An Investigation and Reduction of Electro-Optical Noise in Tunable Diode Laser

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Abstract

A double FFT (DFFT) procedure is developed to reduce the effect of 1/f noise in the spectrum of Distribution FeedBack (DFB) tunable diode laser. Simulations and experimental results are preformed. An obvious effectiveness of the double FFT on the 1/f noise spectrum has been observed. The 1/f noise was monitored in the three terminals. A linear fitting of the 1/f was verified for Single FFT (SFFT) and (DFFT) to calculate the Frequency Exponent Factor (FEF) α and the amplitude of 1/f noise.

Keywords: Fast Fourier transformation, tunable diode laser, Double Fast Fourier Transform.

Introduction

Near infrared InGaAs-InP distributed feedback (DFB) tunable diode laser which can be designed to emit almost anywhere in the spectral range between 1μm and 2μm. These diode lasers are compact and low power consumption, and more importantly, they can operate at room temperature and compatible with commercial optical fiber. As such, **t**unable **d**iode **l**aser (TDL) is considered a key component in many applications such as high resolution spectroscopy, optical telecoms, and metrology. However, its light power spectrum suffers from having a large 1/f noise component. The TDL wavelength is “tuned” either by changing the injection current of the diode laser or by varying the temperature of the junction region (p-n junction) of the diode. This injection current is a source of 1/f noise due to the generation recombination process of charge carriers (electrons and holes) [1]. Also, the noisier injected current to the diode laser will generate noisier stream photons from the laser diodes [2]. The 1/f spectra from intensity fluctuations in the optical spectrum and current noise of the diode laser were first noted by Tenchio [3], in the range of $2 - 3 \times 10^5$ Hz.

A cross- correlation between the electrical noise and optical fluctuations was also monitored [4, 5]. Moreover, Dandridge and Taylor observed a correlation between l/f intensity fluctuations and frequency fluctuations in the optical emission [6, 7]. 1/f noise is actually observed in frequency noise spectra which would expand the line-width of the laser light [8-12]. The the 1/f noise spectrum is one of the most important contributors in the sampling data that has been measured to evaluate reliability and stabilizing of TDL [13-18]. Therefore, the1/f noise is considered an important aspect of diode lasers to investigate.

Several methods have been used to reduce the effect of 1/f noise of the laser diode light spectrum. For example, an optical feedback from an off-axis confocal cavity has been used to narrow the linewidth of lasers to kHz level [19] or using a single-mode fiber resonator [20]. Optimizing design parameters, such as cavity length, power, and gratings have been conducted to reduce the linewidth of the extended cavity diode lasers (ECDL) below 100 kHz [21]. A frequency discriminator, such as a fiber interferometer [22–26] and narrow optical filter [27] which converting the frequency fluctuation of lasers into intensity variations using electrical feedback methods has been developed to reduce the linewidth of diode lasers. In order to measure the linewidth broadening of the diode laser due to 1/f noise, the self-heterodyne linewidth method has been performed on the different types of diode laser [28, 29] . However, this method is not fully characterized the linewidth broadening because it only measures 3dB linewidth [30,31]. The delay self-heterodyne linewidth method with phase detection has also been employed to measure the linewidth broadening of the DFB and SGDBR diode lasers [32].

The Fast Fourier Transform (FFT) is the one of the most important analysis methods used to investigate information that is carried by a signal in the frequency domain. With Fast Fourier transform analysis, it is necessary to sample the input signal with a sampling frequency f_s that is at least twice the bandwidth of the signal, due to the Nyquist limit [33,35]. A Fourier transform will then produce a spectrum containing all frequencies from zero to $f_s/2$. A new method is developed to reduce the effect of 1/f noise using an FFT on simulation data [36-38]. A DFFT (Double Fast Fourier Transform) of the 1/f noise spectrum converts the spectrum to approximately flat [| F (A/f) | = | -i π A sgn (f) | = A π], where | F (A/f) | is the magnitude of an FFT of the (A/f^{α}) noise. An FFT procedure is demonstrated to evaluate the Power Spectral Density (PSD) of the noisy components (e.g., electronics and optical devices) experimentally in the TDL. The relation between the injected current to the tunable diode laser and α which represents the exponent parameter that determines the type of 1/f noise spectrum (A/f^{α}) was evaluated. Also, the relation between the injected current and the amplitude of the 1/f noise which represent by the factor (A) was performed.

It is worth mentioning, a DFFT has been used in various applications [39-42]. However the double FFT procedures employed in those applications differ from the purpose, method and application used in this work. For example, a double Fourier integral analysis is used as an analytical approach to determine the phase-leg switched voltage spectrum under conditions of natural sampling of a four-switch three-phase (B4) voltage source inverter in [43]. In [44], a fast acquisition method was put forward for high dynamic DSSS signal catching based on double layers of short FFTs. The first FFT layer was used for quick acquisition of code and carrier. It can only give a coarse carrier frequency. The second FFT layer was used for accurate frequency calculation based on the result of the first FFT layer. In [45], a double Fourier Transform process process was implemented in a sequential form in a beam forming network using a Two-Dimensional Double Fast-Fourier-Transform Beam-Forming-Network (2D-Double-FFT-BFN) concept.

Theory of 1/f Noise in the Tunable Diode Laser

The noise sources $F_i(t)$ which describe the relation among the carrier number $n(t)$, photon number $s(t)$ and optical phase $\phi(t)$ are presented by two rate expressions [46].

$$\frac{dn(t)}{dt} = \frac{i(t)}{q} - \frac{n(t)}{\tau_n} - g\frac{n(t)-n_0}{1+\epsilon\, s(t)} + F_n(t) \qquad (1)$$

$$\frac{ds(t)}{dt} = g\frac{n(t)-n_0}{1+\epsilon s(t)}\, p(t) - \frac{s(t)}{\tau_p} + \frac{\beta_{sp} n(t)}{\tau_n} + F_s(t) \qquad (2)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha_{lw}}{2}\, g\left(n(t) - \bar{n}\right) + s(t) - F_\phi(t) \qquad (3)$$

where $i(t)$ is the modulated current of the diode laser; q is the electron charge; τ_n is the carrier lifetime; τ_p is the photon lifetime; g is the gain slope constant coefficient; ϵ is the nonlinear gain compression factor; n_0 is the carrier number of transparency; β_{sp} is the fraction of spontaneous emission coupled into the lasing mode; α_{lw} is the linewidth enhancement factor; $\bar{n}$ is the time-averaged carrier number.

