Injection locking of a 13-W cw Nd:YAG ring laser

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A lamp-pumped, 13-W cw Nd:YAG ring laser at 1.064 μm is injection locked using a 40-mW single-frequency diode-laser-pumped Nd:YAG laser as the master oscillator. The phase fidelity of the injected slave to the master is measured using an all-optical technique.

Injection locking[1] is a technique for coupling two oscillators so that their frequencies and phases are highly correlated. As applied to lasers[2] this technique is most interesting when a low-power laser with desirable frequency properties (the master) is used to impose its frequency and mode structure onto a higher-power laser (the slave) whose spectral properties would otherwise not be so good. This technique offers the advantage of single-frequency operation of a high-power laser without the use of étalons or other intracavity elements that reduce the efficiency and output power of the oscillator.[3] This is accomplished by injecting the master laser's output into the slave laser's cavity. As the frequency of the master laser approaches one of the axial mode frequencies of the slave laser, light from the master laser is regeneratively amplified to higher intensities, eventually saturating the gain in the slave laser to such an extent that the original free-running mode of the slave is extinguished. Within this locking range the output of the slave laser is frequency locked to the master laser's output.

Injection locking has been demonstrated in a number of laser systems, including ion lasers,[4,5] dye lasers,[6] and diode lasers[7] and in low-power Nd:YAG lasers.[8] The problem has been extensively studied theoretically and rigorously treated for both classical oscillators and lasers[1,9] (including quantum effects and issues such as cross saturation). In our research we sought to build a multiwatt, cw, injection-locked Nd:YAG laser at 1.064 μm suitable for use in high-efficiency nonlinear optics, optical radar, and interferometric gravity-wave detection.[10]

The master oscillator in our experiment is a monolithic, isolated, single-mode, nonplanar ring oscillator[11] pumped with a laser diode. The laser power incident upon the slave is up to 40 mW in a single axial mode. The frequency stability of the master oscillator is excellent, with typically less than 20 kHz of linewidth[12] and the potential for stabilization to the subkilohertz level.[13] The temperature of the monolithic laser crystal is maintained at approximately 38°C to stabilize the laser's frequency and to ensure that the gain center wavelengths of the master and slave oscillators coincide.[14]

The slave laser is configured as a ring, with the Nd:YAG rod/lamp assembly from an Antares Model 76-s laser (manufactured by Coherent, Inc.) used as the gain medium. The twin-lamp head consumes 9 kW of electrical power and is temperature stabilized at 36°C by a primary–secondary water cooling system. The ring laser cavity consists of four flat optics: two high reflectors, a Brewster-angle polarizer, and the output coupler. Transverse-mode stability was provided by the thermal focusing of the Nd:YAG rod, such that the laser ran in a TEM_{00} mode without an aperture. The cavity length is 133 cm, corresponding to a free spectral range of 225 MHz, and can be adjusted with mirrors mounted on piezoelectric transducers (PZT's). A half-wave plate, a FR-5 glass Faraday rotator, and the thin-film polarizer form an optical diode and enforce unidirectional operation. The output coupler has $T_s = 17\%$, $T_p = 45\%$, which is undercoupled for this system. As much as 12 W can be obtained in a single direction, with the output power controlled by rotation of the intracavity half-wave plate. Below 4 W the laser operates in a single axial mode.

A schematic of the experimental apparatus is shown in Fig. 1. The master oscillator is mode matched into the slave cavity with a lens and is protected from the slave power with a Faraday isolator. Injection locking is accomplished by the Pound–Drever FM sideband technique.[4,15] A $LiNbO_3$ phase modulator imposes FM sidebands onto the injecting light, and a small portion of the output beam is sent to a homodyne receiver, which detects a dispersive-shaped error signal when the master and slave are coherent. The cavity length of the slave is then servo locked to hold the slave at the lock point using the two PZT-mounted mirrors, one with a large dynamic range and one with a high bandwidth. The servo is of the cascaded-integrator type, split into fast and slow loops, and provides a net gain of 56 dB at dc and a unity-gain bandwidth of ≈30 kHz. The fast loop is ac coupled to avoid dynamic range problems with the high-bandwidth PZT.

