A method for characterizing the stability of light sources

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Abstract: We describe a method for measuring small fluctuations in the intensity of a laser source with a resolution of 10^{-4}. The current signal generated by a PIN diode is passed to a front-end electronics that discriminates the AC from the DC components, which are physically separated and propagated along circuit paths with different gains. The gain long the AC signal path is set one order of magnitude larger than that along the DC signal path in such a way to optimize the measurement dynamic range. We then derive the relative fluctuation signal by normalizing the input-referred AC signal component to its input-referred DC counterpart. In this way the fluctuation of the optical signal waveform relative to the mean power of the laser is obtained. A "Noise-Scattering-Pattern method" and a "Signal-Power-Spectrum method" are then used to analyze the intensity fluctuations from three different solid-state lasers. This is a powerful tool for the characterization of the intensity stability of lasers. Applications are discussed.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (140.0140) Lasers and laser optics.

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1. Introduction

Among the ubiquitous applications of lasers, many cases are really demanding in terms of stability. Examples can be found in many fields of physics, chemistry and engineering, like the dynamic light scattering technique, confocal microscopy, particle-counting methods, interferometry [1–5]. All these methods are based upon the measurement of the changes (fluctuations) of the light intensity over time, from which substantial information about key physical/chemical parameters of the sample is extracted. The laser stability is one of the main limitations to the sensitivity of these methods, because the signals are ultimately hidden within the noise of the light source.

Recent development and widespread exploitation of novel solid-state laser sources allows for the design of new compact, power-effective, flexible and cheap instruments. In principle, these sources may represent a breakthrough also from the point of view of the stability, although little information is typically available in this regard and the physical origin of the noise is not always fully understood. The fast increasing count of technological solutions makes it difficult to give general rules for a full characterization and optimization of the light sources. This can be compared to the completely opposite case of other well-known and widely used lasers, like the ubiquitous He-Ne, the ultimate secretes of which have been uncovered since several decades. A lot of work, both theoretical and experimental, has been devoted to understanding the laser instabilities, often related to fundamental laws of physics of nonlinear systems [6–8]. Nowadays the time stability of many laser sources has been widely studied and accurate descriptions of the origin of intensity fluctuations have been given.

Semiconductor lasers typically show a relatively high root-mean-square (RMS) noise in a bandwidth of interest for many applications (i.e. from 10Hz to 10MHz). This is typically determined by 1) instability of the power (current) supply, 2) temperature instability, 3) internal damage/imperfections in diode junctions and 4) 1/f noise due to trapping of carriers in the device [9]. Moreover, the stability typically degrades as the light power is increased.

In this paper, we present a method for characterizing the intensity fluctuations of a laser light source with a precision with a precision of some 10^{-4} of the total emitted power. Three different solid state laser diodes are characterized and compared. A noticeable reduction of the noise is observed for the laser provided with a stabilized power supply and a temperature-control driver.

We use a photodiode (PD) transduction unit coupled with an original patented Front-End (FE) electronics [10]. The principal issue with the electronic read out is related to the intrinsically large DC component brought about the intense laser beam through the photodiode, which could easily put the circuit into saturation. We designed a smart front end able to discriminate the high- from the low-frequency components, which are physically separated and propagated along circuit paths with different gains. The gain is low for the DC component, which prevents saturation, and large for the AC signal, which helps get a large signal-to-noise ratio. This functionality is implemented in practice with a PI (Proportional Integrative) negative-feedback control loop as described in detail in [10]. Two physically separated output currents are generated: 1) the zero-offset fast signal and 2) the slow signal, proportional to the laser-beam mean intensity. The isolated high-frequency component is amplified as much as possible. In such a way the small, fast signal is easily measured through a fast and cheap digitizer. In parallel, a precise measurement of the DC signal component is performed, which allows for a continuous monitoring of the laser power. In order to verify the response of both the AC and DC gains, we performed measurements with known calibrated particles passed through a laser beam. In such a way, the amplitude of the fast signals is proportional to the power removed from the particle proportionally to its cross section and to the incoming beam power. As an example we show in Fig. 1 the signals obtained with 430nm diameter polystyrene spheres with laser power ranging from 10 mW to 150mW. This proportionality is found within a confidence level of 99%.