The intensity noise and phase noise of diode laser are introduced mainly by Langevin noise forces F_s, F_ϕ respectively [47]. The low frequency intensity noise governs by two factors, gain fluctuations (g) and spontaneous emission related factorβ. These fluctuations were considered to be caused by tow assumptions: 1) the fluctuations in the absorption coefficient, 2) the uncorrelated fluctuations in the density of mobile charge (free electrons and holes) [48]. A voltage noise spectral density $S_D(f)\ (\frac{V^2}{Hz})$ of Laser voltage fluctuations could be represented by the following expression [49].

$$S_D(f) = 4KTR + \frac{\alpha_s}{N\times f} R^2 I_L^2 + S_{D1}(f) \qquad (4)$$

where $4KTR + S_{D1}(f)$ is the white noise term and T (K) the absolute temperature. The 1/f noise between (1 Hz-100 kHz) is presented in second term which relates to R, proportional to I_L^2.Its expression is given by Hooge's relation [50]:

$$\frac{S_i}{I_L^2} = \frac{S_r}{R^2} = \frac{\alpha_s}{N\times f} \qquad (5)$$

Herein, $I_L$is the mean value of the instantaneous current i: $I_L = < i >$; S_r is the spectral power density of the 1/f noise of the resistance R; N is the total number of free charge carriers in the InGaAsP layer as show in Fig. 1; f is frequency at which the measurement is performed; α_s Hooge's parameter; $S_{D1}(f) = \frac{\overline{v_1^2}}{\Delta f}$ is the intrinsic spectral density of the laser junction (v_1: RMS noise voltage). In addition, the optical light power $S_{P_{op}}$ exhibits noise fluctuations which relates to the fluctuations of monitoring photocurrent, and it given by the photocurrent spectral density $S_{I_{ph}}$.

$$S_{I_{ph}}\left(\frac{A^2}{Hz}\right) = \varepsilon\, S_{P_{op}}\left(\frac{W^2}{Hz}\right) \quad (6)$$

where $\varepsilon\left(\frac{A}{W}\right)$ is the apparent sensitivity of the photodiode.

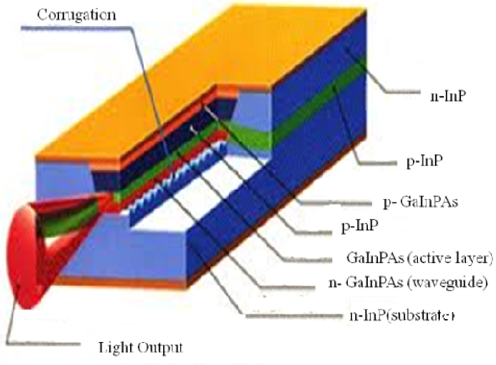

Figure 1. InGaAsP DFB Diode Laser.

1/f Noise Reduction Using DFFT

Application of DFFT Process of The 1/f noise

Noise is a major factor limiting measurement sensitivity in many fields of science. Due to their quantum properties, diode laser exhibit a large 1/f noise spectrum. Many systems try to minimize this effect by using high frequency techniques, or use a huge number of data points so that the noise can cancel each other. However, the requirements of our system make this difficult. We therefore are examining techniques to reduce the effects of 1/f noise on measurements made at lower frequencies, e.g., 500 Hz.

A new method is developed to reduce the effect of 1/f noise by performing multiple Fourier Transforms (FFTs) on the signal received at the photodetector. This method is then tested both in simulation and experiments. In simulation, the 1/f noise signal is generated by calculating the complex numbers of the data points in the frequency domain [51]. The power of the FFT of 1/f noise ($\boldsymbol{A}$) follows a $\mathbf{1/f^{\alpha}}$ profile, where $\boldsymbol{\alpha}$ is usually about a 1.0 and phase angle ($\boldsymbol{\theta}$) is generated randomly using Eq.7. After performing an inverse FFT, the noise data in the time domain are then obtained.

$$n_d(f) = A(\cos\theta + i\sin\theta) \quad (7)$$

If we set $\alpha = 1$ and rewrite A/f^{α} as $g(x) = \frac{A}{x}$, where $-\infty < x < +\infty$, then its Fourier transform will be as follows:

$$G(f) = \int_{-\infty}^{+\infty} g(x)\, e^{-j2\pi f x}\, dx = \int_{-\infty}^{+\infty} \frac{1}{x} e^{-j2\pi f x}\, dx = -i\pi A\, sgn(f)$$

Where $sgn(f)$ Is the sign function, and the magnitude of $G(f)$ is

$$|G(f)| = |-i\pi A\, sgn(f)| = A\pi \quad (8)$$

If the noise spectrum follows a 1/f profile after performing an FFT on it, then performing a second FFT converts this 1/f profile to approximately constant profile.

DFFT Procedure for Looking at 1/f Noise

The following Table 1 and flowchart in Figure 2 describes (the DFFT procedure that is performed on the raw data of the 1/f noise in both simulation and on the experimental data.

Table 1. Describes the DFFT procedure on the simulation and experiment noise data.

a	Sample the signals from the external photodiode (PD). The data sequences are X= {x (1), x (2)… x (M_1)}, where the number of sampling points is M_1.
b	Apply an FFT on the time domain data X to obtain the Power Spectrum Density (PSD), and then remove the DC part of the whole signal of FFT Y1 = {y (2), y (3)… y (M2)}, where M2 is the length of the first FFT computation.
c	Apply an FFT (power spectrum) on the half of the frequency domain data Y1 = {y (2), y (3)… y (M2/2)}, and get DFFT Y2 = {y (2), y (3) … y (M3)}, where M3 is the length of the DFFT.

