PRINCETON OPTRONICS

Low Noise Solid State Laser Technology

1. Ultralow Noise Solid State Laser for the 1550 nm Wavelength Band

Introduction

Princeton Optronics was in the DARPA Phor-Front program (2005-2009) to develop the lowest noise laser at 1550nm in the industry and has developed such a laser. The most important aspect of the low noise laser is its absence of RIN peak. Low noise high power lasers are needed for a number of analog and digital communications systems as well as for sensors and analog signal processing applications. At Princeton Optronics we have developed a low noise, high power diode pumped Er:Yb glass laser technology. A major breakthrough has been achieved in this laser by using a non-linear absorbing material in the cavity. This technique has delivered the most effective noise reduction ever reported in a laser so far. Further optimization of materials and their characteristics will be able to reduce the noise by an additional 50dB more. Current laser output powers up to 100mW are available with RIN of <-140dBc/Hz above 100kHz and –145dBc/Hz @1MHz and higher frequencies and shot noise limited above 100MHz (see fig 3 in this white paper). This is enclosed in a small, 2.4” X 3.25” X 0.5” package. The laser wavelength can be selected over the band 1528-1565nm. . A tunable version of this laser is under development. We have developed a wavelength locker using low finesse ULE glass air spaced etalons for standard laser operation to lock any wavelength. For ultra-stable frequency locking new lockers have been developed that use high finesse etalon and have a separate temperature control from the laser. Both lockers have a laser power monitors for normalization and power control. Laser linewidths of 1.1kHz over 1ms and a frequency control of 250kHz for periods up to 1 hour have been achieved.

Laser Design

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. Therefore co-doping the erbium doped phosphate glass with ytterbium drastically decreases the absorption length at the 976 nm pump wavelength so that small solid-state lasers can be built. Aside from the obvious advantage for packaging a short cavity length results in a large longitudinal mode-spacing (>40 GHz). A single longitudinal mode can be obtained by inserting a low-finesse etalon. By using either an air-spaced etalon with a piezo controlled air gap or a temperature controlled solid etalon consisting of a material with high dn/dT different modes in the 1550 nm telecom wavelength band can be selected. Fine tuning of the lasing wavelength is achieved by controlling the cavity length using a piezoelectric moveable output coupler. Fig 28 shows the optical configuration of the low noise laser.

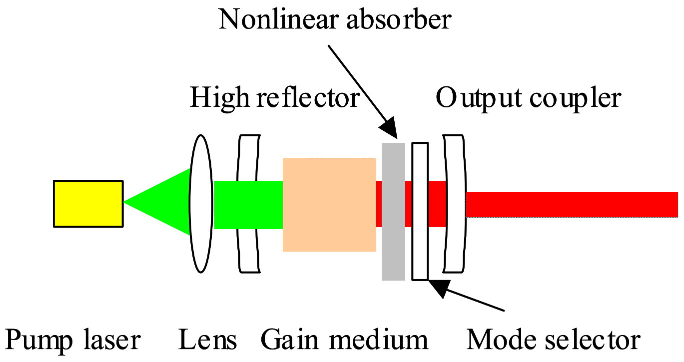

Figure 1. Laser design optical layout.

The singlemode edge emitter pump laser is collimated and directed into the glass. A slight angle is used to prevent back-reflections de-stabilizing the pump laser chip. The gain medium of high phosphate glass doped with Yb and Er ions is Brewster angle wedged to provide a linearly polarized laser output. Both the tunable etalon, for mode selection, and the output coupler, for frequency tuning, use piezo elements.

Noise Reduction

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. Hence the RIN spectrum is mainly determined by cavity loss perturbations. The RIN spectrum of Er:Yb lasers is close to shot-noise limited at higher frequencies (>10 MHz) but shows a strong peak at the relaxation oscillating frequency, which is in the 100 kHz to 1 MHz range, depending on the cavity layout and laser power. Without active stabilization of the laser cavity the typical observed RIN peak is approximately -70dB/Hz. We have developed a noise reduction technology that is based on intra-cavity non-linear absorption. Figure 2 shows measured RIN spectra for Er:Yb laser with and without noise reduction. With noise reduction the RIN at the relaxation oscillation frequency is reduced by more than 50dB with no relaxation peak. Fig 3 shows the noise measurement results at NRL.

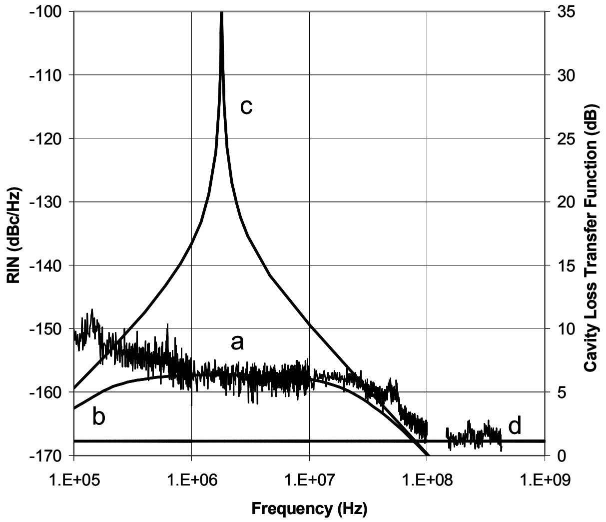

Figure 2. RIN spectrum of laser with noise reduction (a,), (b) is cavity loss transfer function and noise without the noise reducer (c).

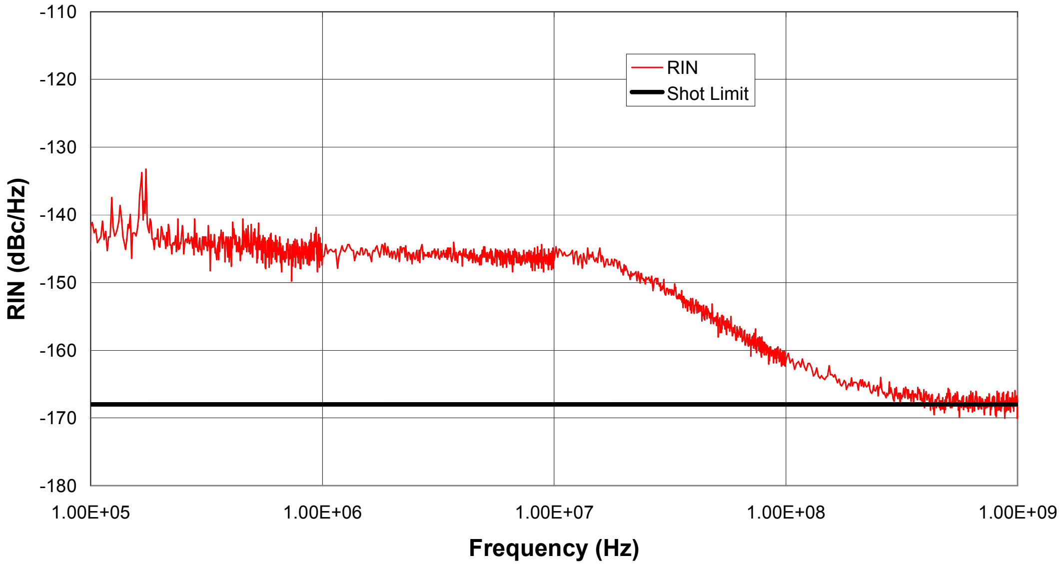

Fig 3. Shows a recent measurement by the Naval Research Laboratory of one of our low noise lasers showing a RIN of –145dBc/Hz at 1 MHz when operated at 95mW output power. The shot noise limit is –168dBc/Hz and the laser reaches this above 200MHz.

