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Intermodal fiber interferometer based on broadband light source and optical spectrum analyzer for external perturbations measurement

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An intermodal fiber interferometer based on broadband light source and spectral signal processing is proposed and experimentally investigated. The perturbation of the parameters of the spectrum analyzer (scanning range and width of the instrumental spectral response function) on the output signal is demonstrated. It is shown that the method of correlation signal processing makes it possible to obtain linear and stable response to external fiber perturbations. The proposed interferometer scheme can be prospective for development of real-time sensors of physical quantities.

Keywords: intermodal fiber interferometer, fiber-optic sensors, fiber optics, multimode fiber, interferometers.

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The use of intermodal fiber interferometers (IFIs) in various measuring schemes is an actively developing area of fiber optic sensors [1]. In recent years, a number of measurement schemes based on IFI have been proposed for measuring various physical quantities, for example, temperature, pressure, vibrations [2–4]. The main advantages of IFI are relatively low cost, simplicity high sensitivity, and the possibility of distributed measurements. The principle of operation of the classical IFI is to analyze the interference speckle pattern at the output of the multimode fiber (MMF) excited by a coherent source: external perturbations on the MMF cause changes in the phase differences of the propagating modes, which leads to transformations of the speckle pattern [5]. The main disadvantages of such a scheme are signal fading and strong non-linearity of the transfer function, which makes it problematic to reproduce the shape and magnitude of signals from external perturbations. The search for methods solving these problems is a current research topic [6,7].

The idea for implementation of IFI using a low-coherence broadband light source (BLS) instead of a laser, and optical spectrum analyzer (OSA) instead of a photodetector seems attractive (WLIFI is the white-light intermode fiber interferometer). Works in this direction have already been carried out earlier [8–10], however, they mainly considered the so-called SMS structures (single mode−multimode−single mode) with relatively short sections of the MMF as sensitive element (< 1 cm). In the existing works, the main emphasis is placed on the study of special configurations of the MMF and the application of complex methods for processing interference signals. At the same time, the issue of improving and stabilizing the parameters of the measuring IFI is not properly considered.

In this work, the scheme of WLIFI with an MMF as the sensitive element is proposed. The operability of the WLIFI is shown experimentally and the effect of the OSA parameters on the characteristics of the output signal has been studied. Effective solution for mitigation of signal fading and nonlinearities is presented using the previously developed method of correlation processing of IFI signals generated by repetitative scanning of the wavelength of light source [6]. The possibility of operation of the WLIFI in the mode of measuring external perturbations of various shapes and amplitudes in real time using a modern high speed acquisition rate OSA (1000 spectra per second) is shown.

The OSA converts the BLS radiation into a set of discrete spectral components ν_a, arranged equidistantly in accordance with the width of the OSA instrumental function $\Delta\nu_a$. Thus, the use of the pair of BLS−OSA allows to consider the IFI not as a single interferometer, but as a set of interferometers, each operating at its own optical frequency ν_a. This opens up wide opportunities for mitigating signal fading and non-linearity of the transfer characteristic.

In the experimental setup (Fig. 1, a), a super luminescent diode Exalos EXS210066-01 (output power 5 mW, wavelength range 1460−1610 nm (FWHM)) with a single-mode pigtail at the output was used as a BLS. We used OSA Yokogawa AQ6370C (scanning range 600−1700 nm, adjustable spectral resolution in the range from 2.5 to 250 GHz) to take frequency scans at different instrumental function widths (Fig. 2, a). For other measurements, we used OSA I-MON 512 USB (scanning range 1510−1595 nm, spectral resolution 160 pm, spectra acquisition rate 1000 spectra per second). The input single-mode pigtail of the analyzer was used as an IFI diaphragm due to the difference in the diameters of multimode and single-mode fibers. The length

