Low noise planar external cavity laser for interferometric fiber optic sensors

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ABSTRACT
A 1550 nm DWDM planar external cavity laser (ECL) is demonstrated to provide low phase/frequency noise, narrow linewidth, and low RIN. The cavity includes a semiconductor gain chip and a planar lightwave circuit waveguide with Bragg grating, packaged in a 14-pin butterfly package. This planar ECL laser is designed to operate under vibration and in harsh environmental conditions. The laser shows linewidth ≤ 2.6 kHz, phase/frequency noise comparable with that of long cavity fiber lasers, RIN ≤ -147dB/Hz at 1kHz, and power ≥ 10mW. Performance is suitable for various high performance fiber optic sensing systems, including interferometric sensing in Oil and Gas, military/security and other applications, currently served mostly by costly and less reliable laser sources.

Keywords: planar external cavity laser, phase noise, linewidth, relative intensity noise, fiber optic sensing, butterfly package, seismic exploration, remote interferometric sensing.

1. Introduction

High performance, fiber optic distributed interferometric technology was developed over the past 15 years for obtaining high quality dynamic measurements, but it has only recently moved into the deployment stage. Due to the technology's historically high cost, applications fall mostly into military surveillance or remote sensing in severe environments (sub-sea or subsurface for the oil and gas industry). These applications are now moving toward cost/performance optimization as the technology matures. Other more cost sensitive applications, which include distributed structural monitoring, large area and perimeter surveillance, seismic monitoring, and communications systems security, are now gaining the benefits of this optimization, and these applications are much larger in terms of market size.

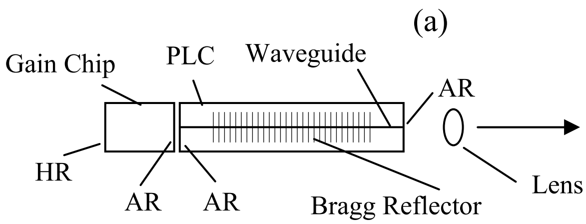
External Cavity Laser (ECL) technology is a compact and robust laser solution for interferometric sensing applications. When compared to DFBs, ECLs provide significantly narrower linewidth and lower frequency noise. Hybrid ECLs based on fiber Bragg gratings (FBGs) have been studied for interferometric sensing applications [1]; however, they suffer from FBG sensitivity to vibration, as do the much more expensive fiber laser based solutions.

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160X

We report here a low frequency noise, low RIN, and narrow linewidth 1550 nm DWDM ECL based on planar Bragg gratings (PBG) on silica-on-silicon planar lightwave circuit (PLC) [2]. We call this planar ECL technology PLANEX^{TM}. This cavity structure offers a significant reduction in vibration sensitivity over other ECL designs. We will show that phase/frequency performance of planar ECL is comparable to long cavity fiber lasers.

2. Planar ECL Design

A schematic diagram of a PLANEX^{TM} planar ECL device is shown in figure 1(a). The cavity is formed by coupling light between the anti-reflection (AR) coated facet of an InP gain chip with an AR-coated waveguide grating on a PLC.



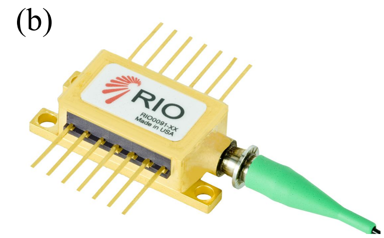


Figure 1. (a) Schematic of planar ECL; (b) Photograph of a PLANEX^{TM} butterfly package.

The PLANEX^{TM} planar ECL is integrated in a standard 14-pin butterfly package on top of a thermoelectric cooler (TEC). Thermo-opto-mechanical design insures minimal temperature gradient, and minimal stress on the cavity over a wide operating case temperature range from -5 to 75ºC.

The optical output beam from the ECL cavity is collimated before going through a double-stage isolator then focused onto either standard or polarization-maintaining single mode fiber. The output optical train of the ECL is designed and assembled using proven methods commonly used in commercial DFBs. The ECL laser is pin-to-pin compatible with commercial DFBs.

3. Test techniques description and outline of the test set up.

3.1. Phase/Frequency Noise Measurement

Test setup includes path mismatched Michelson interferometer with Faraday Reflector Mirror (FRM) elements to insure high interferometric visibility. Internal connectors are implemented to allow placement of different delay lines (replaceable delay) so that different optical path mismatches may be inserted into the interferometer. An Optiphase, Inc. OPD-4000 Optical Phase Demodulator [3] is used to measure the optical phase in the mismatch path interferometer. Demodulation at a 70 kHz rate is accomplished by a phase generated carrier stimulus followed by true-phase digital demodulation. With low self-noise this approach is capable of laser phase/frequency noise measurements of the lowest noise lasers commercially available.

3.2. Linewidth Measurement

Delayed self-heterodyne interferometer [4] has been used for linewidth measurement. 50km of fiber is used as path mismatch in one of the MZ (Mach-Zehnder) arms. This length should be enough to resolve down to 2.5kHz linewidth. The 50km fiber and the acousto-optic frequency shifter are housed in a thermally and acoustically isolated box that also attenuates micro-vibrations. ECL current driver is battery powered to minimize 60Hz and its harmonics from leaking through the power supply. Optical back-reflections throughout the test setup have been minimized.

3.3. Relative Intensity Noise (RIN) Measurement

ECL, photodetector, and low noise amplifier are all battery powered.