Sidemode Suppression

The laser technology uses a high finesse laser cavity and this coupled with the solid-state gain medium gives a very high sidemode suppression ratio. There is a strong mode selector in the laser cavity and the result is very good single frequency characteristics. Fig 4 shows the OSA plot indicating >70dB sidemode suppression. The shape of the laser line is limited by the resolution of the Optical Spectrum Analyzer.

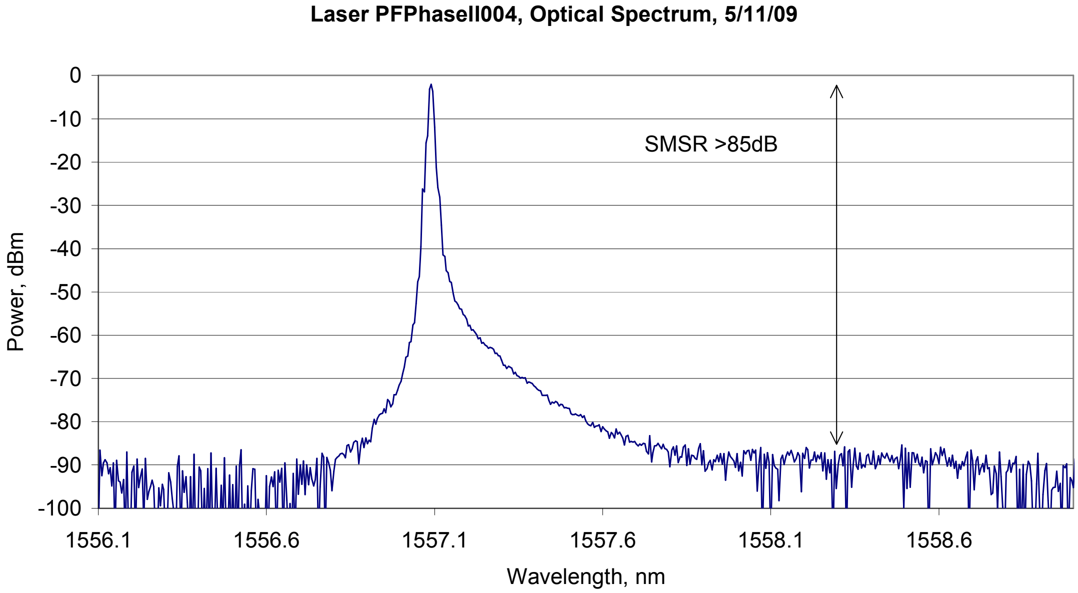

Figure 4. Optical spectrum analyzer chart showing >85dB SMSR

Frequency Stability and Linewidth

The instantaneous linewidth of the laser is ~10Hz or less. The linewidth of the laser is thus primarily governed by mechanical noise. The uncontrolled linewidth is ~1.1kHz over 1ms and this can be reduced by laser frequency control systems. The piezo frequency control systems are limited to a control bandwidth of tens of kHz and this will not significantly reduce the linewidth. There are two developments that we are actively pursuing to reduce the linewidth further. One is to improve the laser packaging to reduce the mechanical noise and increase the piezo tuning bandwith.

The second development is to use electro-optic tuning. This has been demonstrated in our research experiments and now is being developed further. Experiments at NIST laboratories using their combination of piezo control and acousto-optic control demonstrated a linewidth of 10Hz using the Princeton Optronics laser. This is shown in Fig 5 and required a control bandwidth of >300kHz in the acousto-optic control.

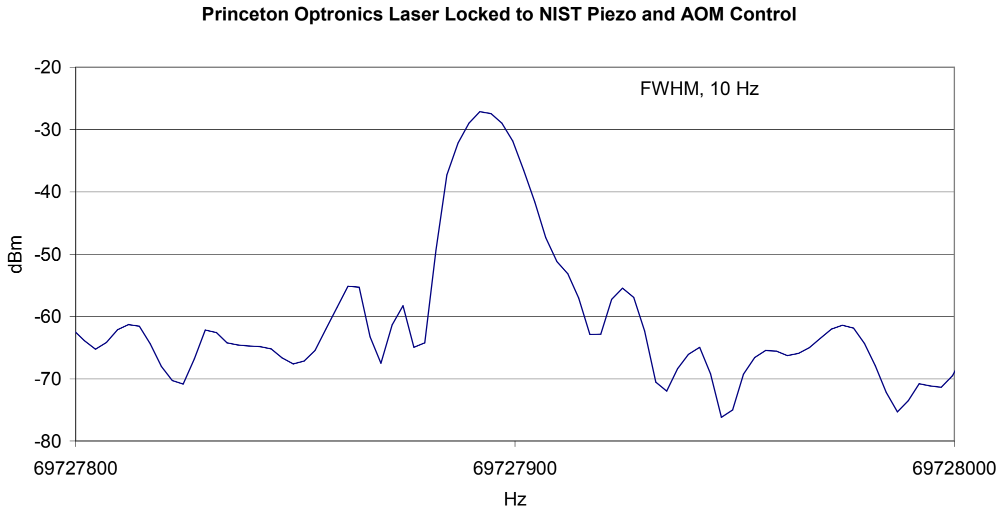

Figure 5. Frequency Spectrum of laser when locked using NIST piezo and acousto-optic controls. Shows linewidth of 10Hz FWHM.

