystal has produced 3W of stable, single-frequency TEM_{00} output at 532nm.

Intracavity second harmonic generation in diode-pumped Nd-doped lasers has for a number of years been an area of active development. Harmonic output powers have steadily risen as available diode powers have increased. With the arrival of diode bars of 20W output capability, the prospect has come closer of an all-solid-state, multiwatt green source as an alternative to the Ar laser. In this letter we describe a Nd:YAG laser, longitudinally pumped by a single 20W cw diode bar, which produces 3W of TEM_{00} output at 532nm by intracavity frequency doubling in KTP. A unidirectional ring laser configuration has been chosen, to ensure single-frequency operation. Thus we avoid the chaotic fluctuation behaviour (the 'green problem'[1]) commonly seen in multimode standing wave resonators. A stable single-frequency green output is obtained.

Under conditions of efficient intracavity harmonic generation, the nonlinear conversion process is the dominant loss for the fundamental. The laser will therefore have a strong tendency to oscillate in alternative ways that avoid this nonlinear loss. We indicate in the description that follows, various steps that must be taken to ensure that the laser is not able to access these alternative ways of oscillating.

The laser configuration is shown in figure 1. The main features are; a Nd:YAG laser rod, pumped by a diode-bar whose beam has been shaped to give a well-confined pump spot, collimated over the length of the rod, a 'bow-tie' ring resonator providing a tight focus at which the KTP frequency doubler is located, a Faraday rotator to enforce unidirectional operation, an etalon to confine oscillation to the 1064nm line and prevent oscillation on other lines, the 1061.4nm line in particular.

The diode-bar beam-shaper has been described elsewhere[2], as has its use for efficient pumping of a Nd:YAG laser[3] in a standing-wave cavity. Here the diode-beam, re-formatted by the beam shaper, was focused to a nearly circular spot-size with a $1/e^2$ beam radius of approximately $290\mu m$ in the 10mm long Nd:YAG. The beam divergence (half angle) corresponding to this spot size was ~ 70mrad, so that the beam had a confocal parameter inside the laser rod (~ 15mm) which was much longer than absorption length (~ 2.6mm) for the diode pump light in the 1.1% Nd-doped YAG. This ensures that the pump beam does not expand significantly over pumped region and so facilitates mode matching to the TEM_{00} beam, whilst providing sufficient gain for efficient lasing. Much smaller spot sizes are possible with this shaped beam, but at these power levels considerable thermally-induced lensing occurs, with focal length proportional to the pump spot-size squared. At 15W input to the rod, the focal length for our chosen spot size was measured to be ~ 170mm. It should be noted that the ring configuration is beneficial in that the rod is traversed once per round trip, thus alleviating the problem of compensating the thermal lens and reducing the losses associated with thermally-induced aberrations.

Great care needs to be exercised in the choice of intracavity components to ensure that as little loss is introduced as possible since for high-efficiency the nonlinear loss must be dominant while the conversion efficiency (from circulating fundamental intensity to harmonic intensity) may only be a few per cent in practice. A travelling wave acousto-optic modulator can provide a very low loss means of inducing unidirectional operation of the fundamental[4]. However the loss difference of such a device is generally not sufficient for use with efficient intracavity harmonic generation, since if the harmonic generation efficiency exceeds the loss difference, bidirectional oscillation results. A Faraday rotator was therefore chosen to provide unidirectional operation. The Faraday medium was a 6mm long TGG crystal (antireflection coated, having a total measured insertion loss of 0.4%), and producing a polarisation rotation of 7.5° at 1.064μm. An equal rotation was provided by a pair of half-wave plates so that for one direction of propagation, rotations added and in the other direction cancelled. The loss difference was calculated to be 16%, which was more than sufficient to maintain unidirectionality for our anticipated conversion efficiency. The two half-wave plates were used in place of a optical rotator, essentially the pair of plates rotates the plane of polarisation of a linearly polarised input by an angle corresponding to twice the angle between the fast axis directions of the two plates. This result is independent of the orientation of the plane of polarisation relative to the axis of the plates. These plates were placed either side of the KTP crystal and the fast axis of the plate between the TGG and KTP was orientated at 26.25° to the vertical. With this arrangement the linearly polarised emission from the laser rod, chosen for convenience to be horizontal and enforced by the Brewster plate polariser shown in Fig.1, was presented to the KTP crystal polarised at 45° to the vertical, as required for type II phase-matching with the z-axis of the crystal in the vertical direction.

