Efficient single-axial-mode operation of a Ho:YAG ring laser pumped by a Tm-doped silica fiber laser

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Efficient single-frequency operation of a Ho:YAG ring laser at room temperature using a traveling-wave TeO_2 acousto-optic modulator to enforce unidirectional operation is reported. Using a 2(at.)% Ho^{3+}-doped 10mm long Ho:YAG rod, end-pumped by a cladding-pumped tunable Tm-doped silica fibre laser operating at 1.9μm, the Ho:YAG ring laser yielded 3.7W of single-frequency output at 2.1μm in a diffraction-limited TEM_{oo} beam with $M^2<1.1$ for an incident pump power of 8.8W. The RF power required for unidirectional operation was 0.3W and corresponded to an increase in cavity loss for the lasing direction (due to diffraction) of only 0.5%. The prospects for further improvement in efficiency are discussed.

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High-power, narrow linewidth sources operating in the eye-safe 2μm spectral region have numerous applications and provide an ideal starting point for the generation of mid-infrared (3-5μm) radiation via nonlinear frequency conversion. Direct (in-band) pumping of Ho:YAG with a diode-pumped Tm-doped bulk laser[1] or a cladding-pumped Tm-doped fiber laser[2,3] is an attractive route to high output power in the 2μm regime. The latter approach is particularly promising for further power-scaling since most of the heat is generated in the fiber laser, which benefits from a geometry that can handle a relatively high heat dissipation with relative immunity from thermal effects[4], and there is very low quantum defect heating (~9%) in the Ho:YAG. The net result is that very high lasing efficiencies are attainable. Moreover, unlike fiber-only systems, this approach is compatible with the requirements for producing both high peak powers and high pulse energies (via Q-switching) and single-axial-mode output due to the very long fluorescence lifetime (~8ms) in the Ho:YAG[5] and the very high threshold for unwanted nonlinear loss processes (e.g. Stimulated Brillouin scattering) respectively.

There are a number of different approaches for achieving single-frequency operation, but many suffer from the drawback of being rather restrictive on resonator design (e.g. microchip or monolithic ring resonators), hence limiting the scope for power scaling, or result in increased resonator complexity and hence cavity loss with a consequent reduction in output power and efficiency. The use of a ring cavity configuration and enforcing unidirectional operation with a traveling-wave acousto-optic modulator (AOM) is an attractive and potentially very low loss method for achieving single-frequency operation, offering flexibility in the choice of resonator design and mode of operation. The non-reciprocal behaviour of a traveling-wave AOM arises from a difference in the Bragg angles for opposite beam directions[6]. Thus, by tilting the AOM slightly away from the Bragg angle and applying RF power it is possible to achieve a loss-difference sufficient to enforce unidirectional operation. This approach has the attraction of a low insertion losses (since only one additional intracavity element is required), wide spectral operating range and polarization-independent loss discrimination. In addition, the AOM used to enforce unidirectional operation can also be used simultaneously as a Q-switch if pulsed mode of operation is desired. This technique has been successfully applied to Nd:YAG[7] and Nd:YLF[8] ring lasers to achieve single frequency operation in the 1μm wavelength regime.

In this letter we report efficient single-frequency operation of a Ho:YAG ring laser at room-temperature, end-pumped by a Tm fiber laser, using a TeO_2 AOM to enforce unidirectional operation. The Ho:YAG produced 3.7W of single-axial-mode output at ~2.1μm for 8.8W of incident pump power at 1.9μm corresponding to an optical efficiency of 47%.

The experimental set-up is shown in Fig.1. The tunable Tm-doped silica fibre laser comprised a 4.7m length of double-clad fiber with a 20μm diameter (0.12NA) Tm-doped alumino-silicate core and a 200μm diameter pure silica inner-cladding coated with a low refractive index (n=1.375) outer-cladding. Wavelength tuning was achieved with the aid of a simple external cavity arrangement containing a diffraction grating (600 lines/mm) in the Littrow configuration. At the maximum available incident pump power (corresponding to 43W launched at 790nm) the fiber laser produced a maximum output power of 10.0W at 1921nm in a beam with $M^2 \approx 3$. The lasing wavelength could be tuned over 215 nm from 1855 to 2070nm at multi-watt power levels, and produced >9.5W at the wavelength (between 1905 and 1908nm) corresponding to the absorption peak in Ho:YAG. Further details about this laser can be found in ref. 9.

