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COHERENCE AND NOISE PROPERTIES OF LASER DIODES

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Introduction

Recently, a great effort has been devoted to the study and characterization of noise in semiconductor lasers both because of the importance they have for the comprehension of the physics of certain phenomena which are peculiar of the semiconductor nature of laser diodes, and mainly, for the practical relevance they have in the evaluation of the performances and in the design of transmission systems employing such devices. In fiber optics systems, due to the low values of attenuation and dispersion of the transmission medium, the main performance limitations can presently be attributed to the noise level of the sources.

The main argument of the lecture will be the study and characterization of frequency noise in single-mode injection lasers, along with the presentation of some experimental methods used to reduce it. The importance of this particular kind of noise, generated by the random fluctuations of the instantaneous phase of the emitted radiation field, stems from the fact that a detailed knowledge of its power spectrum allows to determine the correct shape and width of the laser emission line. This is important for the comprehension of the physics of the device and essential for the applications, e.g. its employment in optical coherent communication systems [1].

Before going into the specific argument, we think it is useful to recall, briefly, all the various kinds of noise associated with the electromagnetic (e.m.) radiation emitted by laser sources and to underline their relevance in the performances of optical fiber transmission systems.

To be more specific, let us write the elctric component of the radiation emitted by a laser operating in a condition of continuous wave (CW) and single transverse mode, as the superposition of the contributions due to N longitudinal modes, that is

$$\mathcal{E}(t)=\sum_{i=1}^{N}\mathcal{E}_i(t)=\sum_{i=1}^{N}\left[E_i+e_i(t)\right]\exp\left\{i\left[\omega_i t+\varphi_i(t)\right]\right\} \qquad (1).$$

Here $e_i(t) < E_i$ is the deviation of the field amplitude of the ith longitudinal mode from its average value E_i and $\varphi_i(t)$, the random phase of the same mode, is such that $\dot{\varphi}_i(t)$ represents the deviation of the instantaneous oscillation frequency from its mean value ω_i, all the above quantities being real.

From eq.(1), three different kinds of noise can be recognized, namely intensity noise, partition noise and frequency noise.

a) Intensity noise (fig.1 and 2)

Except for a proportionalality factor, the total instantaneous intensity of the radiation emitted by the laser can be written as

$$I(t) = \varepsilon(t)\,\varepsilon^*(t) = I_o + \delta I(t) \qquad (2),$$

where the asterisk stands for complex conjugate, ad I_o is the average intensity. Intensity noise is due to the presence of the term $\delta I(t)$, the instantaneous deviation of $I(t)$ from its average value, and has to be taken into account particularly in intensity modulated transmission systems in which random variations of the detedcted power can determine an error in the decision block. In laser diodes this kind of noise is caused by fluctuations in the injection current and, especially, by the presence of the spontaneous emission processes taking place into the laser cavity.

b) Partition noise (fig.2 and 3)

It is caused by the fluctuations of $I_i(t)$, the instantanoeus intensity of the radiation associated to each one of the longitudinal lasing modes, with respect to its average value I_{oi}. In this case one has

$$I_i(t) = \varepsilon_i(t)\,\varepsilon^*_i(t) = I_{oi} + \delta I_i(t) \qquad (3),$$

where $I_{oi} = E_i^2$ and $\delta I_i(t)$ is the term responsible for partition noise.

In a semiconductor laser in which several longitudinal modes are present, partition noise is, in general, predominant with respect to intensity noise. It can also be relevant in cases in which the total emitted power remains practically constant, due to the possibility of the power to be transferred from one mode to another [2].

Partition noise is particularly harmful in high speed optical transmission systems in which, due to the chromatic dispersion of the optical fiber, two pulses emitted at different instants and associated with different lasing modes may happen to superimpose when detected. Partition noise, too, is due to the presence of spontaneous emission processes. In semiconductor lasers, in fact, because of the nearly equal value for the gain coefficient of the various modes, any increase of the spontaneous emission in a given mode acts as a trigger allowing that mode to lase. It is evident that partition noise is drastically reduced in lasers operating in a single transverse and longitudinal mode regime.

c) Frequency noise (fig.4)

Such a kind of noise has to be associated to the presence, in eq.(1), of the random terms $\varphi_i(t)$ which determine stochastic fluctuations, in the instantaneous oscillation frequencies of the lasing modes, equal to $\dot{\varphi}_i(t)$. This fact is responsible for the broadening of the emission lines which, instead, in an ideal situation, should form a comb of frequencies ω_i.

Frequency noise has to be taken into particular account in coherent optical transmission systems employing single mode semiconductor lasers, in which it drastically contributes to the bit-error degradation [1]. Frequency noise is due both to factors which are not directly connected with the lasing process and whose effects can be minimezed (i.e. thermal fluctuations and mechanical vibrations of the cavity, or noise in

the injection current) and to an intrinsic factor, that is, once again, spontaneous emission [3].

Phase noise and emission lineshape in single-mode lasers. Fundamental relationships.

