Utilization of NI PXIe-4844 Interrogator for High Resolution Fiber Extrinsic Fabry-Perot Interferometric Sensing

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Abstract**—An advanced method of fiber extrinsic Fabry-Perot interferometer (EFPI) optical path difference (OPD) measurement with the use of the interrogator NI PXIe-4844 was applied for high precision distance, pressure and temperature measurements with resolutions up to 14 pm, 0.2 Pa and 2 mK respectively. Sub-nanometer resolution in multiplexed schemes was attained with single interrogating channel: from 30 to 80 pm for serial scheme with three sensors and from 40 to 200 pm for parallel scheme with four sensors. An ability to register the oscillating signals with frequencies up to 1000 Hz was demonstrated.**

Keywords—extrinsic Fabry-Perot interferometer, EFPI, fiber optic sensor, tunable laser, spectral measurements, multiplexing, signal processing, wavelength scanning interferometry, displacement measurement, pressure measurement, temperature measurement, spectral interferometery

I. Introduction

National Instruments actively develops the nomenclature of various measurement devices, like traditional electronic devices and peculiar devices, such as optical sensor interrogator NI PXIe-4844. This device based on the technology, developed by the Micron Optics, is mainly dedicated for interrogating fiber optic sensors, based on fiber Bragg gratings (FBG). It registers the dependency of the reflectivity of the tested system on the light wavelength, i.e., measures the reflective spectral transfer function (RSTF) $S(\lambda)$. The device employ on a tunable laser and high-precision synchronization system of the wavelength scanning and signal sampling.

A NI PXIe-4844 interrogator, compatible with PXI chassis, can acquire signals from 4 independent optical channels and demonstrates very high characteristics, such as: measurement spectral range 1510 ÷ 1590 nm (width Λ=80 nm); wavelength stability (0 °C to 55 °C) 1 pm, wavelength sampling step Δ = 4 pm (with stability 1 pm); output optical power P_0 up to 250 μW; 10 Hz full spectrum scan frequency; optical dynamic range 40 dB.

Besides the FBG-based sensors, the RSTF measurement system with such parameters can be used in different scientific and metrological setups, and for interrogation of optical sensors of other types, requiring accurate measurement and consequence analysis of the RSTF. As an example of such sensors, in the current work devices based on extrinsic Fabry-Perot interferometer are considered.

II. Extrinsic Fabry-Perot Interferometer

Fiber Extrinsic Fabry-Perot Interferometer (EFPI) is a modification of an optical Fabry-Perot interferometer, formed by two surfaces, reflecting the light. These surfaces can be represented by a fiber end and a mirror, or two oppositely faced fiber ends, both these situations are illustrated in Fig. 1. In EFPI an intensity of reflected light is registered, demonstrating an oscillating due to interferometric effects [1]. Generally, the relation of reflected light intensity, cavity length L and wavelength λ is described by Airy function, however, since the reflectivity of the mirrors is low and no collimation optics is used, multiple reflections can be neglected and EFPI can be considered as a two-pass low-finesse interferometer. In this case RSTF has a form

$$S(\lambda) = S_0 + S_m \cdot \cos\left(\frac{4\pi L}{\lambda} + \varphi\right), \qquad (1)$$

where λ – wavelength of light, L – optical path difference (OPD), or the baseline of the interferometer, determined as a product or refractive index of the media inside the EFPI cavity and the geometric cavity length. The values S_0, S_m and φ, depend on the EFPI parameters (first of all the reflection coefficients R_1 and R_2 of the surfaces, forming the EFPI), and strictly speaking, depend on the OPD L and the wavelength λ.

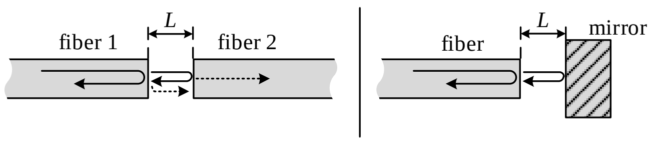

Fig. 1. Structures of fiber EFPI with two fibers and with fiber and external mirror

In a limited wavelength range with center λ_0, the oscillating component in (1) is a quasi-harmonic function with respect to argument λ with frequency $4\pi L/\lambda_0^2$.

