Demonstration of a 1-W injection-locked continuous-wave titanium:sapphire laser

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We report on a 1-W injection-locked cw titanium:sapphire ring laser at 846 nm. Single-frequency operation requires only a few milliwatts of injected power. This relatively simple and inexpensive system can be used for watt-level single-frequency lasers across most of the titanium:sapphire gain region. A brief review of injection-locking theory is given, and conclusions based on this theory indicate ways to improve the performance of the system. © 2002 Optical Society of America

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1. Introduction

Single-frequency cw lasers are central to many experiments in spectroscopy, atomic physics, nonlinear optics, quantum optics, metrology, ranging, communications, and other fields. A number of tunable and fixed-frequency lasers are commercially available to cover the near-ultraviolet, visible, and near-infrared spectral regions. Dye lasers, Ti:sapphire lasers, optical parametric oscillators, Nd:YAG lasers, various gas lasers, diode lasers, and many others regularly find applications in these fields.

A few years ago, high-power single-frequency diode lasers began to compete with moderate-power Ti:sapphire lasers and dye lasers over selected wavelength ranges (see, for example, Refs. 1–5 and many others). These diode lasers were relatively inexpensive and could be frequency stabilized, either by injection locking or by an external cavity, making them ideal for certain classes of experiments. However, many of these high-power single-frequency diode lasers have become increasingly expensive and difficult to obtain at particular wavelengths.

In this paper we describe a moderate-power, cw, tunable, single-frequency Ti:sapphire laser, injection locked with a low-power diode laser. Injection locking a high-power laser with a low-power master laser reproduces the master laser at higher power with good fidelity.[6–10] Injection locking has been demonstrated in a wide range of cw laser systems, including Nd:YAG (for example, Refs. 11–13), argon ion,[14] He–Ne,[15] diode,[16] and dye lasers.[17] It has also been demonstrated for pulsed Ti:sapphire[18,19] and pulsed dye lasers.[20,21] However, to our knowledge it has apparently not been demonstrated in cw Ti:sapphire lasers.

The master laser determines the output wavelength and forces both single-frequency and unidirectional operation. It eliminates birefringent filters and optical diodes in more traditional Ti:sapphire lasers,[22–25] which can in principle translate into higher output power. The wavelength tunability of our system follows the tunability of the diode laser. Although no single diode laser covers the entire tuning range of Ti:sapphire, diodes are available at many wavelengths from 0.66 to 1.1 μm. Furthermore, many kinds of experiment use only a limited wavelength range—some use only several gigahertz of tuning. A Ti:sapphire laser injected with a low-power single-frequency diode laser may be well suited for those experiments. This system is a simple, low-cost method to realize watt-level single-frequency lasers with moderate tunability.

2. Injection Locking

A general theory of injection-locking cw lasers is presented in several publications (see, for example, Ref. 10). A brief sketch of that theory is presented here. We consider a single-frequency laser operating at a frequency ω_0 with an output power I_0. We assume a ring laser cavity geometry, although the discussion is somewhat general. A weak single-frequency beam with frequency ω_1 and power I_1 is incident on the high-power laser cavity's output coupler. The way

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the weak beam is amplified depends on its power and frequency.

Even though the high-power laser is producing maximum power at ω_0, there is still gain at ω_1. This is due to the fact that the high-power laser operates below threshold for the weak beam, and an oscillator below threshold acts like a regenerative amplifier. The regenerative gain for the electric field of a weak beam reflecting from the higher-power laser cavity can be written as

$$g(\omega_1) = \frac{{r_1}^2 - G(\omega_1)}{r_1[1 - G(\omega_1)]}, \tag{1}$$

where r_1 is the electric field reflection coefficient of the output coupler and $G(\omega_1)$ is the round-trip gain (including phase shift) in the cavity at ω_1.