The linewidth of the laser is measured by self heterodyning technique and we obtain a linewidth close of 1kHz as seen in fig 6

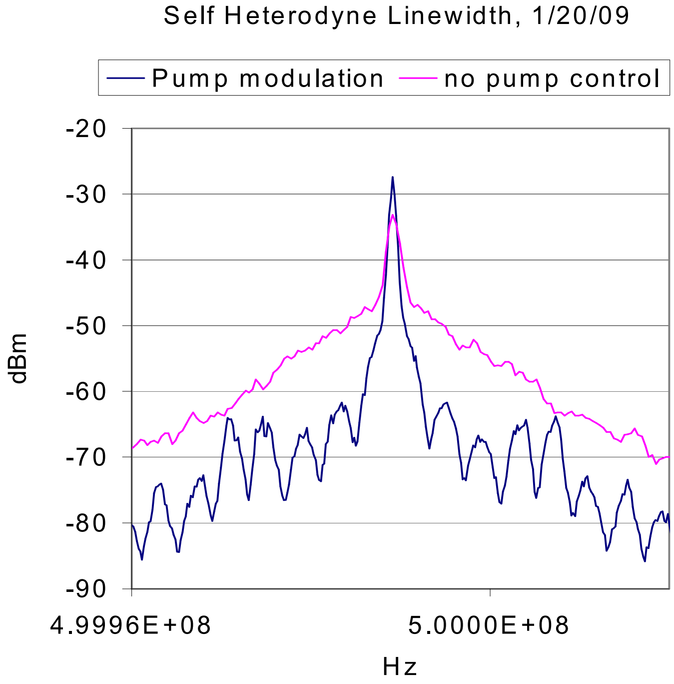

Fig 6. The linewidth (1kHz) of the laser as measured by self heterodyne technique. A fiber of 40km of length is used for the measurement.

Wavelength stability:

Using the standard locker a wavelength stability of a few hundred kHz for 8 hrs is achieved. We have developed a high finesse ultralocker to more accurately control the laser wavelength. The current performance is +/-125kHz over a 8 hour period. This is shown in Fig 7.

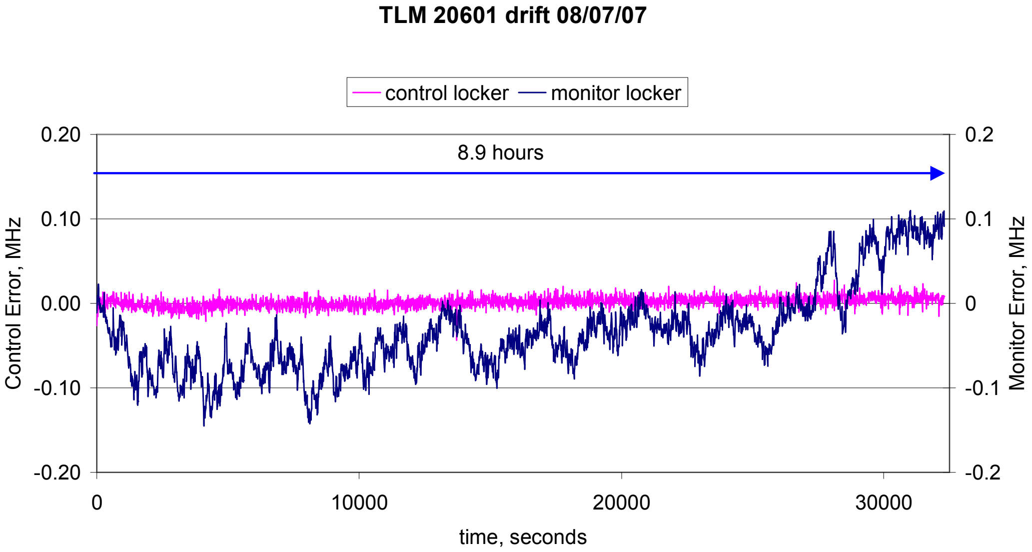

Figure 7. Wavelength stability test performed at NIST. Show wavelength stability of +/-125kHz over a 8 hour period.

Phase Noise
The line width of the laser is very low, below 1kHz. This translates into low phase noise. The freq noise of the laser is shown in Fig 8 in (Hz/rtHz). The measurement of phase noise in dBc/Hz is shown in Fig 9.

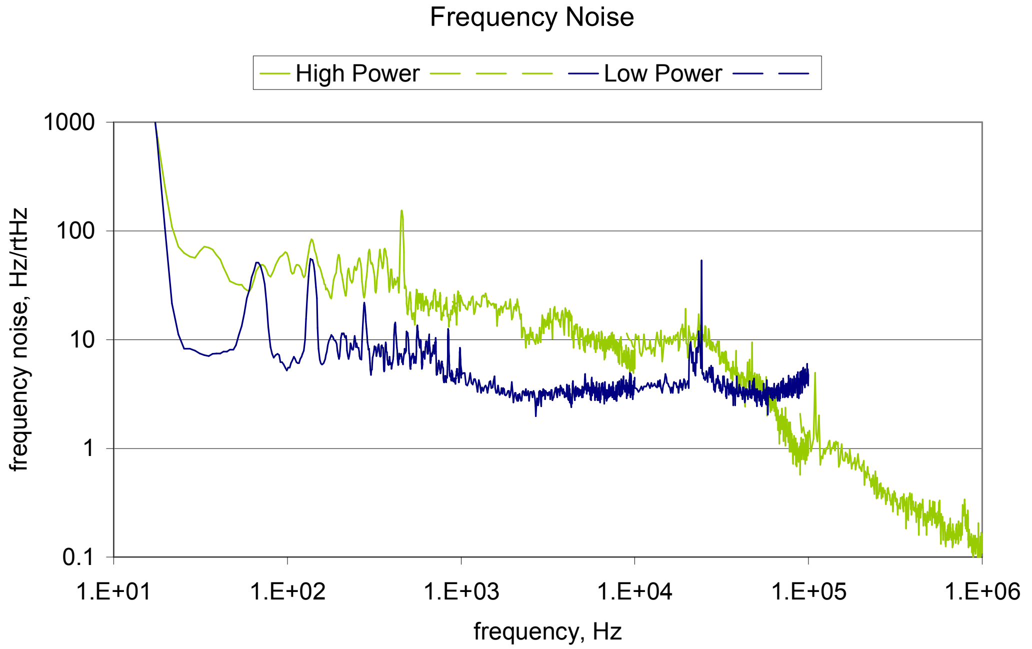

Fig 8: A plot of the frequency noise vs frequency of the laser.

