

Grating-tuned semiconductor MOPA lasers for precision spectroscopy*

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ABSTRACT

A standard grating-tuned extended-cavity diode laser is used for injection seeding of a tapered semiconductor laser/amplifier. With sufficient injection power the output of the amplifier takes on the spectral characteristics of the master laser. We have constructed master-oscillator power-amplifier (MOPA) systems that operate near 657 nm, 675 nm, 795 nm, and 850 nm. Although the characteristics vary from system to system, we have demonstrated output powers of greater than 700 mW in a single spatial mode, linewidths less than 1 kHz, coarse tuning greater than 20 nm, and continuous single-frequency scanning greater than 150 GHz. We discuss the spectroscopic applications of these high power, highly coherent, tunable diode lasers as applied to Ca, Hg⁺, I₂, and two-photon transitions in Cs.

Keywords: diode lasers, tapered amplifiers, injection locking, high resolution spectroscopy, MOPA

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1. INTRODUCTION

Many scientific and technical applications of tunable diode lasers require higher powers than have been available from semiconductor laser sources. Recent advances in tapered gain structures have opened a new frontier in single-mode, single-frequency, tunable, semiconductor laser capabilities.¹ Tapered amplifiers (TA) can have broad gain-bandwidths, providing tremendous potential for tunable lasers with high power. They provide roughly one order of magnitude more power than previous single-spatial-mode devices. However, these tapered amplifiers/oscillators usually operate with many simultaneous longitudinal modes, which limits their usefulness for coherent and high-resolution applications. Using tapered amplifiers in extended cavities for wavelength control (such as optical feedback from diffraction gratings) allows good coarse tuning at high power,² but it is difficult to maintain true single-frequency operation. Extended-cavity TAs often exhibit instabilities which can cause jumps among a few nearby longitudinal modes or result in lasing on a few modes simultaneously.

One powerful solution to these problems is to separate the function of the high-power generation from that of the high-precision single-frequency tuning. A few modern examples of this type of system can be found in the literature and include: distributed Bragg reflector (DBR) laser diode plus tapered amplifier,³ solitary diode laser plus tapered amplifier,⁴ and grating-tuned extended-cavity diode laser (ECDL) plus tapered amplifier. In this paper we describe the applications of extended-cavity diode-laser plus master-oscillator power-amplifier (ECDL-MOPA) systems that are currently under way at NIST. The characteristics of these systems are discussed from a user's perspective, where our applications are primarily in high resolution spectroscopy. Other related systems and applications have been described by Zimmermann et al.⁵ and Goldberg and Burns.⁶

2. EXPERIMENT

By using several different experimental setups we gain some insight into the general characteristics of injection-locked MOPAs. A typical experimental setup is shown in Figure 1; it consists of a standard grating-tuned ECDL in the Littman-

Metcalf (grazing incidence) configuration, which acts as the master laser to inject the TA slave. The light from the master laser is sent through an optical isolator and spatially mode-matched to the beam emitted from the back facet of the TA. Since the front output aperture of the TA is very asymmetric ($\sim 1 \mu\text{m}$ by $100 \mu\text{m}$), a cylindrical lens, in addition to the standard spherical lens is needed to collimate the output beam. (In addition the output beam can have large astigmatism which may be compensated.)

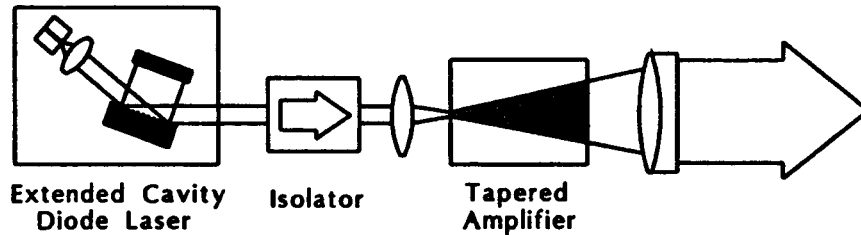


Figure 1. General ECDL-MOPA set-up. The ECDL output is sent through an isolator and then mode-matched to the beam emitted from the rear facet of the tapered amplifier. The collimating optics consist of one spherical and one cylindrical lens.