The full width of the locking range is given by[2]

$$\Delta f_{\text{lock}} = \eta \frac{T \times \text{FSR}}{\pi} \left(\frac{P_{\text{master}}}{P_{\text{slave}}} \right)^{1/2}, \qquad (1)$$

where T is the transmittance of the slave's output coupler, FSR is the slave's free spectral range, and η is an efficiency factor for the overlap of the lasers' spatial and polarization modes. We measured the locking

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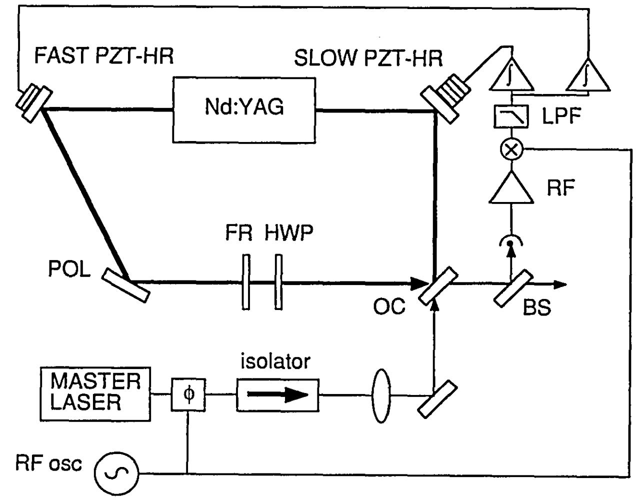

Fig. 1. Injection-locked Nd:YAG laser system. The half-wave plate (HWP), the Faraday rotator (FR), and the thin-film polarizer (POL) form an optical diode in the slave laser cavity. FM sidebands are placed on the light from the single-frequency, diode-laser-pumped master laser, and the slave laser cavity is held at the lock point with the rf homodyne receiver and servo loops to the PZT-mounted mirrors. HR's, high-reflector mirrors; OC, output coupler; BS, beam splitter; LPF, low-pass filter.

range by scanning the slave cavity length and measuring the width of the frequency discriminant from the maximum to minimum of the dispersive-shaped signal. Figure 2 shows the locking bandwidth as a function of root power ratio at a slave power of 4 W. The slope of the line is 13.8 MHz, which shows reasonable agreement with the calculated value of 16.8 MHz based on $\eta = 1$, and an effective output coupling of 23%, which is due to the tilting of the polarization of the slave's circulating field by the half-wave plate in its cavity. The discrepancy can be accounted for by imperfect spatial and polarization mode matching.

We achieved injection locking with slave powers of up to 10 W using the optical diode for unidirectional operation and fast-loop servo control, and powers of up to 5 W using the slow loop only. The total master oscillator power was typically 30–40 mW, with 80% of the power in the carrier. The injection-locking process could be observed with a scanning confocal interferometer (not shown). Both the master and slave frequencies were distinct when the servo loop was open, and all optical power was observed at the master laser's frequency in closed-loop operation.

We investigated the use of injection locking to enforce unidirectional operation of the slave laser. With the Faraday rotator removed from the cavity, the slave laser oscillated in both directions with roughly equal powers and in approximately 10 axial modes. The half-wave plate was retained to control the slave output power by changing the cavity polarization state. Under injection locking, the power in the injected direction was roughly doubled, while the opposite direction was completely suppressed, and as much as 13 W of injection-locked power (measured before the beam splitter) was produced by the slave. The total master power incident upon the slave could be as little as 30 mW, for a slave-to-master power ratio of 400:1.

To determine the phase fidelity of the injection-locked system, a portion of the master oscillator light was picked off before the isolator, frequency shifted with an acousto-optic modulator, and then heterodyned on a photodiode against the injection-locked slave. The rf noise spectrum can be converted into total phase noise spectral density $S_\phi(f)$ using the formula[16]

$$S_\phi(f) = \frac{2P_{\text{ssb}}(f)}{BP_c}\left(\frac{\text{radian}^2}{\text{hertz}}\right), \tag{2}$$

where $P_{\text{ssb}}(f)$ is the single sideband power density, P_c is the carrier power, and B is the resolution bandwidth.

