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Frequency-stabilized Nd:YAG laser with high output power

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Single-frequency emission from a Nd:YAG laser at 1.06 μm at power levels in excess of 1 W would be useful for the investigation of dynamic processes in nonlinear optics and would be an important source for high-resolution nonlinear spectroscopy. However, submegahertz frequency stability for Nd:YAG lasers at high levels of lamp pumping power is very difficult to obtain due to thermal loading of the laser rod.[1–3] In this Letter we describe a single-frequency Nd:YAG laser with output power >1.1 W and frequency stability of 120-kHz rms. This performance is obtained in a ring cavity which largely eliminates problems associated with spatial hole burning and which is designed to minimize laser fluctuations due to noise in the pumping and cooling processes.[4,5]

A number of discussions of frequency-stabilized Nd:YAG lasers are available.[2,6–10] Perhaps the best frequency stability demonstrated in a conventional cw system is found in the work of Gerhardt *et al.*,[7] who measured linewidths of 0.6-MHz long-term and 300-Hz short-term at an output power level of 30 mW. Sun and Byer[8] report a quasi-cw system producing 5-msec pulses of 100-mW peak power and 5-mW average power with a frequency stability of 0.2 MHz. Quite recently Zhou *et al.*[9] described a monolithic Nd:YAG laser with 10-mW output and frequency stabilized to 0.2 MHz over 0.1 sec. For higher power levels, a ring cavity[11] is employed by Andreev *et al.*[10] to obtain more than 1 W of output power stabilized to ~1 MHz. The work that we report here is likewise for high output power but demonstrates frequency stability comparable with the best yet achieved in low power systems (where problems due to thermal gradients can be avoided). The frequency stability is an order of magnitude better than that of any other high power cw system.

A schematic of the laser together with the associated interferometers and electronics for frequency stabilization is shown in Fig. 1. The laser housing itself is an Invar structure on which a four-mirror ring cavity of total optical length 1.2 m is built. The laser head and power supply are commercial instruments chosen for their stability.[12] The Nd:YAG rod is 75 mm in length by 3-mm diameter, is doped at a level of 0.7%, and is pumped by a high pressure krypton arc lamp. Unidirectional operation of the laser is enforced by a Faraday rotator (Hoya FR5 glass, 1 cm in length, in a field of 1.8 kG for 4° rotation of polarization in a single pass) and a halfwave plate, together with mirror $M3$ which is a thin-film polarizer ($R \approx 0.99$ for S polarization, $R \approx 0.05$ for P polarization). An intracavity aperture ensures single transverse mode operation, and a fused silica etalon coated for 0.50 surface reflectivity and

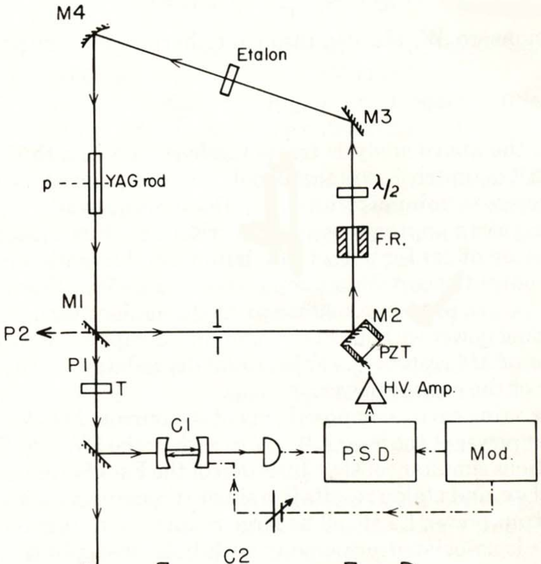

Fig. 1. Optical arrangement for frequency stabilization of the Nd:YAG laser. The laser cavity is formed by mirrors $M1$–$M4$. Confocal interferometers $C1$–$C3$ are used for locking ($C1$) and monitoring ($C2,C3$) the laser frequency. Other elements are as discussed in the text.

of 2-mm thickness selects a single longitudinal mode of the cavity. The output coupler $M1$ has a reflectivity of 0.965. With the exception of the etalon, all intracavity elements are antireflection coated.

