A General Relation Between Frequency Noise and Lineshape of Laser Light

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***Abstract*— Lasers and especially semiconductor lasers (SCLs) are playing a major role in advanced technological and scientific tasks ranging from sensing, fundamental investigations in quantum optics and communications. The demand for ever-increasing accuracy and communication rates has driven these applications to employ phase modulation and coherent detection. The main laser attribute that comes into play is its coherence which is usually quantified by either the Schawlow-Townes (S-T) linewidth, the spectral width of the laser field, or the power spectral density (PSD) function of the laser frequency fluctuation. In this paper, we present a derivation of a general and direct relationship between these two coherence measures. We refer to the result as the Central Relation. The relation applies independently of the physical origin of the noise. Experiments are described which demonstrate the validity of the Central Relation and at the same time suggest new methods of controlling frequency noise at base band by optical filtering.**

***Index Terms*— Laser theory, laser noise, laser applications.**

I. Introduction

LASER light plays a key role in modern technology, in applications ranging from optical communication [1]–[3], optical sensing [4]–[6], imaging [7], [8], spectroscopy [9], [10] and many others. The most important attribute of the SCLs in most of these applications is its temporal coherence quantified most often in terms of the frequency fluctuation noise and/or the laser linewidth. In the ideal quantum-limit case where the dominant source of noise is spontaneous emission into the oscillation modes, the two noise measures are simply related. This, however, is not the case in most real life scenarios. Relevant investigations are numerous [11]–[20].

Among the notable investigations involving the relation between the frequency noise and optical lineshape are those of Daino *et al.* [21] who showed experimentally how the deviation of the laser's frequency noise from white noise affects its lineshape and that the frequency noise and lineshape can possess similar features. Henry [22] showed that frequency noise and lineshape in SCLs can come from the same origin, such as spontaneous emission. Although it has been realized that there exists a strong connection between the frequency noise and lineshape, a simple and rigorous mathematical treatment of such a relation has not been available.

In this paper, we derive a general relation between the frequency noise PSD and the spectral lineshape of the laser light. The validity of the theoretical result is established experimentally. The result suggests methods of noise control yet to be demonstrated.

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II. Mathematical Derivation

The electric field of laser light can be expressed as

$$E = E_0 e^{i\{\omega_0 t + \psi(t)\}} \tag{1}$$

where $\psi(t)$ represents the phase fluctuations due to random or deterministic modulation, whose average value vanishes. E_0 is the amplitude and ω_0 is the angular frequency of the light. The lineshape function (single-sided spectrum) of the laser light is represented by the PSD of the laser field, which is the Fourier transform of the correlation function of the field

$$S_E(\omega) = 2\int_{-\infty}^{+\infty} e^{-i\omega\tau} < E^*(t)E(t+\tau) > d\tau \tag{2}$$

where $<>$ represents the time average.

The correlation function can be calculated as [17], [23]

$$\begin{aligned} < E^*(t)E(t+\tau) > &= E_0^2 e^{i\omega_0\tau} < e^{i\{\psi(t+\tau)-\psi(t)\}} > \\ &= E_0^2 e^{i\omega_0\tau} e^{-\frac{1}{2}[<\{\psi(t+\tau)-\psi(t)\}^2>]} \\ &= E_0^2 e^{i\omega_0\tau} e^{-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df} \end{aligned} \tag{3}$$

Since intensity fluctuations are strongly damped due to gain saturation, E_0^2 is taken as a constant so that our main concern here is phase noise. The frequency noise power spectral density is given by

$$S_{\Delta\upsilon}(f) = 2\int_{-\infty}^{+\infty} e^{-i2\pi f\tau} < \dot{\psi}(t)\dot{\psi}(t+\tau) > d\tau \tag{4}$$

is the single-sided frequency noise power spectral density (PSD). The central frequency of lineshape is just ω_0.

