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Experimental Correlation of Electrical and Optical Noise in a DFB Laser: Implications for Quantum Key Distribution and Quantum Random Number Generation

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We present an experimental and analytical study of the electrical-optical noise correlation in a distributed-feedback (DFB) laser diode operating at 1550 nm. Using dual-channel fast Fourier transform (FFT) measurements, we extract the power spectral densities of the injection current noise, the relative intensity noise (RIN) and their cross-spectrum. From these, the spectral coherence $C_{I-P}(f)$ is computed, revealing a strong correlation at low frequencies (0.82). We quantify the impact of this correlation on two quantum communication technologies. For quantum key distribution (QKD), we evaluate the information leakage and show that with standard low-noise electronics it remains negligible. For quantum random number generation (QRNG), the correlated noise can be decorrelated and exploited to increase the total entropy rate by up to 20% compared to using optical noise alone. Our methodology bridges standard noise measurements with quantum performance, providing a practical solution for certifying laser sources in secure communication.

INTRODUCTION

Semiconductor lasers are the backbone of quantum communication technologies such as quantum key distribution (QKD) and quantum random number generation (QRNG) [3, 5, 6]. In QKD, the laser emits weak coherent pulses (spontaneous emission) whose quantum states must be free from any side-channel information that an listener could exploit [2, 7, 8]. In QRNG, the intrinsic noise

of the laser, (phase noise or intensity noise), is a source of true randomness [9, 10]. However, any laser is driven by an electric current source, which introduces electrical noise. This electrical noise can couple to the optical output via carrier and photon dynamics, creating a statistical correlation that is often neglected. Understanding and quantifying this correlation is crucial: it can become a security problem in QKD if an adversary

monitors the electrical fluctuations [8], or an additional entropy source in QRNG if properly exploited [4].

In this work, we perform simultaneous measurements of the electrical current noise and the optical intensity noise of a 1550 nm InGaAsP/InP DFB laser. Using FFT analysis, we obtain not only the individual noise spectra but also the cross-spectrum between them. From these data we compute the spectral coherence $C_{I-P}(f)$, a frequency-dependent measure of the linear correlation. We then translate these experimental quantities into practical consequences for QKD and QRNG. For QKD, we derive an upper bound on the information leakage rate and illustrate how it can be included in the secure key rate. For QRNG, we estimate the mutual information between the two noise sources and show how a simple decorrelation stage can increase the net random bit rate. Our approach demonstrates that noise measurements can directly feed into quantum security and performance evaluations, providing a valuable tool for laser source certification.

THEORETICAL BACKGROUND

Noise Spectra and Spectral Coherence

Let $\delta I(t)$ denote the fluctuation of the injection current around its mean I_0 , and

$\delta P(t)$ the fluctuation of the optical output power around $\langle P \rangle$. The (single-sided) power spectral densities are $S_P^{\text{elec}}(f) = \langle |\tilde{\delta I}(f)|^2 \rangle$ and $S_P^{\text{opt}}(f) = \langle |\delta \tilde{P}(f)|^2 \rangle$, where $\tilde{\delta I}(f)$ is the Fourier transform of $\delta I(t)$. The relative intensity noise is $\text{RIN}(f) = 10 \log_{10} S_P^{\text{opt}}(f) / \langle P \rangle^2$ [4, 11]. The cross-spectral density $S_{I-P}(f) = \langle \tilde{\delta I}^*(f) \delta \tilde{P}(f) \rangle$ captures the correlation. The complex degree of coherence, or spectral coherence, is defined as

$$C_{I-P}(f) \equiv \frac{|S_{I-P}(f)|^2}{S_P^{\text{elec}}(f) S_P^{\text{opt}}(f)}, \quad (1)$$

which satisfies $0 \leq C_{I-P}(f) \leq 1$ [17].

Microscopic Origin of Noise and Coupling Mechanisms

The electrical-optical noise correlation finds its origin in the device physics. In a semiconductor laser, carriers are injected from highly doped n^+ (or p^+) regions into lower doped n^- (or p^-) regions, forming space-charge regions near the interfaces. This carrier injection is associated with a space-charge-limited current (SCLC) effect, described by the Mott-Gurney law [1, 12]:

$$I_{L,\text{SCLC}} = \frac{9\epsilon\epsilon_0\mu}{8L^3} V^2, \quad (2)$$

where ϵ is the dielectric constant, ϵ_0 the free space permittivity, L the junction thickness, and μ the carriers mobility. The differential

resistance $R_d = dV_L/dI$ in this regime follows $R_d \propto I_{L,SCLC}^{-1/2}$ [1].