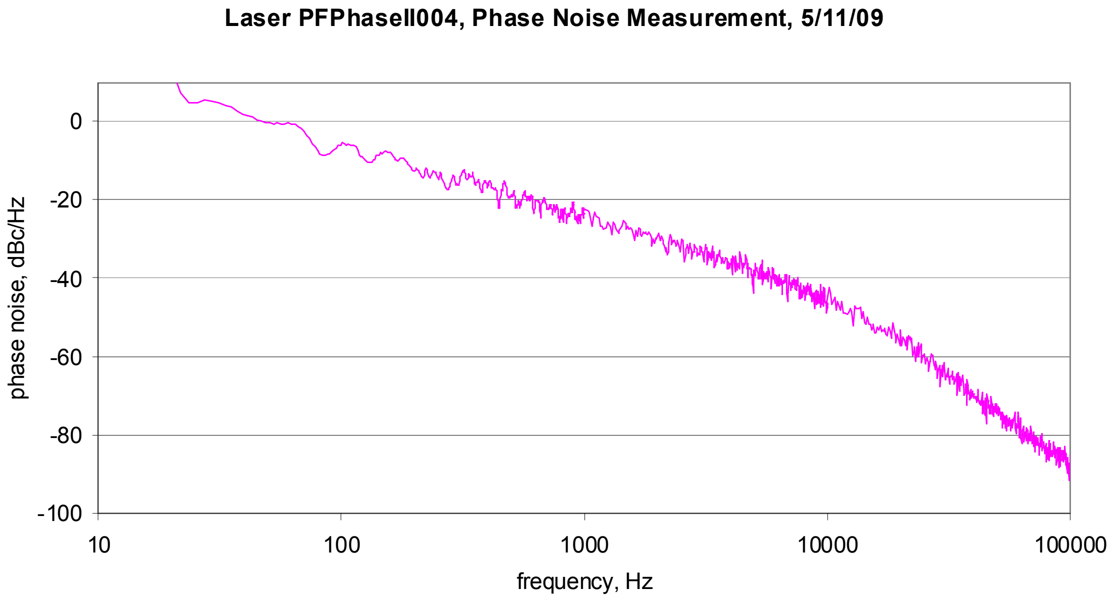

Fig 9. The measurement of the phase noise in dBc/Hz over frequency is shown.

Use of Low Noise Laser for Communication Link Application:

We have used these lasers for communication links and obtained very high dynamic range in some early experiments. Fig 10 shows results of a two tone SFDR (spur free dynamic range) measurement. An SFDR of 116dB/Hz2/3 was obtained, which was the limit of the measurement set up.

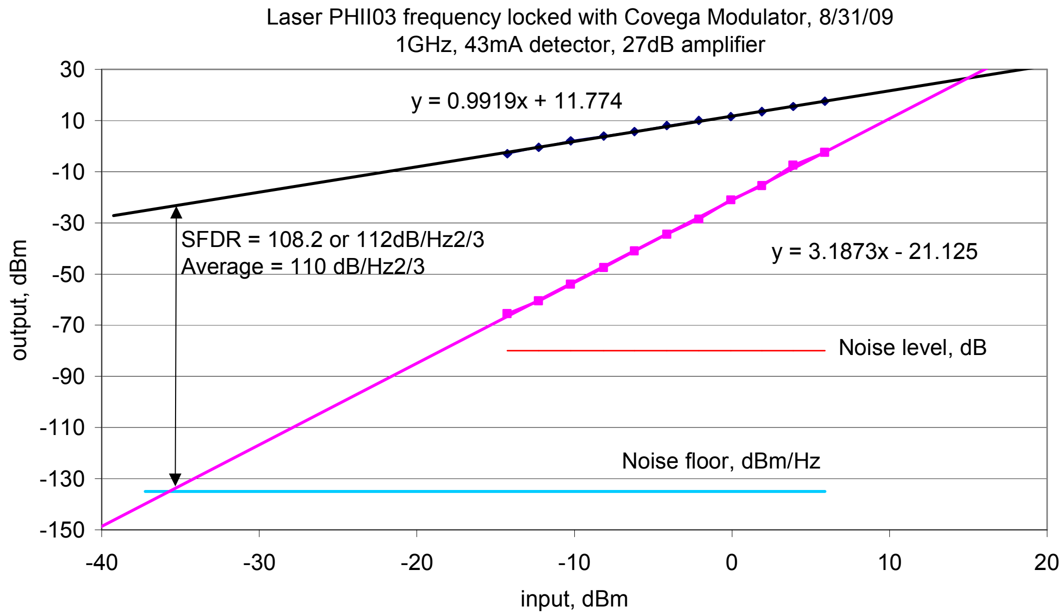

Fig 10. Fiber Link using Laser and Lithium Niobate Modulator - ~40mW into Receiver. The result is measurement limited – RF Spectrum Analyzer SFDR = 116dB/Hz2/3

High Power (10W), Low Noise, Narrow Linewidth Laser:

Princeton Optronics has developed high power low noise, narrow linewidth laser at 1550nm using a low noise laser seed and using a fiber amplifier at 1550nm. The schematic of the high power laser can be seen in Fig 11.

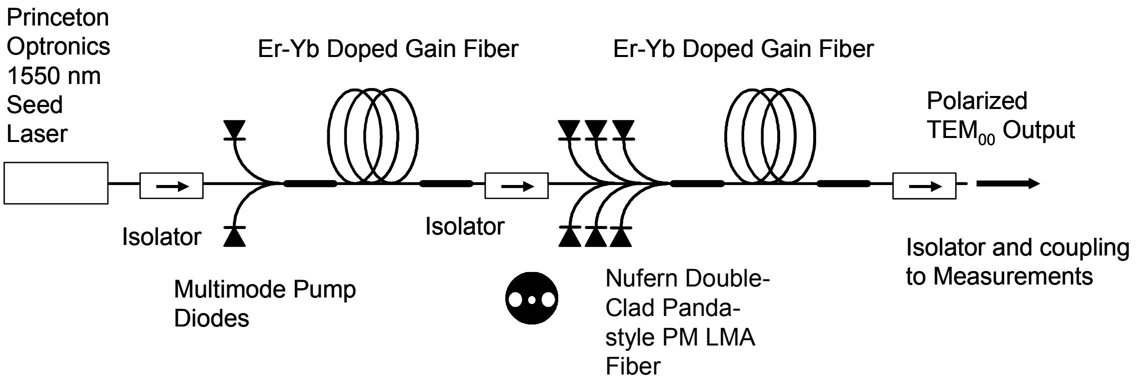

Fig 11. Schematic of a 10W output low noise, narrow linewidth laser developed at Princeton Optronics

The laser has impressive performance with SMSR of >70dB. RIN of ~ -160dB/Hz; linewidth of ~ 1kHz, frequency noise of ~ 10Hz/rt Hz. The laser has an unique capability of being frequency modulated by 5 or 10GHz at a modulation rate of 1-10kHz. Fig 12-15 shows the performance of this laser.

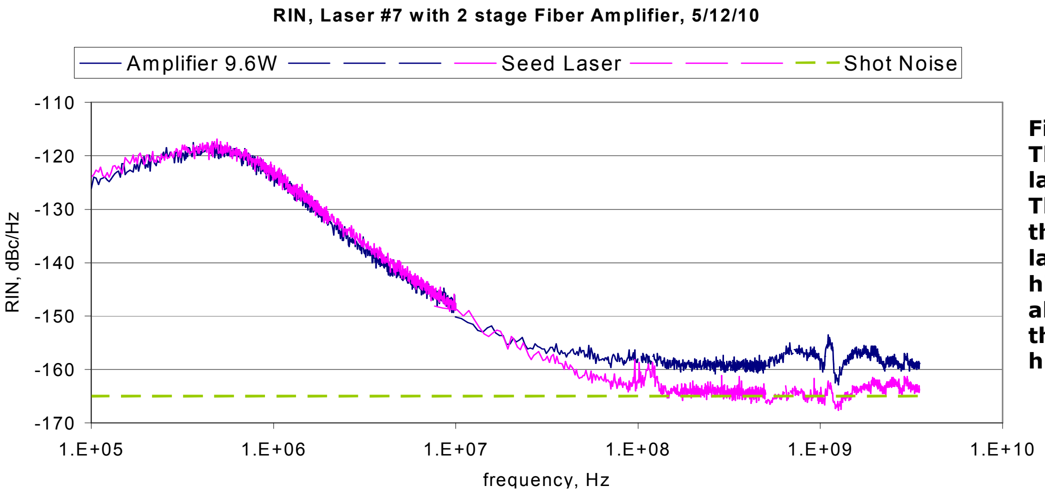
RIN, Laser #7 with 2 stage Fiber Amplifier, 5/12/10

Fig 12.
The RIN of the 10W laser with frequency. The red curve shows the RIN of the seed laser. The RIN of the high power laser is about 5dB higher than the seed laser at higher frequency.

