Low Coherence Optic Source Characterization

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Abstract: This work presents the results of characterization of the coherence length of an optic source using interferometric techniques and digital signal processing. Optic sources are not ideal because of random behavior in the emission process and spectral dispersion. Optical coherence is the ability of light to generate interference, either temporal or spatial. In time domain, coherence is expressed by the autocorrelation function. In case of monochromatic laser, it has larger coherence length, in the order of tenths to hundredth of meters, rather than a superluminiscent diode (SLD), which is shorter, in the orders of millimeters. This work presents a method for measuring coherence length using an automated Michelson interferometer and a SLD with central wavelength $\lambda_0 = 1302.4$ nm and acquisition system by means of a soundcard in a personal computer.

1. Introduction

The term optical coherence refers to the property of light of keeping the same behavior at different times or different places. The first is referred as temporal coherence while the second refers itself as spatial coherence. One of the properties of coherence is the ability to produce interference fringes, in the case of temporal coherence this only occurs while temporal delay $\tau$ is less than or equal the coherence time $\tau_c$. For example, monochromatic light has long coherence time rather than wider spectrum light. For further examination of this, it is possible to refer to [1].

2. Theoretical background

To verify the coherence of an optical source, the autocorrelation function $G(\tau)$ is expressed as:

$$G(\tau) = \langle U^*(t)U(t+\tau) \rangle = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} \langle U^*(t)U(t+\tau) \rangle dt,$$

(1)

where $U(t)$ represents a complex wave function and $T$ a time period where the function is measured. This previous expression represents the intensity of a two wave function from the same source while having a time delay between them. Power spectral density $S(\nu)$ is defined as the Fourier transform of autocorrelation function. The inverse Fourier transform, if the power spectral density is known a priori helps to calculate the autocorrelation function.
This relationship is known as Wiener-Kinchine theorem [1]. This means that is possible to know the power spectral density $S(\nu)$ of a source by means of the autocorrelation function or, if $S(\nu)$ is known a priori, it is possible to compute the autocorrelation function $G(\tau)$.

For the characterization of optical sources, one important parameter is the coherence length. This is computed by

$$\tau_c = \int_{-\infty}^{\infty} |g(\tau)|^2 d\tau$$

where $g(\tau) = G(\tau)/G(0)$, also known as the normalized correlation function. Coherence length is computed as:

$$l_c = \tau_c c$$

All previous expressions are referred to ideal optical sources whose mathematical model is possible to analyze with, such as Gaussian or quasi monochromatic sources. Figure 1 presents the emission spectrum of a sample superluminiscent diode (SLD). From this image it is possible to see that this is not an ideal Gaussian spectrum, but it is possible to approximate it to. Also, specifications vary slightly from each device fabricated. Because of this reason, the motivation for this work is to characterize a SLD with the tools in hand, as an interferometer.

![Emission Spectrum](image)

**Specifications from sample datasheet:**
- Center wavelength: $\lambda_0 = 1314$ nm.
- Spectral width @ 1 nm resol: $\Delta_\lambda = 30$ nm
- Operating current 247 mA.

This work presents one experiment to measure the coherence length of a QSDM-1300-9 SLD using an automated Michelson interferometer as autocorrelator[2] with a moving mirror at constant speed. The use of digital signal processing techniques allows to measure the coherence length of the source. The experimental setup is presented in the next section

### 3. Experimental setup

Figure 2 presents the experimental setup used to measure the coherence length of a SLD. The moving mirror moves at constant speed $v = 1.1$ $\mu$m/s. The photodetector used is a Thorlabs FGA20.
and the data was acquired with the soundcard of a PC computer using sampling frequency $F_s = 44.1$ kSamples/s ($T = 1/F_s = 22.68 \mu s/sample$). The SLD used was Qphotonics QSDM-1300-9 with central wavelength $\lambda_0 = 1302.4$ nm with $\Delta x = 34.96$ nm operating at 247 mA. These values are specific for the diode used in the experiment.

Figure 2. Automated Michelson interferometer used to measure the coherence length of an optical source.

Aproximating the data to a gaussian power spectral density:

$$S(\Delta) = P_0 e^{-\frac{(\lambda - \lambda_0)^2}{2\sigma_\lambda^2}}$$

where $\sigma_\lambda = \Delta x / 6 = 5.827$ nm. To change previous expression to the frequency domain it is necessary to see the variations [1],[3]:

$$\Delta \lambda = \Delta \left( \frac{c}{\nu} \right) = -\frac{c}{\nu^2} \Delta \nu = -\frac{c}{\nu} \Delta \nu = -\frac{\lambda_0^2}{c} \Delta \nu.$$  \hspace{1cm} (6)

The minus sign indicates that this relationship is inverse, so, it is possible to take absolute value to change between domains. Around $\lambda = \lambda_0$, the previous expression changes to $\Delta \lambda = \left( \frac{\lambda_0^2}{c} \right) \Delta \nu$.

