Low Noise High Power Ultra-Stable Diode Pumped Er-Yb Phosphate Glass Laser

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ABSTRACT

We are developing a low noise high power ultra-stable diode pumped Er-Yb co-doped phosphate glass laser. Erbium doped phosphate glass permits high co-doping with ytterbium ions that strongly absorb at 976 nm and efficiently transfer their energy to the active erbium material. This drastically decreases the absorption length at the 976 nm pump wavelength and thus the overall size of the laser. Aside from the advantage for packaging a short cavity length results in a large longitudinal mode-spacing (>40 GHz), which allows for single longitudinal mode operation in the 1530-1565 nm C-band for telecommunication by inserting a tunable low-finesse etalon in the laser cavity. In addition, due to the energy transfer between the co-dopant and the active material, the laser shows a strongly reduced sensitivity to fluctuations in pump power. The strong peak in the RIN spectrum at the relaxation oscillation frequency (0.1-1 MHz) due to cavity-loss perturbations can be drastically reduced with a non-linear absorbing material inside the laser cavity. Using this approach for an optimized laser cavity design we have achieved –160 dB/Hz RIN at 1 MHz for 35 mW output. Above 100 MHz the RIN becomes shot noise limited (-168 dB/Hz @ 20mA photocurrent). The laser has excellent long-term frequency stability when locked to our wavelength locker (<250 kHz). Furthermore, the laser has been shown to have a narrow intrinsic linewidth (~10 Hz) that we are working towards by means of intra-cavity phase modulation.

Keywords: diode pumped solid-state lasers, high power, low noise, ultra stable, narrow linewidth, RIN suppression.

1. INTRODUCTION

The performance of most analog photonic systems is strongly affected by the intensity noise and power of the lasers involved. For coherent applications the laser linewidth is of the utmost importance. Laser noise is often described in terms of relative intensity noise (RIN), which is defined as the ratio of the mean-square optical intensity noise at a specific frequency in a 1 Hz bandwidth to the square of the optical power. In most solid-state lasers, fiber lasers, and semiconductor lasers a strong enhancement in RIN is observed near the relaxation oscillation frequency. Relaxation oscillations are triggered by fluctuations in pump rate or cavity-loss. They are particularly strong in lasers for which the recovery time of the population inversion is much longer than the cavity photon lifetime[1]; this includes most solid-state lasers, fiber lasers, and semiconductor lasers. Solid-state lasers and fiber lasers have relaxation oscillation frequencies that are typically below 1 MHz, while for semiconductor lasers the relaxation oscillation frequency is usually above 1 GHz. Solid-state lasers and fiber lasers have intrinsic line-widths that are orders of magnitude smaller than those of typical semi-conductor lasers. E.g. Spiegelberg et al. report a 2 kHz linewidths for a 100mW single frequency Er-Yb co-doped fiber laser[2]. Compared to fiber lasers solid-state lasers can have very short cavity making them less succeptible cavity length changes that lead to mode hopping. Because of these considerations diode pumped solid-state lasers are well suited for analog photonic systems providing high powers can be reached and RIN can be suppressed.

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At Princeton Optronics we are developing a low noise high power narrow linewidth diode pumped Er-Yb co-doped phosphate glass laser. Diode pumped Er-Yb co-doped glass lasers have been reported to reach 230 mW single longitudinal mode TEM_{00} power without observing any rollover in power[3]. Co-doping erbium glass with ytterbium at high doping levels strongly reduces the 976 nm absorption length of the gain medium. The absorbed energy is efficiently transferred from Yb^{3+} to Er^{3+} ions in which the laser action takes place. The resonant energy transfer process between the co-dopant and the active material acts as low pass filter; this leads to a strongly reduced sensitivity to fluctuations in pump rate, especially at frequencies above 100 kHz. Therefore actively suppressing RIN in this type of laser by providing a feedback signal to the laser diode drive current is limited to low pump rates[4].