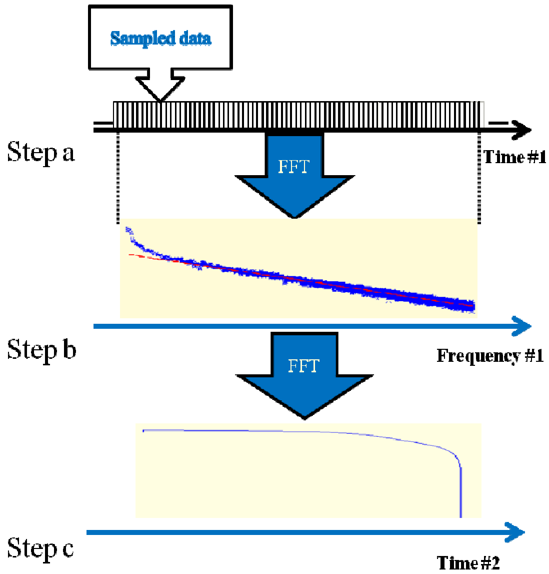

Figure 2. Flowchart of DFFT on the 1/f noise.

Internal Circuit of TDL

Figure 3a present the 14 pin package of the diode laser. Figure 3b shows the internal structure of this package. The main device is an InGaAsP commercial Distribution Feed Back (DFB) butterfly (NLK1655STG) Laser Diode (LD), with (1m) pigtail fiber optics. The nominal wavelength is 1543.75 nm, and the maximum fiber-optic output power is 26.8 (mW). The laser is activated by applying a forward current exceeding the threshold value I_{th} = 19 mA at a diode temperature of T = 22 ^{o}C. The internal circuit of the butterfly DFB consists of an InGaAs PIN monitoring photodiode (internal PD), a thermistor to monitor the laser temperature, and a Peltier cooler to control the temperature of the diode. In this work, this PD is called the internal photodiode and it is monitored to measure the 1/f noise spectrum that is generated by the laser light. The PD is mounted with a tin-lead solder at around 400 picometer from the rear facet of the laser with an angle of 30" to prevent optical feedback in the laser cavity.

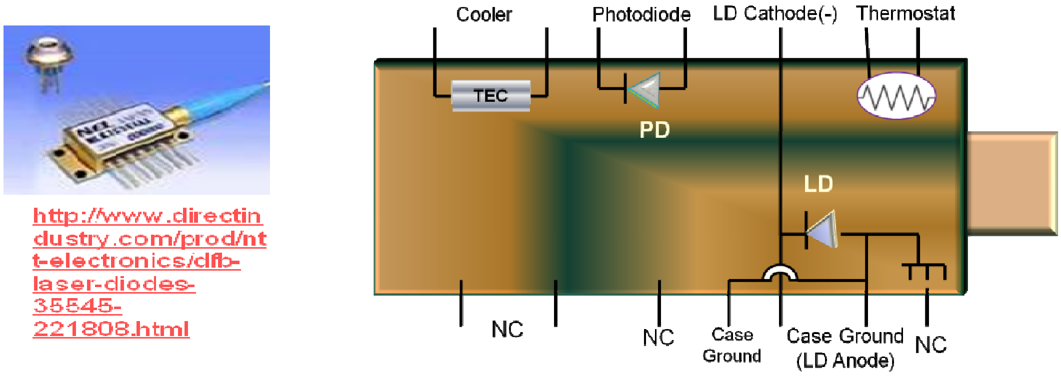

Figure 3. Near-infrared tunable diode laser: package picture of TDL (left), internal circuit of TDL (NLK1655STG) (right).

1/f Intensity Noise Measurements
Experiment Setup

Figure 4 shows the experimental setup of the 1/f intensity and wavelength noise measurements. A low noise ($SNR = 78 \times 10^6$) laser driver (Wavelength Electronics LDTC1020) is employed to drive the diode laser; an InGaAs PIN photodiode (Thorlabs SM05PD5A) with spectral response (800-1800nm), responsivity in near-infrared region is about 1.2 A/W, and Noise Equivalent Power (NEP) is about 3×10^{-14} W/√Hz an electronic PCB board that performs a voltage to current converter and amplification. The data acquisition System (DAC) device has 16-bit analog input and output with a 250K Sample/sec maximum sampling rate. An InGaAs PIN photodiode (external PD) - (Thorlabs SM05PD4A) with spectral response (800-1800nm) is used for the detector, and its Noise Equivalent Power (NEP) is about 3×10^{-14} W/√Hz. The LabView signal Express was the software that was used to collect the data from the external photodiode, internal photodiode, and the laser current terminal. SpectraWiz was the software that used to collect the data from the NIR spectrometer.

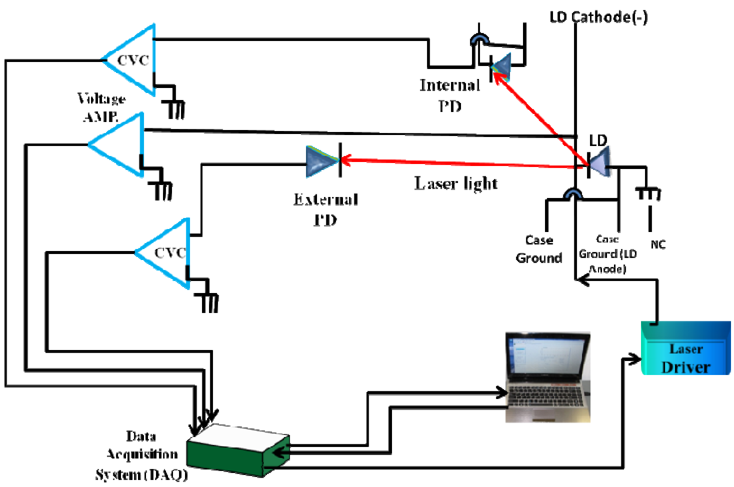

Figure 4. Experimental Setup of 1/f Intensity and Wavelength Noise Measurements.

1/f Intensity Noise (Simulation data)

In this work, the 1/f intensity noise was created in the simulation. The simulation data noise was generated according to the details of which are listed in section 3.1 (A/f^{α}, A= α =1). Figure 5a shows the typical simulated 1/f noise in the frequency domain after the Single Fast Fourier Transform (SFFT) while Figure 5b shows the

DFFT of the 1/f spectrum. In the DFFT, the noise profile is converted from $1/f$ to approximately flat, such that the 1/f noise has less influence on the signal at low frequencies.