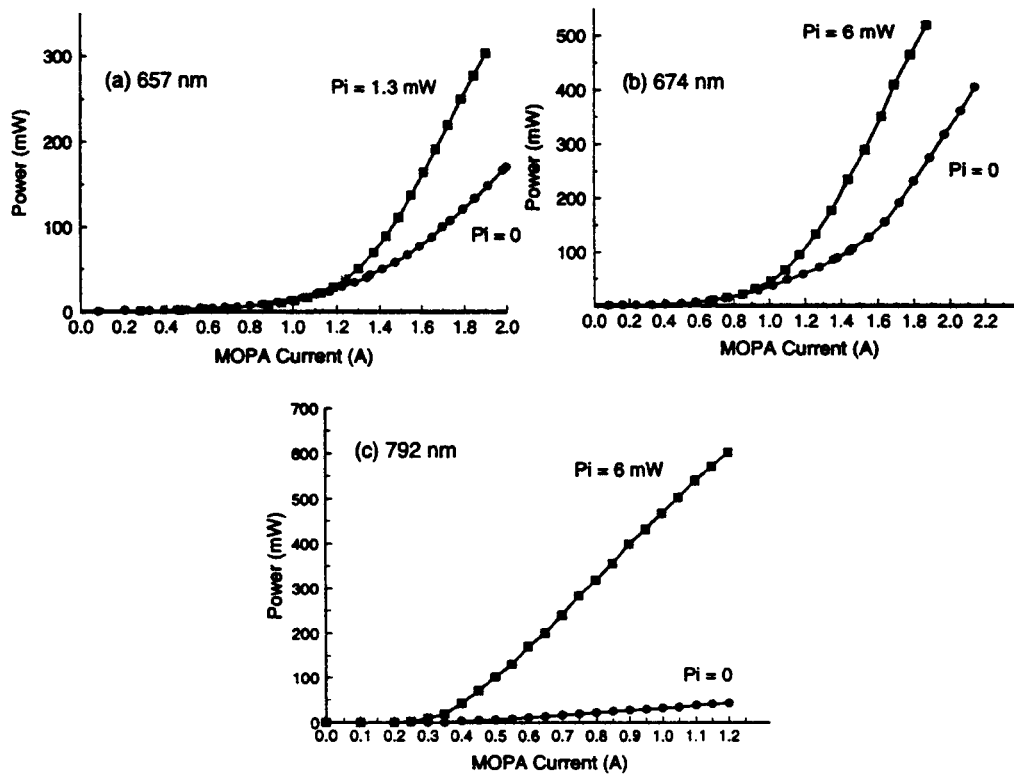


Figure 2. This figure shows the power versus injection current for three of our ECDL-MOPA systems (a) 657 nm, (b) 674 nm, and (c) 792 nm. Each graph is shown with and without optical injection power. Graph (a) and (b) show clearly a lasing threshold of the TA at high currents even without optical injection. The thresholds of all of the systems are lowered, and the slope efficiencies increase with increasing injection power. The optical injection power P_i used in these systems is (a) 1.3 mW, (b) 6 mW, and (c) 6 mW.

With optical injection from the master laser into the TA, the threshold of the TA decreases, resulting in more emitted power and the slope efficiency increases to as much as 0.7 W/A for the 674 nm and 792 nm systems (Figure 2). The MOPA output power quickly saturates with injection power from the master laser. Figure 3 shows the output power of the MOPA as a function of injected optical power. With good mode matching of the master into the TA, the output power saturates with about 2-3 mW of injected power. The different ECDL-MOPA systems vary slightly in this characteristic but they all saturate with less than ~5 mW of injection power due to the high gain and strongly asymmetric nature of the TA.

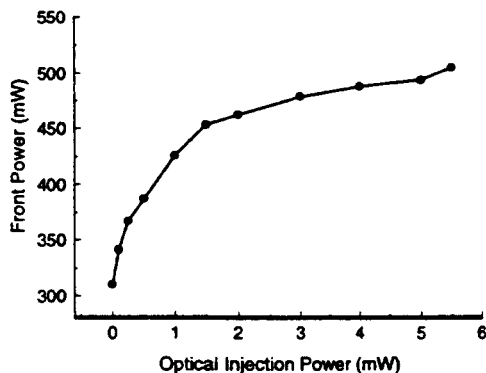


Figure 3. Dependence of output power with optical injection power for the 674 nm system. The output power saturates quickly with as little as 2-3 mW (solid circles).

The isolation required between the master and the slave depends somewhat on system parameters such as master laser power, mode matching, and the power emitted out of the back of the amplifier. We often use another isolator on the output of the amplifier to eliminate feedback into the high power amplifier. Although good quality isolators are needed between the master and the slave for relatively low injection powers (<5 mW), this requirement may be relaxed with higher injection powers. With optical injection from the master laser we have observed a decrease in temperature of the TA due to the large increase in optical power and high efficiency of the TA.

