行政院國家科學委員會專題研究計畫　成果報告

半導體雷射的雜訊：低或然率區之分佈.

計畫類別：個別型計畫
計畫編號：NSC94-2215-E-035-004-
執行期間：94年08月01日至95年07月31日
執行單位：逢甲大學電子工程學系

計畫主持人：陳國良

報告類型：精簡報告

處理方式：本計畫可公開查詢

中　華　民　國 95年8月24日

行政院國家科學委員會補助專題研究計畫成果報告

半導體雷射的雜訊: 低或然率區之分佈

計畫類別：☒ 個別型計畫　　☐ 整合型計畫
計畫編號：NSC 94-2215-E-035-004
執行期間：　94 年　8 月　1 日至　95 年　7 月 31 日

計畫主持人：陳國良
共同主持人：
計畫參與人員： Charlie Wang (Emcore Corp., Sunnyvale, CA, U.S.A.), John Wilks (Avago Technologies, San Jose, CA, U.S.A.), 許雅琴, 張一楠。

成果報告類型(依經費核定清單規定繳交)：☒精簡報告　☐完整報告

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執行單位：逢甲大學電子工程學系

中　華　民　國　95 年　8 月　23 日

中英文摘要：

The laser noise has been well studied theoretically and experimentally. Most of the experimental works were concerned about the standard deviation of the noise, with the implicit assumption that the noise distribution is Gaussian, which disagrees with other publications where the distribution is studied. We employ a new approach to measure the semiconductor laser noise distribution down to a 10^{-11} BER with a measurement time of less than an hour. This method takes advantage of the high sampling rate of BER testers (BERT) available today. We found that the noise distribution for a 1310nm Fabry-Perot semiconductor laser and a 1550nm DFB semiconductor laser are well fitted by Gaussian distributions.

The results have been sent and accepted for publication in IEEE Photonics Technology Letters. The paper title is “Intensity Noise Distribution of Semiconductor Lasers Measured Using Bit Error Rate Testers”.

過去已有不少關於雷射雜訊的理論與實驗研究.大多數是針對雜訊的標準差,而假設是高氏分佈，另有文獻指出其測量結果與高氏分佈不符。我們採用一種新法，利用BERT 快速取樣的特性，在一小時內可以量雜訊分佈至 10^{-11}BER。以此法 測量一個 1310nm Fabry-Perot 半導體雷射與一個 1550nm DFB半導體雷射，它們的雜訊分佈和高氏吻合。

此成果將發表在 IEEE Photonics Technology Letters: “Intensity Noise Distribution of Semiconductor Lasers Measured Using Bit Error Rate Testers”.

關鍵詞：

noise measurement, relative intensity noise, bit error rate, photon statistics, semiconductor lasers, optical fiber communication..

雜訊量測、相對雜訊、誤讀率、光子分佈統計、半導體雷射、光纖通訊。

內容：

I. Introduction

Fiber optics is a major technology for modern-day communication. The noise in a digital communication system increases the bit error rate (BER) and hence limits the communication link distance and data rate.[1] In the fiber-optic communication systems, the noise comes mostly from lasers, fibers and receivers/detectors. In this project, we investigate experimentally the noise distribution of some semiconductor lasers.

The laser noise have been well studied theoretically [2,3] and experimentally [4-6]. Most of the experimental works were concerned about the standard deviation of the noise, with the implicit assumption that the noise distribution is Gaussian. Since BER is a low probability event, a detailed knowledge of the noise distribution in the tail end is important. Liu [5] studied the distributions of several lasers and found them to be non-Gaussian. His setup measured the noise within a certain solid angle accepted by the optics, and likely includes large amount of spontaneous emission. In our experiment, we measure the noise of the laser light after coupling into a single-mode fiber (SMF), which is a more relevant quantity in the communication. We also use a new approach to measure the laser noise. Taking advantage of the high sampling rate of today's BERT, we are able to probe the noise distribution, in about an hour, down to the 10^{-11} regime, a level not reachable with other methods.

