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Dielectric, low-coherence sensors of physical quantities with spectral domain optical signal processing

Optical Wavelength Metrology
Dielectric Measurements
Sensors and Transducers

Jędrzejewska-Szczerska M.[1] , Hypszer R. [2]

[1] Department of Optoelectronics and Electronics Systems, Faculty of Electronics, Telecomunications and Informatics, Gdansk University of Technology, Narutowicza 11/12 Gdansk 80-952 Poland, phone: +48 58 347 13 61, fax: +48 58 347 15 84, e-mail: mjedrzej@eti.pg.gda.pl
[2] Department of Optoelectronics and Electronics Systems, Faculty of Electronics, Telecomunications and Informatics, Gdansk University of Technology, Narutowicza 11/12 Gdansk 80-952 Poland, phone: +48 58 347 13 61, fax: +48 58 347 26 42, e-mail:hyp@eti.pg.gda.pl

Abstract- Low-coherence interferometric sensors are an important group of optical fibre sensors. Combining high measurement resolution with broad measurement range, these sensors can measure accurately several physical quantities. In this article the authors present the fiber-optic sensors using low-coherence interferometry, which has been designed and elaborated. Being made from dielectric materials, sensors can be used in the presence of electromagnetic fields. Sensors use a new, elaborated by the authors, method of signal processing. The presented results will show that the described technique can be an effective method for improving the signal processing in low-coherent measurement systems.

I. Introduction

A low-coherence interferometric measurement system consists of a broadband source, a sensing interferometer and optical processor. The light from the broadband source is transmitted to the sensing interferometer by the coupler and fibre optic link. At the sensing interferometer the amplitude of light is divided into two components and an optical path difference (OPD), which depends on the instantaneous value of the measurand, is introduced between them. The sensing interferometer is designed in such a way that a defined relationship exists between the optical path difference and the measurand. The signal from the sensing interferometer is transmitted back by the fibre to the optical processor. The optical processor consists of a second optical system, the output of which is a function of OPD generated at the sensing interferometer. The sensing interferometer is located inside the measurand field whilst the optical processor is placed in a controlled environment far from the field. The optical processor is either a second interferometer (when the phase processing of the measured signal is used) or a spectrometer (when the spectral processing of the measured signal is used). [1] The measurement system with the phase processing of the measured signal possesses very high value of measurement sensitivity and resolution, much higher than that of the system with spectral processing. However, the system with spectral processing of the measured signal has two important advantages. Firstly, it does not need mechanical elements which establish precise displacements. Secondly, it is a proof for any change of the optical system transmission. This is possible because in the system information about the measurand is encoded in the spectra of the measurement signal.

II. Signal processing

In low-coherent measurement systems it is possible to use two kinds of optical signal processing: phase and spectral. When the temporal signal processing is used, the most critical problem is to identify the position of the central fringe in the interference fringe pattern. It is so important because this position corresponds to the zero of optical path difference, and therefore gives information about the measurand [1]. The intensity difference between the central fringe and the first side fringe can be so small that the signal-to-noise ratio required by the system for direct identification of the central fringe should be at

the range of 50dB, which is hard to reach in real optoelectronics systems.
When the spectral signal processing is used, the measurement signal can be described as [2]:

$$I_{out}(\nu) = S(\nu)[1 + V_0 \cos(\Delta\phi(\nu))] \tag{1}$$

where: *S(v)* - the spectral distribution of the light source; V_0 - visibility of interference fringes, $\Delta\phi(\nu)$ - the phase difference between interfering beams: $\phi(\nu) = \frac{2\pi\,\nu\,\delta}{c}$, □– optical path difference, *c* – velocity of the light in vacuum.
If the light source exhibits a Gaussian spectrum, the normalized spectra pattern is predicted to be a cosine function modified by the Gaussian visibility profile, as shown in Fig.1.