A simple 'bow-tie' ring resonator configuration was employed for the Ho:YAG laser (see Fig.1) comprising two flat mirrors, M1 and M2, with high transmission (>99%) at the pump wavelength and high reflectivity (>99.8%) at the lasing wavelength (~2.1μm), and two concave mirrors, M3 and M4, with 100mm radius of curvature. M3 was coated for high reflectivity (>99.8%) over the wavelength range 1850-2150nm covering both pump and lasing wavelengths, and M4, which served as the output coupler, had a transmission of 10% at the lasing wavelength and high reflectivity (>99.5%) at the pump wavelength. A 2(at.)% Ho-doped 10mm long YAG rod, with both end-faces antireflection coated at the lasing and pump wavelengths was located at the mid-point of the resonator arm M3-M4. The physical length of arm M3-M4 was 107mm. The laser rod was mounted in a water-cooled copper heat-sink to allow efficient heat removal with the water temperature maintained close to room temperature (at 15°C). A TeO_2 traveling-wave AOM with Brewster-angled faces was used to provide the necessary loss difference between counter-propagating beams to ensure unidirectional operation. To avoid possible damage, due to accidental Q-switching during alignment of the cavity, the AOM was placed in resonator arm M1-M2, where the calculated TEM_{00} beam radius (~700μm) was relatively large. Pump light at 1905nm from the Tm fiber laser was introduced into the cavity through mirror M1 and focused by mirror M4 into the Ho:YAG rod. The measured pump beam and calculated laser TEM_{00} radii in the Ho:YAG rod were 73μm and 66μm respectively. The total optical length of the ring cavity was 53.6 cm, corresponding to a frequency separation between axial modes of 0.56GHz. At the highest incident pump power of 8.8W, the single-pass pump absorption in the Ho:YAG rod was measured to be only 43% under non-lasing conditions due to the ground-state bleaching. However, at low pump powers and under cw lasing conditions, the single-pass absorption was measured to be ~79%. To increase the pump absorption, and hence the overall efficiency, the unabsorbed pump light, after a single transit of the laser rod, was re-collimated by M3 and retro-reflected for a second pass of the rod by M5, resulting a total absorption efficiency of ~96%.

Unidirectional lasing was achieved by applying RF power (at 80MHz) to the AOM and carefully optimizing its alignment so as to maximize the laser output power. The minimum RF power required for purely unidirectional operation (i.e. with no measurable output in the counter-propagation direction) was 0.3W. Under these operating conditions, the Ho:YAG laser reached threshold for an incident pump power of 0.31W and yielded a maximum output power of 3.7W at 2114nm (limited by the available pump power). The beam quality was determined to be M^2 1.1 with aid of a PC-Beamscope (Merchantek) hence convincing diffraction-limited TEM_{00} operation. There was no evidence of any detrimental impact of weak thermal lensing in the Ho:YAG rod on laser performance or beam quality. The slope efficiency with respect to incident pump power was 47% (see Fig.2). Single frequency operation was verified with the aid of a scanning plane-mirror Fabry-Perot interferometer with a free spectral range of 8GHz and finesse of 35 (see Fig.3). By changing the tilt angle of the AOM, and hence reducing the loss difference between counter-propagating beam to a level just below that required for purely unidirectional operation, we were able to show, by monitoring the frequency spectrum, that reliable single-axial-mode operation could be maintained for a counter-propagating power of up to 10mW (at the maximum available pump power).

With no RF power applied to the AOM, the laser reached threshold at a pump power of 0.27W and operated bidirectionally and multi-frequency (see Fig.3) with a maximum combined output power of 3.9W, corresponding to a slope efficiency of 49% (see Fig.2). The slightly higher threshold and slightly lower efficiency for unidirectional lasing is due to the small increase in cavity loss for the lasing direction due to diffraction in the AOM when RF power is applied. The resonator losses (excluding output coupling loss) with the RF power on and off were estimated to be 6.1% and 5.6% respectively indicating that the diffraction loss was only ~0.5%. This is a relatively small loss penalty to pay for enforcing unidirectional operation compared to that which would be likely to be incurred if the more conventional approach based on a the use of a Faraday rotator and reciprocal polarization rotator was employed. However, the slope efficiency is somewhat lower than has been demonstrated in simple standing-wave cavity configurations[9]. This is due to a relatively high passive insertion loss (~4%) for the TeO_2 AOM, which results from relatively poor quality input and output polished surfaces. With a lower loss AOM it should be possible to achieve a very significant increase in the slope efficiency comparable with that achieved in standing-wave cavity configurations.

In conclusion, we have demonstrated efficient acousto-optically induced unidirectional operation of a Ho:YAG ring laser pumped by a Tm-doped silica fiber laser. 3.7W of single-frequency output at 2114nm in a diffraction-limited beam with $M^2<1.1$ was obtained for 8.8W of incident pump power at 1.9μm. The combination of in-band pumping of Ho:YAG by a Tm fiber laser with the use of a traveling-wave acousto-optic modulator for enforcing unidirectional operation in a ring cavity configuration is a simple and efficient method for producing single-frequency output at high power levels in the 2.1μm regime, and should find a wide range of applications.