The electric component of the radiation from a single-mode laser can be written (see eq.(1))

$$\mathcal{E}(t) = [E_o + e(t)]\,\exp\{i\,[\omega_o t + \varphi(t)]\} \qquad (4).$$

The shape, and, hence, the width, of the emission line can be found as the Fourier transform of $R_\varepsilon(\tau)$, the autocorrelation function of $\varepsilon(t)$, which, in turn, is given by [4]

$$R_{\mathcal{E}}(\tau) = \overline{\mathcal{E}(t+\tau)\,\mathcal{E}^*(t)} \cong I_o \exp(i\omega_o\tau)\,\overline{\exp\left\{i\int_t^{t+\tau}\dot{\varphi}(t')\,dt'\right\}} \qquad (5).$$

In eq.(5) the bar denotes time average, $I_o = E_o^2$, $\int_t^{t+\tau}\dot{\varphi}(t')dt' = \varphi(t+\tau) - \varphi(t) = \Delta_\tau\varphi(t)$, and terms such as $e(t)E_o(\ll I_o)$ have been neglected.

Since $\dot{\varphi}(t)$ (and, consequently, $\Delta_\tau\varphi(t)$, too [5]) is a zero mean normally distributed ergodic process, eq.(5) can be rewritten as [5]

$$R_{\mathcal{E}}(\tau) = I_o \exp(i\omega_o\tau)\exp\left\{-\frac{1}{2}\int_0^\tau dt'\int_0^\tau dt''<\dot{\varphi}(t')\dot{\varphi}(t'')>\right\} =$$
$$= I_o \exp(i\omega_o\tau)\exp\left\{-\frac{1}{2}\,\sigma^2_{\Delta\varphi}(\tau)\right\} \qquad (6),$$

where the angular brackets denote ensemble average

and $\sigma^2_{\Delta\varphi} = <[\Delta_\tau\varphi(t)]^2> - [<\Delta_\tau\varphi(t)>]^2 = <[\Delta_\tau\varphi(t)]^2>$

is the variance of $\Delta_\tau\varphi(t)$.

At this point we can evaluate the analytical expression for the shape of the emission line given by

$$S_\varepsilon(\omega) = \int_{-\infty}^{\infty} R_\varepsilon(\tau)\, e^{-i\omega\tau}\, d\tau \qquad (7).$$

$S_\varepsilon(\omega)$, the power spectrum of $\varepsilon(t)$, is such that $S_\varepsilon(\omega)d\omega/2\pi$ represents the fraction of optical power emitted in frequency range $(\omega, \omega + d\omega)$. The frequency interval between the half power points of $S_\varepsilon(\omega)$ is commonly chosen to represent the laser linewidth.

On the other side, it can be easily shown that [6]

$$\sigma^2_{\Delta\varphi}(\tau) = \frac{1}{\pi}\int_0^{\infty} S_{\Delta\varphi}(\Omega)\, d\Omega =$$

$$= \frac{2}{\pi}\int_0^{\infty} \frac{S_{\dot\varphi}(\Omega)}{\Omega^2}\left[1-\cos(\Omega\tau)\right] d\Omega \qquad (8),$$

where $S_{\Delta\varphi}(\Omega)$ and $S_{\dot\varphi}(\Omega)$, the power spectra of $\Delta_\tau\varphi(t)$ and $\dot\varphi(t)$, are formally obtained as $S_\varepsilon(\Omega)$. Here we intentionally choose the symbol Ω for the frequency because it indicates the speed of change of $\Delta_\tau\varphi(t)$ or $\varphi(t)$ and not an optical frequency as in eq. (4).

From the above considerations, it follows that in order to evaluate the shape and width of the emission line the knowledge of $\sigma_{\Delta\varphi}(\tau)$, $S_{\Delta\varphi}(\Omega)$ or $S_{\varphi}(\Omega)$ is absolutely equivalent. As a by-product, we can underline that the knowledge of the statistical properties of $\Delta_\tau\varphi(t)$ is essential for the correct evaluation of the error probability function in optical coherent systems [1].

Measurement methods

In this paragraph we will describe some of the experimental techniques used to measure $S_\varepsilon(\omega)$, $S_{\dot\varphi}(\omega)$ and $\sigma_{\Delta\varphi}{}^2(\tau)$, and to verify the statistical properties of the random variable $\Delta_\tau\varphi(t)$.

a) Measure of $S_\varepsilon(\omega)$

Two methods are generally adopted to obtain $S_\varepsilon(\omega)$, namely the measurements performed by means of a Fabry-Perot interferometer [7] and that obtained through the

self-heterodyne technique [8] (see fig.5). In the last technique, the field from a single mode laser is first splitted in two branches, one of which is frequency shifted by means of a very stable acoustooptic modulator and the other one delayed of a time τ_d grater than the coherence time of the source, and then recombined and detected. In the hypothesis of a Lorentzian emission lineshape $S_\varepsilon = \delta\omega/[(\omega-\omega_0)^2+(\delta\omega/2)^2]$, with $\delta\omega$ the FWHM of the spectrum, it is easy to show that the spectrum displayed on the analyzer is also Lorentzian and with a FWHM = $2\delta\omega$. The use of the self-heterodyne technique allows to appreciate linewidths much lower than 10 MHz, which, instead, can represent a typical limiting value for the usually available Fabry-Perot interferometers.