Furthermore, all fibers used should be carefully laid out to prevent micro bending, which in turn would result in RIN distortions.

4. Experimental Results

4.1. LIV and Lasing Spectrum

An ECL LIV characteristics and time-averaged spectrum, obtained with OSA, are shown in figure 2(a). Power ≥ 11mW can be easily obtained at driving current of ≥ 150mA. Lasing threshold current is 12mA. The soft knee at low currents is due to ECL dynamics details and will be explored in a future publication.

High SMSR is achieved by optimizing cavity design. As shown in figure 2(b), the SMSR=54.7dB at output power of 11.4mW and bias current of 152mA.

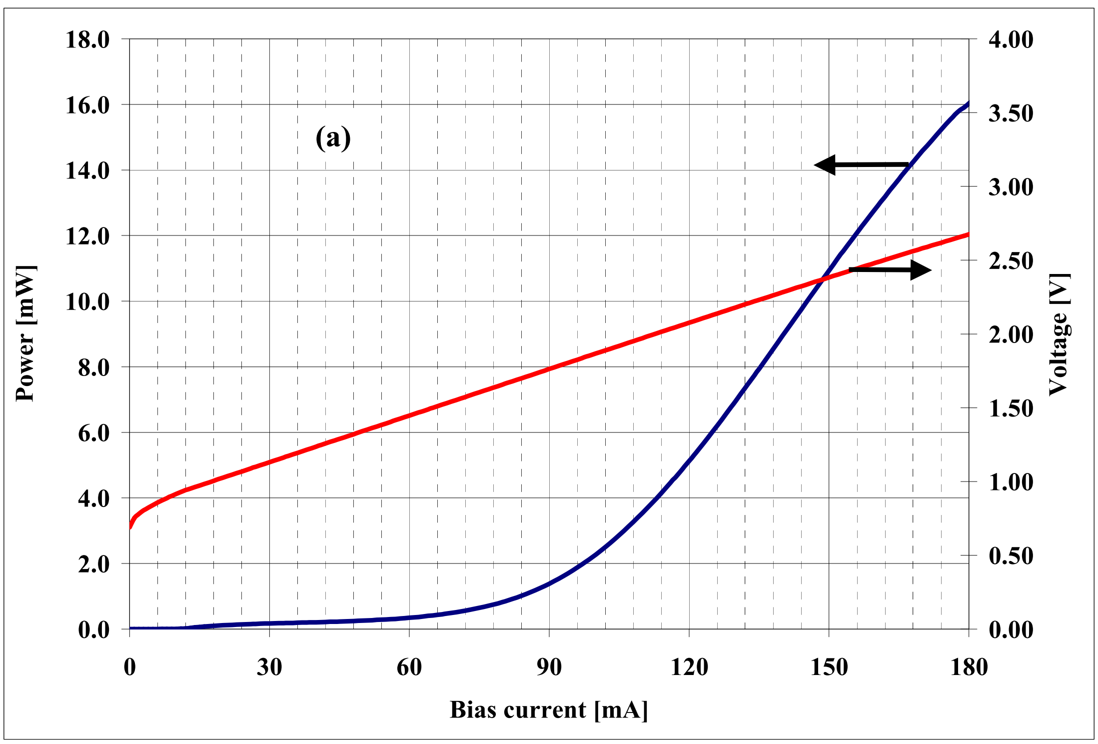


Figure 2. a) LIV

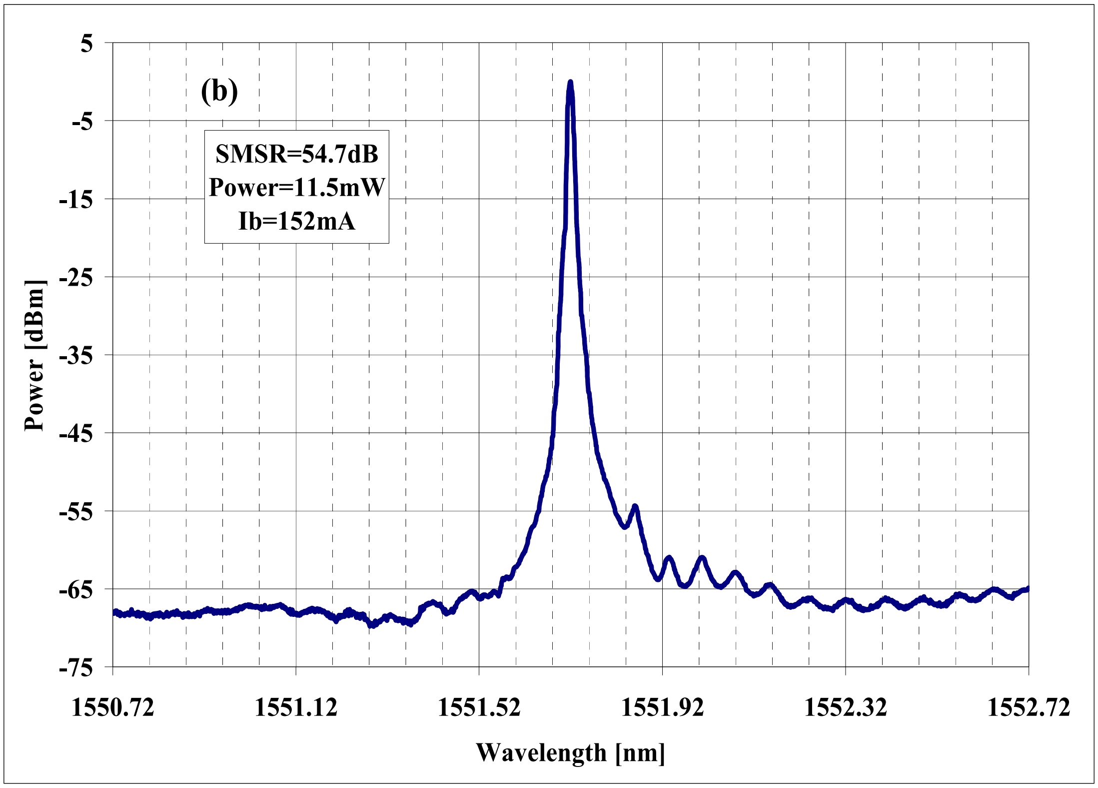


Figure 2. b) Lasing spectrum characteristics.

4.2. Phase/Frequency Noise

Phase/frequency noise performance is shown in figure 3. Phase noise values are normalized to 1meter interferometer optical path difference (OPD). The peaks visible on the phase/frequency noise spectral density characteristic at 60 Hz and multiples of 60 Hz are a result of AC leakage in the ECL bias current source and demodulator.