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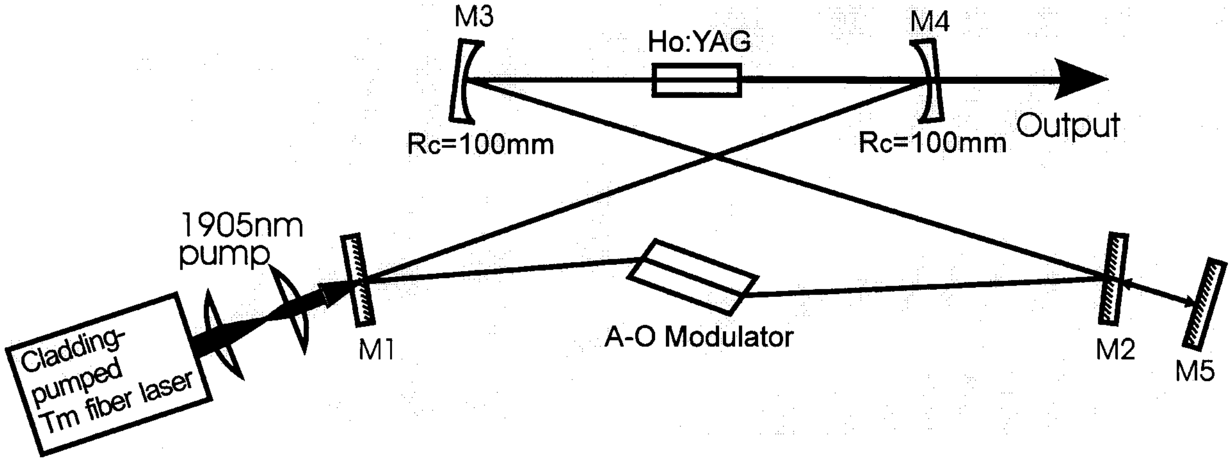

Fig. 1: Schematic diagram of the Ho:YAG ring laser resonator.

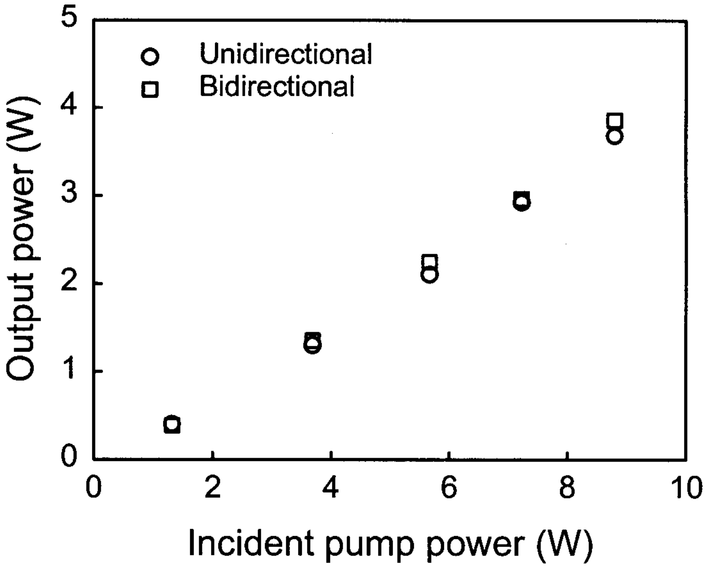

Fig. 2: Output power of the Ho:YAG ring laser versus incident pump power at 1905nm.

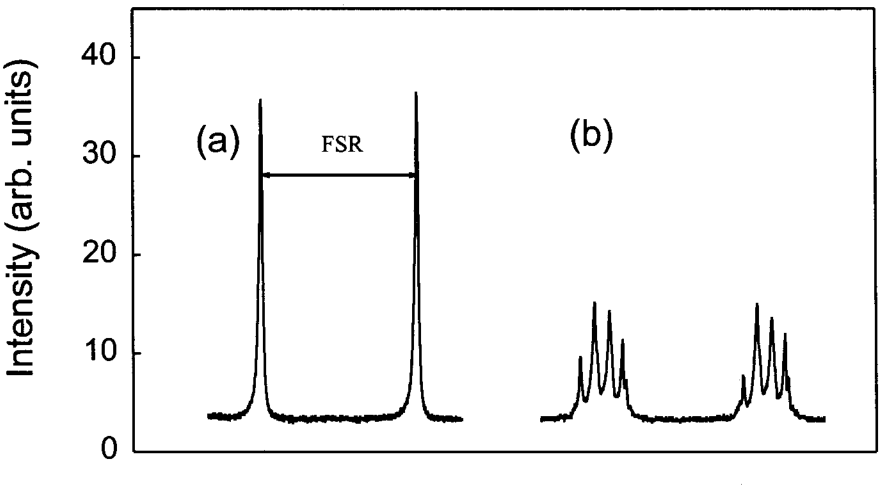

Fig. 3: Frequency spectra of Ho:YAG ring laser for (a) unidirectional operation (RF on) and (b) bidirectional operation (RF off).