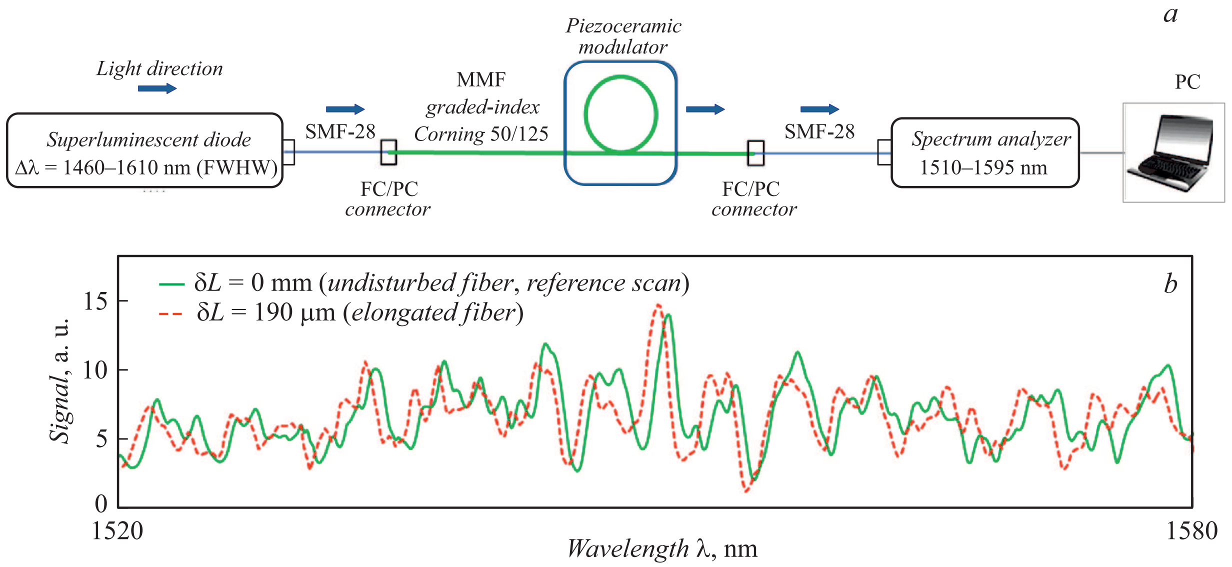

Figure 1. Scheme of the experimental setup of the white-light intermode fiber interferometer (WLIFI) (*a*) and experimentally obtained frequency scans of the WLIFI for unperturbed fiber and the fiber under external perturbation (*b*).

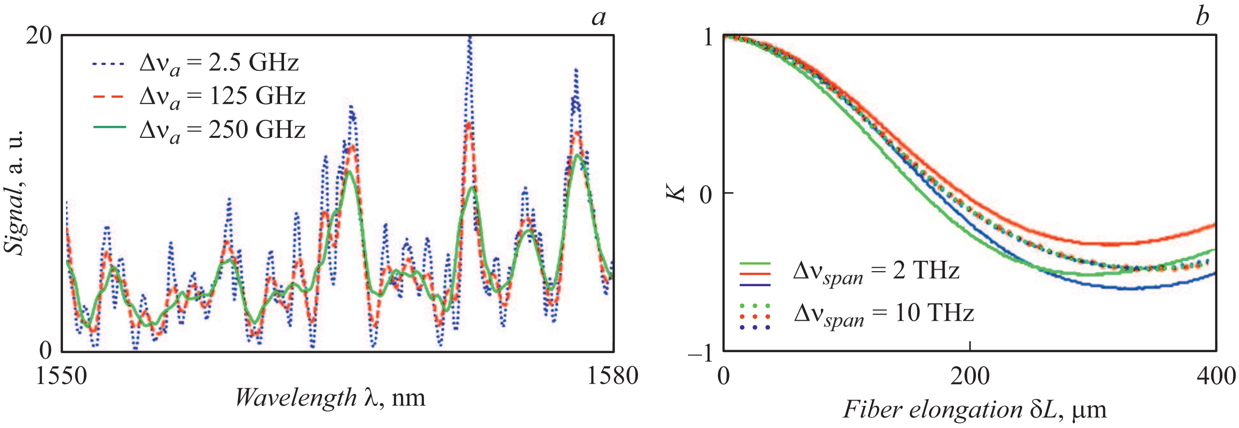

Figure 2. (*a*) are experimentally obtained WLIFI frequency scans for three values of the instrumental function width $\Delta\nu_\alpha$. (*b*) correlation functions obtained with the linear extension of the fiber by $400\,\mu$m. Solid lines — $\Delta\nu_{span} = 2\,\text{THz}$, dashed ones $\Delta\nu_{span} = 10\,\text{THz}$

of the MMF (Corning, 50/125, gradient refractive index profile) in the path was 60 m, of which 50 m were wound (and glued) on the cylindrical piezoceramic modulator with diameter of 5 cm, used to simulate external perturbations of given shape and amplitude. The fiber length was modulated according to harmonic and triangular laws with the rate of $\Omega = 10\,\text{Hz}$.

It is known that the IFI is sensitive both to external perturbations on the MMF and to changes in the laser radiation frequency [11]. In our scheme, taking into account the diaphragming of the speckle pattern, the recorded OSA spectrum in the BLS radiation frequency range is an intermode interference signal, similar to the IFI scheme with the scanning laser and a photodetector considered in [6]. We will call the dependence of the OSA signal intensity on the optical frequency ν_a (i.e., each registered OSA spectrum) as a „frequency scan“. The spectra acquisition rate of the analyzer determines the sampling period of the WLIFI signal.