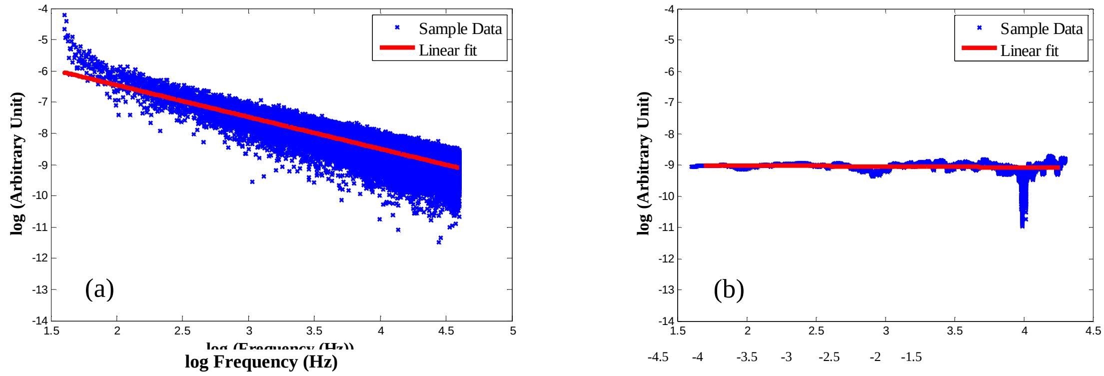

Figure 5. Comparison between SFFT and DFFT of the simulation data of 1/f noise spectrum: a) The spectrum after SFFT, b) The spectrum after DFFT.

1/f Intensity Noise (Experimental Data)

Noise was measured at three points in the system: at the output of the external photodiode, the internal photodiode, and the laser current terminal. External photodiode which measures the total fluctuations that are generated from the following sources **1)** the noise of the output light power of the diode laser, **2)** the noise from laser current, and **3)** the noise of the electronic circuit. The total noise seen at the output of the external photodiode is a combination of the noise that is in these three components. The power spectral density was calculated at different driving currents of the diode laser. The amplitude A of 1/f noise was also calculated at 1Hz and at 1 KHz also calculated. In addition, the Frequency Exponent Factor (FEF) α as shows in Eq. 9 was calculated. For the 1/f power spectrum α has been reported as being (1.0 ± 0.1) [52].

$$S_U(f) = \frac{A}{f^{\alpha}} \qquad (9)$$

Figure 6a shows the experimentally measured noise spectrum when the injected current $\mathbf{i_{in}}$**= 141 (mA)**. The SFFT spectrum from the external PD (optical + electronic noise) is composed of 1/f noise in the low-frequency range (10Hz – 2KHz), with other noise sources (shot noise, white noise, and thermal noise) appearing above 2KHz. Figure 6b displays the DFFT spectrum, which is approximately flat. The main advantage of the DFFT procedure is to convert the 1/f noise profile to an approximately flat profile, the power of noise in SFFT equal the power of noise in DFFT, according to the energy conservation law. However, the power of the noise keeps the same the flat DFFT spectrum indicates noise is evenly distributed over the range of frequencies. Thus, a high noise power at low frequency in the SFFT spectrum will be converted to a lower noise in the DFFTin the measurement signal.

The Frequency Exponent Factor (FEF) of the $1/f^{\alpha}$ noise ($0 < \alpha < 2$) was calculated by performing a linear fitting function of the SFFT spectrum, as shown in Figures 6a. Data was collected from the external photodiode component in the low-frequency range (4 Hz < f < 2 KHz) according to the relation (9). In the same relation, (A) represents the amplitude of the 1/f noise at specific frequencies. The amplitude of the intensity noise (A) was determined by taking data and performing a linear fit to Eq. 9.

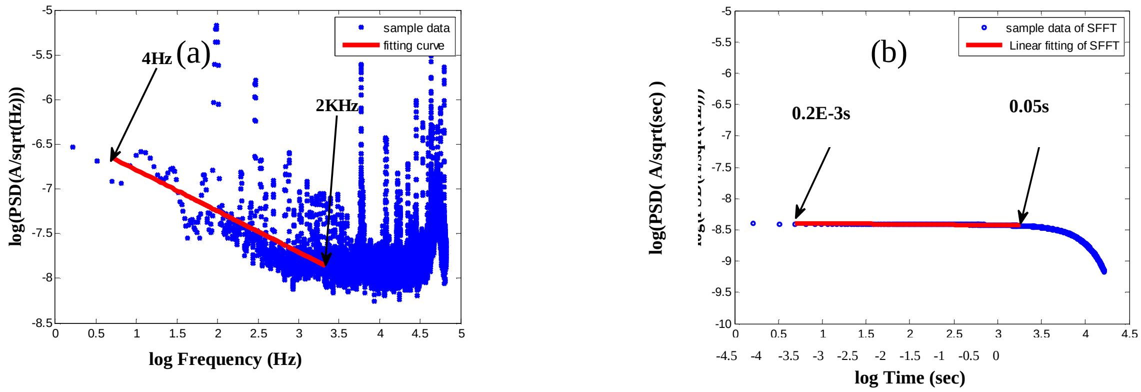

Figure 6. Comparison between SFFT and DFFT of the1/f noise spectrum from a 1543 nm DFB diode laser. a) The spectrum after SFFT showing 1/f noise, and b) The spectrum after DFFT showing a flat spectrum. The raw data from External PD at i_{in}= 141 (mA) and T =22C°.

Measurements of the1/f noise spectrum were repeated three times for every value of the injected current. Then, the relation between α and the injected current i_{in} was obtained. For example, Figure 7a shows this relation for the external PD. It shows three regions:

1. **Under the threshold current region,** of i_{th} = 19 mA, where α < 0.2. This indicates, the value of the injected current isn't able to generate the laser light which consider the most contributor in 1/f noise spectrum. Thus, the spectrum in this region is almost flat.
2. **Near the threshold current region,** where α is increasing as i_{in} increases at 22 (mA). The beginning of the laser operation, the laser power is very low and cannot induce a much more current carriers in the diode laser that will produce 1/f noise spectrum. So that, the spectrum has also a flat characteristic.
3. **The laser operation region**, $i_{in} >$ 60 (mA), where α ≈ 0.9. It is worth mentioning that the α value stays constant with increasing injected current after the threshold current is reached. That means the spectrum has 1/f noise characteristics especially, at the interesting point (inside the ellipse) where the value of injected current 141 (mA) which was used to gas measurements were performed.