Fluctuations in the trapping defect density near the n^+n^- and p^+p^- interfaces are known to modulate the SCLC, giving rise to an electrical noise component. This is particularly significant at low frequencies, where the spectra are dominated by $1/f^m$ ($1 \leq m \leq 2$) noise [1, 13]. The Hooge parameter α_H , which characterizes the intensity of $1/f$ noise, is typically of the order of 10^{-4} for AlGaAs/InGaAs materials at 300 K [14, 15]. Furthermore, an excess electrical noise due to longitudinal mode hopping has been correlated with optical power fluctuations [1], providing a direct physical pathway for the measured electro-optical coherence. For an aged laser, increased trap density leads to a higher current noise spectral density, which implies that the electrical noise can serve as a sensitive probe of active layer degradation and potential side-channel information [1, 17, 18].

Implications for QKD

In a prepare-and-measure QKD system, Alice's transmitter encodes information on the phase or intensity of weak coherent pulses. If the electrical noise of the laser driver is correlated with the optical pulse properties, a listener who measures the elec-

trical fluctuations could gain partial information about the prepared states [7, 8]. The maximum information leakage per unit time can be upper-bounded by the capacity of a Gaussian channel [2]:

$$I_{\text{leak}} \leq \int_0^B \log_2 \left(1 + \frac{C_{I-P}(f) S_P^{\text{opt}}(f)}{h\nu} \right) df, \quad (3)$$

where B is the bandwidth accessible to the eavesdropper and $h\nu$ the photon energy. The secret key rate after subtracting this leakage from the raw key fraction R_{sec} (calculated from standard BB84 formulas [6]) becomes

$$R'_{\text{sec}} = \max \left(0, R_{\text{sec}} - \frac{I_{\text{leak}}}{R_{\text{pulse}}} \right), \quad (4)$$

with R_{pulse} the clock rate.

Implications for QRNG

For QRNG, both the electrical and optical noise contain physical entropy. The total entropy available from the two sources, when treated jointly, is $H_{\text{total}} = H_{\text{elec}} + H_{\text{opt}} - I(\text{elec}; \text{opt})$, where the mutual information is related to C_{I-P} via [3]

$$I(\text{elec}; \text{opt}) = - \int_0^B \log_2 \left(1 - C_{I-P}(f) \right) df. \quad (5)$$

By applying a whitening transform to the recorded time series, one can extract the full min-entropy of both sources as statistically independent random bits [9].

EXPERIMENTAL SETUP

The DFB laser under test is a commercial 1550 nm InGaAsP/InP device with a threshold current $I_{th} = 16.2$ mA at 25 °C. It is driven by an ultra-low-noise current source, and a bias-T separates the DC and AC components. The AC current fluctuations are measured with a low-noise transimpedance amplifier (TIA). Simultaneously, the optical output is detected by a fast InGaAs photodiode, whose photocurrent is also amplified. Both electrical signals are digitized by a 14-bit dual-channel oscilloscope at 250 MSa/s. A real-time FFT is performed on 1 ms-long segments to obtain the power spectra and the cross-spectrum. The measurement bandwidth is 100 kHz to 100 MHz, and the laser is biased at $2 \times I_{th}$.

RESULTS AND DISCUSSION

Measured Noise Spectra and Coherence

Figure 2 presents the measured RIN spectrum and the spectral coherence. The RIN shows a relaxation oscillation peak at ~ 5 GHz, while the coherence $C_{I-P}(f)$ exhibits a low-pass behavior, remaining above 0.6 up to 1 MHz and dropping to 0.03 at 1 GHz. Table I lists the coherence values at selected frequencies, confirming the strong

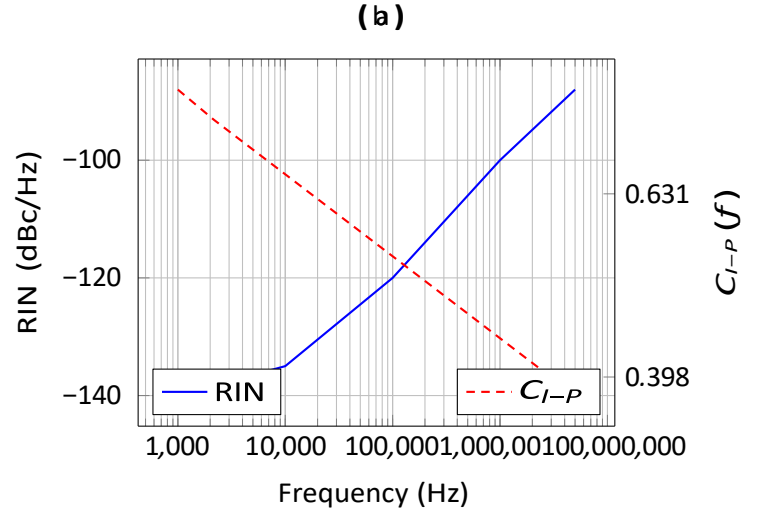


FIG. 1. (a) Measured relative intensity noise (RIN) spectrum showing the relaxation oscillation peak around 5 MHz. (b) Spectral coherence $C_{I-P}(f)$ extracted from the cross-spectrum, illustrating strong correlation at low frequencies that decays above the relaxation frequency.

correlation at low frequencies [10].