The structures, shown in Fig. 1 are attractive for high-precision miniature fiber-optic sensor heads for physical quantities measurements. As can be seen from the structure of RSTF (1), the properties of the interferometric signal are determined by the value of L. If attached to a device, measuring the interferometer RSTF and performing some processing, the L value can be found. Among the EFPI optical path difference measurement techniques one can distinguish two basic classes: conventional white-light [2] techniques utilizing tunable read-out interferometer and wavelength scanning interferometry based on the registration and subsequent analysis of the interferometer RSTF. Second approach demonstrated sub-nanometers resolutions of OPD measuring, high absolute accuracies and large dynamic measurement range [3]–[6]. The best examples of attained OPD resolutions, were attained using wavelength scanning approach, and equaled 10 pm [7].

An ability to precisely measure the optical path difference enables one to measure different physical quantities by means of using special constructions of the sensing heads, providing a variation of the EFPI cavity length with respect to the measured quantity. For example, the scheme with movable mirror (Fig. 1, right) can be implemented for a pressure sensor. Constructions with EFPI spacers depending on the temperature, can be used for temperature sensing. It also should be noted that the measurand can alter the refractive index inside the cavity as well as the geometrical dimensions of the cavity, aiding sensing elements for sensors of different physical quantities, such as temperature, humidity, chemical sensors.

One of the main characteristics of the measuring device is its resolution, i.e. minimal detectable variation of the measured quantity. Sensor resolution is determined by intrinsic fluctuations of the sensor readings. In case of sensors based on EFPI, the resolution of the L value is a unified resolution indicator. Doubled standard deviation of the sensor readings' intrinsic fluctuations σ_{Lr} is often used as a figure of merit of sensor resolution. An overall sensor resolution with respect to some physical quantity V will be given by the equation

$$\delta V_{\min} = \frac{\delta L_{\min}}{K_V} = \frac{2\sigma_{Lr}}{K_V}, \qquad (2)$$

where $\delta L_{\min} = 2\sigma_{Lr}$ is an OPD resolution of the EFPI, determined by the optical scheme, K_V – OPD sensitivity to the value V, determined by the construction of the EFPI sensing head.

On the one hand, the attained OPD resolution $\delta L_{\min}$ is determined by the signal processing approaches, used for demodulating the L value from $S(\lambda)$. One of the most efficient methods is proposed in [8], where an approximation of the registered RSTF $S(\lambda)$ by means of least-squares fitting with an analytical expression (1), where L is an approximation parameter. In our paper [4] this approach was modified, as a result, the robustness and resolution were enhanced, also an amount of required calculations was reduced.

On the other hand, the progress in the field is stipulated by advances in the design of the devices, registering the interferometer spectral function. Fluctuations of the interrogator parameters can be one of the main fundamental factors, limiting the resolution $\delta L_{\min}$ [7]. When using the above-mentioned approach, one of the most important parameters are: the shift of the whole wavelength scale, jitter of individual spectral points; intensity noises of the light source and photodetector noises. The analysis of the influence of these parameters on the resultant sensor resolution is complicated since this influence depends on the properties of the interrogator, such as Λ и Δ and on the parameters of the optical scheme. Analytical expressions, relating the quantity σ_{Lr} with the optical setup parameters were obtained by the authors in [7]. Experiments, supporting the developed model were performed, demonstrating very good correspondence with the theory. As was shown, σ_{Lr} demonstrates nearly linear growth with respect to the OPD L. In the range of L from 30 μm to 1 mm the attained σ_{Lr} level was 7 ÷ 50 pm, see Fig. 2. It is worth mentioning that these values are determined by advanced signal processing approach as well as the characteristics of the NI PXIe-4844 interrogator. Besides the above-mentioned parameters, the others, not specified by the supplier were studied and measured: low relative intensity noise level (-120 dB/Hz), high repeatability of the wavelength scale – the fluctuations of the whole scale shift are about 0.05 pm.