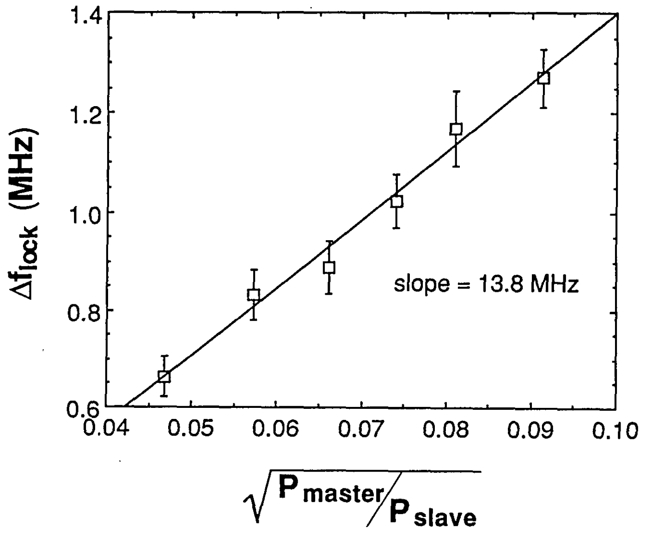

Fig. 2. Locking range versus the root power ratio. The slave laser power is 4 W.

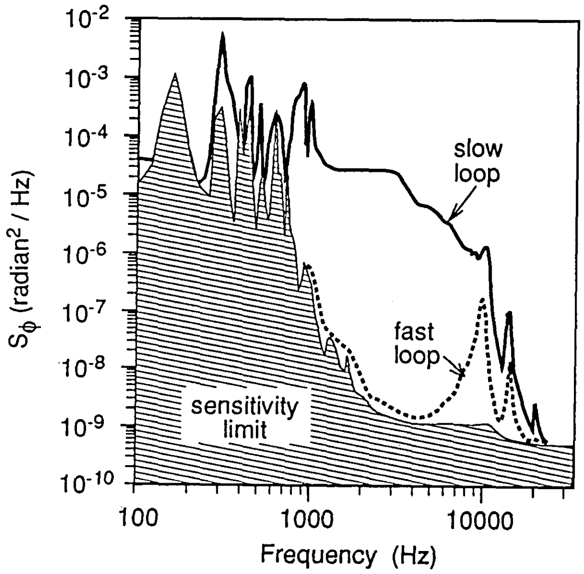

Fig. 3. Phase fidelity of the injection-locked system to the master oscillator phase for fast and slow servo-loop operation. The measurement of phase noise density $S_\phi(f)$ is limited at low frequencies by laboratory acoustics.

We emphasize that this all-optical measurement yields an upper bound for $S_\phi(f)$ (as limited by the sensitivity), whereas techniques relying on measures of the closed-loop error signal yield lower bounds. Figure 3 shows $S_\phi(f)$ (corrected for the spectrum analyzer equivalent-noise amplitude and bandwidth characteristics[17]) plotted for fast and slow servo-loop operation along with the sensitivity limit of the measurement (shaded region) as determined by sending a reference beam through the system and beating it against itself. At low frequencies the sensitivity is severely compromised by acoustic noise on the optical table, with significant contributions from the lamp-pumped slave's water cooling system.

The total rms phase noise is calculated from

$$\Delta\phi_{\mathrm{rms}}{}^2 = \int_{\mathrm{ssb}} \mathrm{d}f\, S_\phi(f), \tag{3}$$

where $S_\phi(f)$ is integrated over a single sideband frequency range. For slow-loop servo operation $S_\phi(f)$ may be integrated in the bandwidth shown in Fig. 3 to yield $\Delta\phi_{\mathrm{rms}} \approx 0.3$ rad of phase noise on the injection-locked slave compared with the phase of the master. For fast-loop operation, $\Delta\phi_{\mathrm{rms}}$ is dominated by the sensitivity limit, and no reliable result can be extracted. The integrated phase noise corresponds to an upper limit of less than 1 kHz of additional linewidth contribution. This linewidth, when convolved with the master's free-running linewidth, yields the width of the injection-locked output. For example, the linewidth of a slave laser locked to a master oscillator with a 10-kHz linewidth would be broadened to 10.05 kHz for Gaussian line shapes.

We have injection locked a Nd:YAG laser with a diode-laser-pumped Nd:YAG laser for a slave-to-master power ratio of 400:1. The 13-W slave output showed excellent frequency stability and little added phase noise. In the future we plan to optimize the output coupling for higher power, replace the FR-5 Faraday rotator with terbium gallium garnet (TGG) for more rotation and reduced insertion loss, investigate injection locking of standing-wave slave lasers, and measure the phase fidelity using an auxiliary Pound–Drever error signal system. We also plan to develop a multiwatt, all-diode-laser-pumped system using 60 W of laser-diode power to pump a Nd:YAG slab laser transversely in order to improve the efficiency and free-running performance of the slave oscillator.

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