The round-trip gain in the cavity can be written as

$$G(\omega_1) = r_m \exp(-\alpha_0 l_0) \exp(\alpha_m l_m) \times \exp[-i(\omega_0 - \omega_1)p/c], \tag{2}$$

where r_m is the product of the electric field reflection coefficients of all the cavity mirrors (except for the output coupler), $\exp(-\alpha_0 l_0)$ represents absorptive losses in the cavity, $\exp(\alpha_m l_m)$ represents gain in the cavity, p is the round-trip cavity path length, and c is the speed of light. Because the laser is already operating in a steady state at ω_0, the magnitude of $G(\omega_1)$ must be 1. The round-trip gain can then be written as

$$G(\omega_1) = \exp[-i(\omega_0 - \omega_1)p/c] = \cos[(\omega_0 - \omega_1)p/c] - i \sin[(\omega_0 - \omega_1)p/c]. \tag{3}$$

When $\omega_1 \approx \omega_0$, Eq. (1) can be approximated as

$$g(\omega_1) = \frac{\gamma_e}{i(\omega_0 - \omega_1)}, \tag{4}$$

where $\gamma_e = (1 - {r_1}^2)c/p$ is the cold-cavity decay rate.

The weak input beam is rapidly amplified as ω_1 approaches ω_0. When it begins to rival the output intensity I_0, the frequency of the laser beam changes from ω_0 to ω_1. With Eq. (4) it is possible to define the frequency range over which this occurs:

$$\Delta\omega = 2\gamma_e \sqrt{\frac{I_1}{I_0}}. \tag{5}$$

For a laser with a 1-m round-trip path length and a 3% output coupler and no other cavity losses, the cold-cavity decay rate is approximately $10^7\ \mathrm{s}^{-1}$. With 1-mW injection power and 1-W output power, the injection-locking range is 0.1 MHz.

In our application, the weak master laser is phase locked to the high-power laser cavity. This is partially because the cavity is mechanically stable and partly because our master laser's control bandwidth (~150 kHz) is greater than the cavity's (~1 kHz). The injection-locking range therefore determines the tolerances of the lock. On the other hand, for a given phase lock, and therefore a given residual frequency jitter between the master laser and the high-power laser cavity, it is possible to rearrange Eq. (5) to calculate the minimum power required to injection lock the high-power laser. Obviously, shorter laser cavities, larger cold-cavity decay rates, and higher injection powers all reduce the requirements of the phase lock.

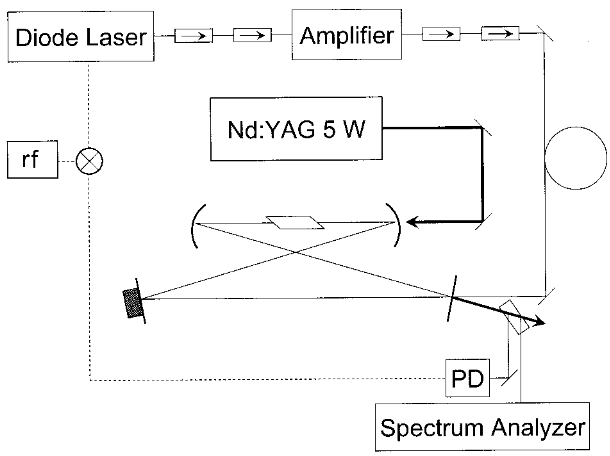

Fig. 1. Schematic diagram of the experimental layout. PD, photodiode; rf, radio-frequency generator.

3. Experimental Setup

Figure 1 shows a schematic diagram of our experiment. The master laser is an extended-cavity diode laser at 846 nm.[26] For these experiments, the master laser is amplified in a higher-power diode, although this is not necessary, as we discuss below. The diode lasers are optically isolated and coupled into a single-mode optical fiber.