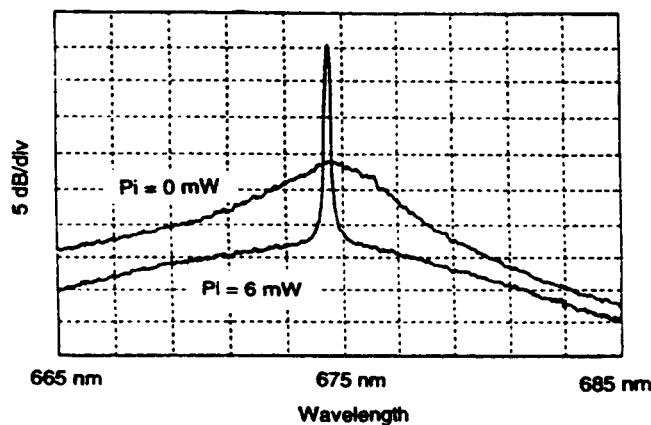


Figure 4. Optical spectrum analyzer trace showing the output of the ECDL-MOPA with and without 6 mW of injection power. The vertical scale is 5 dB/div and the horizontal scale is 2 nm/div. The instrument resolution is 0.1 nm.

The MOPA output power can be quite high (up to 700 mW), in a single spatial mode, while retaining the spectral properties of the master laser. Figure 4 shows an optical spectrum of the TA at 674 nm with and without injection. With injection the broad spectrum collapses into the single strong mode of the master laser. The single-frequency output takes power away from nearby regions and rises 25-30 dB above the background pedestal as measured with a 0.1 nm resolution bandwidth. As the master laser is tuned, the single-mode, coherent output of the MOPA follows exactly.

The residual facet reflectance of the TA can significantly affect the tuning characteristics of the MOPA and varies somewhat with each system. When injection current in the TA is brought above its own lasing threshold, the residual chip modes of the amplifier become important. Since these chip modes tune with slave current and temperature, it is straightforward to reach the desired wavelength and be centered on a "good" MOPA chip mode as well. When the TA shows no threshold behavior (as for the 792 nm system), these chip modes can be suppressed by the optical injection. For those TAs that can operate well above their threshold, the modulation is always present. These characteristics represent two different operating regimes for the MOPA: below the threshold of the TA the system acts like an optical amplifier, while above the threshold of the TA the system behaves like an injection locked laser. Using the 674 nm system near its own lasing threshold (~ 1.2 A) and with ~ 6 mW of injection power, we were able to scan continuously over 150 GHz with an output power of ~ 100 mW.⁷ As a demonstration of this capability, Figure 5 shows absorption of I_2 near 674 nm. Although there is some modulation in the power, the sweep remains single mode for greater than 150 GHz. Even when the chip modes are strong, the system can be scanned ~ 20 -30 GHz without mode jumps. This performance is comparable to that of many single-frequency tunable dye lasers. For most high resolution spectroscopy, this scan range is more than adequate, but some applications, such as molecular spectroscopy, may need longer single mode scanning ranges. In addition, active control of the injection current of the slave can be used to suppress the power modulation due to the residual facet reflectance.

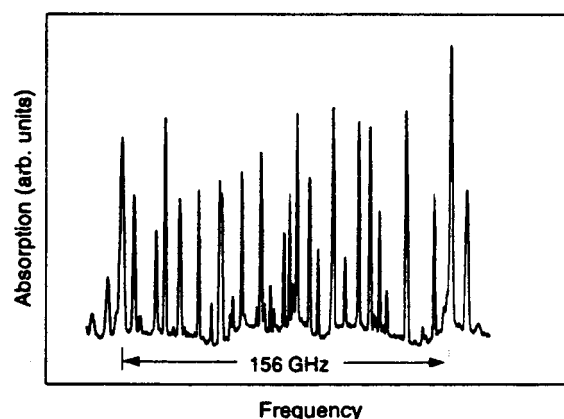


Figure 5. Absorption spectrum of I_2 near 674 nm taken with an ECDL-MOPA system (adapted from ref (7)). A specially designed long-scanning ECDL was used as the master oscillator to obtain this spectrum. The peak absorption was about 30% for a 5 cm long cell with a temperature of about 80°C .

3. APPLICATIONS

Applications of these ECDL-MOPAs provide "real-world" tests of the practicality and usefulness of these systems. The following examples from our laboratory are used to illustrate the performance characteristics of these systems.

