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High-Power Diode-Pumped Room-Temperature Tm:YAG and Intracavity-Pumped Ho:YAG Lasers

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Abstract: Efficient, room-temperature operation of a diode-end-pumped Tm:YAG laser is reported. With 53.4W of incident pump power, provided by two beam-shaped diode bars, we obtained 17.5W of output at 2.013μm in a beam with a beam quality factor, M^2~6. A Ho:YAG laser, intracavity-pumped by the Tm:YAG laser, produced 7.2W of output at 2.097μm.

OCIS codes: (140.3580) Lasers, solid-state; (140.6810) Thermal effects; (140.3410) Laser resonators; (140.3070) Infrared and far-infrared lasers.

Introduction

Scaling output power from 2μm solid-state lasers to meet the demands of applications such as LIDAR and mid-infrared generation via pumping of OPO's is an area which has attracted growing interest over recent years. In this paper we describe a simple strategy for achieving high power operation of a Ho:YAG laser. Singly-doped Ho:YAG is an attractive laser material for 2μm operation with much lower upconversion losses, and hence a much longer effective energy storage time (~8ms) than for Tm-sensitised Ho:YAG. Unfortunately, Ho:YAG has no absorption band in the 780nm-980nm spectral region and hence cannot be pumped directly with commercially available high-power GaAlAs and InGaAs diode lasers. One solution to this problem is to pump the Ho:YAG laser, in-band, with a diode-pumped Tm laser. Recent work by Budni et al. [1],[2] has demonstrated high-power operation of Ho:YAG by direct pumping with diode-pumped Tm:YLF and Tm:YALO lasers. Here we describe an alternative approach for power-scaling of Ho:YAG via intracavity pumping in a Tm:YAG laser.

Tm:YAG laser

A preliminary requirement for high power operation of Ho:YAG via intracavity pumping is a high-power Tm:YAG laser. There are several problems to consider when attempting to power-scale Tm:YAG. Firstly, the relatively small emission cross-section and quasi-three-level nature are demanding on the diode pump laser which must be focussed to a relatively small beam size to achieve the required pump intensity. Secondly, the high pump intensity leads to a highly aberrated thermal lens and thermally-induced birefringence, which can degrade beam quality and increase cavity loss. The low stimulated emission cross-section and quasi-three-level nature of Tm:YAG renders the performance particularly sensitive to these thermally-induced losses. To minimise beam distortion due to the aberrated thermal lens we employ a resonator design with a TEM_{00} beam radius, w_L which is smaller than the pump beam size w_p, since the lens is more highly aberrated in the wings of the pumped region. In addition, we apply a second condition to the resonator design which is that $df_{th}/dw_L<0$ (where f_{th} is the thermal lens focal length) for the strongest thermal lens encountered [3]. This increases the spatial overlap of the fundamental mode with higher-order transverse modes helping to suppress their oscillation without the need of lossy apertures. A typical Tm:YAG resonator design used in our experiments is shown in Fig.1. The Tm:YAG crystal was mounted in a water-cooled heat-sink maintained at a temperature of 17°C and doped with 3% at.Tm^{3+}. This doping

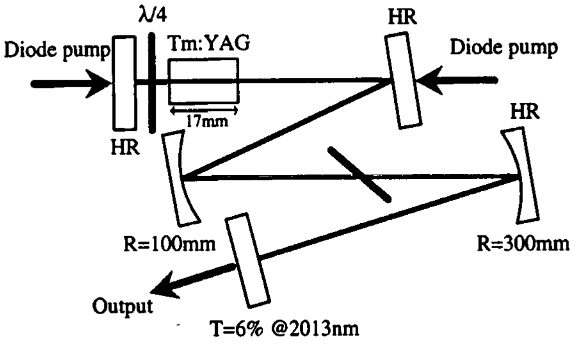

Fig. 1. Tm:YAG resonator with a quarter-wave plate for decreasing the depolarisation loss due to stress-induced birefringence

level helps to reduce upconversion losses whilst maintaining efficient 'two-for-one' cross-relaxation, which is important for efficient operation and helps to minimise detrimental thermal loading. Both faces of the Tm:YAG rod were end-pumped by fibre-delivered, beam-shaped [4], 40W diode bars at 785nm, which were both focussed to beam radii of ~400μm inside the rod. The maximum combined pump power of 53.4W incident on the rod yielded a laser output power of 14.2W at 2.013μm in an unpolarised, near-diffraction-limited beam with M^2=1.3. Linearly-polarised operation, achieved by inserting a simple Brewster-angled glass plate, resulted in a reduced maximum power of 8.4W for 49.7W of incident pump power due to the increase cavity loss resulting from thermally-induced depolarisation. Further increase in pump power resulted in a dramatic reduction in the laser power (Fig.2), believed to be due to the combined effect of