II. The experimental setup and the measurement principle

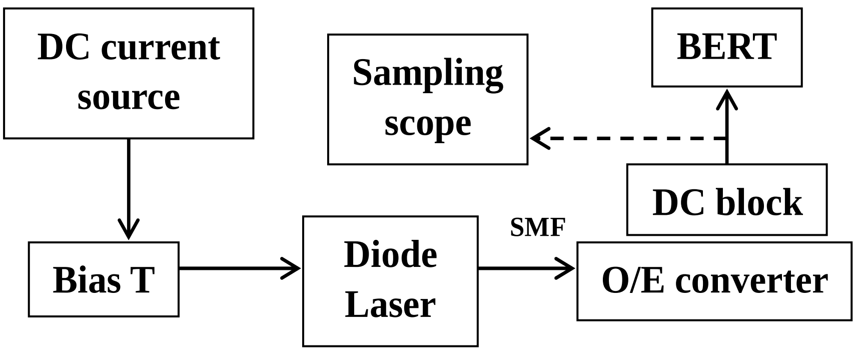


Fig.1 The schematic for the laser noise measurement setup.

The experimental setup is shown in Fig.1. A stable DC current source is used to bias the laser to maintain a fixed output power. The bias T (Picosecond Pulse Lab 5541A-104) is used as a low-pass filter to reduce the drive current noise. Its AC input is terminated with a 50Ω resistor. The laser output is fed to an O/E converter (Tektronics ORS20 which has a 1.87GHz bandwidth) through a 2-m SMF. A DC block (Picosecond Pulse Lab model 5501) removes the DC component of the electrical signal to prevent the input to BERT (HP/Agilent 70843B or Agilent 86130A) from exceeding its limit. This signal can be routed either to the BERT or to a sampling scope (Agilent 86100A with HP83487A plug-in) to measure the noise histogram.

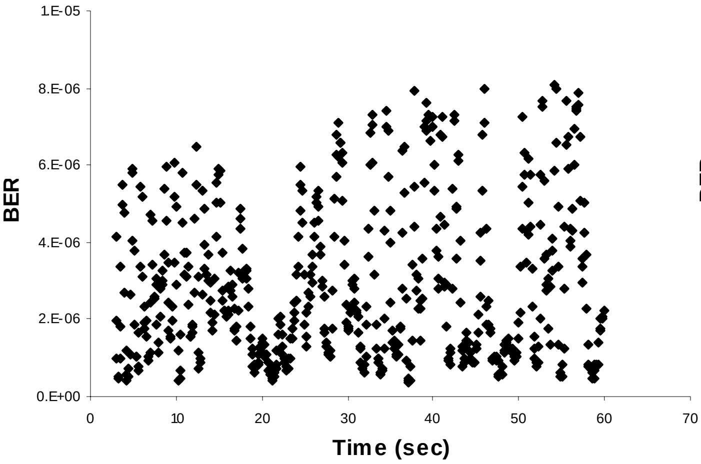
To calibrate for the noise of the test equipments, the noise standard deviation from the OE converter output with the laser turned off is measured by the scope and found be to 0.56mV. Since the laser noise (at 0.5mW) measured on the scope (see below) is about 6mV, the noise due to the O/E converter and the scope is negligible. It will also be shown below that the BERT measured noise standard deviation with 0.5mW laser power is consistent with that measured with the scope. Thus the BERT noise is also negligible.

Our approach of using the BERT to measure the laser noise is as follows. The laser power fluctuates about its average. It is the distribution of this fluctuation that we want to quantify and that is what is what contributes to the BER in an optical communication system. If we vary the BERT 1/0 threshold setting and measure BER, we are effectively measuring the noise distribution. Three different signal patterns can be used for this purpose, a pseudo random bit stream (PRBS), a "1010" periodic pattern, or a continuous wave (CW) pattern. With the former two, the BERT should sample at the bit center for the noise distribution. Since the laser has a finite bandwidth, a PRBS optical pattern has a deterministic jitter (DJ) causing every bit to have a different height. The measured distribution will then be the sum of the DJ and the laser intensity noise, an undesirable situation. With a "1010" periodic pattern, DJ is not present. However, there is still random jitter from the electronics and the laser random turn-on delay, which confound the laser noise. We thus adopt the CW pattern, where the measured noise comes purely from the laser. With this setup, since the intensity is from the sum of all modes. the mode partition noise is not manifested here.