b) Measure of $S_{\dot\varphi}(\Omega)$

This quantity can be measured using an unbalanced Michelson interferometer (fig.6), which allows to turn phase fluctuations into amplitude fluctuations. When the interferometer is adjusted in quadrature, that is for $\omega_0\tau=\pi/2$, τ being its time unbalance, and under the hypothesis that $|\Delta_\tau\varphi(t)| \ll \pi/2$, i(t), the current from the photodiode, can be shown to be given by [6]

$$i(t)=i_0-i_1\Delta_\tau\varphi(t)/2 \qquad (9),$$

where i_0 is its mean value and i_1 its maximum excursion.

Because of eqs. (7) and (8), the power spectra of $\Delta_\tau\varphi(t)$ and $\dot\varphi(t)$ are related to that of i(t) through the relations

$$\frac{i_1^2 R}{4}\, S_i(\Omega) = S_{\Delta\varphi}(\Omega) = 2\,\frac{S_{\dot\varphi}(\Omega)}{\Omega^2}(1-\cos\Omega\tau) \qquad (10),$$

where R is the input impedence of the spectrum analyzer.

c) Measure of $\sigma_{\Delta\varphi}{}^2(\tau)$

This quantity can be measured by replacing, in the same experimental apparatus used to derive $S_{\dot\varphi}(\Omega)$, the spectrum analyzer with an oscilloscope having an effective bandwidth larger than the frequency region in which the noise power spectrum is appreciably different from zero. Under this condition, the width of the trace of the oscilloscope is proportional to the integral of $S_{\Delta\varphi}(\Omega)$ over Ω, which allows an estimate of $\sigma_{\Delta\varphi}^2(\tau)$ (see eq.(8)). A quantitative measurement of $\sigma_{\Delta\varphi}(\tau)$ can be performed by sampling the signal from the photodiode and processing the obtained samples by means of a stastistical analyzer [6]. This technique is powerful because it allows to obtain the statistical distribution of $\Delta_\tau\varphi(t)$ and, consequently, the exact value of $\sigma_{\Delta\varphi}^2(\tau)$. A simpler method which, on the other side, is less precise, consists in evaluating $\sigma_{\Delta\varphi}^2(\tau)$ from a direct measurement of the visibility of the fringes at the interferometer output as a function of τ [9].

Classical theory of quantum noise

Any laser radiation field is made of up two different contributions deriving, respectively, from stimulated and spontaneous recombinations between the upper and lower laser energy levels. Stimulated emission, which is responsible for the light amplification, contributes to the total field with radiation exactly in phase with that surrounding the active medium. Spontaneous emission into the lasing mode, on the contrary, being completely incoherent, adds a small contribution, characterized by a random phase, to the total field, thus changing the stationary value of the light intensity inside the cavity. Because of the coupling between population inversion, in the laser medium, and the radiation field, the overall intensity undergoes damped oscillations until its stationary value is restored. The phase of the field, however, does not suffer any restoring effect and tends to maintain its new value until another spontaneous emission process does happen. Being a memoryless process, the stochastic quantity $\Delta_\tau\varphi(t)=\varphi(t+\tau)-\varphi(t)$, i.e. the difference between the values the phase of the total field assumes at instants separated by a time interval τ, undergoes a Brownian motion (random walk) so that its probability density function is Gaussian with variance $\sigma_{\Delta\varphi}^2(\tau) \propto |\tau|$. The overall result is that the presence of spontaneous emission, usually referred to as quantum noise, gives rise to an emission line whose shape, evaluated

through eqs.(6) and (7), is Lorentzian and whose width, expressed by the Shawlow-Townes' relation [3], reads

$$\Delta\nu_{sp} \approx h\omega_o\Delta\nu_c^2/ P_o \qquad (11).$$

In eq. (11), h is the Planck's constant, ω_o and P_o the mean frequency and the average power of the emitted radiation, and $\Delta\nu_c$ the linewidth of the passive cavity [3].

In most kind of lasers, namely solid state, gas and dye lasers, however, the most important contribution to the broadening of the emission line comes from the mechanical and thermal fluctuations of the cavity length. The effect of such fluctuations, when suitably limited, is to cause a line broadening $\Delta\nu \approx 10^4\ s^{-1}$, which usually is far greater than that due to quantum noise.

In semiconductor lasers, however, due to the low Q cavity factor, $\Delta\nu_{sp} >> \Delta\nu$, that is the width of the emission line is practically determined only by quantum noise. This can be simpy argued by looking at table I, where we compare the data needed to evaluate $\Delta\nu_{sp}$ for an He-Ne and a GaAlAs laser operating at the same level of output power (the great differences in the values of $\Delta\nu_c$ for the two lasers is not surprising being due to their different mirror reflectivities and lengths).

