Hybrid optical and electronic laser locking using slow light due to spectral holes

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We report on a narrow linewidth laser diode system that is stabilized using both optical and electronic feedback to a spectral hole in cryogenic Tm:YAG. The large group delay of the spectral hole leads to a laser with very low phase noise. The laser has proved useful for quantum optics and sensing applications involving cryogenic rare-earth-ion dopants.

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I. INTRODUCTION

Rare-earth-ion dopants in cryogenic crystals provide unique optical capabilities due to their narrow homogeneous linewidths [1,2] while simultaneously having much larger, multigigahertz inhomogeneous linewidths. Spectral hole burning can be used to achieve fine control of the ensemble line shape by optically depleting the ground state. This has led to recent quantum computing [3] and quantum memory [4,5] demonstrations, as well as the optical detection of ultrasound [6,7].

For many applications, diode lasers are low-cost and convenient light sources. However, the large amount of phase noise generally exhibited by free-running diode lasers has limited their use in spectral hole burning, especially in continuous variable quantum optics applications. The phase noise in diode lasers is associated with the broad Schawlow-Townes linewidth exhibited by bare diode lasers, due to their short length and the low Q of their resonators. They are also limited by the extreme sensitivity of their output frequency to driving current [8]. Phase noise is generally dealt with by incorporating some form of electronic feedback on laser current as in the Pound-Drever-Hall (PDH) method [9], and/or by reinjecting some of the output light that has been directed through an external optical system that has a frequency-dependent loss mechanism as shown by [10,11].

PDH electronic stabilization using spectral holes in rare-earth-ion-doped crystals as frequency discriminators have previously been demonstrated in a number of investigations [12–15]. Spectral-hole-based filters have also been used to remove noise on lasers by absorbing unwanted sidebands [16]. Using the same ions in experiment as a frequency reference is advantageous as the laser is locked automatically to the transition frequency. However, at frequencies above several megahertz, significant noise reduction is difficult with electronic stabilization as the servo bandwidth is limited due to signal propagation delays.

Spectral holes are well suited as frequency discriminators, enabling kilometer-scale effective cavity lengths with low loss in a physically millimeter-scale crystal. Compared to optical cavities, spectral holes are insensitive to misalignment and much less sensitive to mechanical vibrations and temperature [15].

Our laser locking system contrasts from previous systems by combining both electronic and optical feedback referenced to a spectral hole. Whereas a hybrid locking scheme using atomic vapor has been demonstrated [17], this study investigates optical feedback locking using a spectral hole. Our system is similar to that described for feedback of light resonant with a Fabry-Perot cavity [10], although the cavity is replaced with a spectral hole. The result is a laser with low phase noise over short (100-μs) time scales, sufficient for subsequent applications such as investigating photon-echo-based quantum information processing [18] and the optical detection of ultrasound [7].

The strong frequency response of the spectral hole due to its steep dispersion also allows us to use a Littrow configured grating to stabilize our laser, allowing most of the output power to be used for further applications. This is in contrast to the previous demonstrations which have used the Litmann-Metcalf grating configuration [19] which, while providing greater frequency stability, results in much lower output powers.

II. THEORY

To describe our laser locking system, we consider the case where output light from the laser is directed through an external optical network and reinjected into the diode. If we assume that the external feedback is low, the intracavity laser field $E(t)$ obeys the equation of motion [20]

$$\dot{E}(t) = -i\delta E(t) + \tfrac{1}{2}(G-\gamma)(1-i\eta)E(t) + H(t) * E(t), \tag{1}$$

where $\delta = \omega - \omega_0$ is the relative frequency of the laser ω to the resonant frequency of the optical cavity ω_0 (with the spectral hole this is equivalent to its center frequency), G is the net rate of stimulated emission, γ is the cavity decay rate, and η is the linewidth enhancement factor which is proportional to the carrier-induced refractive index change.