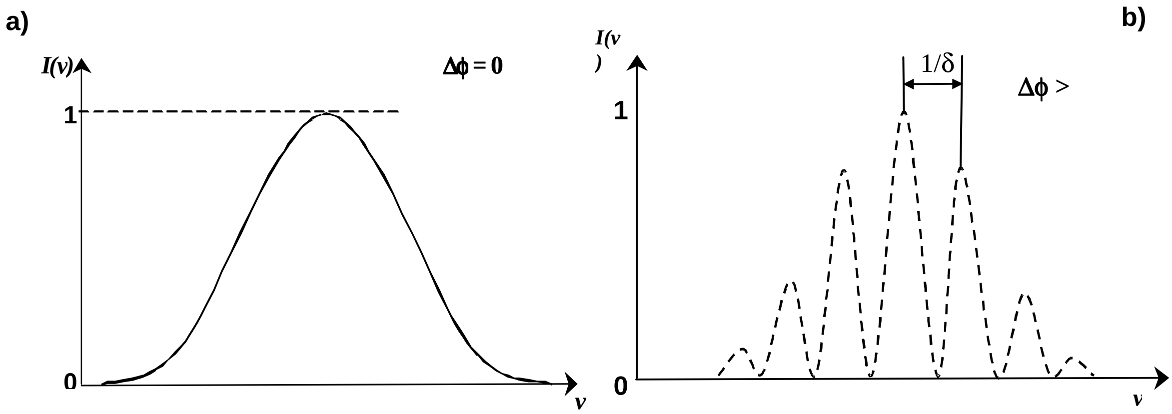


Figure 1. The signal of low-coherence system with spectral signal processing: a) when $\Delta\phi=0$, b) when $\Delta\phi>0$. δ – optical path difference

In the spectral domain signal processing the modulation frequency of the measurement signal gives information about the measurand (equation (1)) [3], as shown in Fig.1. It can be noted that for $\Delta\phi=0$ there is no spectral modulation (Fig.1.a)). If the phase difference between the interfering beams varies from zero, the function takes the form of the cosine curve (Fig.1.b). The spacing of adjacent transmission peak is proportional to the inverse of the optical path difference ($1/\delta$). In this processing, it is necessary to use special measurement equipment and mathematical treatment of the measurement signal, which makes this method comparatively expensive, complicated and time-consuming. Therefore, the authors propose the new method of signal processing in spectral domain which can be used in low-coherence sensors. The main advantage of this method is that low-coherence measurement system based on spectral signal processing does not need precise mechanical scanning. Thus there is no need to use any movable components.

III. Measurements

The scheme of the measurement setup is shown in Fig.2. The superluminescent diode with Gaussian spectral intensity distribution was used as a low-coherence source. The sensor head (sensing interferometer) generated interference signal which was transmitted back to optical spectrum analyzer through a fiber coupler.

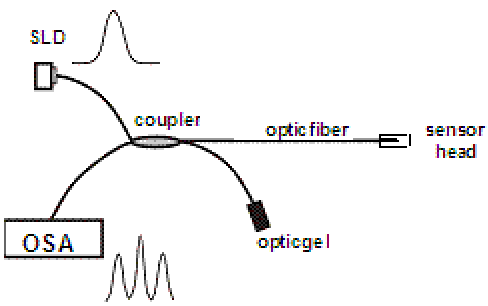


Figure 2**.** The set-up of low-coherence system with spectral signal processing; SLD – superluminescent diode, OSA - optical spectrum analyzer

The sensing interferometer of low-coherence interferometric system shown in (Fig.2) is presented in (Fig.3). The sensor head (transducer) is a low-finesse Fabry-Perot interferometer working in reflective mode. It is made as a thin film deposited at the end of the fibre. This Fabry-Perot interferometer has cavity length *x* and two boundary reflective surfaces: fibre/material and material /air, whose reflection coefficients are R_1 and R_2 respectively [4].