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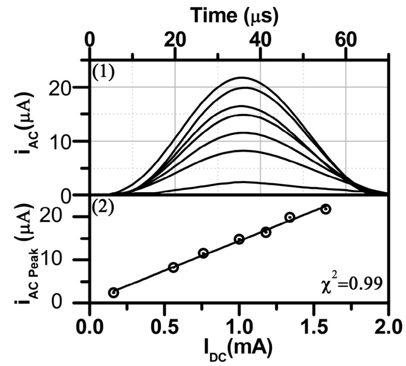

Fig. 1. Experimental results for the fast components as measured for spheres of 430 nm in diameter. (1) AC signals obtained for laser power ranging from 10 mW to 150 mW. (2) Peak signal current vs DC current i.e. laser power. As can be seen the signal height grows linearly with the laser intensity.

2. Data acquisition and data reduction

The scheme is based upon multiple, synchronous measurements of the laser beam as physically subdivided into four parts. This is accomplished by sending the laser beam onto the geometrical center of a quadrant photodiode (QPD), a relatively cheap device often used in optics laboratories for monitoring the position of laser beams. The position of the laser spot relative to the QPD is adjusted by moving the latter along the optical axis in order to equalize the signal amplitudes from each quarter within 1%. This also gives comparable shot noises from each channel. In our measurements we used all four signals, passed through an array of four custom designed FE electronic channels [10].

A 4-channel 12-bit digital oscilloscope (PicoScope 4424, by Pico Technology) is used to digitize the fast signal components at a sampling frequency of 5 MHz. Waveforms of 5×10^5 points are collected, thus sampling the waveform over a time basis of 0.1 s. A National Instrument 12-bit "USB-6008" acquires the slow component of the signals. Both acquisition devices are connected through the USB ports to a PC.

A simplified schematic diagram of the front-end channel is shown in Fig. 2. The current-to-voltage gain of the circuit is 10kΩ for the AC signal component and 1.2kΩ for the DC signal component. The electronic noise is 330μV rms when no light is allowed to reach the photodiode. All technical details on this circuit are shown in [10].

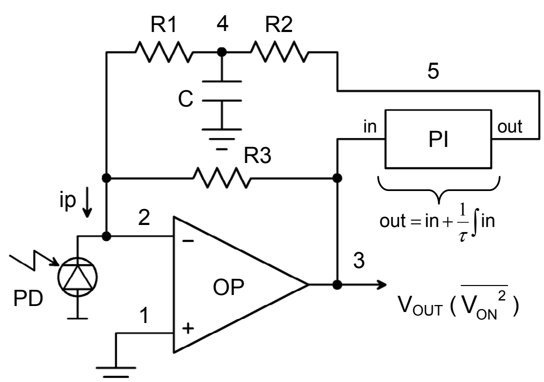

Fig. 2. Simplified schematic diagram of the preamplifier. Fluctuations are read at pin 3. The mean DC signal is read at pin 5.

For each laser source, 100 sets of waveforms have been acquired, each set consisting of four synchronous waveforms, one per quadrant as mentioned above. Due to the presence of a

FET transistor at the input of each FE-electronics channel an offset of ~60 mV is present in all fast component waveforms, which corresponds to the gate-to-source quiescent voltage of the FET. This systematic offset is then subtracted numerically. By simultaneously monitoring the four waveforms from the QPD we observed that the noise is strongly correlated when the laser is allowed to reach the photodiode. This excludes 1) the FE electronics as the main source of noise, because by no means can the mere electronic noises from the preamplifiers be channel-by-channel correlated, and 2) any beam pointing instabilities or beam shape fluctuations determining fake intensity fluctuations. Note that this argument could not be made if measuring the beam with a non-segmented PD rather than a QPD. The data analysis has then been performed with just one noise waveform because the four waveforms are statistically equivalent.