A pair of lenses mode matches the collimated output from the fiber into the Ti:sapphire ring cavity. The coupling efficiency is typically 75% into the TEM_{00} Gaussian mode of the cavity, and higher-order modes are approximately 1% or less than the Gaussian mode. The Ti:sapphire cavity is a four-mirror folded (bow-tie) cavity around a Ti:sapphire crystal. The crystal is 10 mm long, 3 mm in diameter, Brewster cut, with a low-power single-pass absorption coefficient of 2.1 at 532 nm. It is mounted in a water-cooled brass housing. The cavity's flat output coupler reflectivity is 96.6%. The reflectivities of the other three mirrors are all >99.5%. The radius of curvature for the curved mirrors is 100 mm. The short distance between the two curved mirrors, including the path through the crystal, is 114 mm. The long distance between the two curved mirrors is 1020 mm. The angle of incidence on the curved mirrors is 10°. This geometry is chosen to compensate for the astigmatism introduced by the Brewster-cut crystal.[27] The cold-cavity finesse, measured without pumping the crystal, is 110.

Up to 5.5 W from the 532-nm pump laser is focused into the middle of the Ti:sapphire crystal. Not

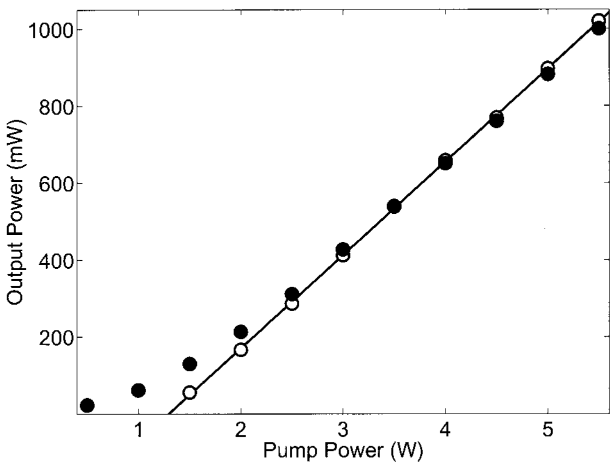

Fig. 2. Input–output data for the Ti:sapphire laser for injection-locked (●) and free-running (○) operation. The straight line shows the fitted threshold power and efficiency. The slope efficiency is 23%.

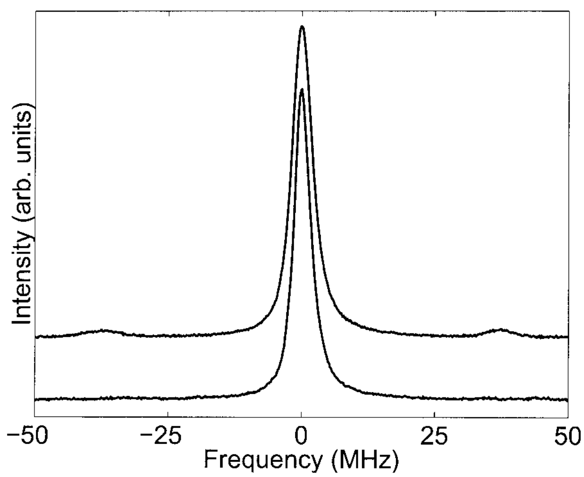

Fig. 3. Optical frequency spectrum of the laser. The top curve shows the spectrum of the injection laser. The bottom curve shows the spectrum of the amplified laser. The curves are offset vertically for clarity.

shown in Fig. 1 is a telescope in the green laser beam, with one lens mounted on a micrometer stage to optimize the focus of the green laser beam into the crystal.

The diode current in the master laser is modulated at 37.15 MHz. This produces the frequency sidebands necessary to lock the master laser to the Ti:sapphire cavity by use of the Pound–Drever–Hall technique.[28] The electronic feedback circuit is a two-stage integrator, with fast feedback to the master laser current and slow feedback to the master laser cavity length. One of the Ti:sapphire cavity mirrors is mounted on a piezoelectric crystal, allowing approximately 8 GHz of continuous frequency tuning. Note that this is much narrower than the 100-GHz single-mode tuning of the master laser. To achieve a particular wavelength from the Ti:sapphire laser, it is necessary first to set the approximate wavelength of the diode laser before the Ti:sapphire laser is injection locked. Fine wavelength tuning is achieved when we scan the Ti:sapphire cavity after engaging the lock. The optical signal used for the feedback circuit comes from a weak reflection from an uncoated quartz optical flat in the high-power output from the Ti:sapphire laser. This reflected beam is attenuated to prevent saturation in the feedback photodiode.