We define a new function $\eta(\upsilon)$ by means of the relation

$$\frac{1}{2\pi}\int_{-2\pi\upsilon+\omega_0}^{2\pi\upsilon+\omega_0} S_E(\omega)d\omega = \{1-\eta(\upsilon)\}E_0^2 \tag{5}$$

Notice that if we integrate over the whole laser lineshape function, we get the total "power" of the laser light, namely

$$\frac{1}{2\pi}\int_{-\infty}^{+\infty} S_E(\omega)d\omega = E_0^2 \tag{6}$$

so that the function $\eta(\upsilon)$ is equal to the total power contained outside the integrated frequency range of width $4\pi\upsilon$ straddling the central laser frequency ω_0. The function $\eta(\upsilon)$ can be expressed as

$$\eta(\upsilon) = \frac{1}{E_0^2}\{\frac{1}{2\pi}\int_{-\infty}^{-2\pi\upsilon+\omega_0} S_E(\omega)d\omega + \frac{1}{2\pi}\int_{2\pi\upsilon+\omega_0}^{+\infty} S_E(\omega)d\omega\} \tag{7}$$

and it vanishes as υ approaches infinity.

The use of (2) and (3) in (5) leads to

$$\frac{1}{2\pi}\int_{-2\pi\upsilon+\omega_0}^{2\pi\upsilon+\omega_0} d\omega\int_{-\infty}^{+\infty} e^{i(\omega_0-\omega)\tau} \times e^{-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df} d\tau = 1-\eta(\upsilon) \tag{8}$$

integrating over the angular frequency ω leads to

$$2\upsilon\int_{-\infty}^{+\infty} \mathrm{sinc}(2\pi\tau\upsilon) \times e^{-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df} d\tau = 1-\eta(\upsilon) \tag{9}$$

We use the following mathematical relations to deal with sinc functions

$$\begin{aligned} \mathrm{sinc}(2\pi\tau\upsilon) &= W(2\pi\tau\upsilon)\text{as } \upsilon\to\infty \\ \mathrm{sinc}(\frac{\pi f}{2\upsilon}) &= W(\frac{\pi f}{2\upsilon})\text{as} \upsilon\to\infty \end{aligned} \tag{10}$$

where $W(x)$ is equal to 1 when $|x| \leq {}^{\pi}/_{2}$ and vanishes otherwise. The upper equation is valid as both $2\upsilon\mathrm{sinc}(2\pi\tau\upsilon)$ and $2\upsilon W(2\pi\tau\upsilon)$ are asymptotically identical to the $\delta(\tau)$ function. The lower equation is simply the Fourier transform of the upper one.

Using the definition of $W(x)$ we can limit the range of integration in (9) to $-\frac{1}{4\upsilon} \leq \tau \leq \frac{1}{4\upsilon}$, which allows us to rewrite it as

$$2\upsilon\int_{-\frac{1}{4\upsilon}}^{\frac{1}{4\upsilon}} e^{-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df} d\tau = 1-\eta(\upsilon)$$

Since the integrand is an even function of τ

$$4\upsilon\int_{0}^{\frac{1}{4\upsilon}} e^{-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df} d\tau = 1-\eta(\upsilon) \tag{11}$$

For sufficiently large υ, the time variable τ in (11) remains small over the entire integration range so that we can Taylor-expand the exponential part and keep only the leading term

$$4\upsilon\int_{0}^{\frac{1}{4\upsilon}} \{1-2\int_0^{+\infty} S_{\Delta\upsilon}(f)\frac{\sin^2(\pi f\tau)}{f^2}df\}d\tau = 1-\eta(\upsilon) \tag{12}$$

Integrating over τ leads to

$$\int_0^{+\infty}\frac{S_{\Delta\upsilon}(f)}{f^2}\{1-\mathrm{sinc}(\frac{\pi f}{2\upsilon})\}df = \eta(\upsilon) \tag{13}$$

The second term on the left side in equation (13) contains a sinc function and using the relation (10), we take the lower limit of integration at ${}^{\pi f}/_{2\upsilon} = {}^{\pi}/_{2}$

$$\int_{\upsilon}^{+\infty}\frac{S_{\Delta\upsilon}(f)}{f^2}df = \eta(\upsilon) \tag{14}$$

The physical meaning of (14) is more apparent in a form, which results from a differentiation of both sides with respect to υ

$$\frac{S_{\Delta\upsilon}(\upsilon)}{\upsilon^2} = \frac{1}{E_0^2}\{S_E(\omega_0+2\pi\upsilon)+S_E(\omega_0-2\pi\upsilon)\} \tag{15}$$

where the differential form of $\eta(\upsilon)$ can be derived from equation (7).