The RIN spectrum at higher frequencies is dominated by cavity-loss modulations. It has been reported in the literature that spiking in pulsed lasers can be effectively suppressed if an intensity-dependent loss is present in the laser cavity[5]. A major breakthrough has been achieved at Princeton Optronics by including a non-linear absorbing material in the laser cavity to passively suppress RIN of Er-Yb co-doped glass lasers under continuous wave (CW) operation. By selecting a material that has a sufficiently high non-linear absorption coefficient and a very small linear absorption coefficient the peak in the RIN spectrum at the relaxation oscillation frequency can be eliminated without a significant decrease in laser power. In this paper we report a 55 dB reduction in RIN at the relaxation oscillation frequency. In addition we found a strong dependence of RIN on intra-cavity power density. With a laser cavity design optimized for low RIN we achieved –160 dB/Hz at 1 MHz for 35 mW laser output.

2. LASER DESIGN

The basic cavity design of the Princeton Optronics low noise laser is shown schematically in Figure 1. An aspheric compound lens collimates the output of a 976 nm laser diode and directs it, through a mirror with a dielectric coating that is highly reflective for the C-band and highly transmissive for the pump wavelength, onto the laser gain medium where a circular waist is formed. A tunable low finesse etalon ensures single longitudinal mode operation. Single transverse mode operation is achieved by carefully matching the spatial profile of the pump to the laser cavity mode. A single polarization mode is selected by the presence of Brewster surfaces in the cavity. A mirror with a partially reflective dielectric C-band coating couples 1550 nm light out of the cavity. One of the mirrors is attached to a piezo-electric actuator providing a mechanism for fine-tuning of the lasing wavelength. The transmitted TEM_{00} output is tunable across the C-band and is coupled into a polarization maintaining fiber with 95% coupling efficiency.

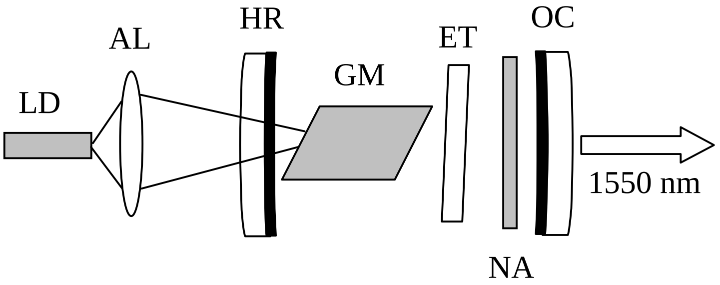

Figure 1: Schematic layout of the Princeton Optronics low noise laser. An aspheric lens (AL) focuses the output of a 976 nm laser diode (LD) through a 1550 nm high reflector (HR) onto the gain medium (GM). A tunable low finesse intra-cavity etalon (ET) selects a single longitudinal mode. An intra-cavity non-linear absorber (NA) reduces RIN. A mirror with a partially reflective dielectric coating (OC) couples 1550 nm light out of the laser cavity.

The laser gain medium is an erbium ytterbium co-doped phosphate glass (Kigre QX:Er). Fig. 2 shows a simplified energy level diagram of the laser gain medium. The 976 nm pump is strongly absorbed by Yb^{3+}ions in the $^4F_{7/2}$ ground state. Direct absorption of pump light by Er^{3+} ions in the $^4I_{15/2}$ ground state is much weaker due to the much lower doping of erbium ions and can be ignored. Energy is resonantly transferred from excited state Yb^{3+} ions to ground state Er^{3+} ions resulting in ground state Yb^{3+} ions and Er^{3+} ions in the excited $^4I_{11/2}$ state. The excited Er^{3+} ions immediately relax from the $^4I_{11/2}$ level to the $^4I_{13/2}$ upper laser level in a fast multi-photon process. Since the $^4I_{11/2}$ Er^{3+} level is essentially empty at any given time the back transfer process from erbium to ytterbium ions van be ignored. The energy transfer efficiency between Yb^{3+} and Er^{3+} ions is determined by the forward transfer rate and the spontaneous decay rate of the excited Yb^{3+} ions and is greater than 90%.