TAB. I

LASER	ω_0	P_o	$\Delta\nu_c$	$\Delta\nu_{sp}$
He-Ne	3×10^{15} rad/s	1 mW	$\sim 10^5\ s^{-1}$	$\sim 10^{-3}\ s^{-1}$
GaAlAs	2×10^{15} rad/s	1 mW	$\sim 10^{11}\ s^{-1}$	$\sim 10^7\ s^{-1}$

Experimental results

Because of the experimental result underlined at the end of the preceding paragraph (that is the shape and width of the emission line is determined by quantum noise only) semiconductor lasers offer the possibility of verifying experimentally the validity of the Schawlow-Townes' formula and, hence, of the theoretical assumptions made to derive it. This has been, in fact, done measuring the lineshape or, alternatively, the frequency noise spectrum by means of the techniques previously described.

The results of such experiments have shown a certain number of discrepancies with respect to the classical theory of quantum noise which we list below, while their theoretical explanations will be outlined in the next paragraph. The first careful measurements of the emission line of GaAlAs lasers showed that it was Lorentzian in shape but had a width which, even if inversely proportional to the emitted power P_o, was about 50 times greater than $\Delta\nu_{sp}$ [10]. Other interesting features of injection lasers were successively discovered when $S_{\dot{\varphi}}(\Omega)$, the frequency noise spectrum, was measured.

The first measurements of such quantity where, however, limited to the KHz frequency region in order to evaluate the influence of frequency noise on the performances of optical fiber interferometer systems such as acoustic, magnetic and acceleration sensors, and showed an inverse linear dependence of $S_{\dot{\varphi}}(\Omega)$ on Ω [11].

Anyway, this low frequency behaviour of $S_{\dot{\varphi}}(\Omega)$ has not to be directly associated to spontaneous emission process, but rather to spatial temperature fluctuations in the bulk material and to recombinations via trap levels, and is masked by quantum noise for frequencies greater than some hundred KHz.

This low frequency behaviour of $S_{\dot{\varphi}}(\Omega)$ seems to be responsible of a power independent contribution to the linewidth which, even if by far lower, in the usual operating conditions, than the power dependent one, has been really observed [12]. Succesively, rigorous measurements of $S_{\dot{\varphi}}(\Omega)$ in the frequency region extending from

some MHz up to some GHz demonstrated that the emission line of single-mode semiconductor lasers is not Lorentzian. Were the apoposite true, in fact, $S_{\dot{\varphi}}(\Omega)$ would result completely flat over the whole frequency range, while, on the contray, besides a flat pedestal, it presents a resonance peak whose position varies with the emitted power P_o as shown in fig.7. The center resonance frequency, which depends also on the particular laser structure, is generally located in the 0.5 ÷ 5 GHz region.

Because of the strict relation between $S_{\dot{\varphi}}(\Omega)$ and $S_{\varepsilon}(\omega)$, see eqs (6,8), the presence of the resonance peak in $S_{\dot{\varphi}}(\Omega)$ reflects into the appearence of side bands in the emission line of semiconductor lasers which therefore, as shown in fig.8, is no longer Lorentzian [6].

This was also confirmed by the first experimental measurements of $\sigma_{\Delta\varphi}(\tau)$ as a function of $|\tau|$. A typical result of such experiment is reported in fig. 9 The dependence of $\sigma_{\Delta\varphi}(\tau)$ on $|\tau|$ is quite different from the simple linear relationship assumed in the framework of the Schawlow-Townes' theory, unless values of $|\tau|$ greater than τ_r, the relaxation oscillation dampling time, are considered. This means that $\Delta_\tau\varphi(t)$ cannot be considered a full random walk process, which, again, because of eq.(6), reflects into a non-Lorentzian emission lineshape.

Intuitive explanation of the experimental results

All the above experimental results can be explained within the framework of semiclassical laser thoery, as it has been shown in several papers published by various authors during these last years.

The first work on this subject is that by Henry [13], in which the author was able to expalin the excessive broadening of semiconductor laser linewidth in terms of a very simple physical model.

As already pointed out, such a linewidth is essentially determined by the spontaneous emission processes that take place into the cavity and alters both the phase and the intensity of the lasing field in a discontinuous manner as illustrated in fig. 10.

Here Re $[E(t)]$ and Im $[E(t)]$ are the real and imaginary componente of the lasing filed $E(t) = E\exp(i\varphi_0)$ normalized is such a manner that its intensity $I = |E(t)|^2$ equals the number of photons in the cavity. When a spontaneous emission process takes place, it alters $E(t)$ by $\Delta E_i = \exp(i\varphi_0 + \theta_i)$, that is by a unit vector (one photon is added!) with random phase θ_i with respect to that of the pre-existing field. This causes a phase change $\Delta\varphi_i$ together with a deviation of the intensity from its stationary value $I = I_0 + \Delta I_i$.