An important feature of the design of the resonator is its insensitivity to thermal fluctuations in the Nd:YAG rod.[1,4,5] For a typical lamp power of 2.2 kW in the elliptical pumping geometry, we find that the laser rod acts as a thermal lens of approximate focal length $f = 1$ m. Modeling this effect as a thin lens located at plane p in Fig. 1, we obtain the following ray matrix for the system, referenced to plane p:

$$\begin{pmatrix} \mathrm{A} & \mathrm{B} \\ \mathrm{C} & \mathrm{D} \end{pmatrix} = \begin{bmatrix} 1 - \dfrac{d}{f_4} & L - \dfrac{d(L-d)}{f_4} \\ -\dfrac{1}{f} - \dfrac{1}{f_4}\left(1 - \dfrac{d}{f}\right) & \left(1 - \dfrac{d}{f}\right)\left(1 - \dfrac{L-d}{f_4}\right) - \dfrac{L-d}{f} \end{bmatrix} . \tag{1}$$

Here L is the total optical length of the cavity, d is the distance from mirror $M4$ to the center of the Nd:YAG rod, and f_4 is the focal length of mirror $M4$. Stability of the spot size W against fluctuations in the thermally induced focal length f requires that[5]

$$\frac{dW}{df} = 0, \tag{2}$$

with[13]

$$\frac{\pi W^2}{\lambda} = \frac{2\mathrm{B}}{[4 - (\mathrm{A} + \mathrm{D})^2]^{1/2}} . \tag{3}$$

Because A and B are independent of f, we obtain from Eq. (2)

$$\frac{dW}{df} = \frac{\partial W}{\partial \mathrm{D}} \frac{\partial \mathrm{D}}{\partial f} = 0, \tag{4}$$

which when evaluated using Eqs. (1) and (3) leads to

$$W\frac{dW}{df} = \frac{\mathrm{B}^2\lambda}{\pi f^2} \frac{\mathrm{A} + \mathrm{D}}{[4 - (\mathrm{A} + \mathrm{D})^2]^{3/2}} . \tag{5}$$

For nonzero W, the condition for thermal insensitivity is then

$$\mathrm{A} + \mathrm{D} = 0. \tag{6}$$

Since the above analysis treats the laser rod as a thin lens, which it definitely is not, the actual operating point of the laser is chosen to minimize intensity fluctuations with Eq. (6) serving as an approximate design criterion. For a radius of curvature of $2m$ for mirror $M4$, minimum fluctuation in the laser output occurs for a lamp power of 2.2 kW. This is the lamp power used in all subsequent discussion; variation of pumping power without a corresponding compensation of the radius of $M4$ results in a substantial degradation in the stability of the output power.

For a ring cavity composed only of the mirrors $M1$–$M4$, the output power of the laser is 2.2 W in each of the CW and CCW directions simultaneously. Insertion of the Faraday assembly, $\lambda/2$ plate, and etalon results in a single direction of oscillation of output power 1.2 W. The large reduction in total output power is associated principally with bulk absorption in the Faraday glass (3% per pass). Reduction of the aperture diameter produces single transverse and single longitudinal mode operation at an output power level of 1.1 W. Examination of the output beam on a reticon display confirms that the laser is indeed operating in the TEM_{00} mode. The ratio of CCW to CW output power is greater than 10^3 to 1.

The spectrum of the laser emission is observed with the three confocal cavities $C1$, $C2$, and $C3$ shown in Fig. 1. The free spectral ranges of the cavities are 1.5, 0.25, 0.75 GHz, and the values of finesse are 410, 1040, 250, respectively. Cavities $C1$ and $C2$ are Invar structures supported by elastomer spacers inside massive brass housings. One mirror in each cavity is mounted on a piezoelectric transducer, with the thermal expansion of the transducer used to compensate the expansion of the much longer Invar structure. This design has been employed in our laboratory to produce thermal expansion coefficients for the assembly as low as $5 \times 10^{-8}/°\mathrm{C}$, as confirmed by comparison to a Lamb-dip stabilized He–Ne laser.

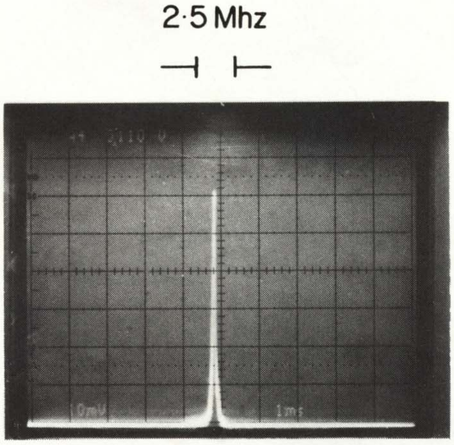

Fig. 2. Photograph of the transmission of the cavity $C2$ as a function of cavity length showing the frequency stability of the locked Nd:YAG laser. The instrument limited FWHM of the line is 240 kHz; the sweep rate is 1 msec/cm.