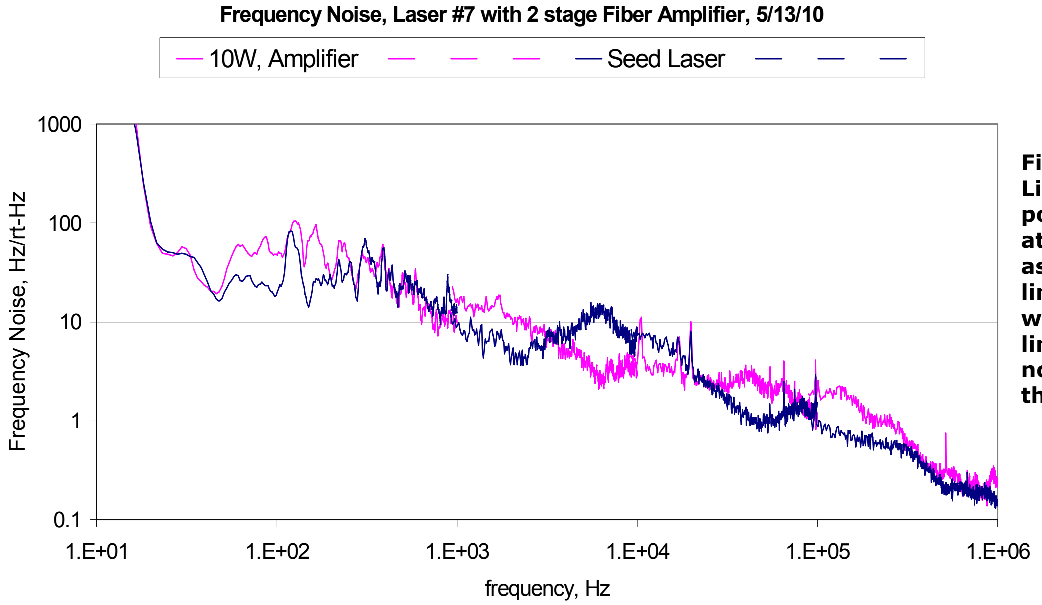
Frequency Noise, Laser #7 with 2 stage Fiber Amplifier, 5/13/10

Fig 13.
Linewidth of the high power low noise laser at 3W output as well as at 9.6W output. The linewidth is compared with the seed laser linewidth which has not changed much through the amplifier.

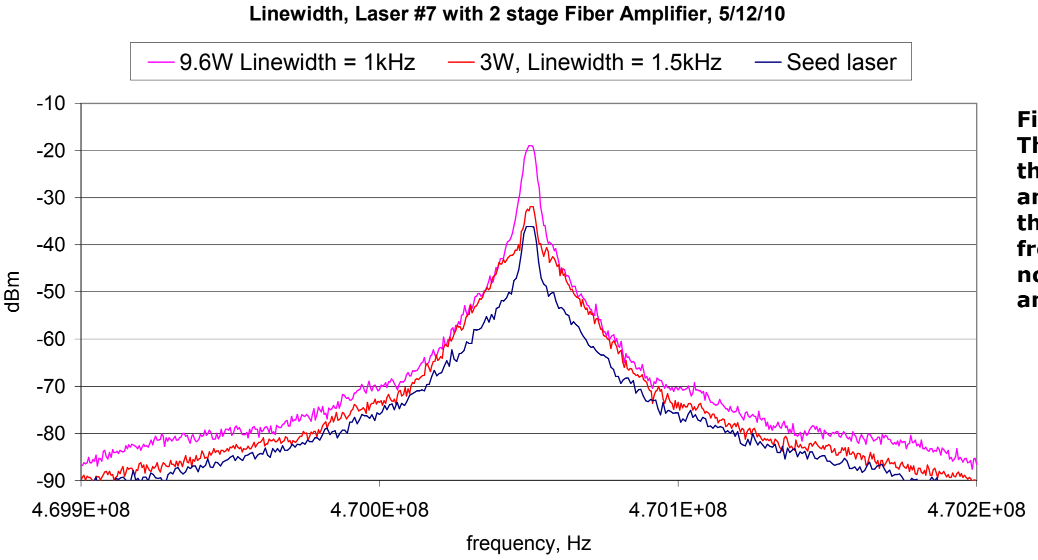
Linewidth, Laser #7 with 2 stage Fiber Amplifier, 5/12/10

Fig 14.
The frequency noise of the high power laser and comparison with the seed laser. The frequency noise does not change through amplification process.

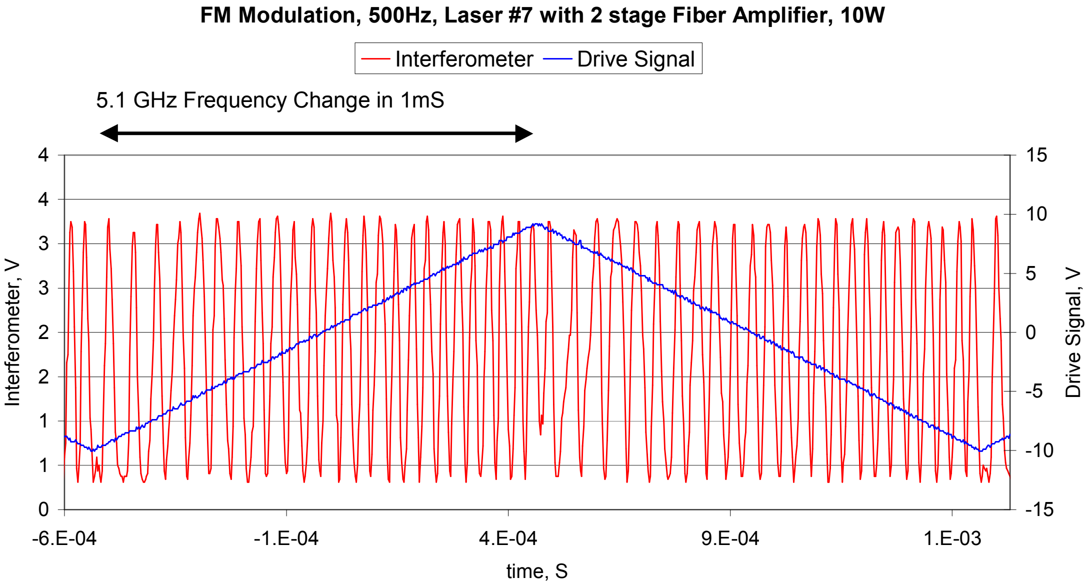

Fig 15. Frequency modulation of the high power laser. A frequency modulation of 5 to 10GHz can be made at a speed of 1-10kHz.