The laser gain medium is considered a quasi three-level system since the lower lasing levels are near the ground level, which leads to re-absorption of stimulated photons. The cross sections for absorption and stimulated emission in the active Er^{3+} material are spectrally broad and have their peak around 1535 nm. At this wavelength at least 50% population inversion is needed for gain. At longer wavelengths the cross-sections are smaller but the cross section for emission is bigger than the cross section for absorption. This means less than 50% population inversion is needed to obtain gain, but also that the maximum gain at long wavelengths is lower.

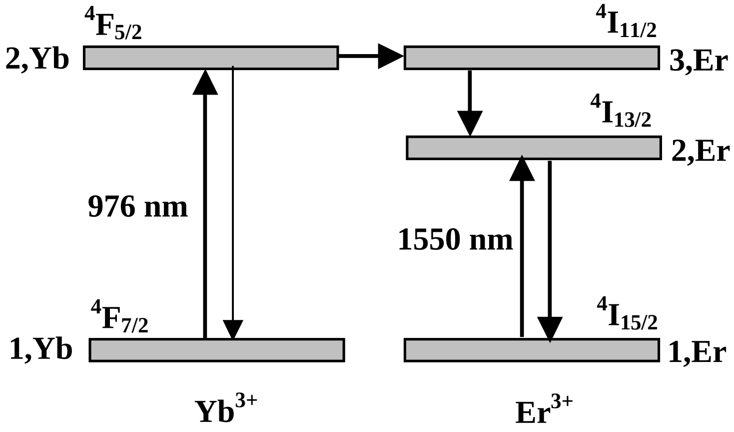

Figure 2: A simplified energy level diagram of the erbium ytterbium co-doped phosphate glass. The 976 nm pump excites Yb^{3+} ions from the $^4F_{7/2}$ ground level (1,Yb) to the $^4F_{5/2}$ level (2,Yb). Energy is efficiently transferred to $^4I_{11/2}$ level Er^{3+} ions (3,Er) that quickly decay to the upper $^4I_{13/2}$ lasing level (2,Er). The Er^{3+} $^4I_{15/2}$ ground level ions form the lower lasing level (1,Er).

Absorption of the 976 nm pump light in the gain medium leads to the formation of a thermally induced lens. The effective lens is positive and helps stabilize the laser cavity. Its focal length depends on the Yb^{3+} doping, the pump power, the pump beam diameter, and the pump beam divergence. The thermal lens has to be taken into account when designing the laser cavity layout. The optimum pump beam parameters have to be carefully determined as the laser glass is susceptible to thermal stress induced laser damage. Bench-top experiments have shown that over 500 mW single transverse mode power can be achieved without damaging the laser glass.

Due to strong longitudinal mode-competition a low finesse intra-cavity etalon is sufficient to select a single longitudinal mode. This etalon can be tuned to select a particular longitudinal mode within the C-band. The lasing mode can be fine tuned by a piezo actuator moving one of the mirrors of the cavity. Fine-tuning exceeds the longitudinal mode spacing so that any wavelength in the C-band can be achieved. Fig. 3 shows the excellent side mode suppression ratio of better than 70 dB that is obtained.

We determined the linewidth of the free running single mode laser using a self-heterodyne technique to be ~10 kHz. The intrinsic linewidth of our laser is much narrower. Testing of our laser at the National Institute for Standards and Technology (NIST) in Boulder, Colorado, revealed that the intrinsic linewidth of our laser is ~10 Hz, and that a 300 kHz loop bandwidth is required to achieve this linewidth.