It should be noted that the experimental results for EFPI sensors with sub-nanometer resolution, performed by other research groups [9], [6], were also made with the use of the interrogator NI PXIe-4844 or analogous devices manufactured by the Micron Optics.

Taking into account the above-mentioned displacement resolution levels, the attainable resolutions for more relevant physical quantities can be derived using eq. (2) and known sensitivities K_V, determined by the sensor head construction. For example, for $\delta L_{\min} \sim 100$ pm and temperature elongation $10^{-4}\,K^{-1}$, for $L = 500$ μm one obtains $K_T \sim 50$ nm/K and temperature resolution $\delta T_{\min} \sim 2$ mK. When using a miniature metallic membrane with pressure sensitivity K_P ~500 μm/MPa, the pressure resolution for the same EFPI parameters comprises $\delta P_{\min} \sim 0.2$ Pa.

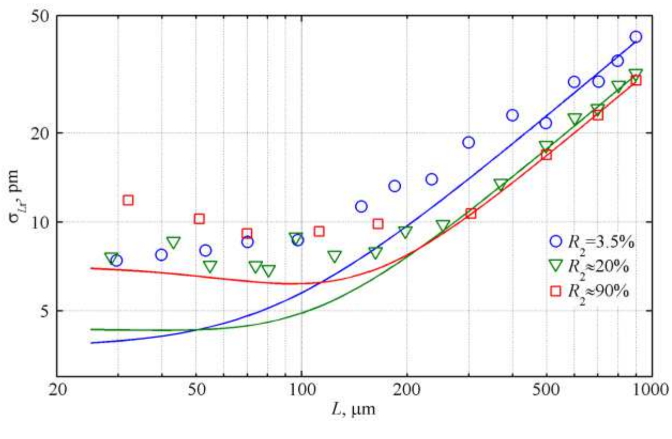

Fig. 2. OPD measurement resolutions for different reflectivity of the second mirror (first mirror R_1=3,5%); experimental (points) and theoretical, calculated according to [7] (solid curves)

III. Multiplexed Sensors

For building practical sensing devices, the task of interrogating several (N) multiplexed sensors with a single interrogating unit is quite important. The distinguishing of the signals produced by different sensors can be made for several EFPIs with different OPD values with the use of frequency-domain multiplexing. The RSTF $S(\lambda)$ of such system will contain several oscillating components of a form (1) with different oscillating frequencies $4\pi L_n/\lambda_0^2$ (L_n is the OPD of the n-th interferometer). Separating individual spectral functions by band-pass filters and individually processing them with the use of conventional approaches [4], [8], one will be able to obtain the readings L_{rn} from each sensor. We have experimentally studied the possibilities of multiplexing EFPI sensors in different configurations in [10]. It was shown, that despite an inevitable decrease of the resolution in multiplexed sensors, for relatively small numbers of multiplexed sensors the sub-nanometer resolution still can be attained. For example, for serial scheme with three sensors (Fig. 3) the attained σ_{Lrn} values were from 30 to 80 pm, and for parallel scheme with four sensors (Fig. 4) the attained σ_{Lrn} values were from 40 to 200 pm. It should be noted that NI PXIe-4844 interrogator has four optical channels, and therefore, a full number of interrogated sensors can be made $4{\cdot}N$.