KTP was chosen for these initial experiments, although LBO also has suitable characteristics, and results from LBO giving comparable efficiency will be described in a separate paper. KTP has a number of features that need attention in the resonator design. It is essential to keep to a minimum any losses due to depolarisation of the fundamental wave. This necessitated adjusting the temperature of the crystal to ensure it acted as a full-wave plate for the fundamental. KTP has proved an attractive medium for frequency doubling of $\sim 1\mu$m radiation since it can be used in a nearly non-critical phase-matching condition. However it is not exactly 'non-critical' for doubling of 1.064μm. This results in a small degree of double-refraction walk-off, with a consequent depolarisation (even when exactly a full-wave plate) due to separation of the extraordinary and ordinary beams. Nightingale[5] has described a special cut of the KTP crystal to overcome this problem and the crystal we have used was cut in this way. The 15mm long antireflection coated crystal had an estimated insertion loss of 0.5%. Under typical operating conditions at the highest harmonic generation efficiency, total depolarisation loss (measured by light reflected from the Brewster plate) was less than 0.7% per round trip.

An additional component that had to be added to the resonator, to allow the highest efficiencies to be achieved, was an etalon, designed to discriminate against the neighbouring transition at 1.0614μm. As noted by Smith[6], efficient intracavity harmonic generation on the 1.064μm transition, which implies a large nonlinear loss, can then result in lasing on other transitions, whose lower gain is offset by their experiencing lower nonlinear loss. The 1.0614μm transition has a gain coefficient a factor of ~0.75 times that for 1.064μm and would readily oscillate with modest harmonic conversion of the 1.064μm. However, the KTP, combined with the Brewster plate, acts as a birefringent filter, and can suppress the 1.0614μm line to a certain extent. Despite this, parasitic oscillation was still observed for single pass conversion efficiencies above 2.5%. A simple uncoated fused silica etalon of 80μm thickness was sufficient to prevent this when aligned for 1.064μm transmission.

A wide range of choice for fundamental spot-size in the KTP is in principle possible since the nonlinearity is sufficient to enable several per cent conversion efficiency even with relatively slack focusing in the crystal. Our best results were obtained with a fundamental spot-size of 70μm in the KTP. A notable feature was the tendency under conditions of high conversion efficiency for the laser to choose a misaligned path round the resonator, which was sufficiently misaligned within the KTP to prevent efficient harmonic generation. Tighter focusing in the KTP exacerbated this behaviour so that for best results the focusing had to be deliberately relaxed.

Experiments were carried out with three different spot radii in the KTP, approximately 90μm, 70μm and 60μm. These were obtained by changing the radius of curvature of the two curved mirrors in the bow-tie cavity, and adjusting their separation to achieve good mode matching in the laser rod. With the smaller spot, high output powers were achieved, but they were not repeatable, due to the alignment difficulties discussed above. The largest spot size gave 3.0W of green light. This corresponded to a single pass conversion efficiency of 2.1%. With the 70μm spot, the conversion efficiency increased, causing the 1061.4nm line to lase. This was suppressed by placing the uncoated etalon in the cavity, allowing an output of 3.1W, corresponding to a single pass conversion efficiency of 3.4%. The birefringence loss was higher, being 0.64% compared to 0.5% for the 90μm spot. A graph of output against pump power is shown in Fig.2. The output was single-frequency, as shown in Fig.3, and was TEM_{00}, with typical M^2 values of 1.08 and 1.12 in the horizontal and vertical planes respectively.