The last term in Eq. (1) is due to the optical feedback, where $H(t)$ is the impulse response of the external optical network

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and $*$ represents convolution. To estimate the effect on the laser linewidth, we assume that the external optical network consists solely of a propagation delay and the spectral hole, given by

$$H(t) = \mathscr{F}^{-1}[\kappa \exp(i[-\omega\tau + \phi_0])h(\omega)_{\mathrm{h}}], \quad (2)$$

where τ is the round-trip time for the external cavity in the absence of the spectral hole, κ is the feedback coupling rate, and ϕ_0 is the phase shift on the light resonant with the spectral hole. The spectral hole itself can be modeled by the complex transfer function [12]

$$h(\omega)_{\mathrm{h}} = \exp\left[-\frac{\alpha L}{2}\left(1 - \frac{\Gamma}{\Gamma - i\delta}\right)\right], \quad (3)$$

where αL is the maximum absorption through the crystal and $\Gamma/2\pi$ is the spectral hole linewidth. Here we have ignored the reflection off the face of the anti-reflection-coated diode and collimation lens and treated the laser cavity as extending from the back facet of the laser diode to the diffraction grating. Furthermore, while we use a diffraction grating to coarsely tune the laser frequency, over the narrow spectral region we are interested in, the reflection of the grating can be taken to be flat in frequency.

For the case where the laser is tightly locked near the center of the hole ($\delta \approx 0$) the hole transfer function is constant in amplitude with a linear ramp in phase; hence, Eq. (2) can be approximated by

$$H(t) \approx \mathscr{F}^{-1}[\kappa_{\mathrm{eff}} \exp(i[-\omega\tau_{\mathrm{eff}} + \phi_{0\mathrm{eff}}])], \quad (4)$$

where $\kappa_{\mathrm{eff}} = \kappa\,\mathrm{Re}\,[(h(\omega \approx \omega_0)_{\mathrm{h}})]$, $\tau_{\mathrm{eff}} = \tau + \frac{\alpha L}{2\Gamma}$, and $\phi_{0\,\mathrm{eff}} = \omega_0\tau_{\mathrm{eff}} + \phi_0$ are the effective parameters including the effects of the spectral hole. Evaluating the convolution after making this approximation gives $H(t) * E(t) \approx \kappa_{\mathrm{eff}} E(t - \tau_{\mathrm{eff}})e^{i\phi_{0\mathrm{eff}}}$, which shows that the effect of our optical feedback network is simply to introduce a time delay. In particular this means that the results obtained by Agrawal [20], in which feedback is obtained from a mirror placed some distance from the laser, can be applied by replacing with the effective parameters for the light coupling constant κ_{eff}, round trip delay time τ_{eff}, and on resonance phase shift in the time domain $\phi_{0\,\mathrm{eff}}$. Hence, the effect of the time delay on the laser linewidth is shown by the expression [20] [their Eq. (28)]

$$\Delta f = \Delta f_0 \frac{1}{[1 + X\cos(\phi_{0\mathrm{eff}} + \phi_R)]^2}, \quad (5)$$

where $X = \kappa_{\mathrm{eff}}\tau_{\mathrm{eff}}\sqrt{1+\eta^2}$, $\phi_R = \tan^{-1}\eta$, Δf_0 is the linewidth of the bare diode, and Δf is the linewidth of the laser with optical feedback. For a large dispersion ($\tau_{\mathrm{eff}} \gg 1$) and appropriate feedback phase ($\phi_{0\mathrm{eff}} + \phi_R \approx 2\pi m$), a large reduction in laser linewidth is obtained. Apart from the reduction in linewidth, previous studies have also shown that the sensitivity of the laser to unwanted optical feedback is also reduced [10,11].

Using parameters relevant for our experiment of $\Gamma = 50$ kHz and $\alpha L = 0.5$, we calculate an effective time delay of $\tau_{\mathrm{eff}} = 5$ μs, which is equivalent to dispersion from a 1.5-km-long external cavity. Larger time delays could be obtained, for example in Pr^{3+} systems [5] where features with linewidths of tens of kilohertz have been prepared in samples with $\alpha L \approx 30$ corresponding to millisecond-scale effective delays.

III. EXPERIMENTAL SETUP AND RESULTS

The setup for an individual laser is shown in Fig. 1. We used an 80-mW single-mode laser diode (Eagleyard) driven using a home-built version of Libbrecht and Hall's current supply [8]. The laser was built using a diffraction grating (1800 lines/mm) in a Littrow configuration and is a modified version of the system given in [21]. We tune the laser using the grating angle, as well as tuning the temperature and current, to operate at 793 nm. The external cavity diode laser (ECDL) was placed within a sealed aluminum box to achieve environmental isolation. Initial measurements yielded a free-running linewidth of 8 MHz.