Figure 7b shows the relation between the amplitude of the noise in (mA) at 1Hz and the injected current. There are also, three regions. **Under the threshold current region,** the amplitude is about 5E-8. **Near the threshold current region,** the value is continue having approximately the same value. **Laser operation region,** the value of the amplitude of noise is nearly independent of the injected current [2,7]. It reaches about 4E-7at 141mA (ellipse point). Investigate the amplitude of 1/f noise at 141 mA is important. Because it is the desired current value which make the absorption peak of ammonia gas be in the middle of the sine wave. As a result, the second harmonic will be the intensive harmonic in the FFT spectrum of the absorption signal.

The same characteristics were also extracted from the DFFT spectrum (α and A value), especially between 0.3 ms - 0.05 s. On one hand, to compare between Figure 7a and Figure 8a, the α value has been shifted from about 0.9 in the SFFT to 0.03 in the DFFT. This indicates a flater noise spectrum in the DFFT, notice that α = 0 indicates a completely flat spectrum. On the other hand, the amplitude of the noise which appears in the Figure 7b and Figure 8b shows a noise amplitude reduction and by a factor of 100 at 1Hz. In addition, An interesting point 141 (mA) which appears inside the ellipse, this is the point we take gas measurements at. From the two figures, it can be verified that the DFFT procedure reduces the amplitude and the fluctuations of 1/f noise density readings as shown in Table 2 (in the end of current section).

Furthermore, the amplitude of noise at 1KHz is also measured for the SFFT and DFFT processes. The intent behind the calculation of the amplitude of noise at 1KHz is to show that the 1/f noise density is reduced after applying the DFFT procedure. If so, the measurement of the absorption signal at the second harmonic (1KHz) will become more reliable. Figure 9 displays the relation between the injected current and the spectral noise amplitude at 1KHz for a SFFT and at 1ms for the DFFT. The circle marks refer to the SFFT and the cross ones belong to DFFT procedure. At the typical operating laser current of (141 mA), the amplitude of the noise at 1 ms is reduced by a factor of 10 after applying the DFFT procedure. Notice that the amplitude of the noise after the

DFFT process has been normalized, so this is a true reduction. Also, the fluctuations in the amplitude of the noise over three measurements is decreased. All the calculations that were described in this regard have been implemented in Matlab code.

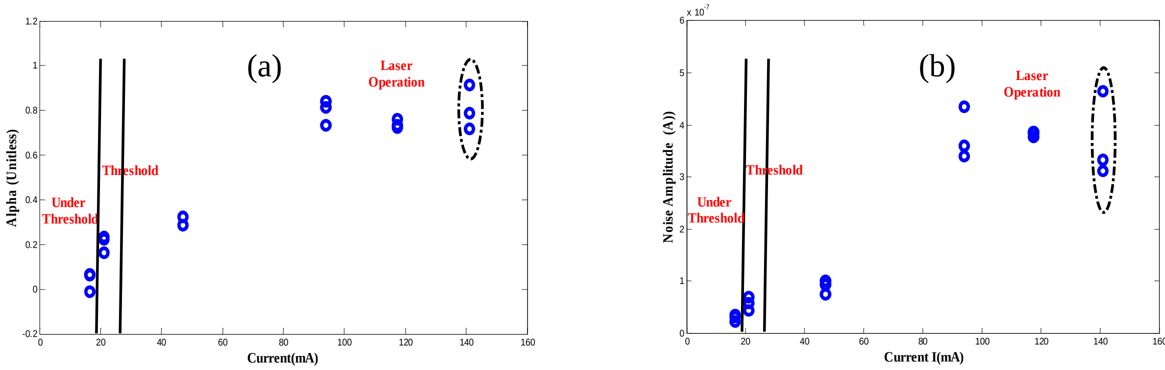

Figure 7a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C° uses the SFFT process. The raw data were collected from the external photodiode.

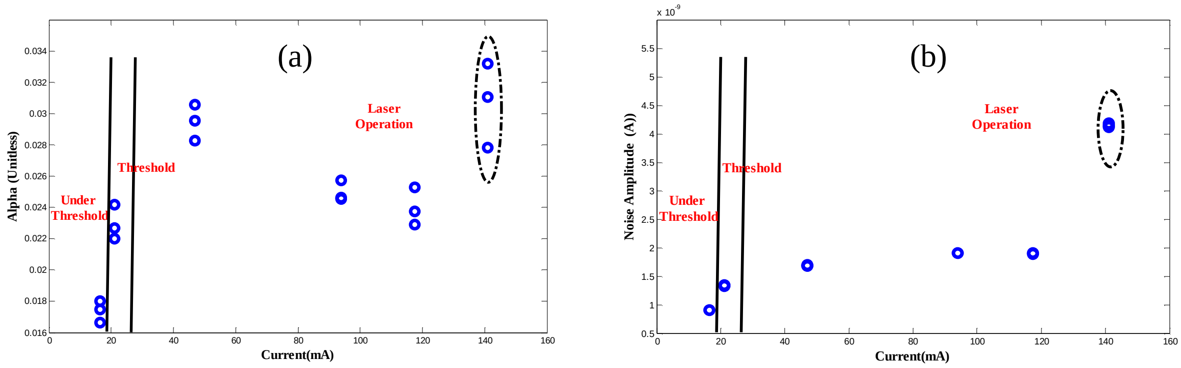

Figure 8a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C° uses the DFFT process. The raw data were collected from the external photodiode.