The first system at 792 nm is used to generate 194 nm light for use in a Hg^+ frequency standard. In this experiment Hg^+ ions are held in electromagnetic traps and laser-cooled to temperatures on the order of 1 mK. Single-frequency radiation at 194 nm, required for laser-cooling the ions, is generated by sum-frequency mixing of radiation at 257 and 792 nm in an external build-up cavity. Radiation at 257 nm is obtained by frequency-doubling 515 nm radiation from an Ar^+ laser. Single-frequency radiation at 792 nm is generated from the ECDL-MOPA system. More than 700 mW of light at 792 nm is generated with optical injection between 3 mW and 20 mW from the master laser. Greater than 90% of the slave laser power can be mode-matched into the sum-frequency cavity, and negligible variation of the mode quality is observed as the slave laser's output power or frequency is varied. The ability to couple such a high percentage of light into the external ring cavity illustrates the excellent spatial mode these systems can provide. Two isolators (net isolation of about 60 dB) were used between the master and the slave laser, but no isolator was used on the output of the ECDL-MOPA. This high level of isolation was required to prevent instabilities of the ECDL-MOPA caused by a small amount of optical feedback from the

build-up cavity.

Using the 792 nm system an experiment to check for the relative coherence between the injection beam and the TA output was performed. We split off part of the master laser beam, frequency-shifted it in an acousto-optic modulator (AOM), and then heterodyned this beam with the output of the TA (Figure 6). The beat signal at the modulation frequency was then heterodyned with the signal driving the AOM, and the resulting DC signal (proportional to the relative optical phase between the master and the slave) was observed on an oscilloscope. In this way phase variations between the master and slave lasers were observed directly. Phase locking between the master and slave laser was observed. The phase difference never exceeded π rad for times of the order of minutes. Similar results have also been reported by Kikuchi et al.⁸

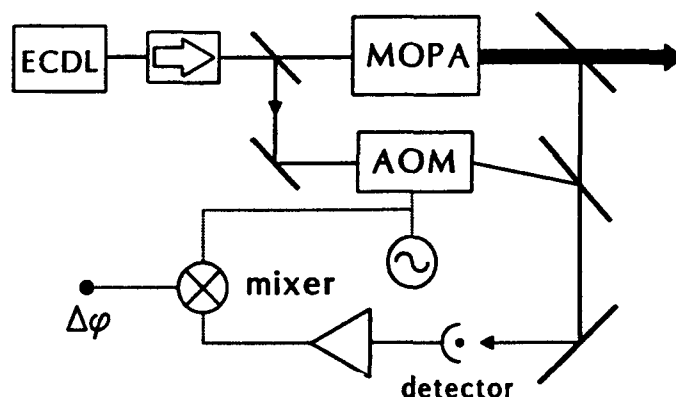


Figure 6. Schematic diagram of the method used to measure the relative phase coherence between the master laser and the slave.

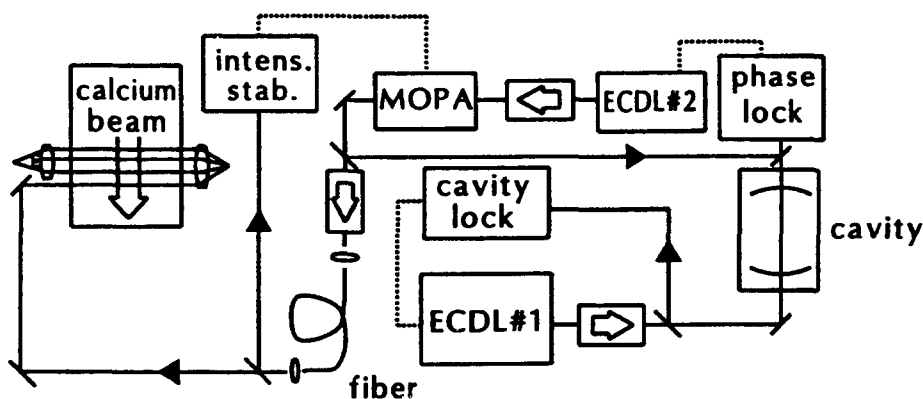


Figure 7. Calcium spectroscopy set-up. The solid lines represent the laser light and the dotted lines represent the servo loops.