In figure 3 the phase/frequency noise is shown at different bias currents (ECL setpoints). In this case, the operating temperature is the same for all three different settings. Here setting the bias current is not similar to conventional lasers such as DFB. With an ECL one can use bias current (Ib) and/or temperature (T) to tune phase/frequency noise, power, and lasing wavelength.

Below 100kHz the phase/frequency noise is dominated by 1/f noise, which is similar to DFB semiconductor lasers [5].

Phase noise at specific frequencies is also tabulated in an inset in figure 3.

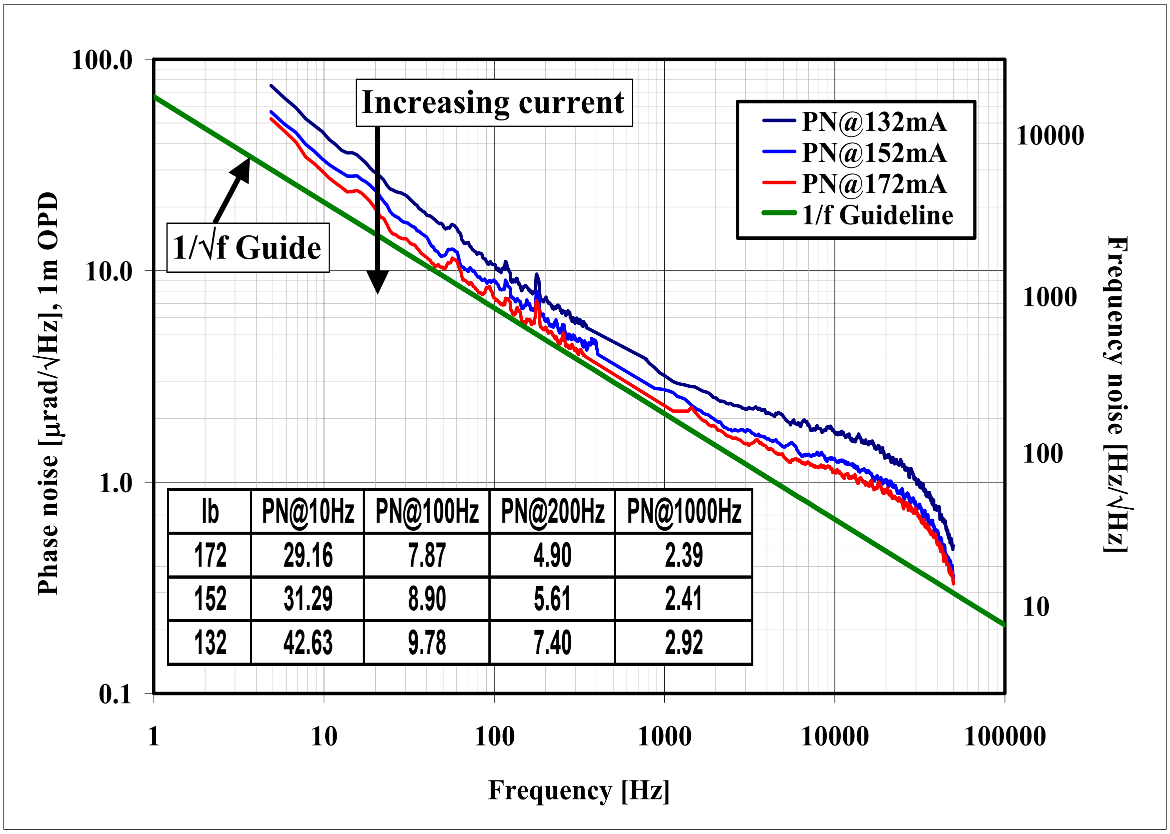


Figure 3. Phase/frequency noise spectrum vs. ECL set point (bias current, Ib). Phase noise values are normalized to 1meter interferometer optical path difference (OPD). The inset table shows the phase noise (PN) at certain frequencies. Phase noise units are $\mu rad / \sqrt{Hz}$. Phase noise spectrum distortions are due to micro-vibration and 60 Hz harmonics leakage.

4.3. Linewidth

Using the same ECL settings as in figure 3, the measured linewidth (δν) using delayed self-heterodyne-interferometer are listed in table 1. A linewidth of 3.3kHz has been achieved.