Figure 1, *b* shows two frequency scans obtained experimentally for the MMF for unperturbed MMF and for MMF elongated by $190\,\mu$m. It can be seen that the external perturbation that causes changes in the length of the fiber leads to the change in the form of the frequency scan similar to [6]. Therefore, the processing of the WLIFI signals can be carried out by the method of correlation processing of frequency scans [6]. The essence of this method is to measure the correlation coefficient $k(t)$ of the reference (in the absence of external perturbations) and current frequency scans in real time. As was shown in [6], this approach makes it possible to effectively suppress the IFI signal fading and achieve linearity of the IFI transfer function.

First of all, let us consider the perturbation of the parameters of the WLIFI scheme on the quality of the measured

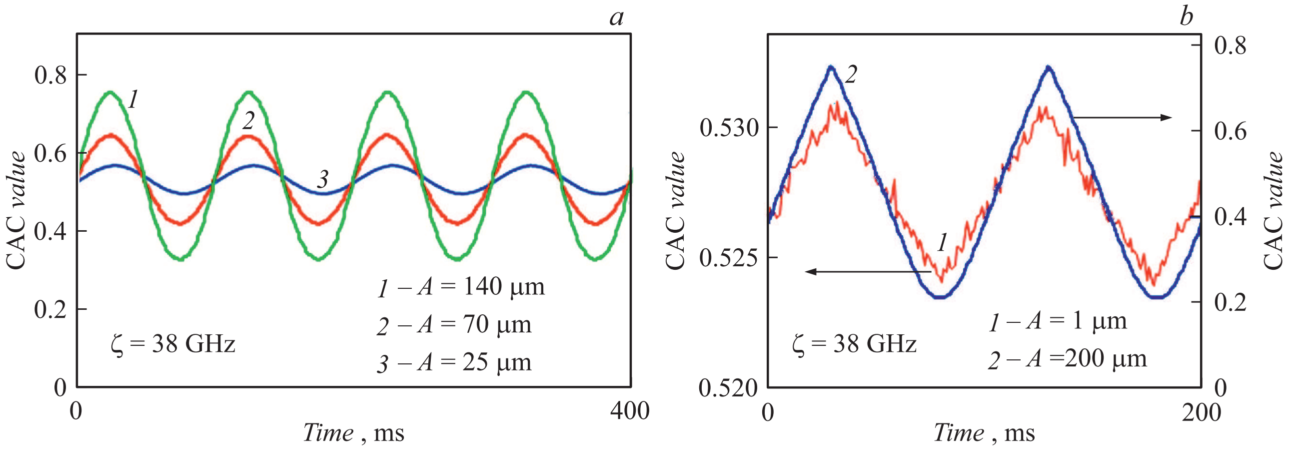

Figure 3. The experimentally obtained responses of the WLIFI to the change in the length of the fiber according to the harmonic law $\delta L = (A/2)\sin(\Omega t)$, $\Omega = 10$ Hz (*a*) and change in the fiber length according to the triangular law $\delta L = (A/2)\text{triangle}(\Omega t)$, $\Omega = 10$ Hz (*b*).

signals. Figure 2, *a* shows the frequency scans obtained for different values of the width of the instrumental function of the OSA. To carry out these measurements, we used the OSA Yokogawa AQ6370C, since it provides a instrumental capability to change the width of the instrumental function in the range from 2.5 to 250 GHz. It can be seen that with the increase in the width of the instrumental function, the contrast and the number of signal extrema decrease, as a result of which the sensitivity of the WLIFI decreases: pairs of modes with a time delay exceeding the coherence time of the equivalent source, determined by the width of the instrumental function of the OSA, cease to contribute to the interference.

During the experiment, external perturbations on the WLIFI were carried out by modulating the fiber length using a piezoceramic modulator. Magnitude dependency of the correlation coefficient k on the fiber elongation is denoted by the correlation function $K(\delta L)$. Figure 2, *b* shows examples of the $K(\delta L)$ correlation functions obtained experimentally in the MMF elongation range from 0 to 400 μm, for two width values of OSA scanning range $\Delta\nu_{span}$ (the change in the value of the scanning range was carried out during the processing of frequency scans recorded in the form of numerical arrays). For each range $K(\delta L)$ were measured several times; each measurement was preceded by the procedure for changing the position of the free sections of the MMF, which ensures the implementation of various random relationships between the phases of the modes before the elongation of the MMF [7]. It can be seen that for the case of small $\Delta\nu_{span}$, the dependences diverged significantly, which clearly illustrates the instability to the perturbation of external conditions (the presence of signal fading). In the case of larger $\Delta\nu_{span}$, the correlation functions almost coincided. This example shows the importance of choosing the size of the frequency scan to ensure the stability of the WLIFI signal and the suppression of signal fading.

