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# Computer Support of Analysis of Optical Spectra Measurements †

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**Abstract:** The verification of measurement errors has a big impact on the assessment of the accuracy of conducted measurements and obtained results. In many cases, computer simulation results are compared with measurement results in order to evaluate measurement errors. The purpose of our research was to check the accuracy of measurements made with a Fabry–Perot interferometer working in the transmission mode. In the measurement setup, a 1310 nm superluminescent diode light source, single-mode optical fibers and an optical spectrum analyzer were used. The influence of the length of the resonating cavity and refractive index on the envelope of the optical spectrum was investigated. A program was created that models the envelope of the optical spectrum on the basis of the length of the resonating cavity, the refractive index and the light source output spectral characteristic, which in simulation was assumed to have the shape of Gaussian distribution. After the simulation the program compares the simulated and measured optical spectrum. The comparison of simulated and measured optical spectra proved to be challenging due to the shift in the position of the central peak between the simulated and measured optical spectrum. There are two ways to perform model fitting: by adjusting the position of central peaks or minimums next to the central peak. It was observed that the second solution was more optimal and was implemented in the program.

**Keywords:** sensors; fiber-optic; interferometer

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## 1. Introduction

Nowadays, fiber-optic sensors based on the Fabry–Perot interferometer construction have become popular. They ensure stable and repeatable measurements [1]. They can be placed in hard-to-reach places because they have small physical dimensions [2]. Moreover, they are resistant to electromagnetic waves [3]. Standard telecommunication optical fibers can be used for their construction, which potentially reduces the cost of sensor production. Fiber-optic sensors can be used to measure physical parameters such as temperature [4], displacement [5] and the refractive index [6]. They can be found in many fields of science and technology, including biological [7] and chemical research [8].

An important issue in metrology is the verification of the accuracy of the measurements when analyzing the results [9]. Imprecise measurements can lead to erroneous conclusions after the analysis and interpretation of such defective data. However, the detection of errors that may have occurred while performing measurements is possible. These errors may result from the finite precision of the devices used to set the width of the cavity of the interferometer or from parallax error. Some of them may result from imperfections of devices, e.g., fluctuation of the light source. Depending on the cause of their occurrence, various types of errors can be distinguished, such as outliers and systematic and random errors. However, they can all have a significant impact on the accuracy of the measurements. The accuracy of interferometric measurements depends mainly on the parameters of the interferometer cavity. These are the width of the cavity and the refractive index of its filling medium. Checking the accuracy allows us to determine the exact parameters of the measurements, which may be crucial when examining the influence of slight changes in the refractive index on the obtained results.

The purpose of our research was to find a way to check the accuracy of measurements performed with a Fabry–Perot interferometer.

## 2. Materials and Methods

Figure 1 shows the setup that was used for the measurements. It was a fiber-optic implementation of the Fabry–Perot interferometer working in the transmission mode. Two single-mode optical fibers (SMF-28 Ultra Optical Fiber, Corning, Glendale, AZ, USA) were used. They are commercially available and can be applied in communication, meaning that we could easily connect our system to the existing network infrastructure. The first fragment of the fiber connected a 1310 nm superluminescent diode (SLD1310-36, FiberLabs Inc., Fujimino City, Japan) with a micromechanical system, and the second one connected the system with the optical spectrum analyzer (Ando AQ 6319, Yokogawa, Musashino, Japan). The use of a micromechanical system made it possible to set the resonance cavity with an accuracy of 5 µm.

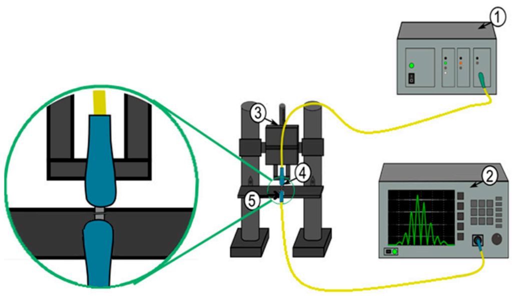



**Figure 1.** Measurement set up, where 1—light source working at the central wavelength of 1310 nm, 2—optical spectrum analyzer, 3—a micromechanical setup, 4—two single-mode optical fibers.

This system was used to study the effect of changing the width of the resonance cavity and changing the refractive index of the substance filling this cavity on the observed optical spectra.