By means of simple geometrical considerations one finds

$$\begin{cases} \Delta\varphi_i' = I_0^{-1/2} \sin\theta_i \\ \Delta I_i = 2 I_0^{1/2} \cos\theta_i + 1 \end{cases}$$

Once the filed intensity is altered, it does not remain to the new value, but undergoes relaxation oscillattions until its average value I_0 is restored. This happens in a time interval whose duration is of the order of 10^{-9} sec.

During this time, the laser suffers a net gain change $\Delta G(t) = (-2\omega_0/c)\,\Delta\eta_i(t)$, $\Delta\eta_i(t)$ being the deviation of η_i, the imaginary part of the cavity refractive index $\eta = \eta_r + i\,\eta_i$, from its steady-state value. The change in η_i, which is due to a change in the carrier density, reflects into an analogous deviation $\Delta\eta_r(t)$ of the real part of η from its stationary value.

This last variation $\Delta\eta_r(t)$, occurring during the period in which relaxation oscillations are present, causes an additional phase shift $\Delta\varphi_i''$ (and, hence, an additional contribution to the broadening of the emission line) whose total amount can be found to be

$$\Delta\varphi_i'' = -\frac{\alpha}{2I_0}\left(2 I_0^{1/2}\cos\theta_i + 1\right) \tag{12}$$

where $\alpha = \Delta\eta_r/\Delta\eta_i$ is called "enhancement linewidth factor" [13].

As shown in the enclosed paper, the equations describing the evolution of the laser system after every spontaneous emission are linear. This implies that $\Delta_\tau\varphi(t)$, the total

change in the phase of the field over a time interval τ is equal to the sum of the individual phase changes $\Delta\varphi_i$ caused by anyone of the spontaneous emissions occurring during τ, that is

$$\Delta_\tau\varphi(t) = \sum_i \left(\Delta\varphi_i' + \Delta\varphi_i''\right) =$$

$$= \sum_i \left\{ I_0^{-1/2}\left(\sin\theta_i - \alpha\cos\theta_i\right) - \frac{\alpha}{2I_0} \right\} \tag{13}$$

If we denote by R_s the average rate of spontaneous emission in the mode, the first and second moments of $\Delta_\tau\varphi(t)$ are given by

$$\langle \Delta_\tau\varphi(t) \rangle = -\frac{\alpha R_s \tau}{2 I_0} \tag{14a}$$

$$\sigma^2_{\Delta\varphi}(\tau) = \langle [\Delta_\tau\varphi(t)]^2 \rangle - [\langle \Delta_\tau\varphi(t) \rangle]^2 = \frac{R_s}{2I_0}(1+\alpha^2)\,\tau \tag{14b}$$

Equation (14a) shows haw, due to the presence of spontaneous emission, the angular frequency of the emitted radiation suffers a shift $\Delta\omega = \langle \Delta\varphi(t) \rangle = -\alpha R_s/2I_0$. Furthermore, eq.(14b) indicates that the phase of the lasing field executes a Brownian motion so that the emission line is Lorentzian in shape with a FWHM

$$\Delta\nu_{sp} = \frac{R_s}{4\pi I_0}\left(1+\alpha^2\right) \tag{15}$$

which is greater than the Shawlow-Townes' formula by a factor $(1+\alpha^2)$. This factor arises because semiconductor lasers operate as detuned oscillators, that is regenerative oscillatorss in which the cavity resonance and optical transition frequencies do not coincide. Detuning has the effect of coupling the phase and the amplitude of the lasing optical mode via the α factor, since any change in the instantaneous intensity, reflecting into a refractive-index variation, affects the phase of the emitted field. This does not happen in tuned oscillators where α is very small compared to unity thus giving and unappreciable contribution to the linewidth.

As far as semiconductor lasers, values of α in the range 2÷7 have been found, or estimated, depending on the composition and physical structure of the considered devices [14], which gives reason for the excessive linewidth. Henry's theory, however, even if accounting for the anomalous broadening, is valid only when an equilibrium, or, to be more precise, a quasi-equilibrium condition exists (see fig.11). In fact, it takes into account only changes of the instantaneous phase of the lasing field over time intervals during which the relaxation oscillations undergone by the system after any spontaneous emission process have completely died out. In order to face the problem correctly, one should resort to the rate equations, which are able to describe the physical problem in a satisfactory way (see enclosed paper).