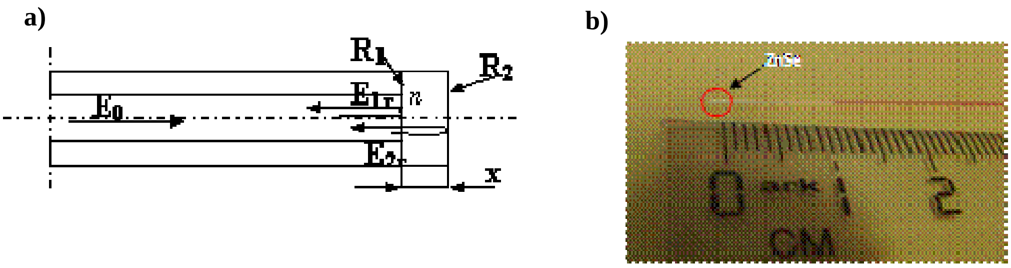


Figure 3. Sensing interferometer: a) scheme of the low-finesse Fabry – Perot interferometer working in reflective mode, E_{1r} – amplitude of wave reflected from the surface of reflection coefficient R_1; E_{2r}– amplitude of wave reflected from the surface of reflection coefficient R_2; *x* – length of the Fabry-Perot cavity;
b) the view of the elaborated sensing interferometer.

The Fabry-Perot interferometer works in reflective mode and has low refractive coefficients R_1 and R_2. A relatively high contrast of interferometric fringes can be obtained in such interferometer. Moreover, the finesse of such an interferometer is low and its transfer function is essentially that of a two-beam interferometer. Taking this into account, amplitudes E_{1r} and E_{2r} of waves reflected from the first and the second surface can be written as [5]:

$$\left.\begin{aligned} E_{1r}(v) &= \sqrt{R_1}\,E_0(v) \\ E_{2r}(v) &= (1-R_1)\sqrt{\alpha(x)R_2}\,\exp\left[-\frac{4\pi j\;nx}{c}\,v\right]E_0(v) \end{aligned}\right\} \qquad (2)$$

where: E_0 – amplitude of light incident on the first boundary surface, *x* - length of the Fabry-Perot cavity,
n - the refractive index of the Fabry-Perot cavity; $\alpha(x)$ - the attenuation coefficient of the optical intensity due to divergence of light beam in the Fabry-Perot cavity.

Optical intensity at the output of such an interferometer can be expressed by [6]:

$$I_{out} = \left\langle E_r E_r^* \right\rangle \qquad (3)$$

where: $E_r = E_{1r} + E_{2r}$; the brackets $\langle\rangle$ – denote time averages; the asterisk $*$ – the complex conjugate. By substituting from (2), equation (3) can be rewritten as:

$$I_{out}(v) = I_c\left[1 + V_0 \cdot \cos(\Delta\varphi(v))\right]$$

where:

$$I_c = I_0\left[R_1 + (1-R_1)^2 \cdot R_2\alpha(x)\right]$$

where: $I_o = E_o^2$ – intensity of light incident on the first boundary surface of the interferometer. In order to attain the maximum resolution and accuracy of the sensor, visibility of fringes, which can be expressed as:

$$V_0 = \frac{2\sqrt{\alpha(x)R_1R_2}\,(1-R_1)}{R_1 + (1-R_1)^2\alpha(x)R_2}$$

should be maximized.

The described equations can be used when changes of reflection indexes R_1 and R_2 with v can be neglected and when the used source fulfills the condition [7]:

$$\frac{\Delta v}{v_0} \langle\langle 1$$

A source such as LED, SLD (Super Luminescent Diode) or LD (Laser Diode - working below lasing threshold) can be used.
In the described sensor semiconductor the film made of zinc selenide has been implemented. In such a case reflection coefficients are: $R_1 = 0{,}069$ and $R_2 = 0{,}181$.
Spectral signal processing is based on equation (1) and the normalized spectra pattern is as shown in Fig.1. In the presented sensors, the phase difference $\Delta\phi$ between interfering light beams reflected from boundaries of sensing interferometer depends on physical quantity changes. For example, the temperature influences the changes in the described interferometers in two ways: changing the length x and changing the refractive index n of the sensing interferometer cavity. As a result, the phase difference $\Delta\phi$ introduced between the interfering beams is as follows:

$$\Delta\phi = \frac{2\pi}{\lambda}\left[n\frac{\partial x}{\partial T} + x\frac{\partial n}{\partial T}\right]\Delta T \qquad (4)$$

where: λ – central wavelength of source; T – temperature.