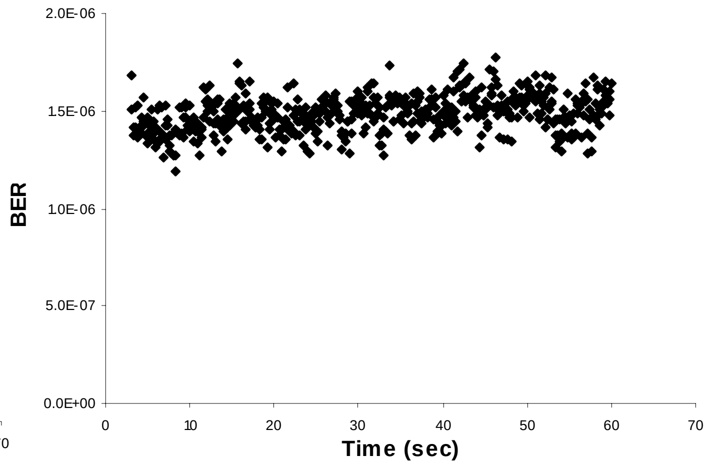
If the laser intensity distribution is f(x), then the probability, $P_L(x)$, that a sampled intensity is below x is given by $P_L(x) = \int_{-\infty}^{x} f(u)du$. Similarly the probability, $P_H(x)$, that a sampled intensity is above x is $P_H(x) = \int_{x}^{\infty} f(u)du$. With the laser running CW, we inform the BERT that the data pattern is "1111" when we sample the noise distribution below the average to find $P_L(x)$, and "0000" " when we sample the noise distribution above the average to find $P_H(x)$. With a Gaussian distribution with an average x_0 and a standard deviation σ, $f(x) = \frac{1}{2\sqrt{\pi}\sigma} \exp\left[-\frac{(x-x_0)^2}{2\sigma^2} \right]$, $P_L(x)$ and $P_H(x)$ are complementary error functions $\frac{1}{2} erfc\left(\frac{-(x-x_0)}{\sqrt{2}\sigma} \right)$ and $\frac{1}{2} erfc\left(\frac{(x-x_0)}{\sqrt{2}\sigma} \right)$ respectively.

III. Results and discussion

Early in the experiment, we observed an unusually large instability in the measured BER when the test condition is fixed. Figure 2 shows the BER versus time. Each data point corresponds to the BER averaged over a 0.1 second interval. In Fig.2(b) the laser pigtail output was directly connected to the O/E converter, while in Fig.2(a) it went through 4 additional directly . The fluctuation in 2(b) follows a Poisson distribution, which what would be expected for a stable laser noise. The much larger fluctuation in 2(a) is due to reflections at the additional connectors. Consequently the additional connectors were removed in later experiments.