4. Injection-Locked Performance

Figure 2 shows a plot of the power out of the injection-locked laser as a function of pump power. It also shows the free-running laser output power, when the injection laser is blocked. The injection-locked and free-running lasers have essentially the same maximum power output and slope efficiency. However, the injection-locked laser has a significantly lower threshold power. Without injection locking, the laser does not oscillate until photons are spontaneously emitted into the cavity mode. However, the master laser puts photons into the cavity mode, and the laser oscillates at pump powers below the noninjected threshold.

Our measured slope efficiency (23%) matches calculations based on a theoretical model.[24] However, the threshold power (approximately 1.2 W) is considerably higher than the calculation (approximately 0.3 W). This implies that either the cavity waist or the pump laser waist (or both) are not as small as they should be. This is probably due to thermal lensing and to a mismatch between the confocal parameter for the pump laser beam and the crystal length.

When properly injected, the Ti:sapphire laser output is a single frequency. We monitor the optical frequency spectrum of the Ti:sapphire laser output with a scanning Fabry–Perot cavity (free spectral range of 2 GHz, finesse of 400). The optical frequency spectrum of the injection beam (i.e., the transmission through the scanning Fabry–Perot cavity) is shown in Fig. 3 (top curve). The bottom curve shows the optical frequency spectrum for the amplified beam. In both cases, the measured spectral width of the laser reflects the limit of resolution of the scanning Fabry–Perot cavity (5 MHz).

Although the scanning Fabry–Perot cavity does not have enough resolution to measure the spectral width of the laser, it can still give us an indication of the frequency content of the beam. For a given pump power, we can reduce the power in the master laser until other frequencies appear in the optical spectrum. As already mentioned, this minimum injection power depends on the round-trip cavity losses, the cavity size, the output power, and the frequency jitter of the master laser relative to the high-power laser cavity. For our laser with a 1134-mm round-trip cavity length, the minimum power for single-frequency operation, P_{min}, for different pump powers is shown in Table 1.

We also made a smaller amplifier cavity, with

Table 1. Minimum Injection Power for Single-Frequency Output P_{min} and Output Power P_{out} for Different Pump Powers[a]

Pump Power (W)	P_{min} (mW)	P_{out} (W)
2.0	3	0.22
3.0	6	0.49
4.0	12	0.74
5.0	15	1.00

[a]Approximately 75% of the input beam couples into the Gaussian TEM_{00} mode of the Ti:sapphire laser cavity.

50-mm radius of curvature mirrors and an overall cavity length of 360 mm. The smaller cavity has the same waist size and operates similarly to the longer-cavity laser in both output power and slope efficiency. However, the minimum power required to maintain single-frequency operation is lower by a factor of 2. Because the cold-cavity decay rate is inversely proportional to the cavity length, the minimum injection power should be smaller by a factor of 1134 mm/360 mm = 3.15 [see Eq. (5)]. However, when the cavity length changes, so does the slope in the error signal, which also changes the frequency jitter of the master laser relative to the high-power cavity.

5. Conclusions

We have demonstrated a single-frequency cw injection-locked Ti:sapphire laser at 846 nm, continuously tunable over an 8-GHz range, with an output power of 1 W. The wavelength range of the laser is determined by the wavelength range of the laser diode used to inject the Ti:sapphire laser. A broad range of laser diodes are available that cover much of the Ti:sapphire gain region. At those wavelengths, an injection-locked Ti:sapphire laser will produce output powers in the 1-W range at relatively low cost. A brief analysis of this laser based on injection-locking theory indicates that a tight lock of the injection laser to the high-power cavity, a shorter cavity length, and higher cold-cavity decay rates all result in a lower minimum injection power required to maintain single-frequency output from the laser.

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