In conclusion, we have demonstrated a ring Nd:YAG laser system, longitudinally pumped by a single diode-bar, generating 3W of single-frequency TEM_{00} output by intracavity frequency doubling in a KTP crystal. The choice of resonator, intracavity components and their disposition has been broadly dictated by the needs of minimising loss, compensating thermal lensing in the rod, and suppression of oscillations which avoid frequency-doubling.

There is clearly scope for further significant increase in generated power as there are many parameters relating to the resonator and intracavity components that can be further optimised. However what is highlighted by these experiments is the additional design complexity which stems from the tendency of the laser to oscillate in ways that avoid the nonlinear loss due to efficient doubling. One major parameter of choice is that of the nonlinear medium. LBO, while having a smaller nonlinearity than KTP has other features, such as its effect on polarisation, which simplify the design procedure. Results obtained from using an LBO crystal will be reported shortly in a separate paper.

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References

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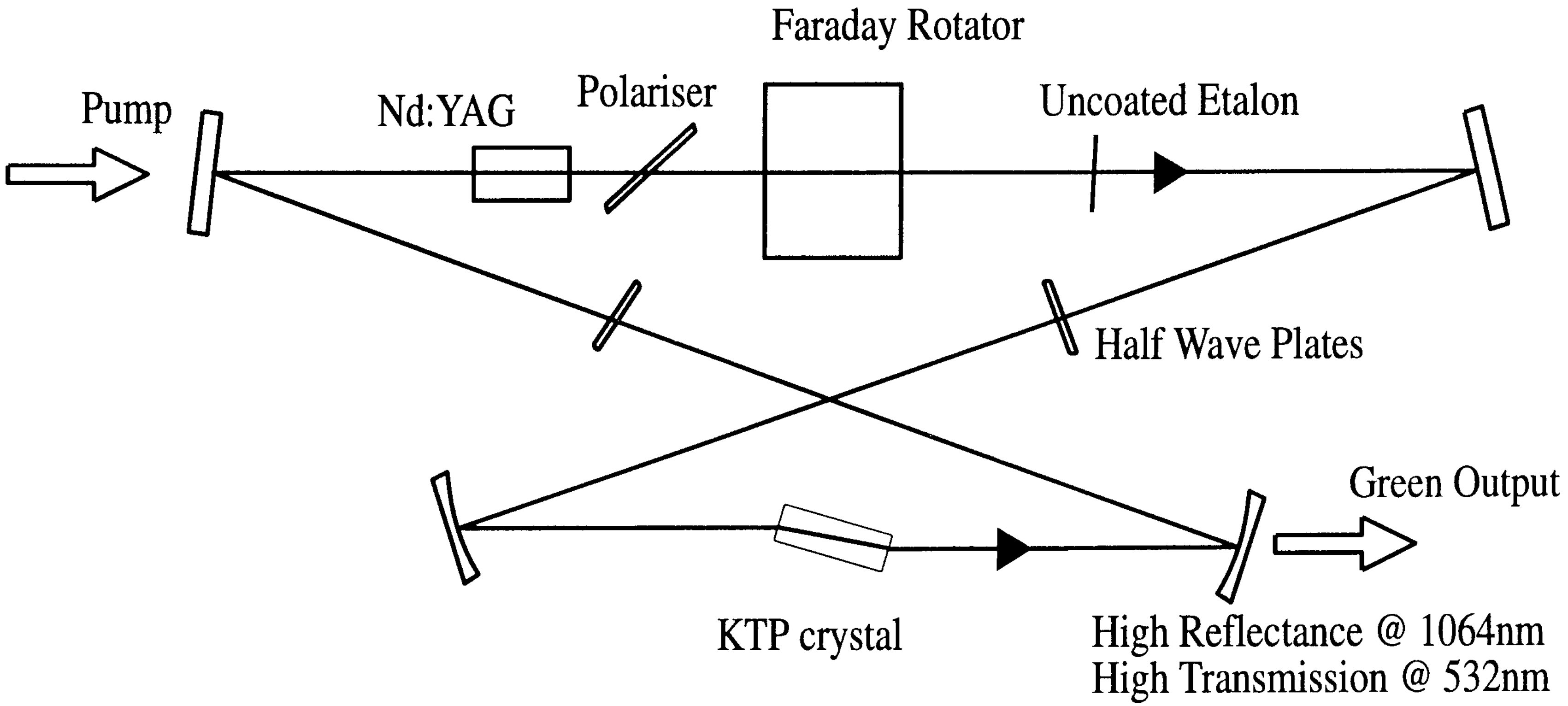
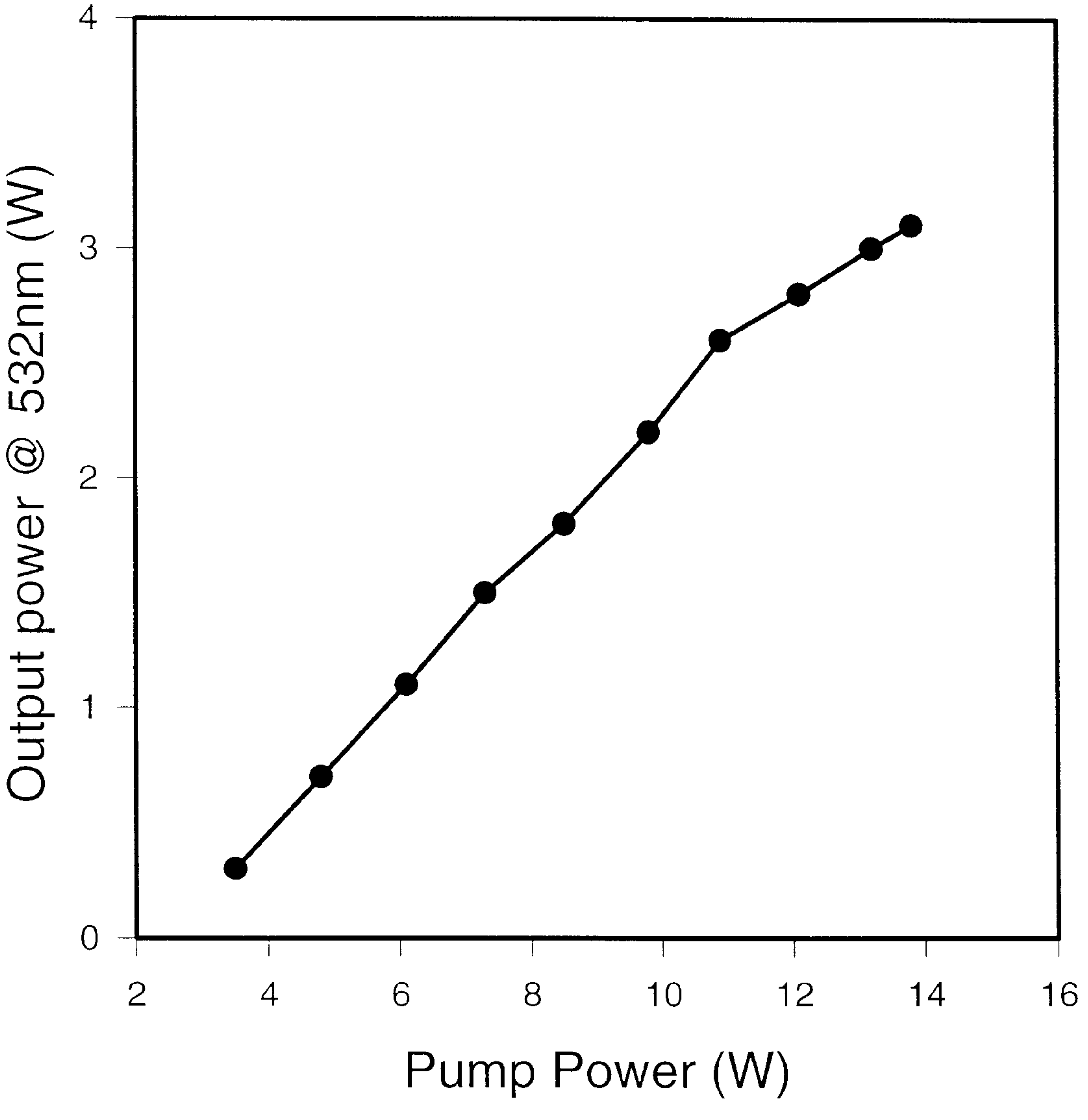
Figure Captions

Fig. 1 Diagram of the intracavity-frequency-doubled Nd:YAG ring laser.