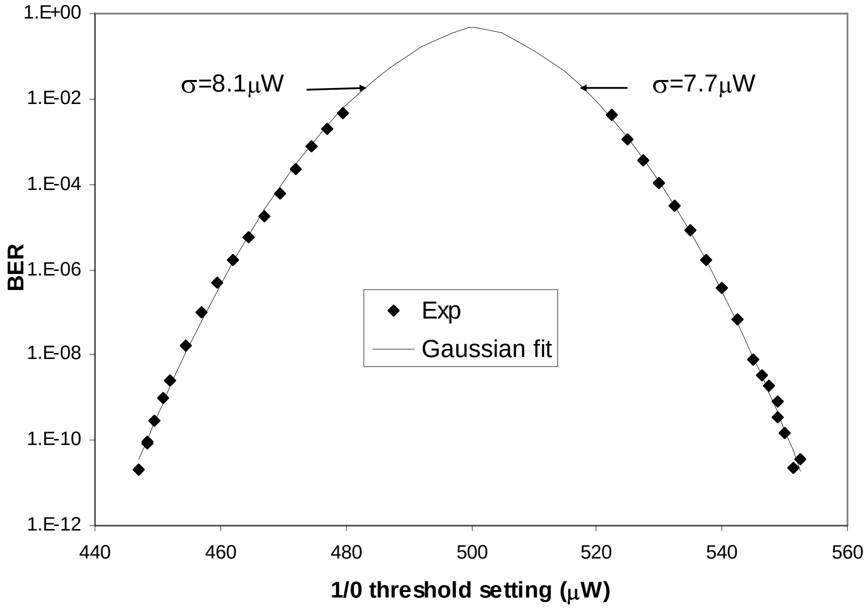
(a)



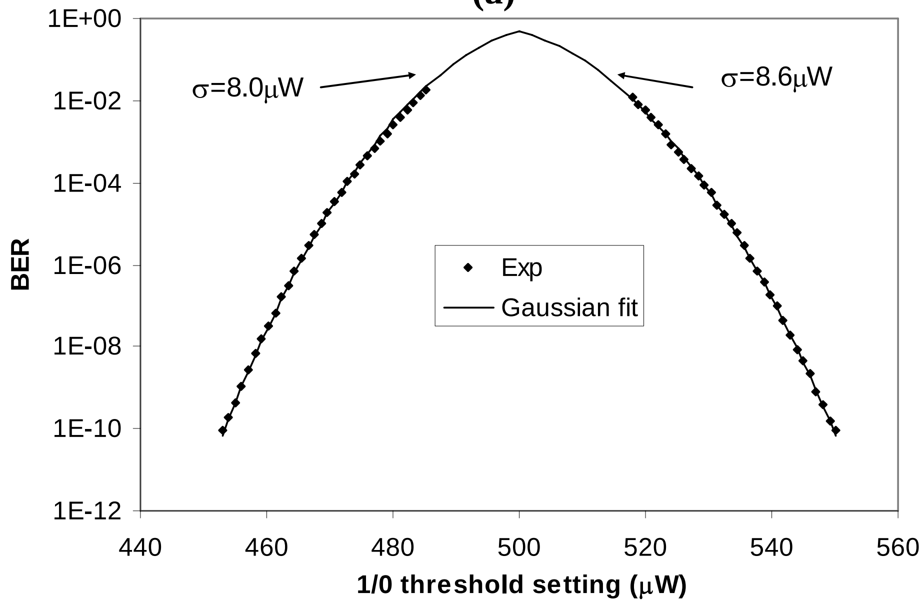
(b)

Fig.2 BER instability over time. (a) has 4 additional connectors and (b) has none.

Two commercial semiconductor lasers from Gigacomm Corporation were studied, a 1310nm Fabry-Perot (FP) laser and a 1550nm distributed-feedback (DFB) laser, both with a SMF pigtail. With biased CW to produce a 0.5mW power into the SMF, the measured BER (with a BERT sampling rate of 3Gb/s) corresponding to the probability distribution P_L and P_H are plotted in Fig.3(a) and (b) for the FP and the DFB lasers respectively. The 1/0 threshold setting was in mV and has been converted to mW using the calibrated O/E responsivity of 760V/W at 1310nm and 874V/W at 1550nm. The FP laser was tested with a BERT in Emcore and the DFB with a similar BERT in Avago.