With the laser cavity in the configuration shown in Fig. 1, single-mode operation is observed with a free running jitter of approximately ±10 MHz over several seconds. Active control of the laser frequency is achieved in a standard fashion with a simple servo consisting of the cavity $C1$, a phase sensitive detector, and a high voltage amplifier. The upper limit on the frequency response of the servo is set by mechanical resonances of the piezoelectric transducer which lie in the low kilohertz range. Note that cavity $C1$ is our frequency reference; its length is modulated rather than that of the laser cavity so that there should be no modulation of the laser frequency.

The short-term stability of the laser frequency under the control of the feedback loop is indicated in Fig. 2, which is a single-sweep photograph of the output of the monitor cavity $C2$ as a function of cavity length. The FWHM of 240 kHz of the transmission profile is determined by the instrumental finesse, with the small asymmetry and structure of the profile resulting from a lack of precise confocal spacing. Figure 3 provides a different perspective of the laser frequency stability. Shown is the power transmitted through the interferometer $C3$ for a fixed length of the cavity corresponding to a detuning of half of the linewidth of the transmission profile. Fluctuations in frequency are thus translated into intensity fluctuations as indicated in the figure. Generally, the frequency excursions are seen to be less than ±200 kHz. The signal in Fig. 3 measured with a rms voltmeter (from 10 Hz to 100 kHz) allows us to infer a frequency stability of 120-kHz rms.

The long-term frequency stability of the locked laser is tracked with the monitor cavity $C2$. Deviations of 200 kHz occur over 1-min intervals with a net frequency drift of 1 MHz over 10 min. We can currently make no statement about the

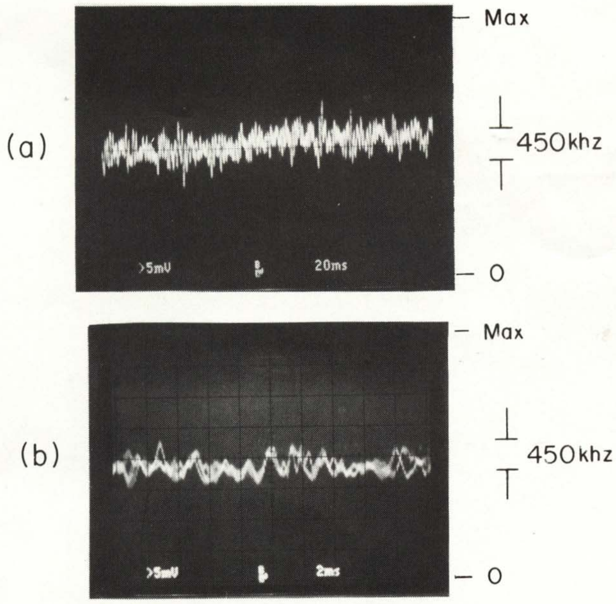

Fig. 3. Photographs of the transmission of the cavity $C3$. The cavity length is fixed at a point corresponding to a detuning from resonance of half of the instrumental width. Frequency deviations are thus transformed to intensity fluctuations with the appropriate conversion shown in the photographs. Horizontal scales are (a) 20 msec/cm and (b) 2 msec/cm.

absolute stability of the laser frequency since our measurements refer to the differential rate of drift of the reference cavity $C1$ and the monitor cavity $C2$. By referring the laser frequency or its harmonic to a spectroscopic standard,[8] we expect to be able to increase the observed locking times and to reduce the long-term frequency drift.

Tunability of the locked laser frequency is obtained by varying the length of the reference cavity, as indicated in Fig. 1, with a range of ±200 MHz achieved before a mode hop to an adjacent cavity mode occurs. By synchronously tuning the tilt angle of the etalon, we observe that this range can be significantly increased. However, angle tuning introduces large walk-off losses, so that extended tunability will be accomplished by replacing the solid etalong with a two-element assembly capable of length tuning.

Recent work with a 1.25-cm fused silica rod in place of the high loss Faraday glass has yielded 1.8 W of output power with comparable frequency stability but with increased alignment sensitivity due to the lack of sufficiently large differential loss for the two directions of circulation. A longer rod should alleviate this problem.

To summarize: we have described the operation of a frequency-stabilized cw Nd:YAG laser. Output power >1.1 W with a frequency stability of 120-kHz rms has been demonstrated in a ring cavity designed to reduce sensitivity to thermal fluctuations associated with the pumping process. Substantial improvements in frequency stability beyond this level will require a greatly increased bandwidth for the locking system since the residual noise in our system is associated with turbulence in the flow of coolant and in the heat dissipation in the laser rod. In this regard the techniques employed in the stabilization of dye lasers with free-flowing jets should be successful.[14]

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