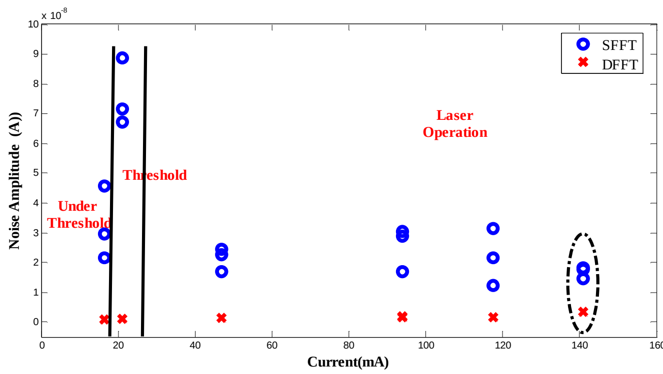

Figure 9 Comparison between the amplitude of the noise as a function of the injected current to the diode laser at 1KHz using SFFT and 1ms using the DFFT. The raw data were collected from the external photodiode.

A photodiode embedded in the laser package (Internal Photodiode) was used to monitor the power spectrum of the 1/f noise in the laser light intensity alone. This is different from noise in the external photodiode, which includes noise from the laser electronic circuit, laser driver and power supply. The sample data was collected from the internal photodiode (see Figure 3) using a pre-amplifier and current circuit. After the data were sent to an analog to digital converter and then to the computer. LabView signal express is used to control the data acquisition process. Then, the data were processed using Matlab.

The interest of monitoring noise across laser diode is to identify the type of the noise. We can measure the noise in the light intensity from within the laser diode package, and determined its spectrum when the normal driving current of 141 (mA). Also, it is important to evaluate the amplitude of the noise at 1KHz of the SFFT spectrum and compare the result with what obtain after applying DFFT process. Figure 10a shows the SFFT spectrum of the data that was collected from the internal photodiode. It is obvious the SFFT spectrum is comprised mainly of 1/f noise between 16Hz-50KHz. This measurement was obtained at i_{in}= 141mA and T= 22C^{o}. The DFFT process was then applied to the data, with the results shown in Figure 10b. As can be seen the whole spectrum has been converted to the nearly flat spectrum between 0.3E-3s - 0.1s.

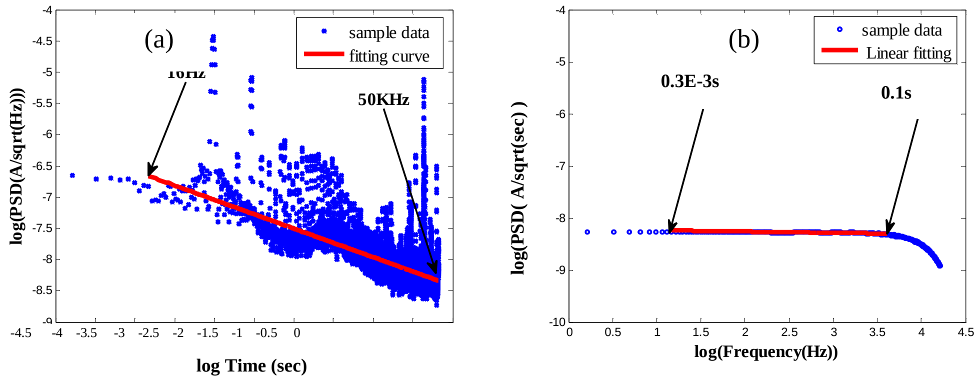

Figure 10. Comparison between SFFT and DFFT of the1/f noise spectrum from a 1543 nm DFB diode laser. a) The spectrum after SFFT showing 1/f noise, and b) The spectrum after DFFT showing a flat spectrum. The raw data from External PD at i_{in}= 141 (mA) and T =22C^{o} at I_{in} = 141 mA, T= 22 C^{o}. The raw data were collected from the internal photodiode. a) SFFT spectrum, and b) DFFT spectrum.

Figure 11a shows the alpha parameter from Eq. 9 as a function of the injected current. The graphs display the three operating regions of the laser versus injected current. 1) **Under threshold current**; 2) **Threshold current**; and 3) **Laser operation**. α fluctuates around (0.5) in the 1st , and 2nd region, while it varies from (0.6- 0.9) in the 3rd region. However, the exact value of alpha at the interesting point (141 mA) is about o.95. In addition, the relation between the (A) parameter which represents the amplitude of the noise and the injected current was plotted as illustrated in the Figure 11b. The amplitude of noise fluctuates around (0.4 E-6 Amp.) after the threshold current is reached. However, it increases at i_{in} = 141mA (ellipse point) to reach (0.75E-6 Amp.).

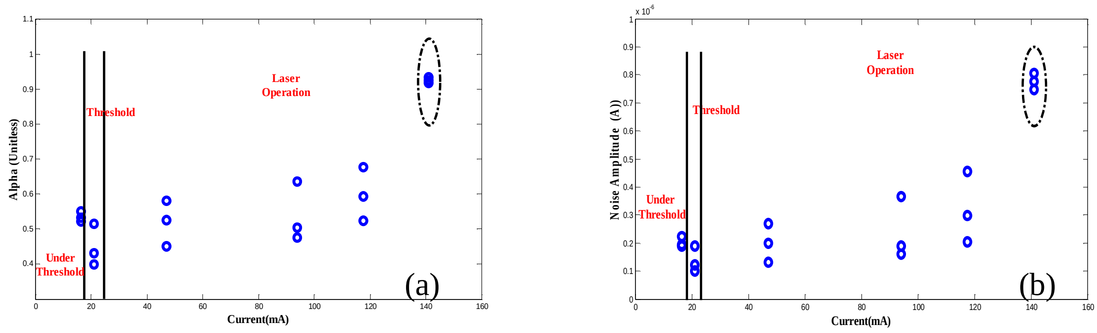

Figure 11a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C^{o} uses the SFFT process. The raw data were collected from the internal photodiode.