(a)



(b)

Fig.3 Noise distribution plot for (a) 1310nm FP laser and (b) 1550nm DFB laser

In each figure, the data points are fitted separately above and below the average power point with an error function which would result from a Gaussian intensity distribution. Though the Gaussian fits the experimental data well, the standard deviation, σ, above and below the average differ slightly. With the FP laser, σ is larger below the average, while the DFB trend is opposite. Since the same DFB laser measured with the Emcore BERT skewed in the same direction as the FP, the difference observed here cannot be attributed to the lasers. To find the cause, the DFB intensity histogram at 0.5mW is taken with the sampling scope. The histogram in Fig. 4 clearly is symmetrical. Since the voltage scale of the scope is expected to be much more accurate than that of the BERTs, we conclude that both noise distributions are symmetrical and the observed difference is due to the scaling uncertainty above and below the 0 mV in

BERT. (Note that the average is 0 mV due because the DC block removed the DC component.)

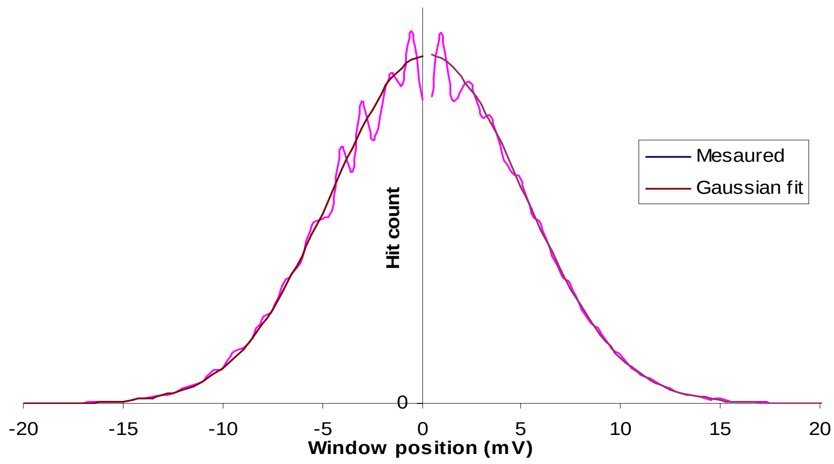


Fig.4 Intensity histogram of the DFB laser at 0.5mW measured with a sampling scope.

This symmetric Gaussian laser noise distribution disagrees with the Liu's results [5] where the distribution is observed down to about 10^{-8}. In his setup, the optical power is taken from an emission area and a solid angle which is likely much greater than that which would be coupled into a SMF. Thus the noise signal to noise ratio would be higher than that in this experiment. It is not clear whether this can explain the difference in the 2 experiments.

Due to the high BERT sampling rate (3Gb/s), the time to measure a distribution down to 10^{-11} is about one hour. The FP and the DFB lasers have an estimate bandwidth of 2.8GHz and 2GHz respectively. With a 1.87GHz O/E converter bandwidth, the overall system bandwidth is 1.6GHz with the FP and 1.4GHz with the DFB. In analogy to the Shannon's sampling theorem, a higher sampling rate than 3Gb/s is unlikely to produce statistically more meaningful results with the same test time. As to whether the sampling scope can be used to probe the noise distribution, the answer is yes but with a very limited range. Due to its sampling rate of about 40K samples per second, it would take over a year to collect a statistically meaningful 20 sampling points beyond 10^{-11} regime.

IV. Conclusion

We have devised a new method to measure the laser noise distribution. Relying on the high BERT sampling rate, this approach is more efficient in probing down to the low probability regime. Using this method, we characterized a 1310nm FP laser and a 1550nm DFB laser and found their noise distribution to be Gaussian down to 10^{-11}.

V. References

[1] IEEE Standard 802.3-2002. Information Technology – Telecommunications and information exchange between systems – Local and metropolitan networks specific requirements – Part 3: "Carrier sense multiple access with collision detection (CSMA/CD)