2. VCSEL Based 1064nm Low Noise Laser

VCSEL Device Structure & Fabrication

We have a new approach for low noise laser with extremely low noise using VCSELs. For high-power operation, efficient heat-removal is required and therefore a junction-down, bottom-emitting structure is preferred to improve current injection uniformity in the active region and to reduce the thermal impedance between the active region and the heat-spreader. A schematic of the structure without the heat-spreader is shown in Figure 16.

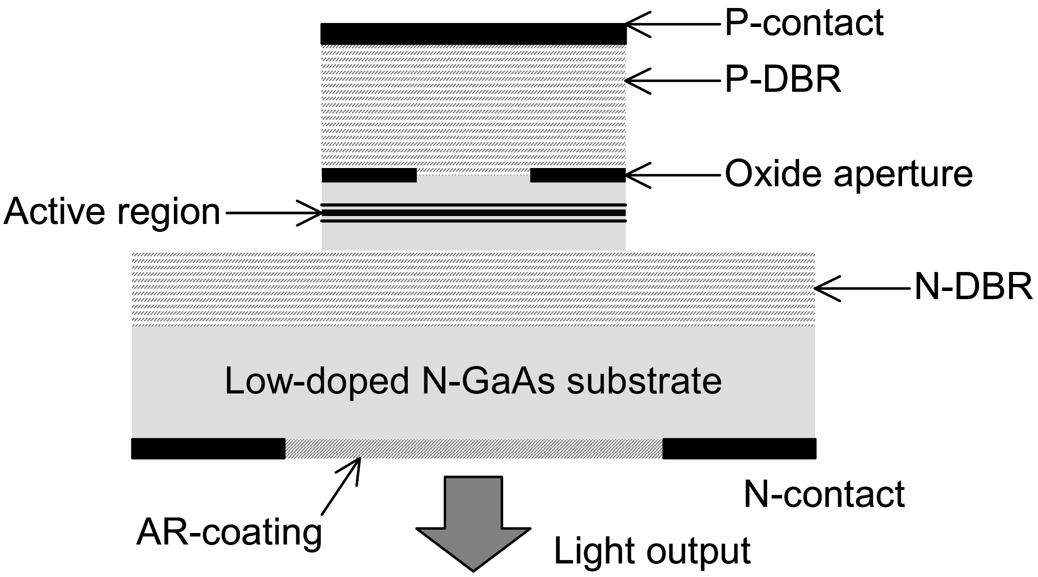

Figure 16. Schematic of the selectively oxidized, bottom-emitting 1064nm VCSEL structure.

For current and optical confinement, the selective oxidation process is used to create an aperture near the active region to improve performance. A low-doped GaAs N-type substrate is used to minimize absorption of the output light while providing electrical conductivity for the substrate-side N-contact. The growth is performed in a MOCVD or MBE reactor and starts with an AlGaAs N-type partially reflecting distributed Bragg reflector (DBR). The active region consists of InGaAs quantum wells designed for 1064nm emission and strained-compensated using GaAsP barriers. The active region is followed by a high-reflecting P-type DBR. A high-Aluminum content layer is placed near the first pair of the P-DBR to later form the oxide aperture. The placement and design of the aperture is critical to minimize optical losses and current spreading. Band-gap engineering (including modulation doping) is used to design low-resistivity DBRs with low-absorption losses.

Low noise laser cavity:

The low noise laser cavity s shown in Figure 44. The Optical aspect of the setup consists of VCSEL device and an output coupler. A high-quality Etalon and a Brewster plate in the cavity control the single-wavelength operation and linear polarization, respectively. The optical isolator prevents optical feedback from outside of the cavity to maintain the single-wavelength operation. The beam is then coupled into a PM fiber with a focusing lens for the mode matching.

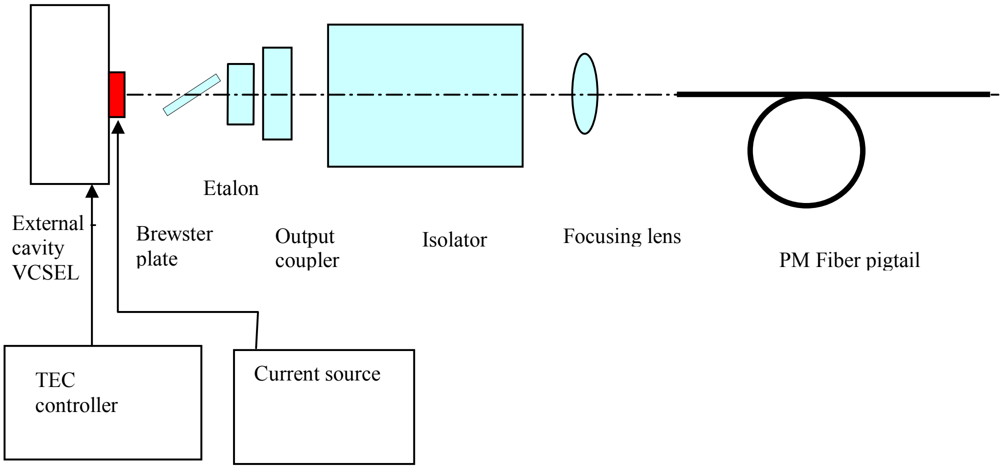

Figure 17. The low noise laser cavity with an etalon and a Brewster plate can be seen.

The RIN results on the laser can be seen in Fig 18

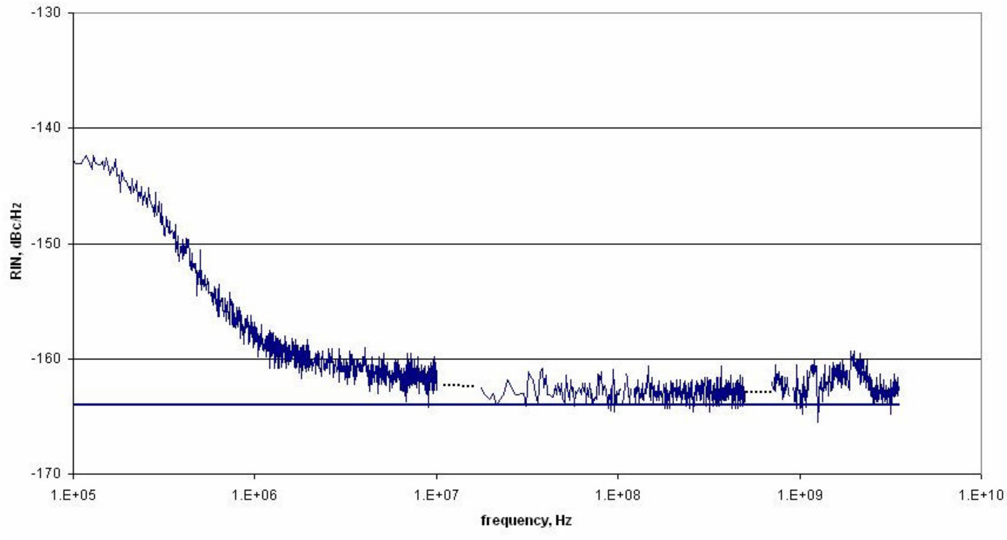

Fig 18. Shows the plot of RIN vs frequency of the laser. There is no RIN peak in the output of the laser. The power output of the laser is about 100mW.