We used a 0.1% Tm:YAG crystal cryogenically cooled to 2.7 K with dimensions of $8 \times 4 \times 4$ mm^3. Light is propagated 4 mm along the $[1\,\bar{1}\,0]$ direction. The transition of interest is the $^3H_6 \rightarrow {}^3H_4$ with corresponding wavelength 793.3 nm [22]. The incident beam on the sample had a power of 400 μW and a diameter of 4 mm. The laser frequency is then kept at the center of the hole by using a PDH servo loop on the laser current [12,13]. To generate the error signal, a portion of the output beam is directed through an electro-optic phase modulator (EOM) to generate the frequency-modulated sidebands at 30 MHz. The modulation frequency was chosen to be high enough that the resulting phase sidebands would not interfere with the laser linewidth at the frequency band of interest when optical feedback is applied. The dithered beam is then directed through the sample, burning a spectral hole which acts as the frequency discriminator.

In Tm:YAG at zero magnetic field, the predominant hole-burning mechanism is optical pumping to the metastable (12-ms-lifetime) $^3F_4$ level. The spectral holes therefore decay with the same 12-ms lifetime without continuous optical

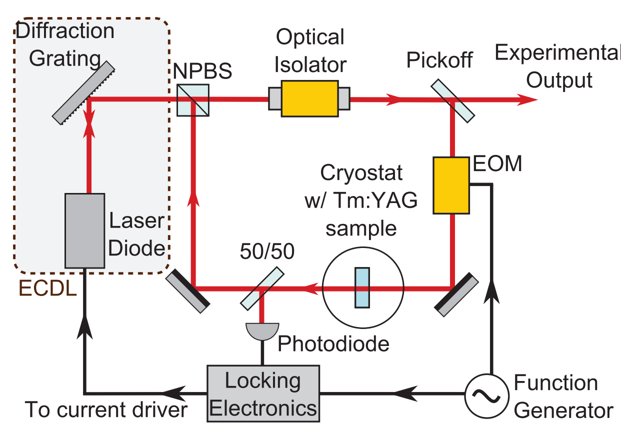

FIG. 1. (Color online) Laser locking setup. We use an external cavity diode laser (indicated by the shaded dotted box) which is then locked to a spectral hole reference using PDH locking and optical feedback. The pickoff has reflectivity of 1%. Since taking the data for this paper, we have reconfigured the system to inject the feedback light via the polarizing beam splitter at the output of the optical isolator. Compared to using a nonpolarizing beam splitter (NPBS), this approach wastes less laser power, allowing more light at the experimental output.

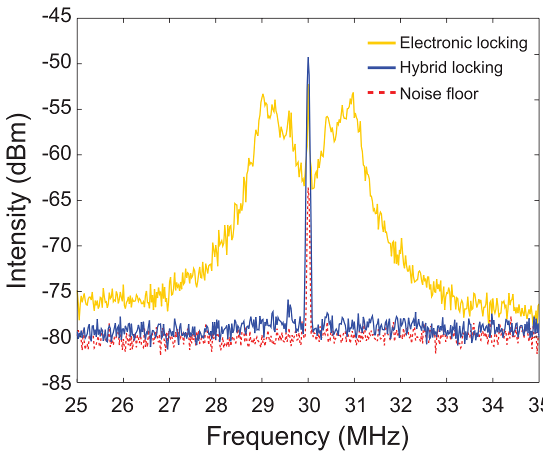

FIG. 2. (Color online) Spectrum of the signal on the locking detector which is modulated at 30 MHz. To obtain the locking signal, this is mixed down to dc. The curves indicate (i) optical feedback disabled (yellow/light curve), (ii) optical feedback enabled (blue/dark curve), and (iii) the detector noise floor (dotted red line), which is measured with the detector blocked. The resolution bandwidth was 30 kHz.