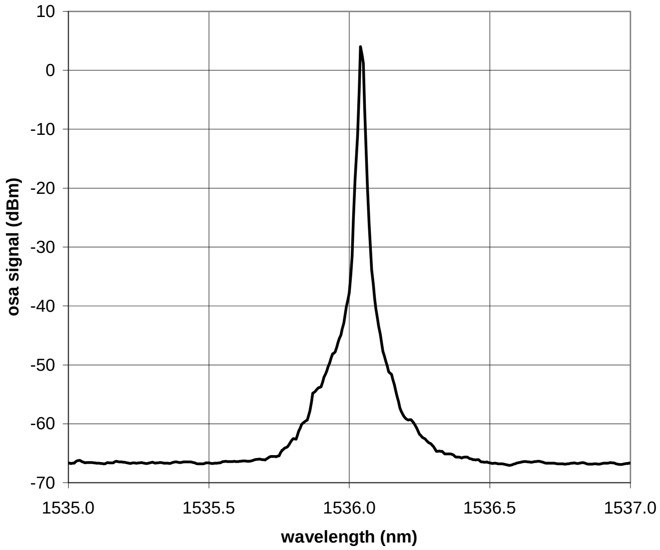

Figure 3: OSA spectrum of the Princeton Optronics low noise laser showing 70 dB side mode suppression ratio.

3. NOISE REDUCTION

To reduce RIN a non-linear absorbing material is inserted into the cavity. As illustrated in Fig. 4 we observed a ~55 dB reduction in RIN at the relaxation oscillation frequency in a low power erbium ytterbium co-doped phosphate glass laser by inserting a non-linear absorber.

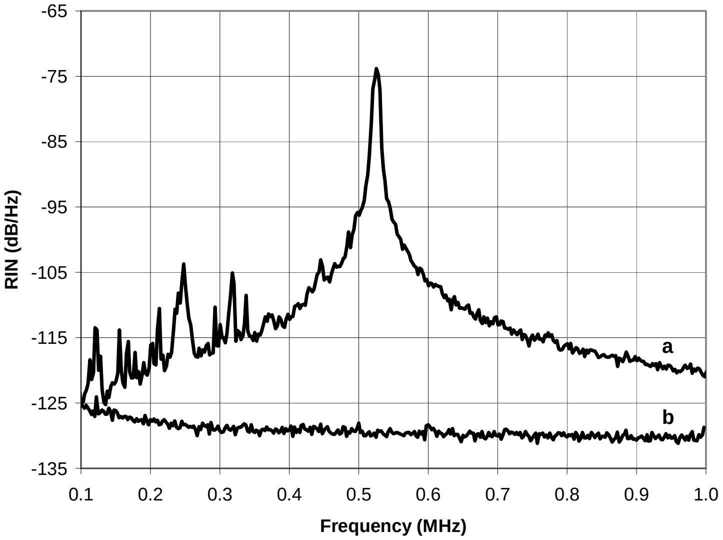

Figure 4: Observed RIN spectra of a low power erbium ytterbium co-doped phosphate glass laser without (a) and with (b) a non-linear absorber in the cavity

The reduction in noise can be understood by a rate equation analysis of the erbium ytterbium co-doped phosphate glass laser system. The dynamics of this laser can be described by the following set of rate equations[6]:

$$dN_{2,Yb}/dt = \sigma_{a,Yb}\, N_{1,Yb}\, F_P - K\, N_{2,Yb}\, N_{1,Er} - N_{2,Yb}/\tau_{Yb}\,, \qquad (1)$$

$$dN_{2,Er}/dt = (\sigma_{a,Er}\, N_{1,Er} - \sigma_{e,Er}\, N_{2,Er})\, F_L + K\, N_{2,Yb}\, N_{1,Er} - N_{2,Er}/\tau_{Er}\,, \qquad (2)$$

$$dn/dt = -\int_{V_a} (\sigma_{a,Er}\, N_{1,Er} - \sigma_{e,Er}\, N_{2,Er})\, F_L\, d\mathbf{r} - n/\tau_c\,, \qquad (3)$$