Power output from the Laser:
The L-I characteristics of the laser can be seen in fig 19. We can achieve a very high power of ~1W from the laser, but we cannot get commercial small isolators to handle powers >100mW for such lasers. Therefore we are restricted to output power of ~100mW from the laser. However, if anyone is interested in using larger isolators which can handle higher power, we can deliver power levels of 600-700mW from these lasers.

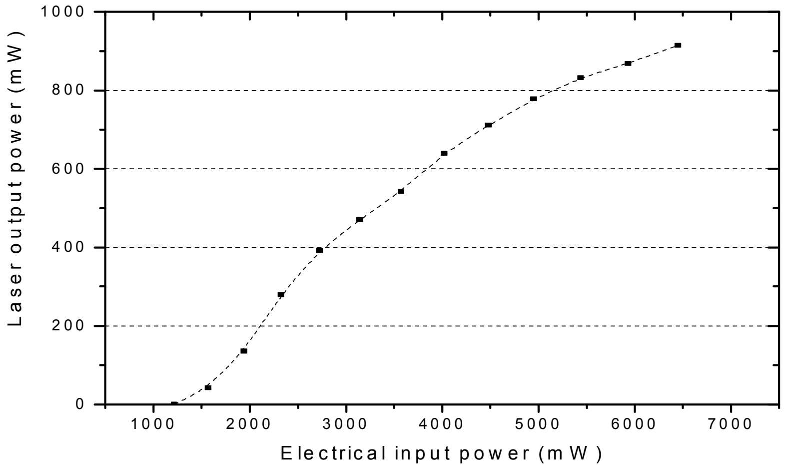

Fig 19. The L-I Characteristics for the VCSEL low noise laser

Laser Linewidth:
The linewidth of the VCSEL lasers is in the range of 50-200kHz from interferometric measurements (fig 20).

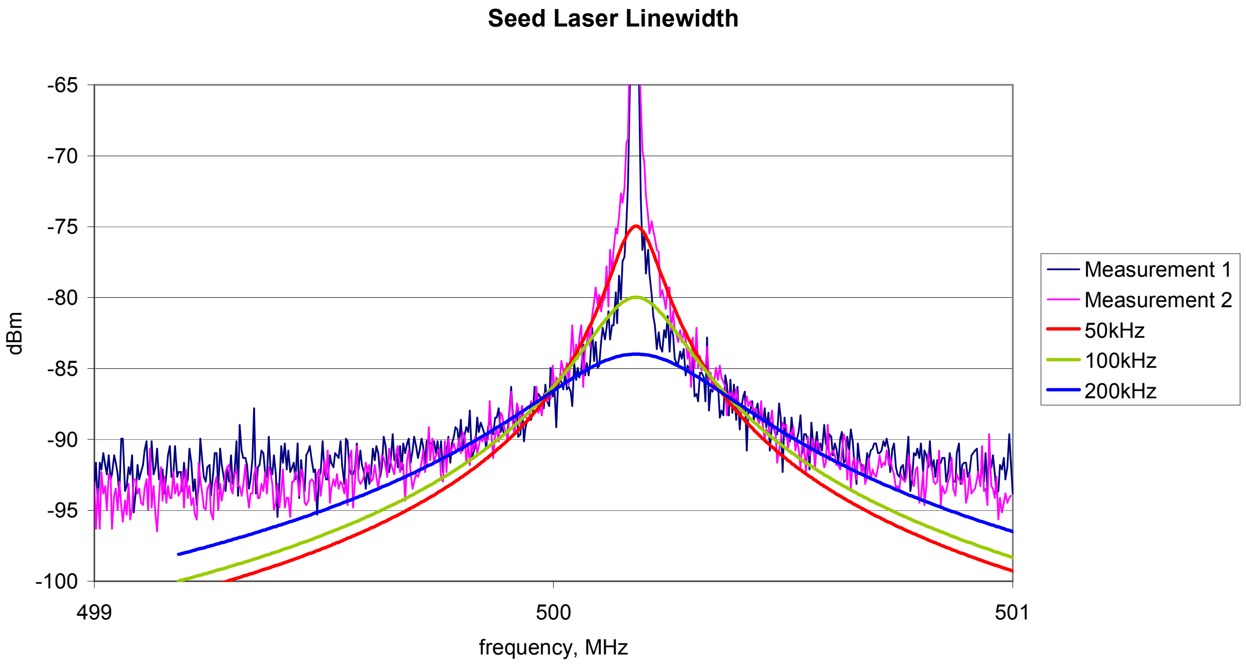

Fig 20. The low noise laser linewidth is between 50-200kHz as can be seen in different measurements of the laser at different current settings.

Package Dimension:
The laser is housed in a small package of 89 x 38 x 15 mm as can be seen if fig 21.

Fig 21. The low noise laser package dimensions are 89 x 38 x 15 mm.

1064 and 1550nm Seed Lasers:

CW and pulsed seed lasers are needed to seed the DPSS and fiber lasers. Low noise, narrow linewidth and wavelength stability are important characteristics of the seed lasers. We have developed external cavity VCSEL seed lasers at 1064nm for seed laser and a variant of low noise stable laser for seed laser at 1550nms.

Pulsed and CW Seed Laser at 1064nm:

Several types of the semiconductor seed lasers have been developed for the MOPA fiber laser systems, based on edge-emitting distributed feedback (DFB) lasers and Fabry-Perot lasers. However, those edge-emitting diode lasers have some limitations for the pulsed fiber lasers, such as the slow pulse response and low single mode power, or otherwise incorporating a tapered laser or amplifier portion in the seed laser module to boost its power. Basically, a seed laser in a MOPA fiber laser system affects the fiber laser's spectral line width, noise, pulse parameters, and wavelength tuning, etc., compared to the DBR-type fiber lasers. A high-power seed laser can also eliminate the pre-amplifier stage(s) for simplicity and lower cost.