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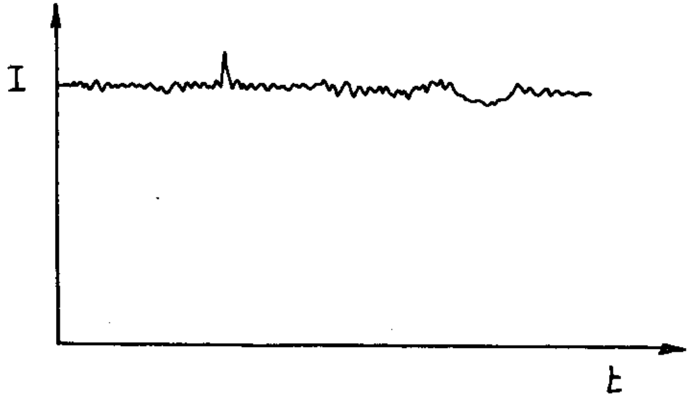

Fig. 1

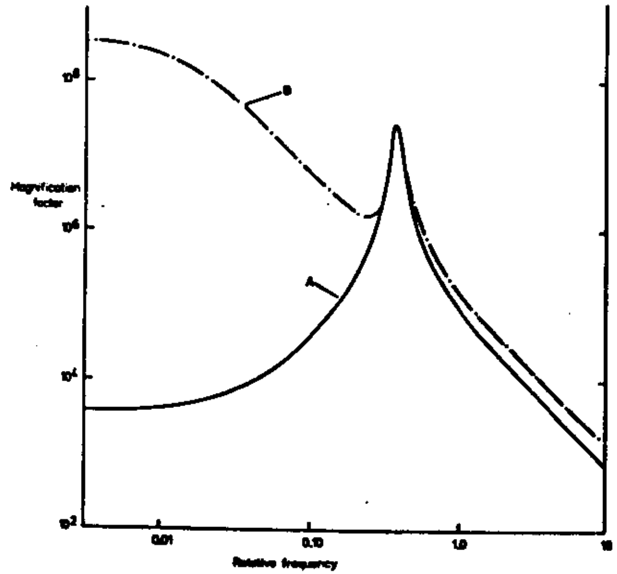

Fig.2- Intensity noise fluctuations in laser output as a function of frequency for a typical laser diode. Quantity plotted is the power spectral density of intensity. Curve A, noise power in all modes; Curve B, noise power in one out of total two modes.

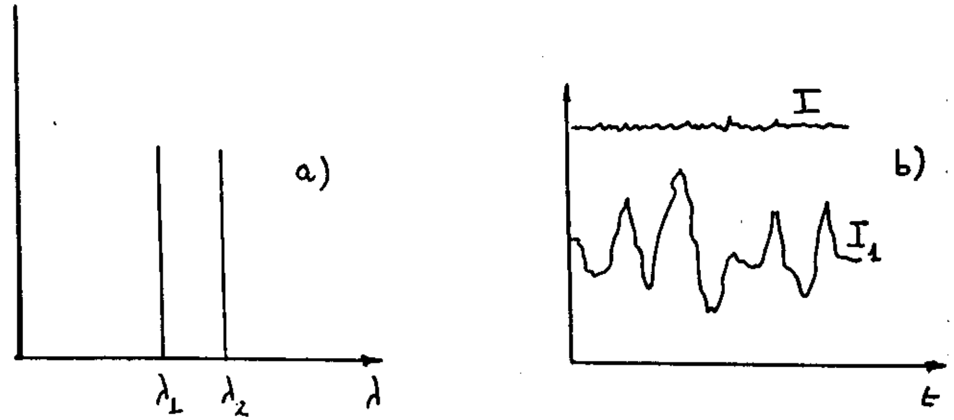

Fig.3- a) Spectrum of a laser having two modes. b) Output power vs. time associated with the total intensity (I_1+I_2) or to one of the two modes (I_1).

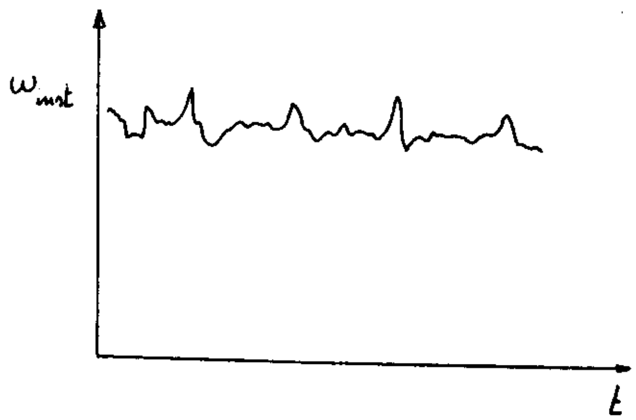

Fig.4 - Instantaneous oscillation frequency of the e.m. field vs. time

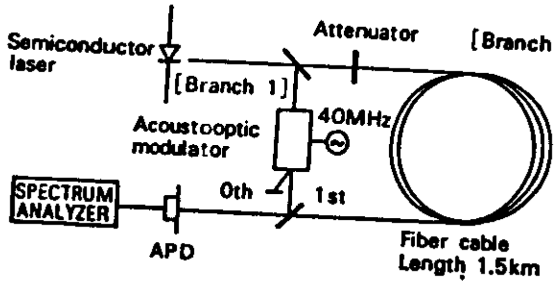

Fig.5 - Setup for the delayed self-heterodyne method.