where F_P and F_L are the pump photon flux and laser flux respectively, K is the energy transfer coefficient from Yb^{3+} to Er^{3+}, $\sigma_{a,Yb}$, $\sigma_{e,Yb}$, are the Yb^{3+} cross sections for absorption and emission at the pump wavelength, $\sigma_{a,Er}$, $\sigma_{e,Er}$, are the Er^{3+} cross sections for absorption and emission at the lasing wavelength, $N_{i,Yb}$ and $N_{i,Er}$ are population densities of the i,Yb^{3+} and i,Er^{3+} levels (i=1,2,3), τ_{Yb} and τ_{Er} are the radiative lifetimes of the upper Yb^{3+} and Er^{3+} levels respectively, n is the cavity photon number, and τ_{cav} is cavity photon lifetime. The integral is taken over the mode volume V_a in the active material. The cavity photon lifetime is defined as $\tau_c = L_o/c\gamma$, where c is the speed of light in vacuum, L_o is the optical length of the laser cavity, and γ is single pass total loss. The set of coupled equations (1-3) is numerically solved for continuous wave (CW) operation by setting the left hand side of the equations to zero. The loss parameter γ is the only free parameter and can be adjusted to fit the observations. An example is given in Figure 5. It shows the observed power of a Princeton Optronics tunable laser pumped by a 380 mW laser diode as a function of wavelength as well as the tuning curve calculated for $\gamma = 0.5\%$.

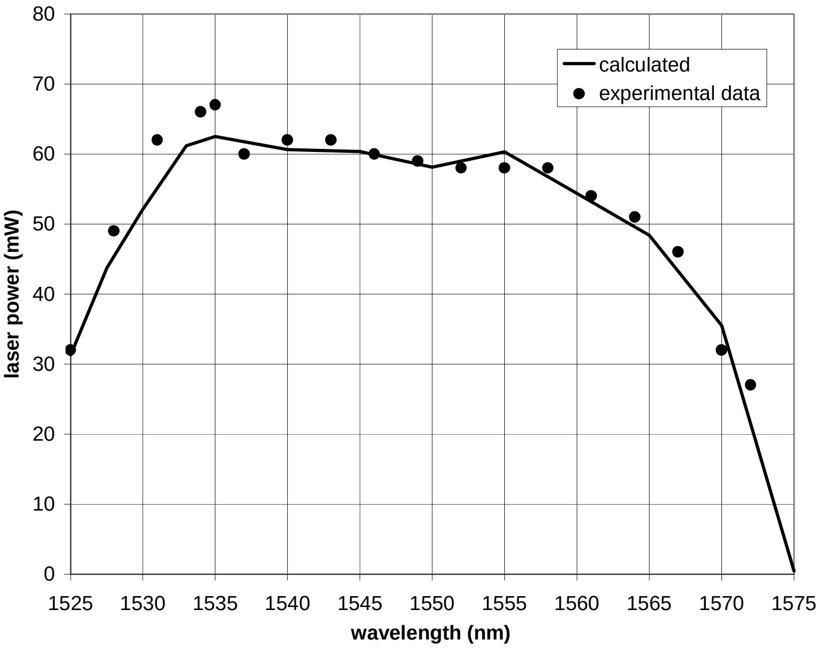

Figure 5: Observed single mode laser power from a Princeton Optronics tunable laser as a function of lasing wavelength (solid circles) and calculated tuning curve for $\gamma = 0.5\%$.

Small perturbations in cavity-loss or pumping rate will trigger relaxation oscillations that result in laser intensity noise. Transfer functions for cavity-loss perturbations and pump-rate fluctuations can be calculated numerically from the set of equations given above by applying a small sinusoidal perturbation in cavity-loss and pump rate respectively after steady-state conditions have been reached and inspecting the phase and the magnitude of the response of the laser system to these perturbation in terms of fluctuations in laser output power. Inserting a non-linear absorber into the laser cavity results in a non-linear loss term in the photon rate equation, Eq. (3), through the cavity photon lifetime τ_c. A sufficiently large intensity-dependent photon decay rate can result in critically damped relaxation oscillation. For typical solid-state lasers the non-linear loss required for critical damping is only 0.1% of the total loss in the laser cavity[5]. This is particularly important in a low gain medium like erbium-ytterbium doped glass, where small losses will result in significant reductions in laser power.