In VCSELs, single-mode operation is generally possible for small diameter devices, and is typically limited to a few mW of power. To improve the single-mode power of VCSELs, an external-cavity configuration can be used in which a longer distance between the device and the external mirror forces it into a single-mode operation. In this scheme, much larger VCSEL apertures can be used, and therefore much higher single-mode powers can be obtained. Several previous research using either optical injection (pumping) or direct electrical injection have successfully demonstrated this approach. There are many advantages to single mode VCSELs which include low-cost manufacturing and high reliability.

Our high-power and low-noise seed laser at 1064nm is based on our newly developed large-aperture, and high-power VCSEL devices with nearly-diffraction-limited beam quality and low RIN, as well as fast pulse response, which is ideal for this high performance seed laser applications. Besides fiber amplifiers, this seed laser can also be used in many other applications, such as spectroscopy, and sensing, etc.

Seed Laser Cavity:

The cavity configuration of a VCSEL seed laser can be seen in fig 22.

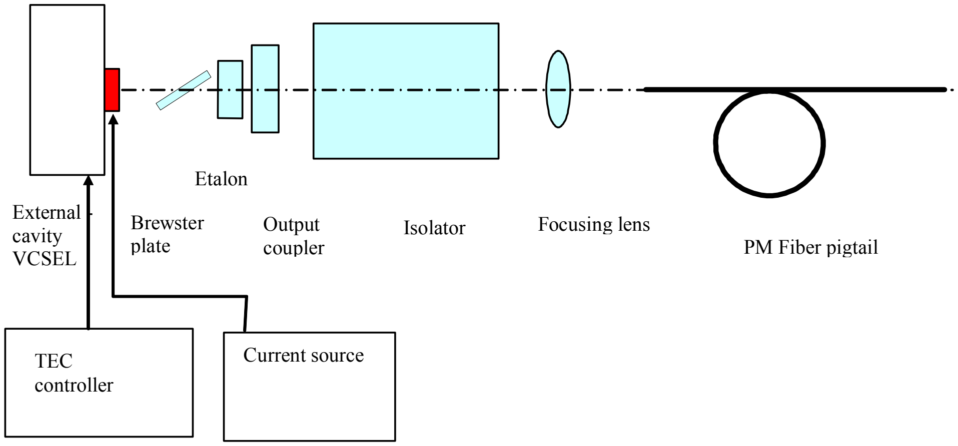

Fig 22: Shows the cavity configuration of a VCSEL seed laser. It has an etalon and a Brewster plate in the cavity for wavelength selection and polarization. For pulsed operation, fig 24 shows the optical and electrical pulses

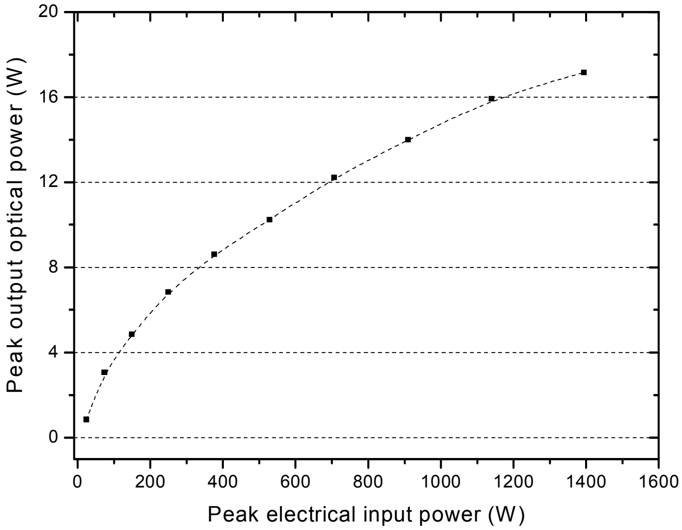

Figure 23. Shows the LI curve of a VCSEL pulsed seed laser. A peak power of 18W has been obtained. More recently, we have obtained peak power of >30W from the laser. Fiber coupled power output of >15W has been obtained

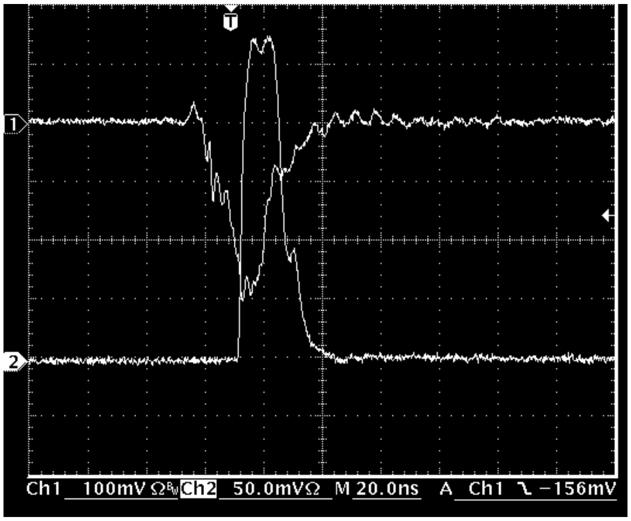

Fig 24. Electrical and optical pulse shape traces on an oscilloscope. Ch 1 is the Electrical pulse from the pulse driver's current monitor port, and the Ch 2 is the optical pulse measured at the laser's output by a fast Silicon detector

Fig 25 shows the L-I characteristics of a CW seed laser. A power output of 1W has been obtained with good M2. A fiber coupled power output of 600mW has been obtained out of such devices

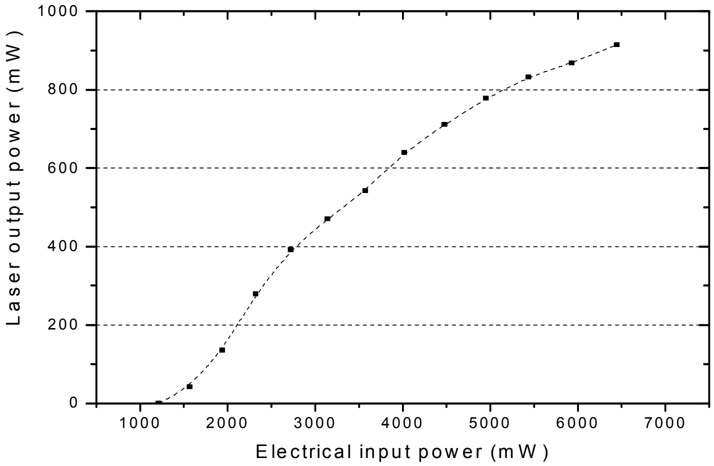

Fig 25. Shows the L-I characteristics of a VCSEL CW seed laser.

Seed Laser Package:
The laser is housed in a small package of 89 x 38 x 15 mm as can be seen if fig 26.

Fig 26. The seed laser package dimensions are 89 x 38 x 15 mm.

1550 nm Seed Laser:
Our 1550nm seed laser technology is the same as our low noise laser technology and a description of it can be found in the 1550nm low noise laser technology description. We make 50, 100, 150 and 200mW seed laser at 1550nm.