Equation (15) constitutes a general relation between the frequency noise PSD $S_{\Delta\upsilon}(\upsilon)$ and the lineshape function $S_E(\omega)$ of the laser light. We will refer to it as the Central Relation. It shows that at high frequencies υ there is a one-to-one correspondence between the frequency noise and the lineshape function. Empirically, frequencies which are more than ten times the linewidth (full width half maximum (FWHM)) of the optical lineshape can be considered as sufficiently high for the Central Relation to apply; such a rule of thumb is confirmed by the experiments described in the following sections. Notice that we have made no assumptions regarding the physical origin of the frequency noise.

It is worth pointing out that the left side of equation (15) is essentially the phase noise PSD of the laser. The meaning of equation (15) can be interpreted as following. The frequency noise at a high base band frequency affects the lineshape at the same frequency offset with respect to the optical central frequency. If the lineshape is symmetrical about the central frequency, which is true for laser lineshape, then any feature in the phase noise PSD at high frequency will appear identically in the lineshape and vice versa. To the best of our knowledge, and after a considerable search, we have not found a result similar to (15) in the published literature.

III. The Validity of the Central Relation

A well-known special case involving the relation between laser frequency noise PSD and lineshape is that of the quantum limit of spontaneous emission described above. In that case, $S_E(\omega)$ is known to be a Lorentzian. Here, we show that it obeys the Central Relation (15).

Assume the FWHM of the Lorentzian lineshape is h, then the value of the single-band frequency noise PSD is [24]

$$S_{\Delta\upsilon}(\upsilon) = \frac{h}{\pi}$$

which makes the left-hand side of (15)

$$\frac{h}{\pi\upsilon^2}$$

The Lorentzian lineshape $S_E(\omega)$ can be expressed as

$$S_E(\omega) = \frac{2\pi E_0^2 h}{(\omega-\omega_0)^2+(\pi h)^2}$$

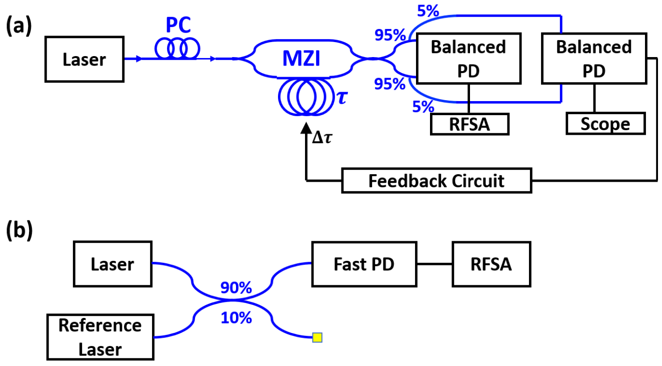

Fig. 1. Measurement setups for (a) frequency noise power spectral density and (b) lineshape. PC: polarization controller; MZI: Mach-Zehnder interferometer; RFSA: radio frequency spectrum analyzer. A narrow-linewidth fiber laser is used as the reference laser.