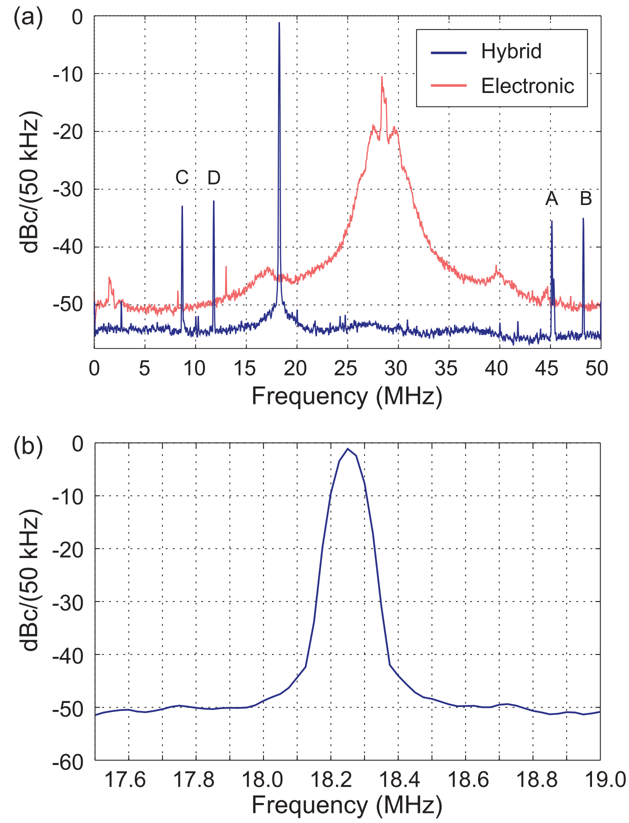

FIG. 3. (Color online) (a) The power spectrum of the beat note between two independent lasers, either with electronic feedback only (red/light curve) or with electronic and optical feedback applied (blue/dark curve). The power spectra were calculated from 8 ms of recorded beat note data using FFTs. The resolution bandwidth is 50 kHz. Peaks A and B correspond to the PDH locking sidebands at 27 and 30 MHz injected back into the diode. The left-hand peaks (C and D) are aliases of the negative-frequency signals. (b) Main peak of the power spectrum when electronic and optical feedback were applied.

pumping from the laser. The transient nature of the spectral holes means that they are not good long-term references. The error signal rolls off at low frequencies as well as high frequencies. Because of this, the PDH servo gain is rolled off at low ($\sim$1 Hz) frequencies as well as at high frequencies ($>$1 MHz). This ensures that the laser servo will not be driven to its rails by integratorlike transfer functions acting on small offsets.

We monitor changes to the laser linewidth using the spectrum of the error signal as shown in Fig. 2. As can be seen, the electronic locking reduces noise within about 1 MHz of the carrier but at higher frequencies it is ineffective due to the finite bandwidth of the servo loop. To demonstrate the effects of optical feedback, about 150 μW of the light that was transmitted through the crystal is directed back to the laser. A dramatic reduction in the high-frequency components of the error signal can be seen in Fig. 2 when optical locking is present. The resulting noise spectrum with optical locking is close to being limited by the dark noise of the detector.

To better characterize the noise on the laser, we constructed a second laser and interfered it with the first to produce a beat signal. The second laser was as independent as practical, having a PDH dither frequency of 27 MHz. The two lasers shared the same Tm:YAG crystal but the two beams in the crystal were well separated. The beat signal was amplified and frequency down-converted by mixing with a local oscillator at a frequency close to the frequency difference between the lasers. The signal was sampled at 1×10^8 samples/s for 8.1 ms, linear drift corrected, and the fast Fourier transform (FFT) calculated. The resulting power spectrum was then convolved with a Gaussian with FWHM of 50 kHz and the result is shown in Fig. 3.

One can see a dramatic reduction of the phase noise caused by the optical feedback (blue/dark curve). At 100 kHz from the carrier, the power spectral density was -89 dBc/Hz, and 2 MHz away from the carrier, the beat signal was at the electronic noise floor (-101 dBc/Hz) of the measurement. The peaks around 45 and 48 MHz (marked A and B in Fig. 3) are 27 and 30 MHz from the beat frequency, respectively. These are due to the fact that a portion of the phase modulation sidebands used for locking are injected back into the laser diode. The two other peaks marked C and D are also due to the PDH modulation, in this case being aliases of the negative-frequency sidebands.