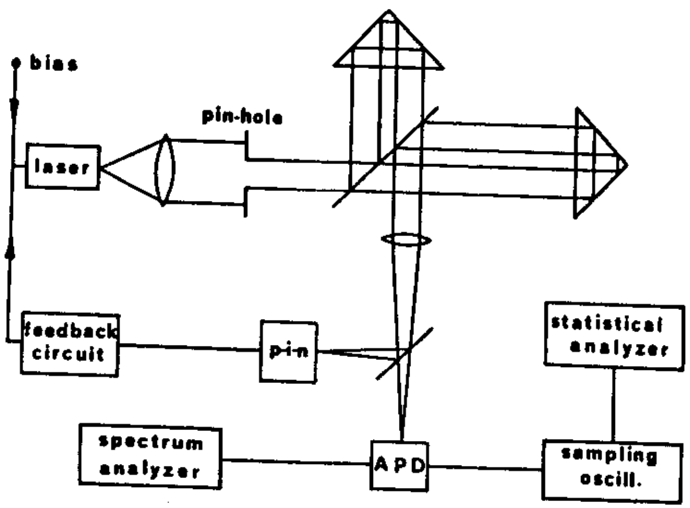

Fig.6 - Set up for measuring $S_{\dot{\phi}}(\omega)$

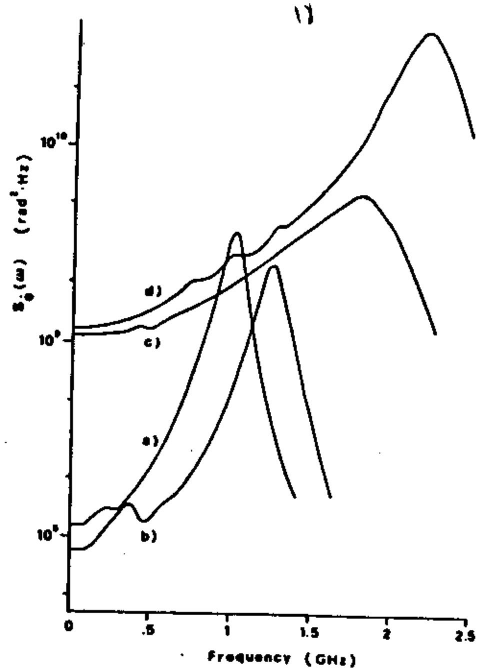

Fig. 7. Two-sided power spectral density $S_{\dot{\phi}}(\omega)$ versus frequency. Curves *a* and *b* refer to an ITT LS 7709 laser at output powers 4 and 7.5 mW, respectively, curve *c* to an RCA C86014 laser at 1.6 mW, and curve *d* to a Laser Diode LCW10 at 3 mW.

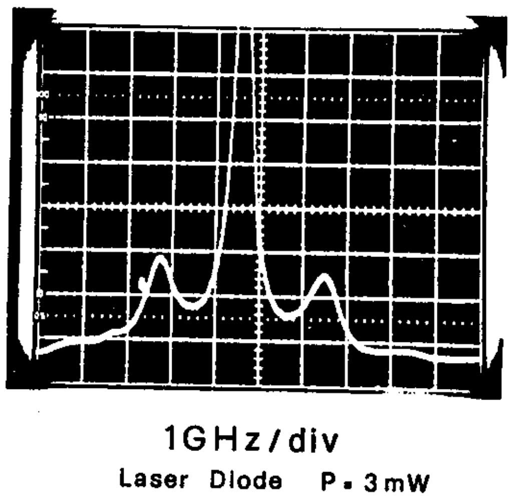

Fig.8 - Lineshape of a GaAlAs semiconductor laser.

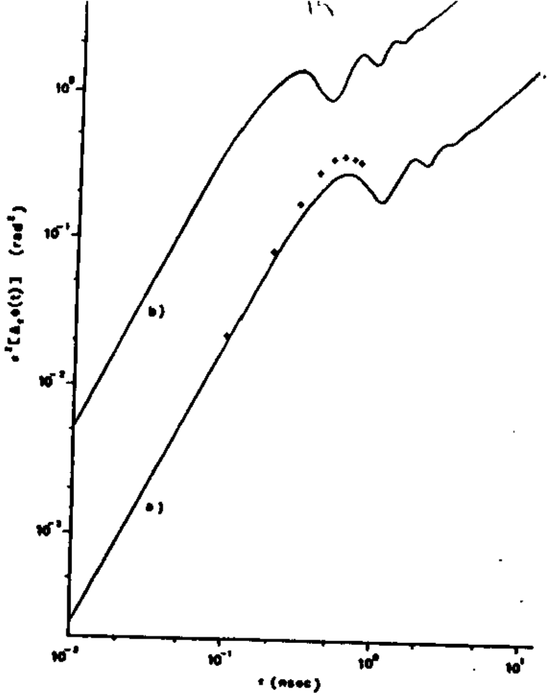

Fig.9 Variance $\sigma^2(\Delta_\tau\phi(t))$ versus τ for the ITT LS 7709 laser (curve *a*) and the Laser Diode LCW10 laser (curve *b*) operating in the same conditions as Fig. 4. Crosses represent values directly measured and refer to the ITT LS 7709 laser.