The temperature coefficients of refractive index and linear expansion for silicon are: $\frac{dn}{ndT} = 0{,}5 \cdot 10^{-4} \quad K^{-1}$ [8] and $\frac{dx}{xdT} = 7{,}1 \cdot 10^{-6} \quad K^{-1}$ [9]. Hence, in the case when the Fabry-Perot cavity is made from the zinc selenide the shift of phase introduced by thermal changes of refractive index predominates.

According to the equation (4), any change of the phase difference between interfering beams occurs in measurement signal. In the spectral domain signal processing the modulation frequency of the measurement signal gives information about the measurand (equation (1)), which can be observed in Fig.1. [3]. However, the authors perceived that any changes of the phase difference between interfering beams modify not only the modulation frequency of the measurement signal but the position of maximums in the spectral pattern as well. This method of signal processing has been applied in the fiber-optic sensors of physical quantities such as: temperature and displacement. For example, the dependence of the spectra pattern of the temperature sensor on the temperature over the range from 30 to 400 $^{\circ}$C is plotted in Fig.4.

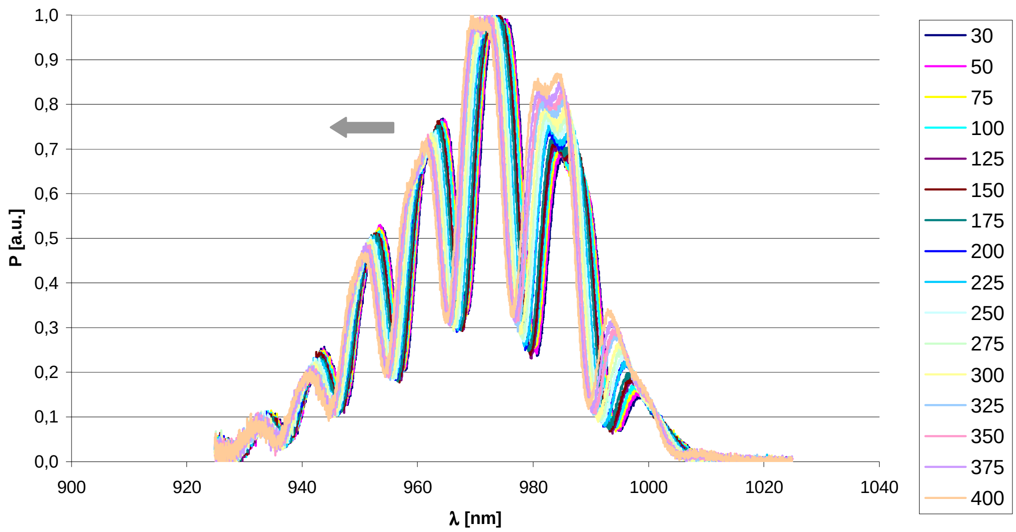
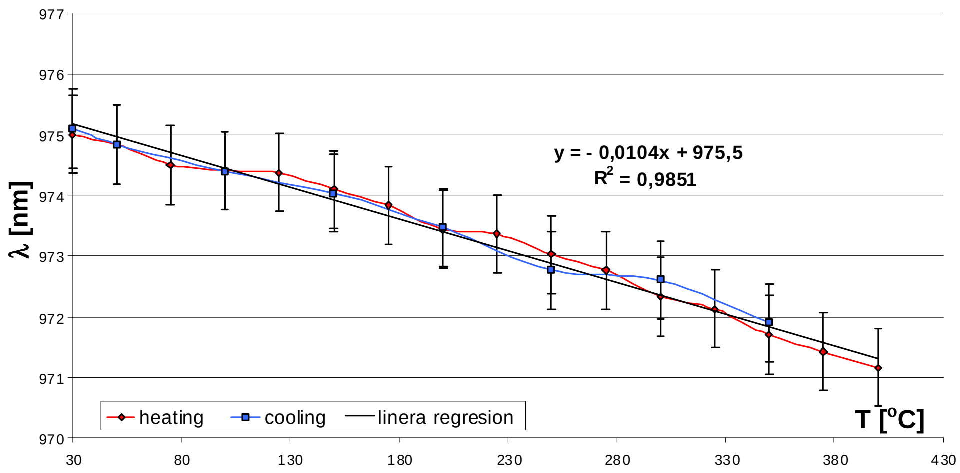