Figure 6 shows that, without a non-linear absorber in the cavity, both the transfer function for cavity-loss perturbations (trace a) and the transfer function for pump rate fluctuations (trace c) display a strong peak around the relaxation oscillation frequency, which is typically near 1 MHz for this laser. Adding a non-linear loss term to the photon rate equation eliminates both the peak in the transfer function for cavity-loss fluctuations (trace b) as well as the peak in the transfer function for pump-rate fluctuations (trace d). The decrease of the pump-rate transfer function with frequency reflects the low-pass filtering attributed to the energy transfer between Yb^{3+} and Er^{3+} ions. As a result the erbium-ytterbium co-doped phosphate glass laser is quite insensitive to pump-rate fluctuations at frequencies greater than 100 kHz; this means that the RIN spectrum is predominantly determined by fluctuations in cavity-loss. The change in the cavity-loss transfer function at the relaxation oscillation frequency is ~30 dB corresponding to a ~60 dB reduction in RIN.

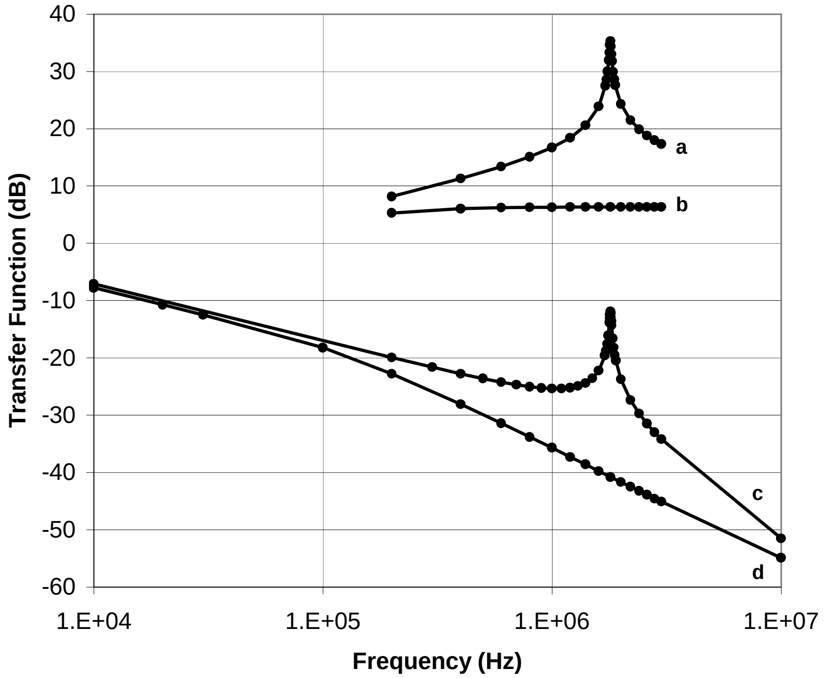

Figure 6: Calculated transfer functions for cavity-loss fluctuations without (a) and with (b) intra-cavity non-linear absorber and for fluctuations in pump rate without (c) and with (d) intra-cavity non-linear absorber.

Further improvement in RIN can be achieved by increasing the intra-cavity laser power density. Figure 7 shows that we observed a linear decrease in RIN with increasing intra-cavity laser power. The cavity design of our laser was specifically optimized for lowest RIN by reducing cavity-losses, increasing pump rate, and optimizing laser mode diameter. Inspection of equations (1-3) shows that the cavity-loss transfer function is expected to decrease linearly with intra-cavity power density with a slope that is in good agreement with our observations.