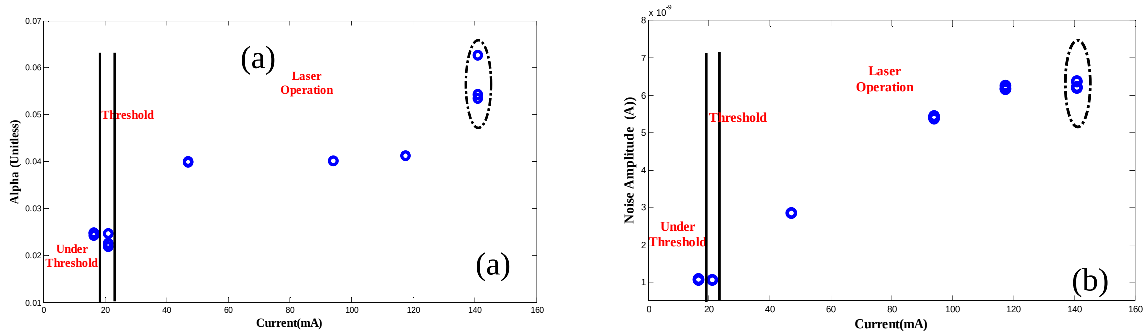

Figure 3-12a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C^o uses the DFFT process. The raw data were collected from the internal photodiode.

The DC term of the SFFT was removed and a second FFT was performed on the data (DFFT). Then, alpha was extracted from the linear fitting curve of Figure 10b. The relation between alpha values and the injected current was plotted as shown in Figure 12a. It is obvious that the alpha value (α = 0.06) has significantly decreased to an extent that can be totally assertion that the1/f noise spectrum has disappeared. Also, the amplitude of the noise was extracted from the same fitting curve at 1Hz, and the relation between the amplitude of the noise and the injected current was plotted, as shown in Figure 12b. The amplitude of the noise at 141mA (ellipse point) is about 6.5E-9 Amps.

Figure 13 shows a comparison between a SFFT and the DFFT procedures, and the relation between the amplitude noise and the injected current to the laser diode at 1KHz. The amplitude of 1/f noise at 141 mA (ellipse point) is about 4E-8 Amp from the SFFT procedure (circle marks) and 1E-9 Amp from DFFT (cross points). This indicates that the DFFT procedure was reduced the amplitude of noise by a factor of 10. If we compare between the value of the amplitude of noise from a SFFT at 1Hz and the DFFT procedure. This value is reduced by a factor of 100 after the DFFT process. For more details see Table 2 (in the end of current section).

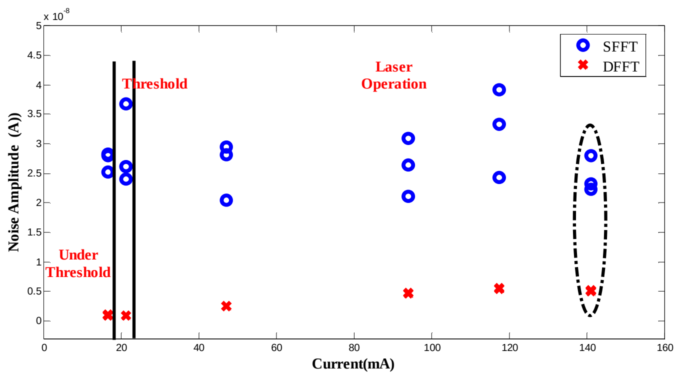

Figure 13 Comparison between the density of the 1/f noise as a function of the injected current to the diode laser at1KHz using SFFT and at 1ms using DFFT. The raw data were collected from the internal photodiode.

Laser current. The laser current terminal which feeds to the laser chip from the laser driver (as shown in Figure 3) was monitored. The current contains an amount of noise however, the kind of noise that is in the laser current does not exhibit 1/f spectrum. Figure 14a shows the noise spectrum after the SFFT process, and it appears the noise might follow a 1/f spectrum. But, after the value of alpha was calculated (see Figure 15a), it became clear that the type of noise isn't purely 1/f noise. This partially explains the reason that why the noise spectrum after the DFFT process, isn't a completely flat spectrum. Although , there are a lot fluctuations around the linear fitting of the sample data from the DFFT spectrum, the value of alpha from that fitting has still been reduced significantly, as shown in Figure 16a.

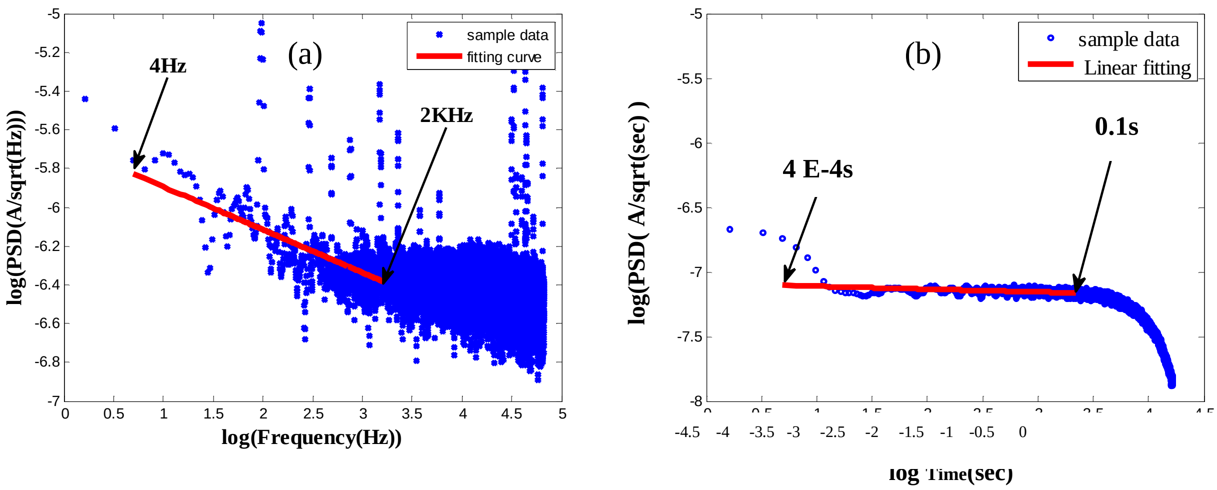

Figure 3-14. Comparison between SFFT and DFFT of the1/f noise spectrum of the raw data from laser current terminal at i_{in}= 141 (mA) and T =22C° a) The spectrum after SFFT, and b) The spectrum after DFFT.