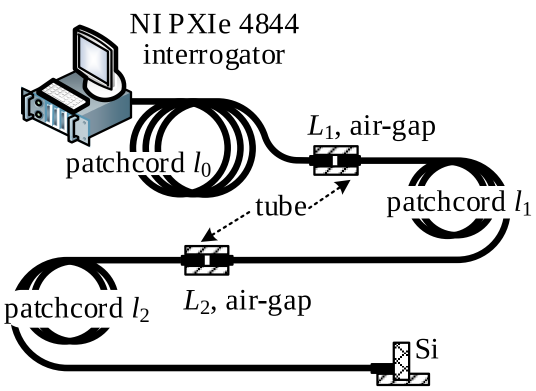

Fig. 3. Experimental setup for the parallel configuration

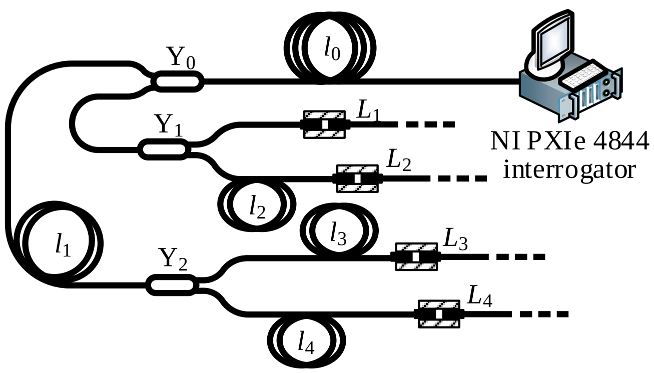

Fig. 4. Experimental setup for the serial configuration

IV. Oscillations Measurement

Despite the high efficiency of NI PXIe-4844 interrogator for wavelength-domain interferometry interrogation of EFPI sensors, one of the severe limitations is low (~1-10 Hz) frequency of the registered signals, which is equal to the spectrum acquisition rate. For many tasks, such as temperature or quasi-static pressure or strain measurements this is acceptable, yet, in some applications higher frequencies are desirable. However, taking into account practical sample rate of the $S(\lambda)$ signal, which is about 600 kHz, this device enables one to demodulate the information about L variations during the interval of the RSTF acquisition. Of course, a special signal processing approach, such as proposed by the authors in [11] is required. The performed experiments with variable perturbations of the EFPI OPD by a PZT actuator proved the capability of measuring fast oscillations $L(t)$. In Fig. 5 a corresponding experimental setup is shown. Examples of registered OPD oscillations in case of mean OPD value ~720 μm are shown in Fig. 6: two harmonic test signals with frequency 500 Hz and amplitude 90 nm and frequency 1000 Hz and amplitude 15 nm. The attained resolution δL_{min} of the OPD oscillations was about 2 pm/Hz$^{1/2}$.

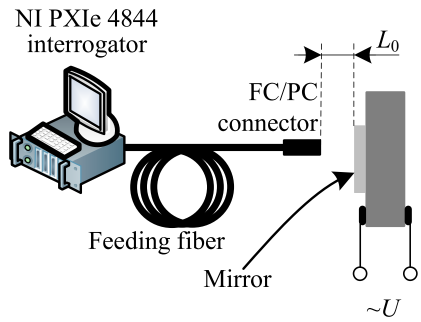

Fig. 5. Experimental setup for oscillations measurement

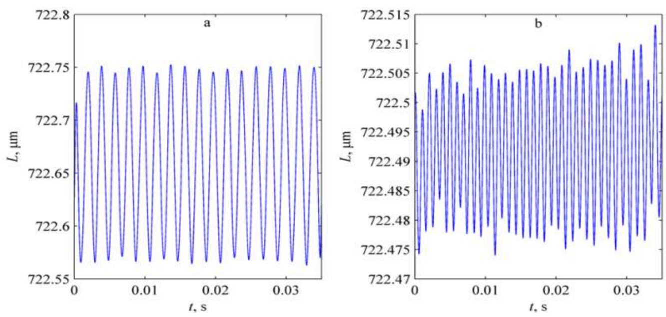

Fig. 6. Demodulated OPD oscillations

Conclusion

In the current work we have presented the methods of efficient interrogation of the EFPI-based sensors utilizing NI PXIe-4844 optical sensor interrogator. With the use of the signal processing approaches, developed by the authors, high-precision measurements were performed, also multiplexing of up to four EFPIs, and an ability to register the oscillating signals with frequencies up to 1000 Hz were demonstrated. The attained resolutions were from 14 to 90 pm for micro-displacements in range from 30 to 1000 μm, about 2 mK for temperature, and 0.2 Pa for pressure.

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