Each waveform is analyzed in terms of the so-called Noise-Scattering-Pattern (NSP) method [9] and the Signal-Power-Spectrum (SPS) method. The NSP method allows for a first qualitative characterization of the main contributions to the signal noise. It allows distinguishing among: 1) Gaussian statistic noise, like the thermal, shot, 1/f or generation-recombination noise, and 2) non-Gaussian statistic noise, like single generation–recombination center and avalanche noise (for more details see [9]).

A two dimensional (2D) NSP plot has been computed for each waveform through the following scheme. First, the fast signals are normalized by using the slow component as mentioned above. Voltage signals are therefore converted into relative, adimensional signals. The NSP method has then been applied to each waveform as described in [9]. For the sake of convenience, each NSP pattern is binned into a 50 × 50 2D symmetric histogram, spanning from -5×10^{-3} to $+ 5 \times 10^{-3}$ with a resolution of 2×10^{-4}. Finally an averaged NPS histogram is obtained from all the waveforms.

A more quantitative characterization has been performed via SPS analysis. For computational convenience, each waveform has been divided in 10 sub-waveforms to evaluate the power spectra in the spectral range 100Hz → 5 MHz. All the 10 × 100 power spectra are then averaged. A very crucial check is to verify if the contribution to the noise due to the QPD and FE electronics is negligible with respect to the laser one. In Fig. 3 curve (1) the SPS analysis is shown with the FE electronics and/or the laser switched on or off. It allows a comparison between the different contributions. As can be seen, when the laser is switched on (curve (4)), the contribution due to the electronics is completely negligible compared to that due to the laser itself in the whole frequency range of interest (1kHz to 1 MHz). Note that we used the most stable laser available to us in this measurement. The method is thus suitable for characterizing the small and fast noise of a broad range of lasers.

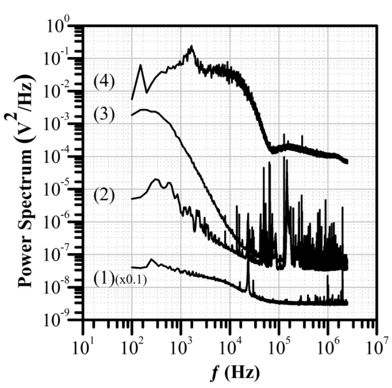

Fig. 3. SPS analysis example. (1) digitization unit noise; (2) hardware connected to the digitization unit, all hardware is switched off; (3) QPD and FE electronics switched on, laser switched off; (4) laser switched on.

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3. Description of the used lasers

Three laser sources have been tested: two relatively cheap diode lasers (Global Laser Inc., model Acculase-LC and Coherent, model ULN) and a source which is both temperature and current controlled (Omicron, model CWA-L). In the following (Table 1) we refer to them as A, B and C, respectively. See Table 1 for the main specifications. Laser A is connected by a laboratory power supply, whilst B and C are provided with their own power suppliers. The last one is connected to an external unit with active current and temperature controls. The emitted power specification shows huge differences.

Table 1. Laser model/producer, maximum optical power, wavelength, presence of a stabilized power supply and/or a temperature controller driver.

	Laser	Max O.P.	λ	P.S.	T.C.
A	GL Acculase - LC	100mW	660nm	No	No
B	Omicron CWA-L	150mW	647nm	Yes	Yes
C	Coherent ULN	5mW	638nm	Yes	No

4. Characterization of the lasers

Typical fast signals obtained with the lasers and the corresponding NSP patterns are shown in Fig. 4.