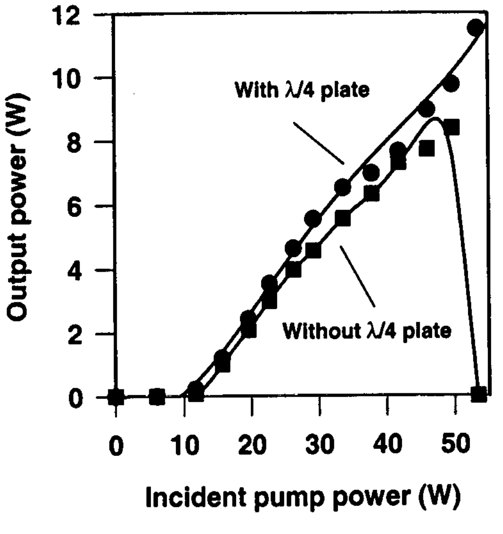

Fig. 2. Tm:YAG laser output power versus incident pump power

thermally-induced birefringence and increased thermal loading due to upconversion, compounded by the use of resonator which was designed to operate close to the edge of it's stable regime. To reduce the effects of thermally-induced birefringence, a quarter-waveplate, aligned with its fast and slow axes parallel (or perpendicular) to the preferred plane of polarisation defined by the polariser, was inserted between the cavity end mirror and the Tm:YAG rod [5]. This resulted in a dramatic reduction in the depolarisation loss from >5% to <0.4% and an increase in laser power to 11.5W (fig.2), limited only by the available pump power.

Higher output power ~17.5W (unpolarised) could be achieved, at the expense of beam quality, by using a modified cavity design (fig.3) with a smaller TEM_{00} beam radius of ~200μm, which did not change significantly with varying thermal lens focal length. Using a similar cavity design to that shown in Fig.3,

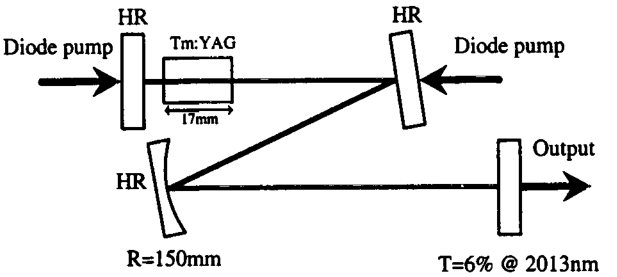

Fig. 3. Tm:YAG resonator for high-power operation

and replacing the Tm:YAG rod by Tm:(Lu,Y)AG rod, doped with 3% Tm, and with 50% of the ytterbium ions replaced by lutetium, we obtained a slightly higher output power of 18W (fig.4). This laser operates at a slightly longer wavelength (~2.020μm) than for Tm:YAG, which has higher atmospheric transmission, making it of potential interest for LIDAR.