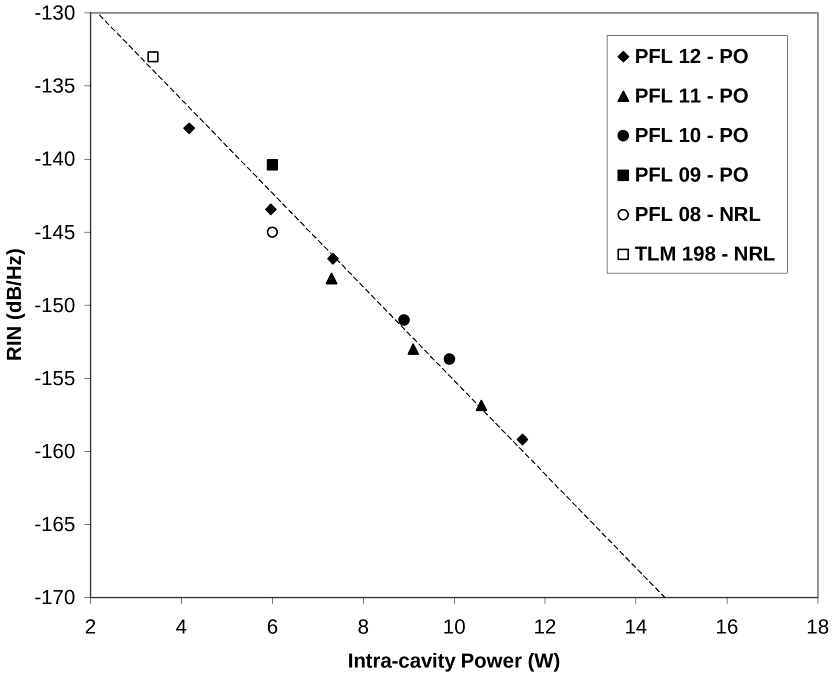

Figure 7: Measured RIN at 1 MHz for various Princeton Optronics low noise lasers. Measurements were taken at Princeton Optronics (PO) and at the U.S. Naval Research Laboratory (NRL). The dashed line is a linear fit to the data.

Fig. 8 shows a measured RIN spectrum from 100 kHz to 1 GHz. (trace a). Trace d marks the shot-noise limit at the detected photocurrent. Calculated cavity-loss transfer functions with (trace b) and without (d) non-linear absorbing material in the laser cavity are overlaid in the graph. The peak in the RIN spectrum has disappeared as result of the intensity-dependent loss in the cavity. If the spectral density function of the cavity-loss fluctuations does not dependent on frequency (white noise) the shape of the transfer function multiplied by two (because RIN is measured in terms of electrical noise rather than optical noise) should match the shape of the RIN spectrum[6]. This is the case at frequencies greater than 1 MHz. The measured RIN spectrum starts to decrease at 30 MHz until the shot-noise limit for 19 mA dc photo-current is reached at 100 MHz. Here the slope of the decline in RIN is 20 dB per decade as expected from the theoretical analysis of the rate equations.

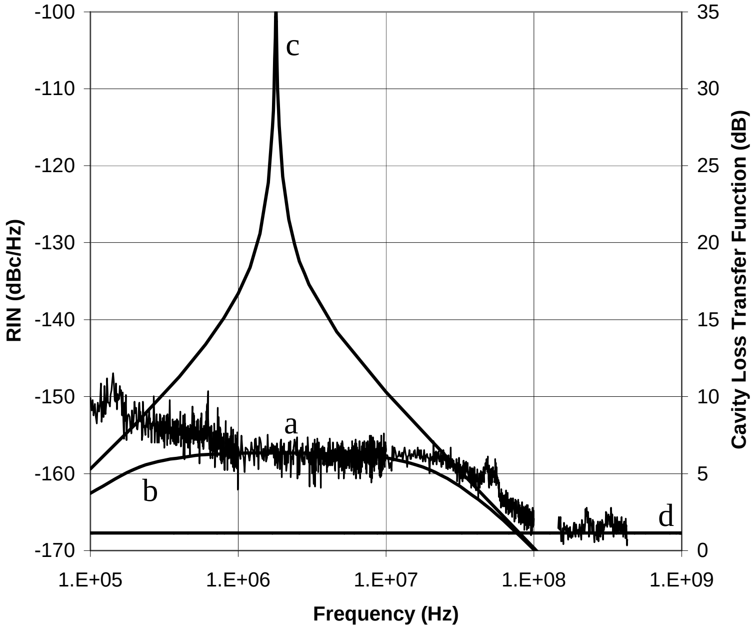

Figure 8: Measured RIN spectrum of the Princeton Optronics low noise laser (a); Calculated cavity-loss transfer functions with (b) and without (c) intra-cavity absorber; shot noise limit at 19 mA dc photo-current (d)

4. FREQUENCY STABILITY

Directing a small portion of the fiber-coupled output to an in-house developed ultra-stable wavelength locker locks the lasing frequency of the low noise laser. The beam enters the wavelength locker through a polarization-maintaining fiber, and then passes through a collimator to produce a large, well-collimated beam. An isolator between the collimator and the rest of the locker prevents back reflections into the laser and ensures a stable, linearly polarized beam. A beam splitter directs a portion of the beam at right angles to the monitor diode. The remainder passes through the beam splitter, through the etalon and onto a detector. In this locker the etalon reflectors were made from the same ultra-low expansion (ULE) glass as the spacers, to minimize strain due to differential thermal expansion.