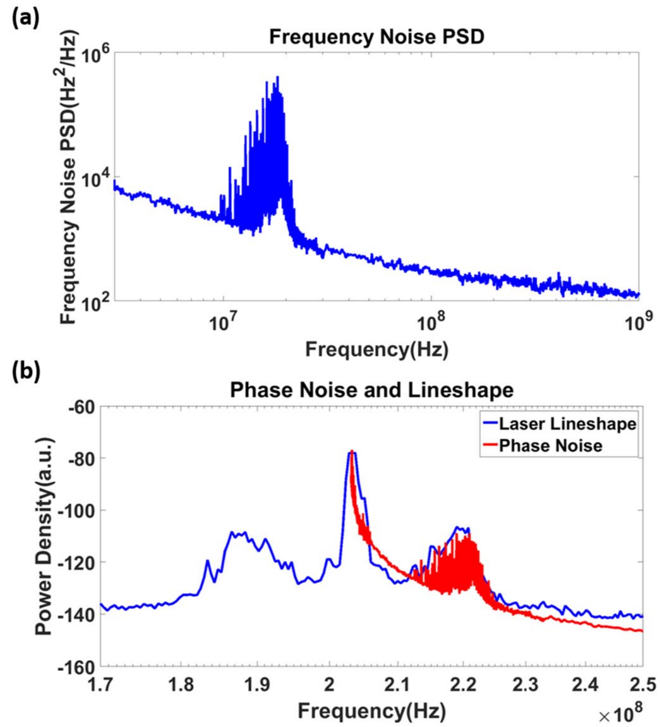

Fig. 2. (a) Frequency noise PSD of the laser (b) corresponding phase noise PSD and lineshape of the laser.

subject to (6). The right-hand side of (15) becomes

$$\frac{4\pi h}{(2\pi \upsilon)^2 + (\pi h)^2}$$

In the limit of $\upsilon \gg h$, which means at high frequencies (the premise of the Central Relation (1)), the previous formula is reduced to

$$\frac{h}{\pi \upsilon^2}$$

which is the same as the left-hand side of (15). Q.E.D.

To illustrate experimentally the validity of the Central Relation, both the frequency noise PSD and lineshape of a single laser have been measured. The measurement setups are shown in Fig. 1. The frequency noise PSD is obtained in the following manner. The laser frequency is locked using the feedback circuit to a quadrature point of a Mach-Zehnder interferometer (MZI) with a free spectral range (FSR) of roughly 1.5 GHz and a spectrum analyzer measures the power spectrum of the resulting electrical signal from the balanced photodetector. The frequency noise PSD is then calculated based on the power spectrum [25]. To measure the laser's lineshape, its output field is beat against the field of a narrow-linewidth fiber laser and the power spectrum of the beat signal is measured.

The laser's frequency noise obtained in this manner is shown in Fig. 2(a). There exists some jitter at tens of megahertz in the spectrum, which comes from the controlling circuit of the laser. The lineshape of the laser is displayed in Fig. 2(b) and it contains two bumps, which are symmetrical about the central frequency. To show that the frequency noise and lineshape indeed obey the general relation (15), we first calculate the phase noise PSD, namely the left side of equation (15), based on the measured frequency noise PSD and then match it with the lineshape, as is shown in Fig. 2(b).

The jitter in the phase noise PSD is located at the same frequency as the bumps in the lineshape with respect to the central frequency. In addition, the bump shape reproduces the envelope of the jitter in the phase noise PSD. Because of the measurement resolution of the spectrum analyzer, we are unable to observe the individual lines in the lineshape. The general relation describes closely the match between the frequency noise and lineshape and therefore we show experimentally the validity of the general relation.

IV. Engineering the Frequency Noise PSD

Being able to control laser frequency noise in chosen frequency region is of great importance for technologies and applications which employ phase modulation of lasers and/or coherent detection. The corresponding phase noise of the system in general can be estimated with

$$\int_{\frac{1}{T}}^{\frac{1}{\tau}} S_{\Delta\upsilon}(f)\mathrm{d}f$$

where T is the total acquisition time of the signal and $1/T$ is usually very small; τ represents the time interval between two successive samplings and therefore $1/\tau$ is the sampling or modulation frequency. $1/\tau$ is typically orders of magnitude larger than $1/T$ and varies from one application to another. For example, in high-speed coherent optical communications, the modulation frequency can be as high as tens of GHz. However, for applications such as phase-sensitive LIDAR and imaging, a sampling frequency on the order of tens of MHz may be enough. $S_{\Delta\upsilon}(f)$ represents the frequency noise PSD of laser light.