Figure 4. Measured spectra pattern shift with the change of temperature



The maximum position shift to the range of the wavelength of smaller value during heating. The dependence of the maximum position in the spectral pattern on temperature during cooling and heating is shown in Fig.5. It should be noticed that the maximum position change per temperature unit is almost constant over the investigated range.

Figure 5. Dependence of the maximum position shift in the spectra pattern with the temperature change ;
R^2 – correleation coefficient

Investigation of the group of interferometers was made. Each senor has another value of the Fabry-Perot cavity, which influences its parameters, which is shown in Table 1.

Sensor parameters			
Fabry-Perot cavity length x	340 nm	510 nm	680 nm
Sensitivity ***S*** [nm/°C]	0,0104	0,0086	0,0083
Visibility ***V***	0,785	0,685	0,647
Correlation coefficient $\boldsymbol{R^2}$	0,985	0,98	0,965
Response time	0,89	0,92	0,97

Table 1. Parameters of the elaborated sensor head

The sensors characterization was made in temperature range extending from 25 to 400°C with resolution equal to 1°C. The output signal was analysed by measurement of the maximum of the spectra pattern shift. We used optical spectrum analyzer Ando AQ6319. The best configuration of the sensor head allowed us to obtain sensitivity of temperature measurement at 0.01 nm/°C; visibility of the measured signal of 0,785 and correlation coefficient of 0,985. Time required for single measurement was in range 0.89÷0,97 s.

The new method of signal processing has been applied in other sensors as well. The dependence between the shift of the maximum position of the measurement signal spectra and the displacement have been found (Fig.6). The displacement fiber-optic low-coherent sensor has sensitivity S=0,225 nm/μm and allows to measure displacement with resolution about 1μm.

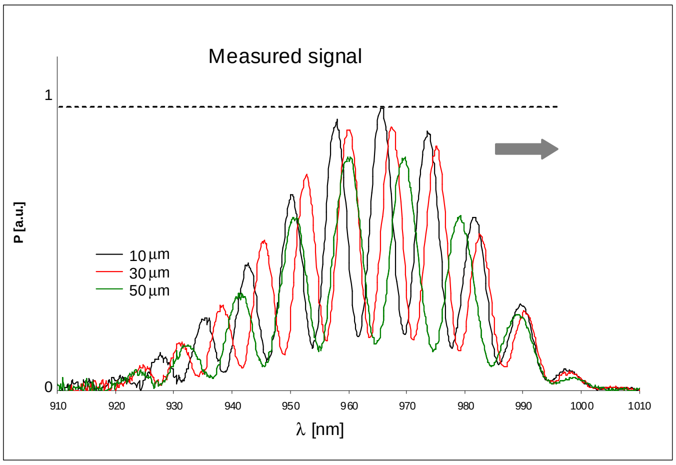


Figure 6. Measured spectra pattern shift with the change of interferometer mirror displecement

IV. Conclusions

In this article the fiber-optic sensors using low-coherence interferometry with spectral signal processing have been presented. Elaborated sensors have many advantages: relatively simple configuration, potentially low cost, high resolution and low thermal inertia. Because of their small size it is possible to make nearly point wise measurement. What is important, being made from dielectric materials, sensors can be used in the presence of strong RF or microwave electromagnetic fields. The investigation of these sensors confirms their ability to control temperature with appropriate measurement parameters. The presented preliminary results can be the base for building temperature sensor ready for practical applications.

Furthermore, the results of experimental works have shown that the application of the new method of signal processing in spectral domain, which depends on the measurement of the optical wavelength of the maximum of the signal, can be an effective method for improving the signal processing in low-coherent sensors.

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