Table 1. Linewidth vs. setpoint.

Ib [mA]	FWHM Gaussian δυ [kHz]	FWHM Lorentzian δυ [kHz]
172	7.0	3.3
152	7.9	3.7
132	10.0	4.7

The linewidth is due to the contributions of white noise resulting from spontaneous emission noise and 1/f noise. It is believed that 1/f noise is due to dangling bonds at the buried-heterostrucure surfaces, which act as non-radiative recombination centers [6,7].

White noise results in Lorentzian lineshape while 1/f noise results in Gaussian line shape. From figure 3 and table 1 it is obvious an ECL has both white and 1/f noise. This results in Voigt lineshape, which is the convolution of Lorentzain and Gaussian lineshapes [5,8].

Figure 4 shows that Gaussian lineshape has a good fit to the measured data down to -5dB.

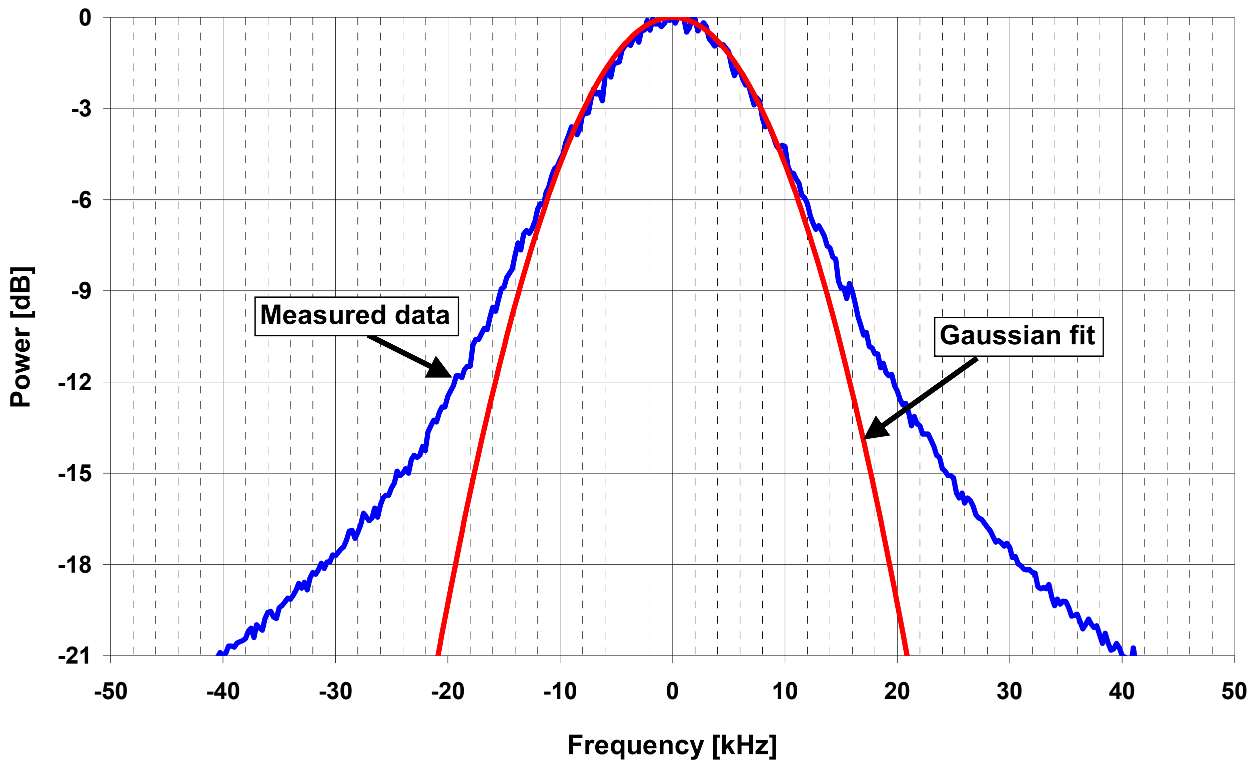


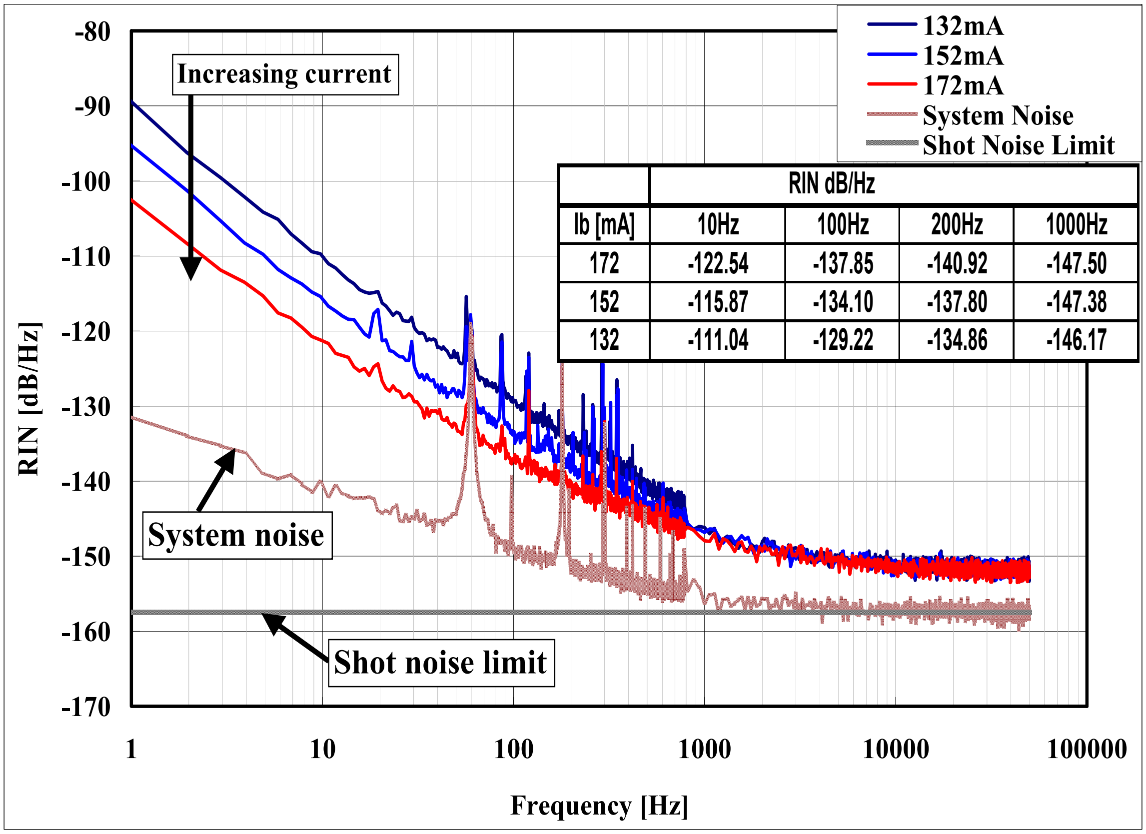
Figure 4. Lineshape. Measured FWHM Gaussian linewidth=7.9kHz Measured FWHM Lorentzian linewidth=3.7kHz.

4.2. Relative Intensity Noise (RIN)

RIN spectra vs. bias current (setpoint) are shown in figure 5.