## 3. Results

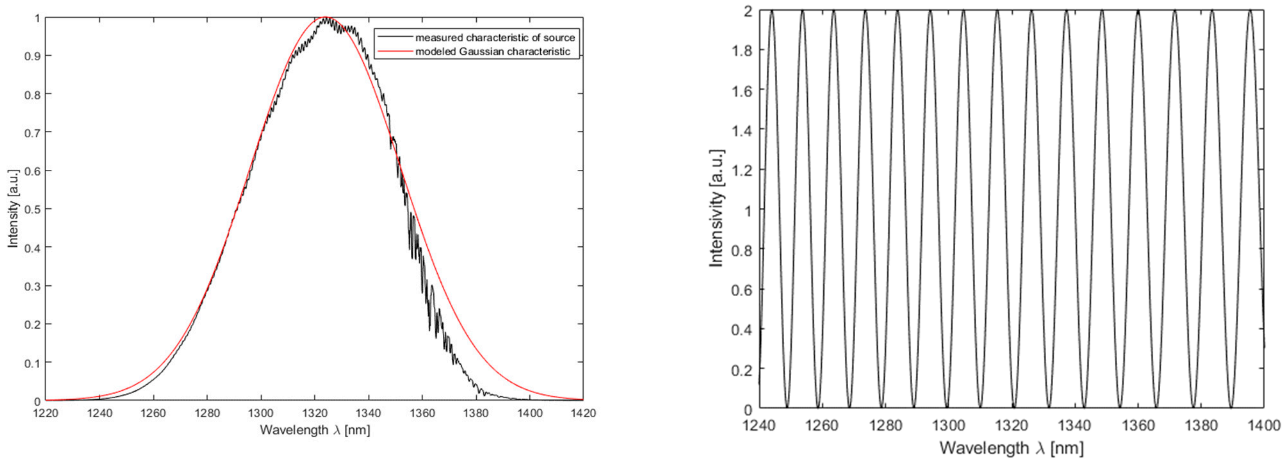
Generating a mathematical model of the optical spectrum and comparing it with the measured optical spectrum is a way to check the accuracy of the interferometric measurement. To create a spectral model, the spectral characteristic of the light source that was used for the measurements was used. To achieve better results, this spectrum was assumed to have an ideal shape of a Gaussian distribution [10]. The comparison between the spectrum characteristics is shown in Figure 2a.

The measured characteristic differs from the modeled characteristic. This is due to errors at the stage of production of the light source and imperfections of its elements. The simple mathematical model that was used ignores these drawbacks.

Then, the transmission signal of the interferogram was modeled according to Equation (1) [11]:

$$T = 1 + \cos \frac{4\pi \times n \times l}{\lambda}, \tag{1}$$

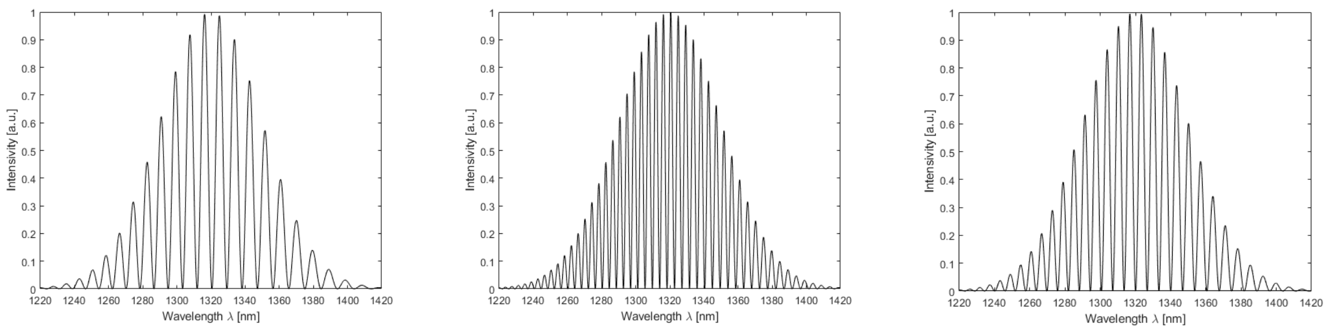
where $n$ is the refractive index, $l$ is the cavity length and $\lambda$ is the wavelength. The modeled optical spectrum of the transmission signal is shown in Figure 2b.