Expression (5) in the frequency domain is

$$S(\nu) = P_0 e^{-\frac{(\nu - \nu_0)^2}{2\sigma_\nu^2}},$$

where $P_\nu = (c/\lambda_0^2) P_0$, $\sigma_\nu = (c/\lambda_0^2) \sigma_\lambda = 1.031$ THz, $\nu_0 = c/\lambda_0 = 230.3$ THz.

By the use of (2), the autocorrelation function can be expressed as:

$$G(\tau) = \frac{P_0 \sigma_\nu}{\sqrt{2\pi}} e^{-\frac{\tau^2 \sigma_\nu^2}{2}} e^{j2\pi \nu_0 \tau}.$$  \hspace{1cm} (8)

This function shows a gaussian function in time domain that multiplies an harmonic function with frequency $\nu_0$.

The coherence length can be computed by (3) and it is equal to[3]:

$$\Delta x = \frac{\lambda_0^2}{\nu_0}.$$
Then, the theoretical coherence length using (4) is \( l_c = 82.08 \mu m \).

By using the experimental setup we took several measures. Figure 3 presents an example of an interferogram for the SLD.

In order to measure the coherence length it is necessary to determine it from the measurements. The following procedure with the help of digital signal processing [4] was used to achieve this.

- Signal was filtered with high-pass filter; helping with this that any DC component was diminished.
- Signal was processed to obtain its absolute value.
- Signal was low-pass filtered; the objective is to get the envelope of the signal and then it was normalized. This shows a gaussian shape function that covers the coherence length.
- Using previous data, the position of the two closest values to 0.5 were taken. The number of samples is multiplied by the period \( T \) to get the distance time. This time distance is considered as full width at half maximum \( \text{FWHM} \) for the new gaussian-shape function.
- From this value, its corresponding standard deviation \( \sigma \) is computed by
  \[
  \sigma = 0.4247 \Delta_{\text{FWHM}}
  \]  
  \[
  \tau^* = 6\sigma
  \]  
- Finally, the coherence length of the optical source is calculated with the help of the speed of the interferometer displacement arm by
  \[
  l_c = \tau^* v
  \]

Figure 4 shows the example of the envelope obtained using this approach.

\[
\tau_c = \left( \frac{1}{4\pi \sigma_v^2} \right)^{1/2} = 273.6 fs.
\]  

(9)

4. Results

For this experiment, 15 measures were made, and the results are presented in table 1. For these measurements, the coherence length \( l_c \) found is 50.2 \( \mu m \). This differs from the theoretical value of 82.08 \( \mu m \). Statistically, the deviation coefficient is acceptable but it has to be improved.
5. Conclusions

A different approach for measuring the coherence length of a SLD is presented. This approach tries to fit measures obtained by the use of a Michelson interferometer used as an autocorrelator device. This gives the opportunity of a less expensive method rather than an expensive optical analyzer. The coherence length can be explained with the fact that current SLD power spectral density is not an ideal gaussian function, but it approximates to that. Also, it presents ripples that modifies the right autocorrelation function. Improvements in electromechanical devices have to be done to get better measurements. Further work will be in the direction of calculating $l_c$ for different optical sources with other spectral densities.

| # Meas | $\Delta_{FWM}$ (s) | $\sigma$ (s) | $\tau$ (s) | $l_c$ (m) |
|-------|---------------------|------------|-----------|-----------|
| 1     | 1.74E-02            | 7.39E-03   | 4.43E-02  | 4.88E-05  |
| 2     | 1.88E-02            | 7.98E-03   | 4.79E-02  | 5.27E-05  |
| 3     | 1.74E-02            | 7.93E-03   | 4.43E-02  | 4.88E-05  |
| 4     | 1.86E-02            | 7.90E-03   | 4.74E-02  | 5.21E-05  |
| 5     | 1.91E-02            | 8.11E-03   | 4.87E-02  | 5.35E-05  |
| 6     | 2.00E-02            | 8.49E-03   | 5.10E-02  | 5.61E-05  |
| 7     | 1.80E-02            | 7.64E-03   | 4.59E-02  | 5.04E-05  |
| 8     | 1.62E-02            | 6.88E-03   | 4.13E-02  | 4.54E-05  |
| 9     | 1.73E-02            | 7.35E-03   | 4.41E-02  | 4.85E-05  |
| 10    | 1.77E-02            | 7.52E-03   | 4.51E-02  | 4.96E-05  |
| 11    | 1.87E-02            | 7.94E-03   | 4.76E-02  | 5.24E-05  |
| 12    | 1.59E-02            | 6.75E-03   | 4.05E-02  | 4.46E-05  |
| 13    | 1.76E-02            | 7.47E-03   | 4.48E-02  | 4.93E-05  |
| 14    | 1.85E-02            | 7.86E-03   | 4.71E-02  | 5.19E-05  |
| 15    | 1.76E-02            | 7.47E-03   | 4.48E-02  | 4.93E-05  |
| MEDIA |                     |            |           | 5.02E-05  |
| STD. DEV. |                     |            |           | 3.0079E-06 |
| DEV COEF (%) |                     |            |           | 5.99%       |

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