Below 1kHz RIN is dominated by 1/f noise. Figure 5 shows that above 1kHz RIN converge to the same values for all three currents. System noise floor does not explain this convergence, which will be addressed in the future. RIN distortions are due to micro-vibrations while the sharp spikes are due to 60Hz and its harmonics leakage even though all current sources are battery powered.

Planar ECL has relaxation oscillation frequency $\geq$ 2GHz compared to ~ 1MHz [9] for fiber lasers. Therefore, planar ECL has a superior RIN up to GHz frequency range.



	RIN dB/Hz			
Ib [mA]	10Hz	100Hz	200Hz	1000Hz
172	-122.54	-137.85	-140.92	-147.50
152	-115.87	-134.10	-137.80	-147.38
132	-111.04	-129.22	-134.86	-146.17

Figure 5. RIN spectra vs. bias current. Inset tabulates RIN at specific frequencies. RIN distortions are due to micro-vibrations. The sharp spikes are due to 60 Hz harmonics leakage even though all current sources are battery powered.

5. Noise and Linewidth Correlations

Frequency noise and linewidth should be highly correlated since the linewidth is a manifestation of frequency noise [10, 11]. Figure 6 shows the frequency noise-linewidth correlation of a single device. Both phase noise and linewidth decrease with setpoint (current in this case) and enter saturation at the same time.

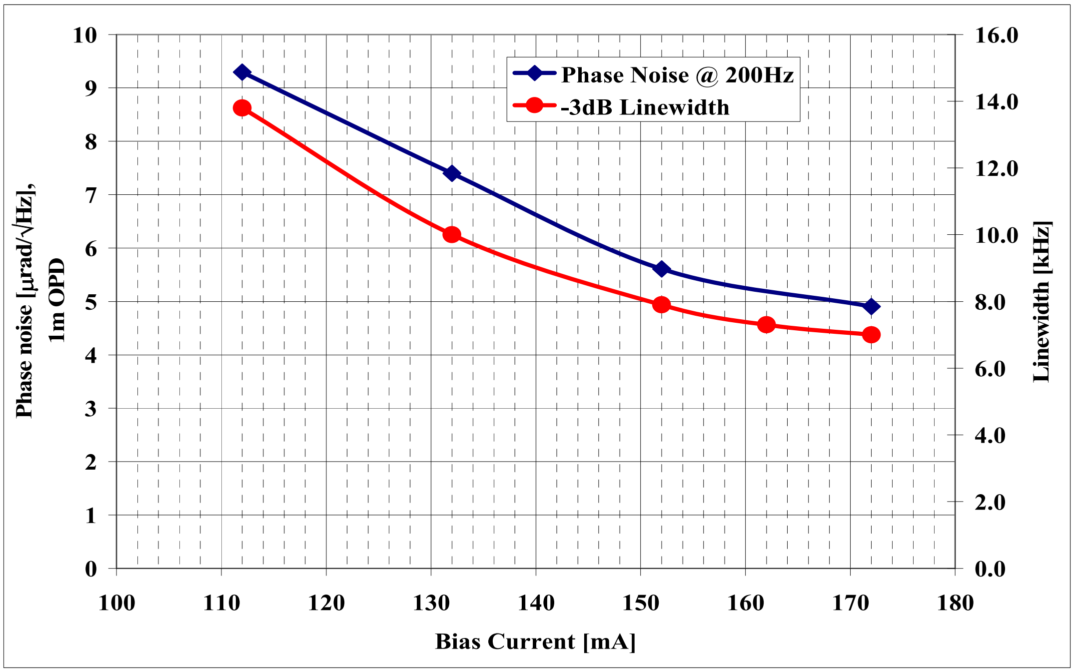


Figure 6. Linewidth and Phase noise (at 200Hz) correlation.