In order to reduce the phase noise in the system, it is crucial to suppress the laser frequency noise PSD at frequencies close to the sampling or modulation frequency, namely

$$S_{\Delta\upsilon}(f)|_{f\sim\frac{1}{\tau}}$$

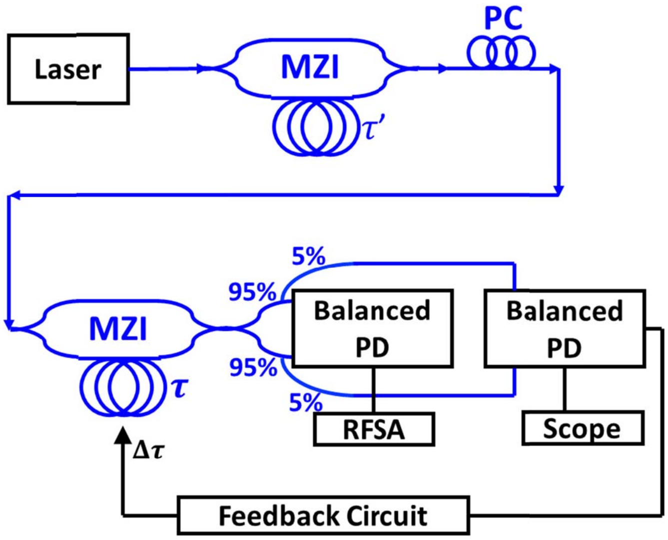

Fig. 3. Measurement setup for the frequency noise PSD of laser output modified by the MZI with the free spectral range of 203 MHz.

because it occupies the largest bandwidth and thus contributes mostly to the phase noise.

The Central Relation (15) is valid for any laser light and can be used as a guide to custom-tailor the frequency noise PSD by optical filtering.

Consider the case when the laser light passes through a generalized optical filter, whose power transmission is the function $H(|\omega-\omega_0|)$, which is centered at the same frequency as the laser. It is assumed to be symmetric about the central frequency. Without loss of generality, we allow the filter to possesses unity transmission near ω_0 and to have a negligible effect on the total power of the light. The output lineshape function is thus changed from $S_E(\omega)$ to

$$S'_E(\omega) = S_E(\omega)H(|\omega-\omega_0|) \quad (16)$$

The Central Relation (15) also applies directly to the light exiting the filter, which leads to

$$\frac{S'_{\Delta\upsilon}(\upsilon)}{\upsilon^2} = \frac{1}{E_0^2}\{S'_E(\omega_0+2\pi\upsilon)+S'_E(\omega_0-2\pi\upsilon)\} \quad (17)$$

where $S'_{\Delta\upsilon}(\upsilon)$ represents the frequency noise PSD of the light modified by the filter. From equation (15), (16) and (17), it follows that

$$S'_{\Delta\upsilon}(\upsilon) = S_{\Delta\upsilon}(\upsilon)H(2\pi\upsilon) \quad (18)$$

where $S_{\Delta\upsilon}(\upsilon)$ is the original frequency noise PSD of the laser. Equation (18) indicates that the frequency noise PSD at a baseband frequency υ is modified by the same transmission function of the filter at an optical frequency $\omega_0 \pm 2\pi\upsilon$. This equation indicates that the frequency noise at some high baseband frequency υ can be controlled by optically filtering the tail of lineshape at the frequency offset υ from the center. By correctly designing the transmission spectrum of the filter, the frequency noise can be tailored correspondingly.

Equation (18) appears alarmingly simple but consider the fact that it predicts a tailoring of, for example, a microwaves spectrum near υ by optical filtering at frequencies $\omega_0 \pm 2\pi\upsilon$, which are orders of magnitude larger. To demonstrate the significance of equation (18) and further illustrate the validity of (15), we pass the laser output field through a MZI with the FSR of 203 MHz, as shown in Fig. 3. The laser frequency is tuned to match one of the maximum-transmission frequencies of the MZI, which is schematically shown in Fig. 4. Notice that the Lorentzian linewidth of the laser is actually much smaller than the FSR, therefore the MZI doesn't affect the total power. However, equation (18) predicts that the frequency noise should be affected by the MZI.