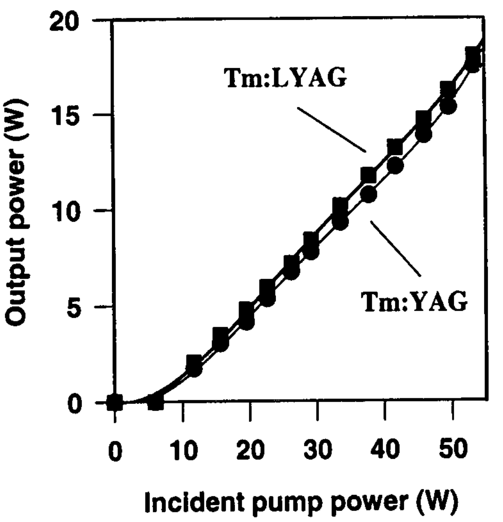

Fig. 4. Tm:YAG and Tm:LYAG laser power versus incident pump power

Intracavity-pumped Ho:YAG laser

For scaling to higher power and maintaining good beam quality, thermal loading is going to be an important factor. Inband pumping of Ho:YAG at 1.9-2μm offers a route to much lower quantum defect heating (<10%). In addition, Ho:YAG has a ~3 times larger στ product than Tm:YAG and, for typical Ho^{3+} doping levels of ~0.5%, it has much lower upconversion losses than Tm:YAG [6]. These factors combined with its long energy storage time suggest Ho:YAG is an attractive candidate for high power CW and high-energy Q-switched operation. Intracavity pumping of Ho:YAG in a Tm:YAG laser [7] offers the advantages of a nearly uniform axial pump deposition and reduced quantum defect heat loading compared to direct inband pumping with Tm:YLF [1] or Tm:YALO [2] lasers, but at the expense of a slightly more complicated resonator design. The design used in our preliminary work (shown in Fig.5) is based on the Tm:YAG laser resonator shown in Fig.3. A 0.5% Ho-doped YAG rod (9mm long), mounted in a water-cooled copper heat-

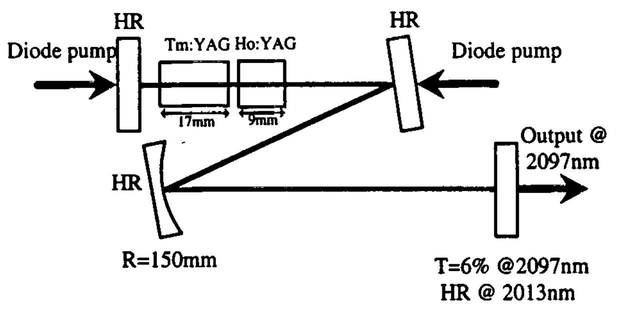

Fig. 5. Intracavity-pumped Ho:YAG laser

sink maintained at a temperature of 17°C was inserted into the Tm:YAG resonator and the output coupler replaced by one with high reflectivity at the Tm:YAG wavelength and with a transmission of ~6% at the Ho:YAG wavelength (~2.1μm). The Ho:YAG laser reached threshold for a diode power of ~10W incident on the Tm:YAG rod (Fig.6), and produced a maximum power of 7.2W at 2.097μm for 53.4W of incident

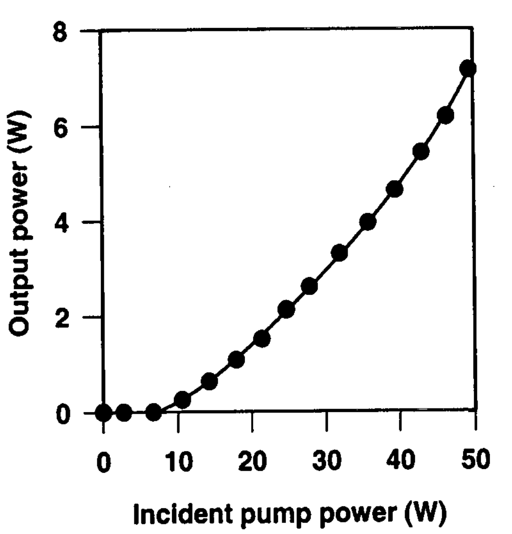

Fig. 6. Ho:YAG laser output power versus diode power incident on Tm:YAG rod

pump power, corresponding to a slope efficiency with respect to incident diode power of 17.5%. The output beam had M^2 values in orthogonal planes of ~5 and ~6. This relatively poor beam quality resulted from the use of a resonator designed for high Tm:YAG laser power rather than good beam quality, and also because the Ho:YAG laser beam experiences some beam distortion due to thermal lensing in the Tm:YAG rod.

Summary

In conclusion we have demonstrated efficient room-temperature operation of Tm:YAG, Tm:(LuAG) and intracavity-pumped Ho:YAG lasers with output powers of 17.5W, 18W and 7.2W respectively for 53.4W of incident diode power. To access the full benefits of the low fractional heating in the Ho:YAG it will be necessary to decouple the Ho:YAG and Tm:YAG cavities, so that the Ho:YAG laser beam does not propagate through the Tm:YAG rod. This should allow a significant improvement in efficiency and beam quality. Thus, with the appropriate cavity design, intracavity-pumping of Ho:YAG promises to be a very attractive route to high output power in the 2μm spectral region.

Acknowledgments

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