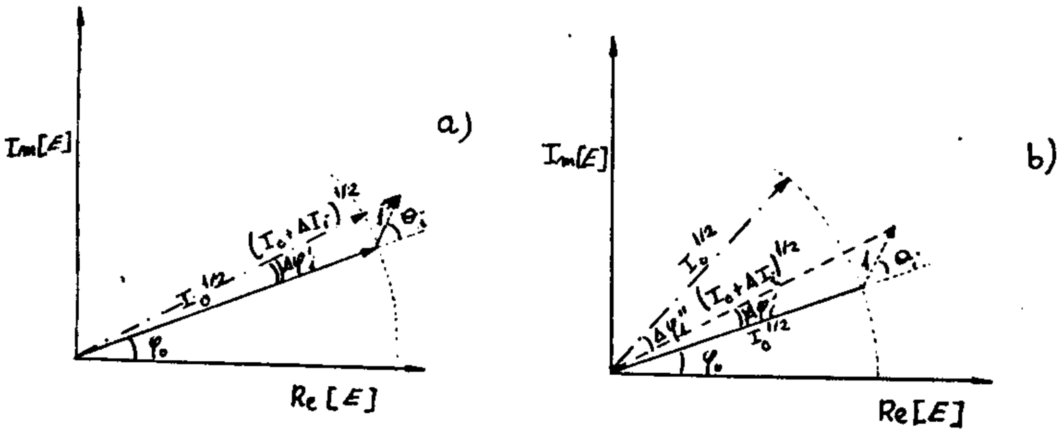

Fig.10 - Electric field representation in the complex plane. a) case corresponding to a gas laser. b) case corresponding to a semiconductor laser. (—) field before spontaneous emission, (---) field just after a spontaneous emission event, (---) field after a new stationary state has been reached.

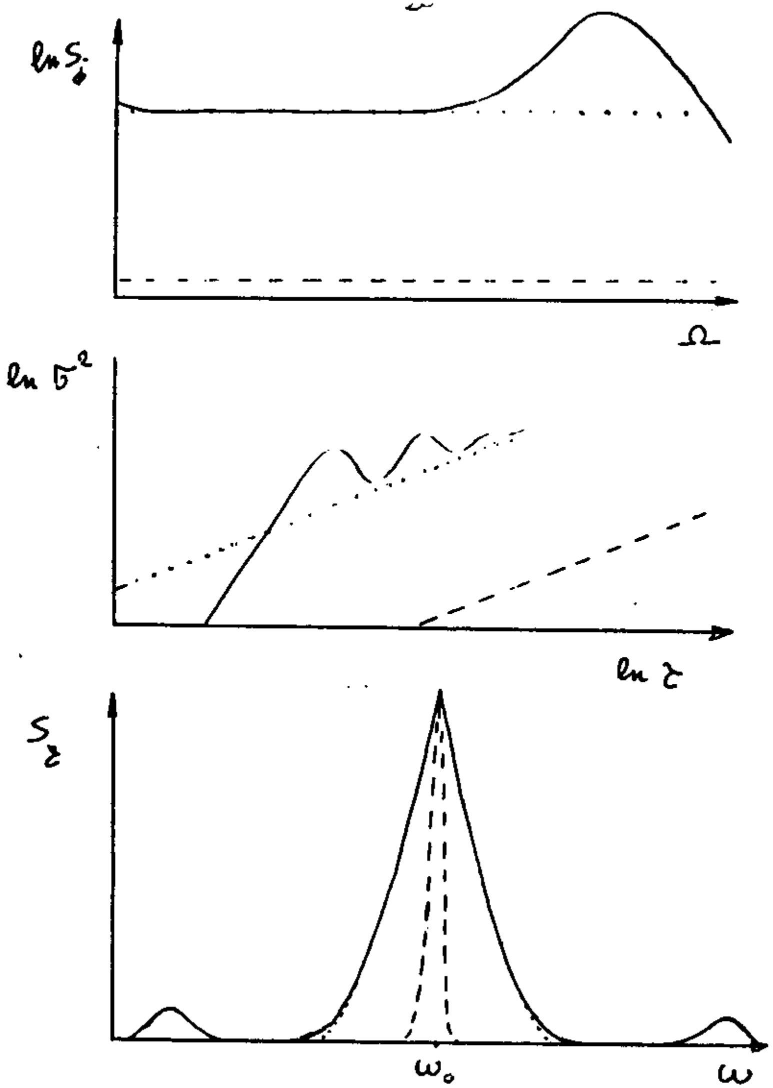

Fig.11 - Quantities characterizing frequency noise. (—) experimental data; (---) results obtained by standard theory; (···) results obtained by modified standard theory.