A good demonstration of the narrow linewidths and high optical resolution that can be achieved with these ECDL-MOPAs is provided by the 657 nm system we use for Ca spectroscopy. The system is shown in Figure 7. ECDL1 is locked to an ultra-stable high finesse Fabry-Perot cavity (fringe width ~ 50 kHz FWHM) using the Pound-Drever-Hall technique. The beam transmitted through the cavity is used to phase-lock the 657 nm ECDL2-MOPA. This ECDL-MOPA output is then spatially filtered using an optical fiber which delivers the light to the Ca atomic beam system. In addition, the output of the fiber is intensity-stabilized by active feedback control to the MOPA current. This is done to compensate for the intensity fluctuations due to polarization changes and thermal drifts of the fiber system. The very high resolution achievable with this system is evident in Figure 8. This figure shows the optical Ramsey spectra of the 657 nm calcium line. The FWHM of

approximately 11.5 kHz, with a signal-to-noise ratio of about 30 in a 1 Hz bandwidth, corresponds to what would be a noise-limited frequency stability $\delta\nu/\nu$ of about $8 \times 10^{-13} \tau^{-1/2}$ (where τ is the averaging time). The resolution is limited here by the physical size of the windows on the atomic beam apparatus which limits the distance between interaction regions. Using the Ca lineshape and the Fabry-Perot cavity as frequency discriminators we measure the residual FM noise of the ECDL-MOPA to be ≤ 1 kHz dominated by the acoustical mode coupling between the laser table and the reference Fabry-Perot cavity (at about 1-2 Hz).

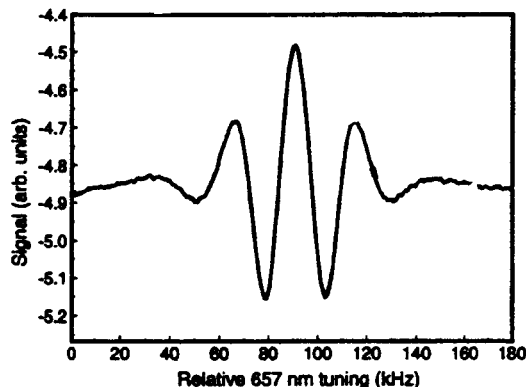


Figure 8. Ramsey fringe of calcium using the ECDL-MOPA setup shown in Figure 7. The FWHM of the fringe is ~11.5 kHz, at an optical frequency of 456 THz.

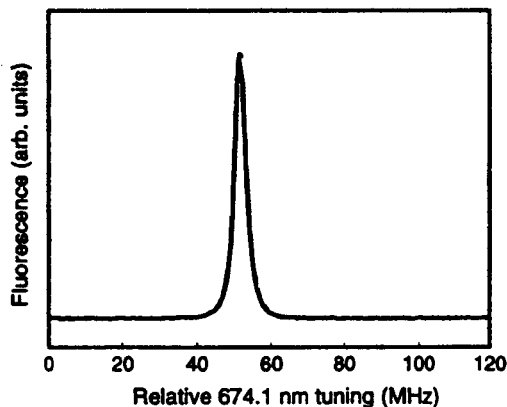


Figure 9. Fluorescence spectroscopy of the $6S_{1/2}, F=4 \rightarrow 12S_{1/2}, F=5$ two-photon transition in cesium (1 Hz bandwidth).

A third ECDL-MOPA system is used for high resolution and high sensitivity nonlinear spectroscopy in cesium atoms. The 674 nm system provides 500 mW of usable output power which is sufficient for two-photon spectroscopy on weak optical transitions without the need of a build-up cavity. The 674 nm light is scanned over the $6S_{1/2} \rightarrow 12S_{1/2}$ two-photon transition in a cesium vapor cell heated to $\sim 80^\circ\text{C}$; the transition is detected by the decay fluorescence from the $12S_{1/2}$ state to the $6P_{1/2}$ state at 541 nm (Figure 9). The nonlinear signal is quadratic in laser power, yet the signal-to-noise ratio is excellent (>1000 in a 1 Hz bandwidth). This demonstrates that the MOPA output has low AM noise.

4. LIMITATIONS

This new technology is exciting and appears to have a bright future. However, there are some limitations. One limitation is that the ECDL-MOPA systems are roughly one order of magnitude more costly to build than the standard low power counterparts. Although more expensive they are still an order of magnitude less expensive than many other high-power tunable laser systems such as dye and Ti:Al₂O₃ lasers. As with low power diode lasers, these ECDL-MOPAs are very susceptible to optical feedback and often require good quality isolators.

5. CONCLUSIONS

With these ECDL-MOPA lasers a new era in diode laser spectroscopy is opened. Power is increased by an order of magnitude or more over conventional diode lasers while the systems retain the good spectral characteristics and tunability of the lower power ECDL lasers. We have demonstrated the ability to use these lasers in several different experiments including the high resolution spectroscopy of Ca, Hg⁺, I₂, and Cs. Although the systems have slightly different characteristics, our experiments demonstrate that tunable, highly coherent, spatially single-mode, high power laser systems are achievable. These lasers will undoubtedly play an increasingly important role in the high resolution spectroscopy and nonlinear optics of the future.

6. ACKNOWLEDGMENTS

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