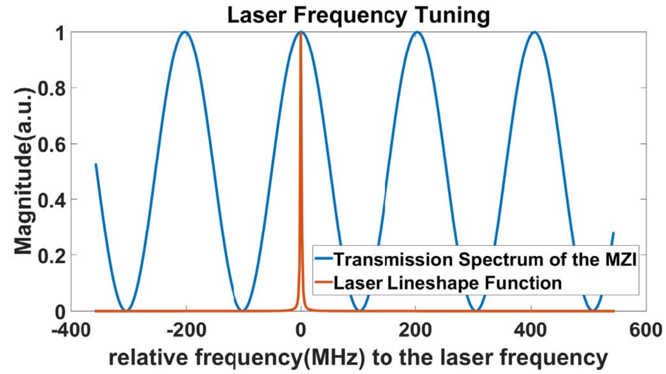

Fig. 4. Schematic plot of the laser lineshape and transmission spectrum of the MZI; the laser frequency aligned to maximum transmission frequency of the MZI.

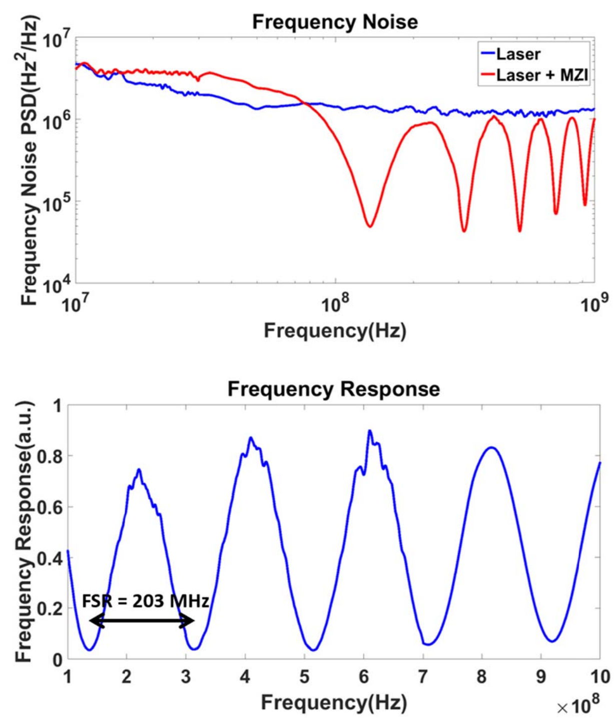

Fig. 5. (a) Frequency noise PSD of the laser and laser passing through the MZI (b) ratio between the two frequency noise PSDs.

We compare the measured frequency noise with the intrinsic frequency noise of the laser, as shown in Fig. 5(a). We find the frequency noise is modified drastically by the MZI. To confirm the validity of equation (18), we take the ratio between those two frequency spectra. The resulting ratio is plotted in Fig. 5(b). The function is indeed the transmission spectrum $H(|\omega - \omega_0|)$ of the MZI, which is sinusoid with a FSR of 203 MHz.

V. Conclusions

We have derived a general relation, the Central Relation, between the frequency noise PSD and lineshape of laser light. It constitutes a one-to-one correspondence between the frequency noise and lineshape at high frequencies. The predictions of (15) are verified experimentally. In addition, we propose a new method based on the Central Relation for control and spectral shaping of the frequency noise and demonstrate it with an experiment.

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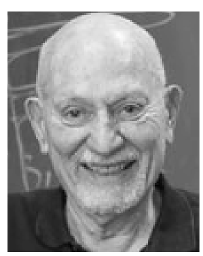

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Dr. Yariv is a member of the American Academy of Arts and Sciences, the National Academy of Engineering, and the National Academy of Sciences.