Fig. 2 Green output power at 532nm versus incident diode pump power for the case where the fundamental beam radius in the KTP is $\sim 70\mu m$.

Fig. 3 Typical scanning Fabry-Perot trace for the 1064nm leakage while generating $\sim 3W$ at 532nm, confirming single-frequency operation.


Faraday Rotator
Pump
Nd:YAG
Polariser
Uncoated Etalon
Half Wave Plates
Green Output
KTP crystal
High Reflectance @ 1064nm
High Transmission @ 532nm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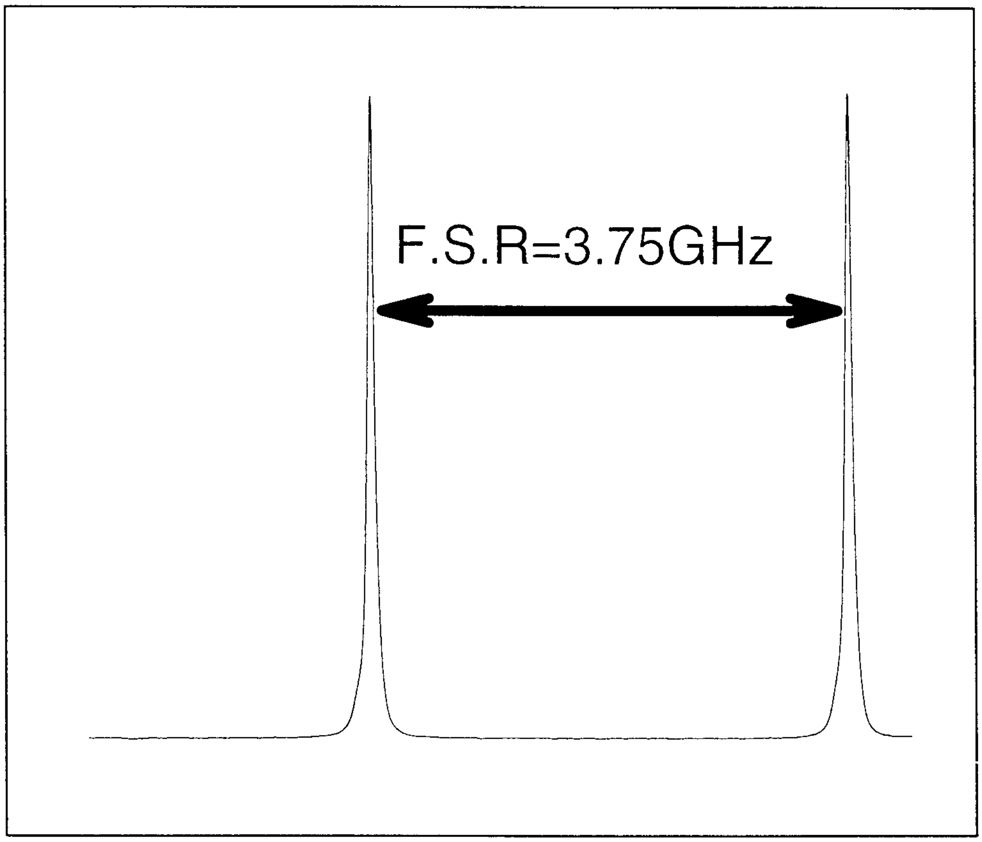
3
2
1
0
Output power @ 532nm (W)
2
4
6
8
10
12
14
16
Pump Power (W)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