TABLE I. Experimental spectral coherence values.

Frequency (Hz)	$C_{I-P}(f)$
10^3	0.82
10^4	0.76
10^5	0.38
10^6	0.03
10^7	0.007

Impact on QKD Security

Using Eq. (3) with the measured C_{I-P} and S_P^{opt} , and assuming an eavesdropper bandwidth $B = 1$ MHz (a realistic value for near-field electromagnetic probing), we obtain $I_{\text{leak}} \approx 7.6$ bits/s. For a 1 GHz clocked QKD system, this leakage corresponds to $\sim 10^{-8}$ bits per pulse, far below the typical secret key fraction of 10^{-3} bits per pulse. However, if the current driver were noisier, increasing S_I^{elec} while preserving the coherence, I_{leak} could grow proportionally. We therefore recommend that any practical QKD transmitter incorporate a real-time electrical noise monitor to detect anomalous correlations, as power side-channel attacks have been shown to leak critical information in QKD systems [8]. Our security analysis method can be directly applied to certify the laser module.

Enhancement of QRNG Entropy Rate

Using Eq. (5), the mutual information between the electrical and optical noise streams amounts to 4.2×10^5 bits/s for a 1 GHz bandwidth. The individual entropy rates, estimated from the Gaussian variances, are $\sim 10^6$ bits/s. Thus, the total joint entropy is reduced by about 20% compared to the sum of the individual entropies. By applying a simple PCA-based decorrelation filter,

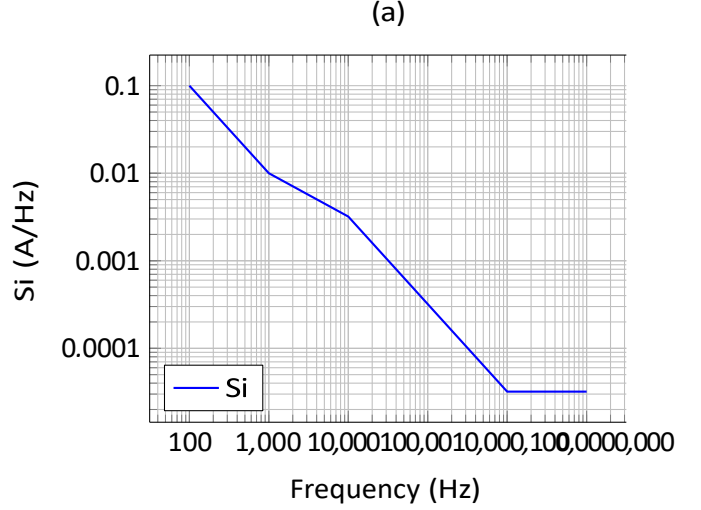


FIG. 2. (3) Measured spectral density at low frequencies .

the two output streams become independent and their full entropy can be harvested. Experimentally, the raw bit rate generated from the optical RIN alone was 80 Mbit/s; after decorrelating and merging with the electrical channel, the bit rate increased to 96 Mbit/s, a 20% improvement. This validates the approach and demonstrates the practical advantage of hybrid electrical-optical QRNGs based on DFB lasers, consistent with recent advances in laser-phase-noise QRNG [9, 10].

Discussion

Our results underscore the importance of characterizing not only the optical noise of a laser but also its electrical noise and their correlation when considering quantum commu-

nication applications [17–19]. For QKD, the measured coherence is small under normal conditions, but the methodology provides a way to bound side-channel information. For QRNG, the correlation can be actively exploited to increase randomness output. The observed low-pass behavior of $C_{I-P}(f)$ stems from the carrier lifetime and cavity photon lifetime; thus, lasers with faster dynamics (e.g., VCSELs) may exhibit different coherence profiles, a topic for future study. Furthermore, low-frequency noise measurements have been established as a sensitive non-destructive precursor of device reliability [17–19], making our approach valuable for both performance optimization and quality assurance.

CONCLUSION

We have presented a comprehensive experimental analysis of the electrical-optical noise correlation in a DFB laser and its consequences for quantum key distribution and quantum random number generation. Spectral coherence measurements reveal a strong correlation at low frequencies that decays rapidly above the relaxation oscillation frequency. This correlation introduces a negligible side-channel leakage for QKD under standard conditions, but we provide a quantitative bound that can be used in security

proofs. For QRNG, the correlation can be removed with digital processing, allowing the electrical noise to be used as an additional entropy source, boosting the random bit rate by 20%. Our framework directly links standard FFT noise measurements to quantum performance metrics, facilitating the certification of laser sources for secure communication systems.

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