Comparing the reduction linewidth to what can be expected theoretically is difficult because uncertainty in how well the feedback light is coupled to the laser makes it hard to obtain an independent value for κ_{eff}. However, by assuming 10% mode matching, we arrive at $\kappa_{\mathrm{eff}} = 7 \times 10^7$ s^{-1}. Using Eq. (5) with a τ_{eff} of 5 μs and assuming that the optical loop containing the spectral hole is resonant, i.e., $\phi_{0\,\mathrm{eff}} + \phi_R = 2m\pi$, gives a theoretical linewidth reduction factor of 1.2×10^6 over the plain Littrow laser. Note that we have ignored η in this calculation as it is on the order of unity [23] and hence $\tau_{\mathrm{eff}}\kappa_{\mathrm{eff}} \gg \sqrt{1+\eta^2}$. This very large expected reduction is consistent with our observations which show a phase noise decrease of at least 35 dB, limited by noise in the measurement.

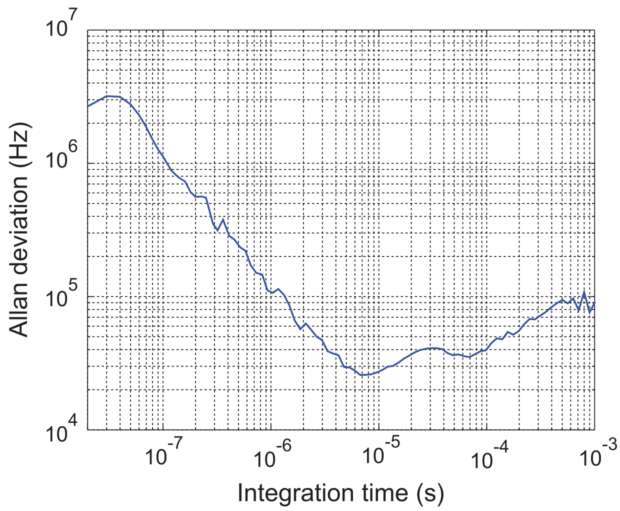

FIG. 4. (Color online) Allan deviation of beat measurements of the two independent and identically locked lasers with both electronic and optical feedback. The deviation has a minimum on the order of tens of kilohertz at the tens of microseconds time scale.

While the reduction factor indicates a large improvement to the fundamental linewidth, the laser is still sensitive to environmental factors such as the movement of optical components. Currently no effort was made to lock the phase of the large external cavity which contributes to the frequency drifts at longer time scales. For most situations where laser frequency is stabilized using optical feedback, the phase of the feedback arm must be controlled [10]. However, because our spectral holes are transient, they, and in turn the laser frequency, can follow the slow movements of the internal cavity. This means that the short-term noise properties of the laser were favorable; however, there was significant drift (on the order of 100 kHz/s) and occasional frequency jumps of tens of MHz, corresponding to the free spectral range of the optical feedback loop.

To further characterize the laser linewidth with integration time, the Allan deviation [24] was calculated from the beat signal between the two lasers. A 30-MHz-wide brick wall filter, centered on ±18.25 MHz, was first applied using FFTs to the digitized beat signal. The analytic signal, whose argument gives the instantaneous signal phase, was then calculated. The signal phase was unwrapped to obtain a continuous function of time. The Allan deviation, shown in Fig. 4, was calculated in the standard way [24], by using the difference in phase between two time points divided by the time separation as the average frequency for that time interval, analogous to the measurement that a frequency counter would make. The minimum deviation is on the order of tens of kilohertz around time scales of tens of microseconds.

One of the lasers described here was used for experiments on the optical detection of ultrasound [7] where the very low amounts of phase noise at ultrasonic ($\approx$1 MHz) frequencies were useful. It was also used for experimental demonstrations of rephased amplified spontaneous emission (RASE) [18], which relied on the ability of the laser to stay phase coherent with the Tm^{3+} ions within their 26-μs coherence time.

IV. CONCLUSION

In conclusion, we have demonstrated the use of optical feedback in conjunction with PDH electronic locking in stabilizing a laser frequency to a spectral hole in Tm:YAG. Optical locking was simple to implement and, apart from making the optical spot size on the crystal as large as possible to reduce power broadening, no matching of the optical mode to the rare-earth ions was needed. As the same crystal could be used for locking and experiments, the laser can be locked directly to the transition required. While there was significant drift at long time scales, the short-term noise properties were favorable and these deficiencies did not affect our subsequent applications of the laser in investigating photon-echo-based quantum information processing [18] and the optical detection of ultrasound [7]. Furthermore, due to the low phase noise, only a small-bandwidth servo would be needed to stabilize the external cavity should longer-term frequency stability be required.

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