(**a**) (**b**)

**Figure 2.** Base elements of the model: (**a**) modeling a light source as an ideal Gaussian distribution; (**b**) model of interferometer transmission.

In the next step, the modeled signals of the source and the transmitting signals of the interferometer were multiplied. The shape of the obtained optical spectrum depends on the source model used, the value of the resonance cavity width, and the refractive index. Since only one light source was used in this research, the focus was on changing the remaining parameters. Figure 3 shows the obtained models depending on the value of the width of the cavity and its refractive index.




(**a**) (**b**) (**c**)

**Figure 3.** Prepared models of interferograms with parameters equal: (**a**) refractive index 1.0003 (air) and length of cavity 100 µm; (**b**) refractive index 1.0003 (air) and length of cavity 200 µm; (**c**) refractive index 1.33 (water) and length of cavity 100 µm.

To check the accuracy of the performed measurements, the modeled optical spectra were compared with the measured ones. For this purpose, the position of the simulated optical spectrum was shifted to have the minima in the same position on the x-axis. The result of this shift is shown in Figure 4a.

Good coverage of the modeled optical spectrum with the measured optical spectrum was achieved. The best fit appeared on the rising slope of the graphs, as shown in Figure 4b. This leads to the conclusion that the proposed method of spectra modeling can be a useful tool for the assessment of the measurement results' accuracy.

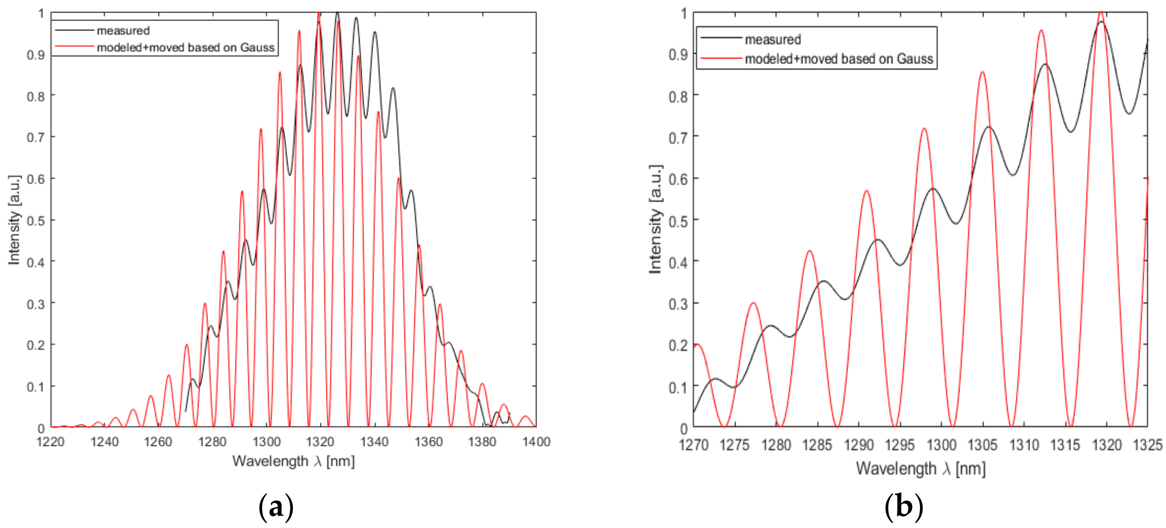



**Figure 4.** The comparison of simulated and measured interferograms: (**a**) full interferograms; (**b**) the region with the best fitting.

## 4. Conclusions

The created modeling program is easy to use. It can be used for a light source of any wavelength. It allows you to simulate changes in the refractive index and the width of the resonant cavity. It allows you to compare the model and the measured spectrum characteristics. It was created for modeling measurements made with a Fabry–Perot interferometer operating in transmission or reflection mode, but it is not excluded from simulating optical spectra from other double-beam interferometers.

In summary, the program is very user-friendly and allows you to check the accuracy of the measurements carried out and to determine the measurement errors. Moreover, it facilitates the determination of the width of the resonance cavity and the value of the refractive index. The model can be used as a control or reference measurement.

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**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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