RIN-to-Phase-Noise correlation can be explained by the coupling of the phase fluctuations to intensity fluctuations through carrier density/refractive index fluctuations [12, 13]. Figure 7 shows the correlation between phase noise and RIN.
Also from figure 7 one can observe that the correlation between phase noise and RIN starts to break down as phase noise enters saturation region.

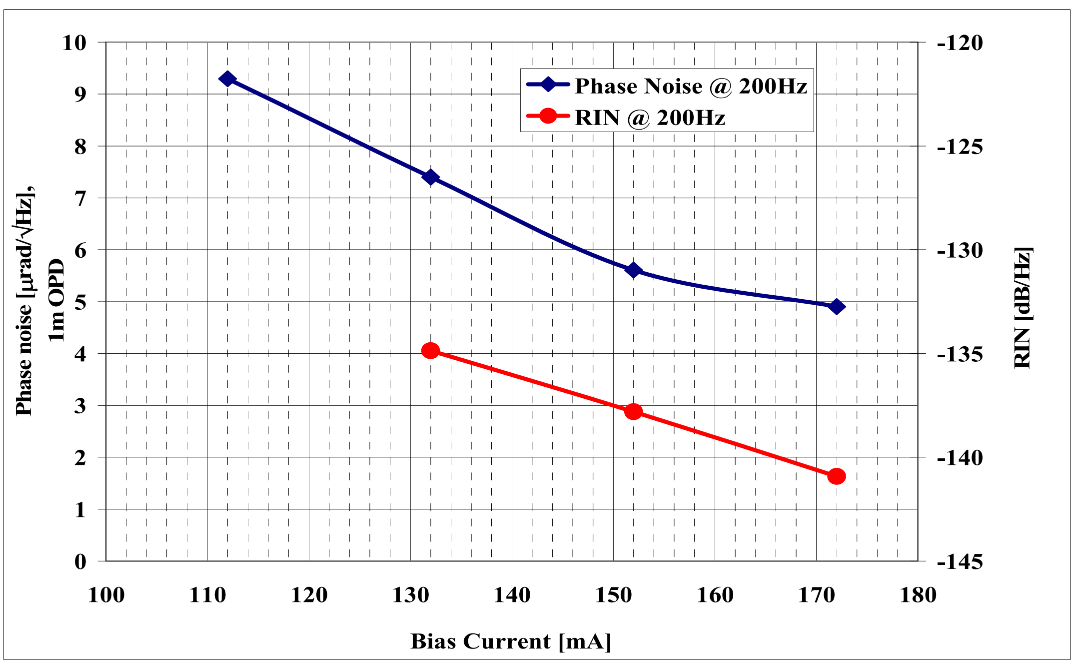
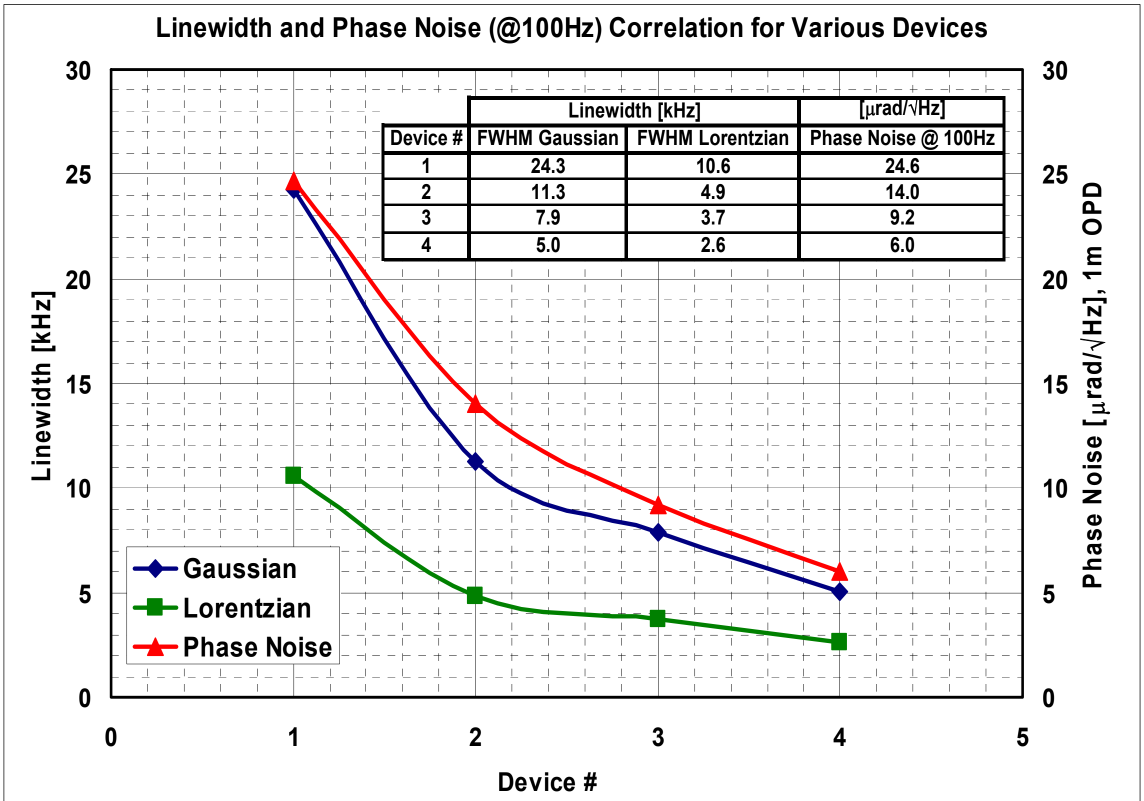


Figure 7. RIN and Phase noise (at 200Hz) correlation.