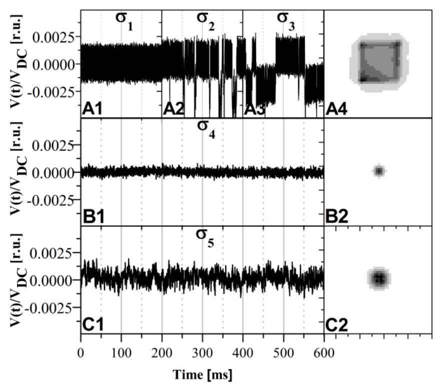

Fig. 4. AC signals and NSP patterns for the three sources studied in the present work. A1, A2, A3 are non-stationary behaviors of the lasing mode of A. The rms signal measured in the three lasing modes are $\sigma_1 = 1.2 \times 10^{-3}$, $\sigma_2 = 1.7 \times 10^{-3}$ and $\sigma_3 = 1.8 \times 10^{-3}$. The highly non-stable lasing mode of A is also characterized by a non-Gaussian noise, as the NSP pattern clearly shows in panel A4. In panels B1 and B2 the AC signal of B and the corresponding NSP pattern are shown. The noise is Gaussian and the rms is $\sigma_4 = 2.3 \times 10^{-4}$. In panels C1 and C2 the AC signal of C and the corresponding NSP pattern are shown. The noise is Gaussian and the rms is $\sigma_4 = 5.5 \times 10^{-4}$.

Laser A shows a non-stationary behavior, randomly switching over time from Gaussian noise (small rms) to non-Gaussian noise (high rms). Under non-Gaussian noise conditions the stability of the laser is really poor. Typically the Gaussian noise lasts long enough to permit an acquisition of 100 waveforms. The behavior of the non-Gaussian noise is less stable, and data reduction has been performed with single waveforms. Use of this laser in applications relying on small intensity fluctuations is very difficult or impossible (see [3]).

Laser B is specifically developed for research purposes. It is equipped with an electronic driver, a dedicated power supply and a temperature control for the crystal. NSP analysis indicates a limited, pure Gaussian noise. The shape of the NSP pattern shows a small intensity rms, indicating the very good stability of this source.

Laser C is a compact laser diode developed for OEM applications, where very low noise is required. It is equipped with an electronic driver and a dedicated power supply. Also in this case a pure Gaussian noise is observed and the NSP pattern shows a narrow intensity distribution. Notice that the AC signals and the rms noise represented in Fig. 4 are expressed

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in dimensionless units. In fact we all-the-way normalized the fluctuations, i.e. the AC component, to the corresponding mean intensity, i.e. the DC component, of the laser beam. The normalized rms fluctuation of laser B is smaller than for laser C even if the absolute fluctuations of the light intensity are larger. This is due to the broad range of light powers of the studied lasers, approximately a factor 30 as can be seen in Table 1.

A more quantitative analysis can be performed via SPS. We define the dimensionless power spectrum of the normalized signals as:

$$S(f) = \left| F\left\{ \frac{i_{AC}}{i_{DC}} \right\} \right|^2 , \quad (1)$$

where "F{}" stands for "Fourier transform of". Then, the relative variance of the signal is:

$$\sigma^2 = \int S(f)\, df \, . \quad (2)$$

In Fig. 5 we show the averaged relative spectra for the three lasers. Notice that due to the non-stationary behavior of laser A, the corresponding power spectrum has a peculiar statistical meaning, different from the other two sources.

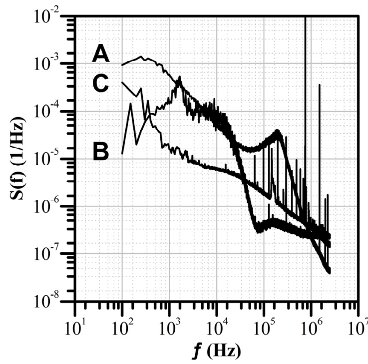

Fig. 5. Power spectra of the three sources studied in the present work.

5. Conclusions

The novel method shown here is a very valuable tool for the characterization of the light-intensity stability of laser diodes. It is particularly suitable for high-power lasers, since the developed FE electronics allows the digitazion and characterization of the small ripple of the laser intensity over its high mean value, using in a very convenient way all the signal dynamic range.

As an example we applied the method to three different lasers. We found that the quality of the laser, in terms of the dedicated control devices and purpose, reflects upon the quality of the emitted beam in terms of its power RMS noise. In particular the novel method is suitable to perform both long statistical analyses for stationary systems and real-time monitoring of the quality of the beam. We believe it could be very attractive for laser applications and studies for which the lasing light noise is to be kept monitored to avoid misunderstandings in the measurements.