The finesse of the etalon is ~200 and the transmission peaks have a 125 MHz full width at half maximum (FWHM). The etalon is sealed to reduce the variation in index of refraction of the air in the gap with temperature. The assembly is mounted on a thermo-electric cooler (TEC). The TEC controller is able to control the temperature of the locker assembly to about 0.007°C. Two lockers were constructed and care was taken to adjust the etalons so that the resonant peaks were very close to each other in wavelength. This was so that one locker could be used to lock the laser wavelength and the second locker used to measure the stabilized laser wavelength. Fig. 9 shows that the stability of the laser is +/-100 kHz over an 8-hour period.

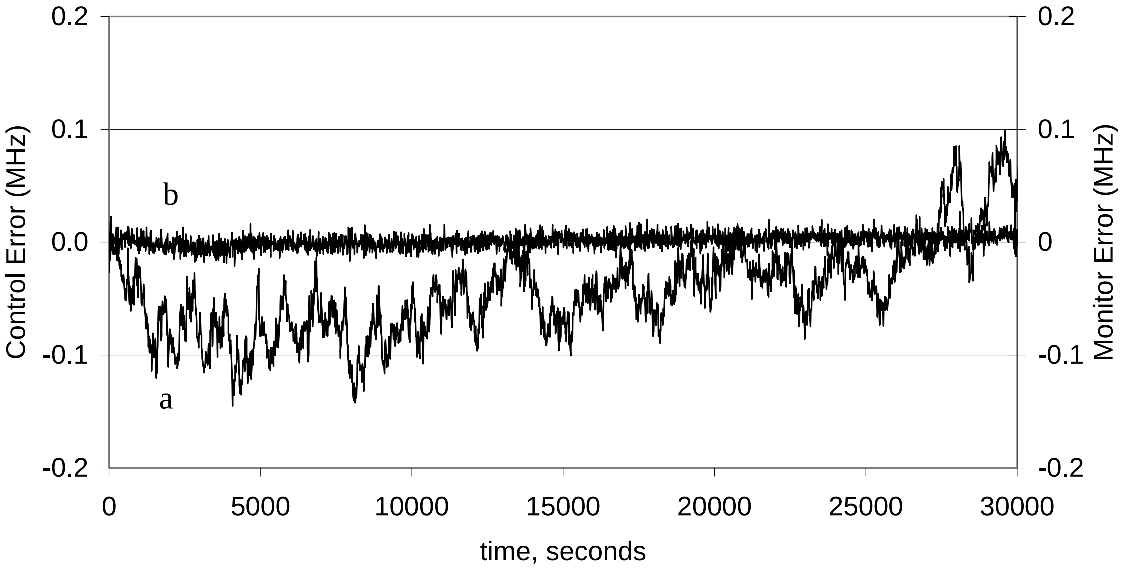

Figure 9: Frequency stability of Princeton Optronics low noise laser locked to wavelength locker 1 and monitored by wavelength locker 2. Trace a shows the monitor signal, while trace b shows the control error signal of our control circuit.

5. CONCLUSIONS

We have demonstrated that the strong peak in the RIN spectrum at the relaxation oscillation frequency of an Er-Yb co-doped phosphate glass laser can be suppressed by ~55 dB with a non-linear absorbing material inside the laser cavity. By optimizing the laser cavity design for high intra-cavity power density we have achieved –160 dB/Hz RIN at 1 MHz for 35 mW output. Above 100 MHz the RIN becomes shot noise limited (-168 dB/Hz @ 20mA photocurrent). When locked to our in-house developed ultra-stable wavelength locker our laser has excellent long-term frequency stability (<250 kHz).

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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