Figure 8 shows the phase noise to linewidth correlation for various devices. *A linewidth of 2.6kHz was obtained for device number 4.*



Device #	Linewidth [kHz] FWHM Gaussian	FWHM Lorentzian	[µrad/√Hz] Phase Noise @ 100Hz
1	24.3	10.6	24.6
2	11.3	4.9	14.0
3	7.9	3.7	9.2
4	5.0	2.6	6.0

Figure 8. Linewidth and Phase Noise (at 100Hz) correlation for various devices.

6. Stability Under Vibration and Acoustic Noise

Planar ECL laser is designed to operate under vibration and in harsh environmental conditions. Planar ECL cavity is robust and intrinsically stable, if compared to FBG based laser design.

- The SiO_2 waveguides with Bragg gratings are part of the solid-state substrate
- The polarization maintaining waveguide has a rectangular cross-section, and therefore is free from intracavity phase delay for orthogonal polarizations if vibration introduces birefringence

The laser package design has been optimized for operation under vibration by proper integration of the cavity sub-assembly inside the 14-pin butterfly package. Phase noise test was performed under broadband (10-100 Hz) vibration in 3 orthogonal directions.
Normalized phase noise sensitivity to vibration for 3 different planar ECL lasers is shown in figure 9 for the most sensitive direction. The vibration sensitivity is measured as the change in phase noise [dB] normalized to 0.01G acceleration (rms over 1 Hz) applied to the laser under test.

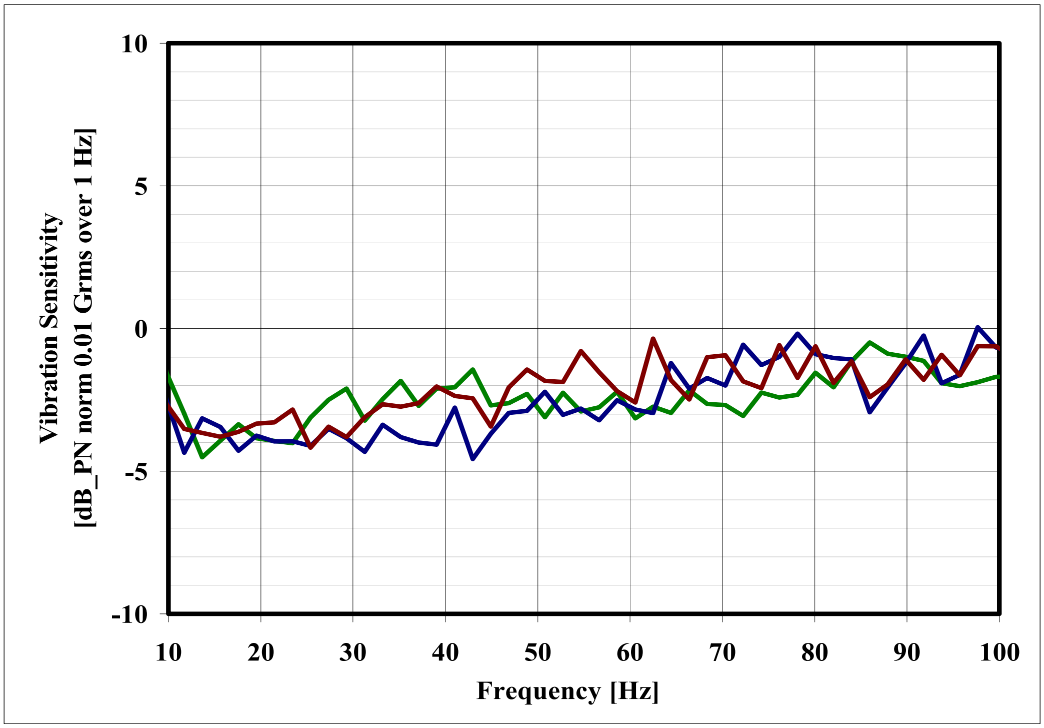


Figure 9. Normalized phase noise sensitivity to vibration for 3 different planar ECL lasers is shown for the most sensitive direction. PN=Phase Noise. The vibration sensitivity is measured as the change in phase noise [dB] normalized to 0.01G acceleration (rms over 1 Hz) applied to the laser under test.

7. Reliability and Wavelength Stability

The laser is designed for long-term operation under demanding environmental stress conditions. All sub-components and packaging technology for the planar ECL have been previously Telcordia qualified for telecommunication applications.

The laser has shown excellent wavelength stability and consistency of performance parameters over long-term operation and over case temperature range.

- Wavelength change vs. TEC temperature: ~15 pm/ºC, ~6 times less sensitive than typical DFB
- Wavelength change vs. bias current: ~0.2 pm/mA
- Wavelength change over operational case temperature range: < ± 20 pm
- Total "end of life" wavelength deviation < ± 100 pm

The wavelength stability is sufficient for demanding applications without additional wavelength locker.