access method and physical layer specifications." Clause 38.6.12. Available:http://standards.ieee.org/getieee802/802.3.html.
[2] Joseph W. Goodman, "Statistical optics." new edition, Wiley-Interscience, 2000, Chapter 4
[3] *K. Vahala,.; A. Yariv," A* Semiclassical theory of noise in semiconductor lasers--Part II" IEEE J. Quantum Electronics, 19(6), Jun 1983,pp.1102 – 1109.
[4] T. Paoli, "Noise characteristics of stripe-geometry double-heterostructure junction lasers operating continuously--I. Intensity noise at room temperature", IEEE J. Quantum Electronics, 11 (6), 1975, pp.276-283.
[5] Pao-Lo Liu, "Photon statistics and mode partition noise of semiconductor lasers", in Coherent, Amplification and Quantum Effects in Semiconductor Laser, Ed. Y. Yamamoto, Wiley-Interscience, 1991.
[6] K. Sato, "Intensity noise of semiconductor laser diodes in fiber optic analog video transmission", IEEE J. Quantum Electronics, 19(9),1983, pp.1380-1391.

成果自評：

Overall the project ran better than expected. Before the experiments were performed, we did some estimate of the noise from the other sources such as the receiver, the scope and the BERT, and decided that they should not be a problem. Yet there was a concern that they may somehow overwhelm the laser noise. Fortunately they turned out to be an order of magnitude smaller than the laser noise.

We made a modification of test data pattern from the proposed plan. The original plan called for using periodic “1010” waveform to drive the lasers. Since this pattern can still have timing jitter which would confound the laser noise, we eventually used a constant current (CW), eliminating the possibility of timing jitter. The BERT was able to deal with this kind of data. This helps make the results very clean. And the experiment clearly indicates that the laser noise distribution is Gaussian all the way to the 10^{-11} BER for the 2 lasers studied.

Compared with the previous published laser noise experiments, this setup has 3 advantages. First, the BERT samples the data at $3*10^9$ (3G) times per second. With a 20-minutes test time, we were able to collect a statistically meaningful 36 errors when the BER is 10^{-11}. Thus the whole distribution can be obtained in about an hour. With a longer test time of 5 hours, which we did not try, the distribution can be probed to 10^{-12}. Second, we measured the noise of the light into the SMF, not into free space. This noise distribution is what is affects BER in the optical fiber communication. Third, the setup is simple. The only key equipment is the BERT.

This method is valuable in determining the noise distribution of other noise sources. Today’s optical communication links requires a BER of 10^{-12} or less. It is important to be able experimentally probe the noise distribution there in order to see whether it is Gaussian, a commonly assumed distribution used in calculation the overall system performance. This method offers the most efficient way to this end. As such, this result is suitable for publication, and we intend to submit it to a well-read international journal at the later date.

We have accomplished our proposed objective of furthering the knowledge of laser noise. As for second goal of training students in the fiber communication area, due to my personal decision to leave my teaching post to go back to U.S. where my family is, my sole graduate student switched to work with another faculty. The experiments were performed by myself with the help my ex-colleagues Charlie Wang and John Wilks using their BERTs in U.S. Thus the training portion did not pan out.

可供推廣之研發成果資料表

□ 可申請專利　□ 可技術移轉　　日期：95年6月19日

國科會補助計畫	計畫名稱：半導體雷射的雜訊: 低或然率區之分佈 計畫主持人：陳國良 計畫編號：NSC 94-2215-E-035-004 學門領域：光電子材料元件與模組。
技術/創作名稱	Noise distribution measurement using a bit error rate tester (BERT).
發明人/創作人	陳國良
技術說明	中文： （100~500 字）
	英文：The noise distribution of the semiconductor laser is measured using a bit error rate tester (BERT) down to a bit error rate (BER) of 10^{-11}, much lower than previously capable using other methods. A lower BER can be attained with a 10 times test time. This is relevant to today's fiber-optic communication need which generally requires a BER of 10^{-12} or less.
可利用之產業 及 可開發之產品	Fiber optic transmitters, receivers, or communication links.
技術特點	The noise measurement using a BERT is a very simple setup. It can be applied to either AC or DC signals. Due to the high sampling rate of BERT, it allows for finding the distribution to very low probability region.
推廣及運用的價值	This approach can be applied to the noise measurement of other devices or systems.

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