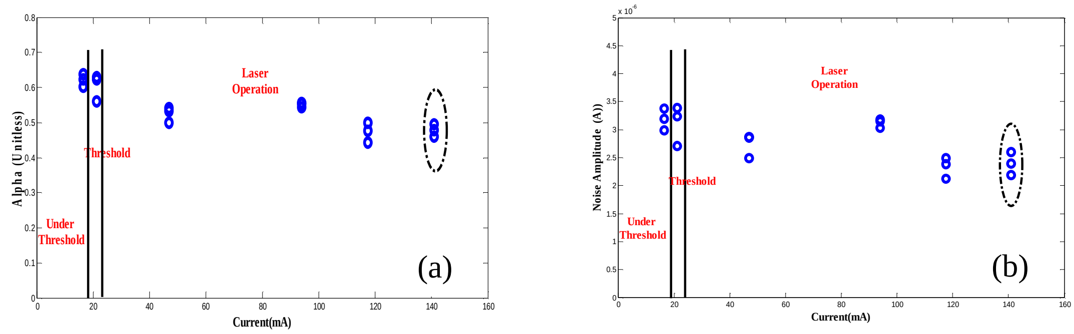

Figure 15a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C° uses the SFFT process. The raw data were collected from the laser diode current terminal.

The amplitude of the noise was calculated from the linear fitting of the SFFT process and the DFFT process. Figure 15b and Figure 16b show the 1/f noise amplitude at 1Hz vs. the injected current to the laser diode for SFFT and in the DFFT process, respectively. This value has been reduced significantly after DFFT process by a factor of 100. In addition, the amplitude of the noise was also calculated at 1KHz for the SFFT spectrum and at 1ms for the DFFT spectrum as appear in Figure 17.

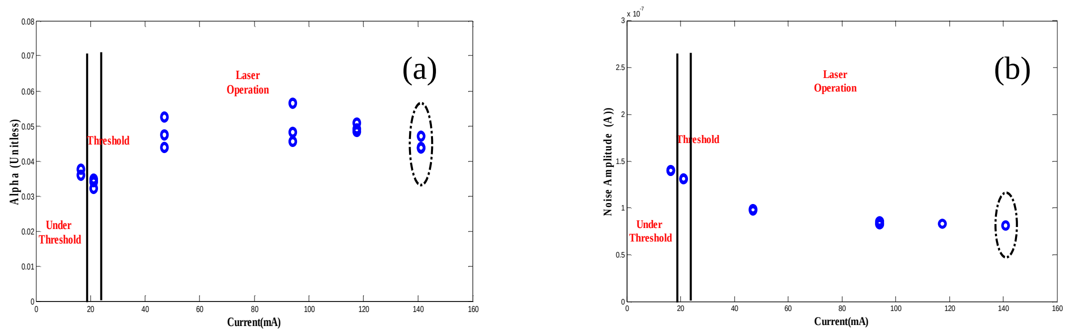

Figure 16a The relation between the injected current of the laser diode and alpha values process. b-The relation between the injected current of the laser diode and the noise amplitude at 1s. When T= 22 C° uses the DFFT process. The raw data were collected from the laser diode current terminal.

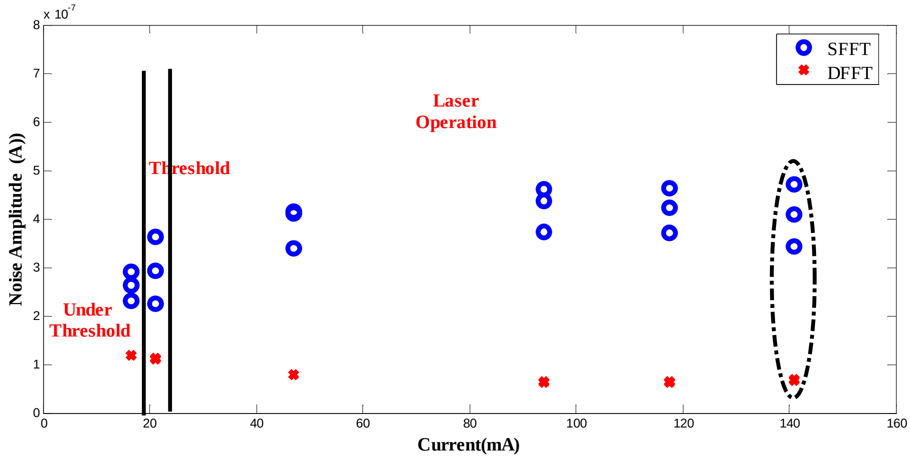

Figure 17 A comparison between the density of noise as a function of the injected current to the diode laser at1KHz using SFFT and at 1ms using DFFT. The raw data were collected from internal photodiode.

The results have been shown a reduction in the amplitude of the noise after DFFT process by a factor of 100 at 1Hz. However, the amplitude of noise decreases by a factor of 10 at 1KHz, The values of the amplitude of noise at 1Hz and 1KHz for a SFFT, also at 1s and 1ms for the DFFT were listed in Table 2.

Table 2. The comparison between the amplitude of noise density at 1Hz and 1KHz from the SFFT process, also at 1s and 1ms from the DFFT process.

Domain (Frequency or Time)	Procedure	Amplitude of Noise Density (Amps.)		
		External Photodiode	Internal Photodiode	Laser Driver Current
1Hz	SFFT	4E-7	2E-6	2E-6
1KHz		1E-8	2E-8	3E-7
1s	DFFT	4E-9	5E-9	8E-8
1ms		4E-9	5E-9	6E-8

Conclusion

In this work a DSP technique was used by performing a DFFT procedure on the sample data. Several conclusions can be listed in the following steps.

1. The results showed that 1/f noise has multiple contributing sources, including the injected current and the laser light generated by the diode. The noise profile can determine by the value of α, which should be $1 < \alpha < 2$. α varies with the amount of the current injected into the diode laser. For example, in case of external photodiode, the α value of a 141mA injection current was about 0.9, indicating a strong 1/f noise component.
2. The intensity noise was manipulated using a Double Fast Fourier (DFFT) procedure after performing a Single FFT (SFFT) procedure. The DFFT procedure reduced the power of 1/f noise, especially in the low frequency ranges (4Hz-4KHz).

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