8. Planar ECL Applications

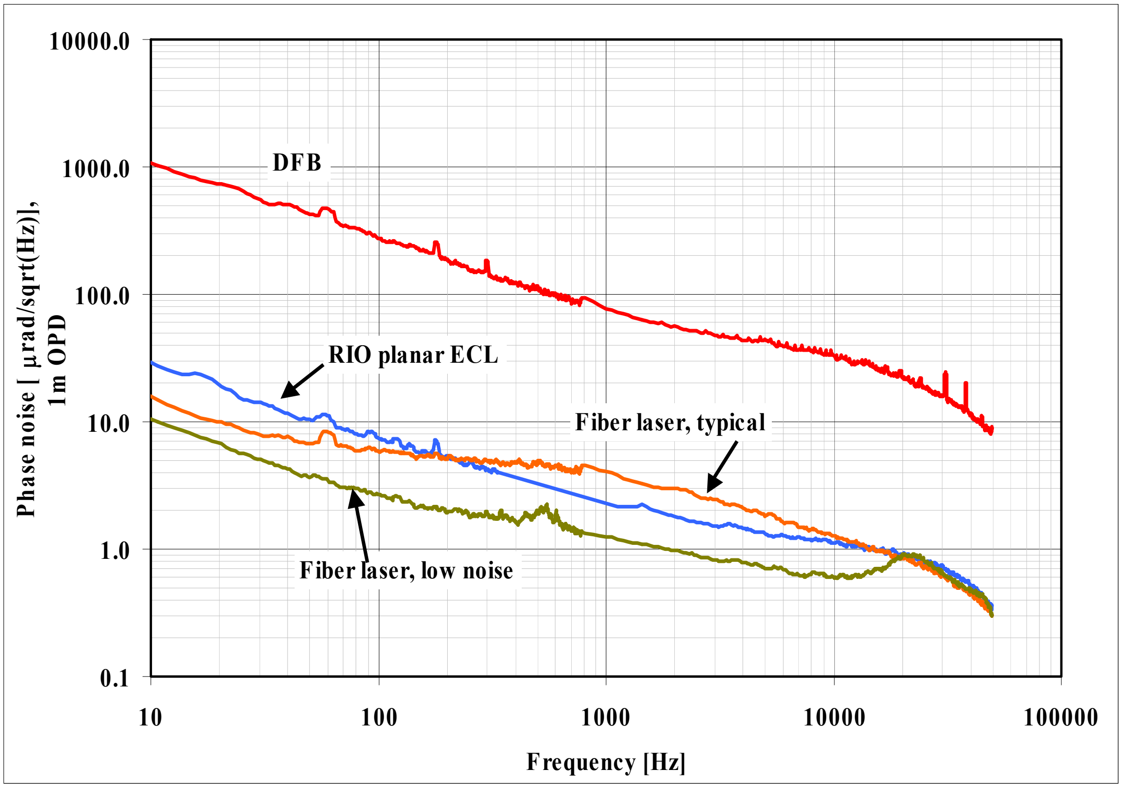


Figure 10. Normalized phase noise of various laser types (semiconductor DFBs, RIO planar ECL, and two performance grades of fiber lasers) used for remote interferometric sensing. The phase noise performance of the planar ECL is approaching the performance of the typical fiber laser, which indicates a high performance capability and suggests suitability for a wide range of distributed sensing applications. Phase noise values are normalized to 1meter interferometer optical path difference (OPD). Phase noise units are µrad/√Hz.

Planar ECL phase noise performance is comparable to fiber laser as indicated in figure 10. As there are various design approaches for multi-channel interferometric interrogation, and fiber sensor designs can offer a wide range of sensitivity, it is helpful to segregate interferometric interrogation into two general classes:

- Path Compensated Time Division Multiplexing (PCTDM)
- Path Mismatch Multiplexed (PMM).

Applications for the PLANEX™ (planar ECL) laser are presented in table 2.

Table 2. Low phase noise ECL applications.

Application	PCTDM	PMM
Physical Security (perimeter or boundary, buried or fence	all	most
Civil Structure monitoring	all	most
Oil and Gas (down-hole, sea-bed, streamers)	all	some
Marine surveillance (most active and passive applications)	most	some

Applications identified above can utilize a very large sensor count. Both PCTDM and PMM interrogation approaches are compatible with TDM/DWDM multiplexing to attain high channel counts. When these systems demand multiple wavelengths there is a significant advantage to the use of the PLANEX™ (planar ECL) laser due to its lower cost and high reliability when compared to fiber lasers. The PLANEX™ planar ECL has been designed in several interferometric systems and tested in several field trials. It provided high performance, comparable to that of a fiber laser [14].

9. Conclusions

For the first time, a narrow linewidth and low phase/frequency noise 1550 nm DWDM planar waveguide based ECL was developed to satisfy most of the interferometric sensing performance requirements in a small package, providing high stability, reliability and low cost. We presented planar ECL with linewidth = 2.6kHz, phase/frequency noise comparable with that of long cavity fiber lasers, RIN = -147.5dB/Hz at 1kHz, and power ≥ 11mW. Furthermore, the PLANEXTM planar ECL laser is designed to operate under vibration and in harsh environmental conditions. Results show that planar ECLs meet requirements of interferometric applications with demanding environmental conditions.

10. References

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