Let's show the operability and evaluate the effectiveness of the WLIFI. In accordance with [6], in order to obtain the linear response of $k(t)$ values to the elongation of the MMF, $K(\delta L)$ is transformed into the so-called correlative amplitude characteristic (CAC) using the frequency shift ξ between signal and reference frequency scans:

$$\text{CAC}(\delta L, \xi) = \sqrt{1 - K(\delta L, \xi)/K(\delta L = 0, \xi = 0)}, \quad (1)$$

where $K(\delta L, \xi)$ is the correlation function considered above with the introduced frequency shift ξ. In the experiments, the WLIFI signal was calculated according to (1) in the form of CAC using $\Delta\nu_{span} = 10$ THz (maximum OSA scanning range) and $\xi = 38$ GHz (the matter of choice ξ is discussed in detail in [6]). The reference scan was recorded in the absence of external perturbations on the MMF. The signal perturbations was provided by a voltage of the given shape and amplitude applied to the piezoceramic modulator. The calculation of CAC was carried out in real time.

Fig. 3 shows the WLIFI signal in the case of harmonic (*a*) and triangular (*b*) external perturbations of different amplitudes. It can be seen from Fig. 3, *a* that the signal amplitude depends linearly on the amplitude of the external perturbations. The form of the received response also corresponds to the form of the external perturbation. Note that in the case of weak elongations (Fig. 3, *b*, $A = 1\,\mu$m), the signal is affected by the noise of the WLIFI (mode noise, OSA quantization noise, etc.). In the case of strong perturbation, the shape of the WLIFI response is distorted due to the perturbation of the nonlinear section of the correlation amplitude characteristic (Fig. 3, *b*, $A = 200\,\mu$m). This imposes appropriate restrictions on the dynamic range of the WLIFI scheme, which must be taken into account when choosing the parameters of the WLIFI when implementing the measuring scheme.

Thus, in this work, the intermodal fiber interferometer based on the broadband low-coherence light source and the optical spectrum analyzer is considered. The perturbation of the scheme parameters, such as the width of the instrumental function of the OSA and the width of the scanning range, on the signals of the WLIFI is experimentally shown. The possibility of using the WLIFI to obtain a stable linear response to external perturbations is shown, which is a significant advantage over traditional IFI schemes.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] H.S. Efendioglu, IEEE Sens. J., **17** (7), 2055 (2017). DOI: 10.1109/JSEN.2017.2658683

[2] J.J. Wang, S.C. Yan, F. Xu, in *Int. Conf. on optical communications and networks (ICOCN)* (IEEE, Wuzhen, 2017), p. 1. DOI: 10.1109/ICOCN.2017.8121187

[3] V.M. Sperandio, M.J. Pontes, M.J. Neto, L. Goncalves, Proc. SPIE, **9634**, 96347W (2015). DOI: 10.1117/12.2185464

[4] P.J. Pinzon, D.S. Montero, A. Tapetado, C. Vazquez, IEEE J. Sel. Top. Quant. Electron., **23** (2), 5600406 (2017). DOI: 10.1109/JSTQE.2016.2611596

[5] W.B. Spillman, B.R. Kline, L.B. Maurice, P.L. Fuhr, Appl. Opt., **28** (15), 3166 (1989). DOI: 10.1364/AO.28.003166

[6] A.V. Petrov, I.E. Chapalo, M.A. Bisyarin, O.I. Kotov, Appl. Opt., **59** (32), 10422 (2020). DOI: 10.1364/AO.400345

[7] I. Chapalo, A. Petrov, D. Bozhko, M. Bisyarin, O. Kotov, J. Lightwave Technol., **38** (20), 5809 (2020). DOI: 10.1109/JLT.2020.3002617

[8] P. Wang, S. Zhang, R. Wang, G. Farrell, M. Zhang, T. Geng, E. Lewis, K. Tian, Opt. Expess, **27** (10), 13754 (2019). DOI: 10.1364/OE.27.013754

[9] D. Liu, R. Kumar, F. Wei, J. Lightwave Technol., **36** (17), 3672 (2018). DOI: 10.1109/JLT.2018.2842111

[10] I. Del Villar, J. Goni, A. Vicente, F.J. Arregui, I.R. Matias, J. Lightwave Technol., **37** (18), 4665 (2019). DOI: 10.1364/JLT.37.004665

[11] O.I. Kotov, M.A. Bisyarin, I.E. Chapalo, A.V. Petrov, J. Opt. Soc. Am. B, **35** (8), 1990 (2018). DOI: 10.1364/JOSAB.35.001990