Fast-adaptive fiber-optic sensor for ultra-small vibration and deformation measurement

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Abstract. Adaptive fiber-optic interferometer measuring system based on a dynamic hologram recorded in photorefractive CdTe crystal without applying an external electric field is developed. Vectorial mixing of two waves with different polarizations in the anisotropic diffraction geometry allows for the realization of linear regime of phase demodulation at the diffusion hologram. High sensitivity of the interferometer is achieved due to recording of the hologram in reflection geometry at high spatial frequencies in a crystal with sufficient concentration of photorefractive centers. The sensitivity obtained makes possible a broadband detection of ultra-small vibrations with amplitude of less then 0.1 nm. High cut-off frequency of the interferometer achieved using low-power light sources due to fast response of CdTe crystal allows one to eliminate temperature fluctuations and other industrial noises.

1. Introduction

Measuring systems based on fiber optics are very promising for different practical applications due to a number of advantages of fiber optical elements over their electronics analogues [1]. Additionally an interferometry principle of physical value detection allows to develop an extremely sensitive measuring system capable to detect ultra-small displacements, deformations, vibrations etc. At the same time high sensitivity of fiber-optical interferometers makes them open to influence of environment (changes of temperature, strain, pressure, etc.) which result in to drift the interferometer’s working point. Electronics systems of the drift compensation are too sophisticated and expensive [2, 3]. Alternatively this problem can be solved by two-wave mixing in photorefractive (PR) crystals which allows not only transformation of phase-modulated light of the fiber-optical interferometer into modulation of the output light power but also compensation of any low-frequency modulations caused by change of environmental conditions [4, 5]. However, strong external electric field has to be applied to the crystal for realization of linear regime of phase demodulation [6] as well as for increasing a wave-coupling [7]. This makes the measuring system more expensive, complicated, and energy consuming. Moreover, requirement of high intensity of interacting light beams for providing of fast dynamic hologram recording leads to increasing of light sources power.

In this work we present a highly sensitive and fast-adaptive fiber-optic interferometer measuring system, which is based on dynamic hologram recorded in a photorefractive crystal of cubic symmetry without applying any electrical field with use of low-power light sources.
2. Measuring system architecture

Architecture of the measuring system is very simple (Figure 1). Signal wave is transferred through the standard multimode optical fiber with core diameter 50 µm and numerical aperture NA=0.21. The fiber is reeled on the piezo-electric transducer. Application of ac electric field to the transducer which simulates effect of a vibration or deformation results in periodical change of the fiber length and consequently in phase modulation of light beam transmitted through the fiber. The signal wave is mixed with reference one at a dynamic hologram which is continuously recorded in a semiconductor cubic crystal CdTe.

![Figure 1. Scheme of the adaptive fiber-optic interferometer: QWP is a quarter-wave plate; BS is a beam splitter; M is a mirror; P is a polarizer; PRC is a photorefractive crystal; MOF is a multimode optical fiber; PET is a piezoelectric transducer; SWG is a sine wave generator.](image)

It is known that the space-charge field created without applying to the PR crystal an external electric field is spatially shifted from intensity distribution by a quarter of the interference pattern period (or phase shifted by π/2). In the framework of conventional scalar approach, which treats a photorefractive hologram as a periodic refractive-index pattern, this pattern either spatially coincides or in the counter phase with the space-charge field distribution. Adding the π/2 phase shift that accompanies reflection from the index grating, we obtain a phase difference between the transmitted signal wave and diffracted reference wave that was equal to 0 or π. Therefore, conventional two-wave coupling via a hologram recorded in the diffusion mode does not support linear transformation of small transient phase modulation into intensity modulation. However, in the geometry of anisotropic diffraction (when light diffraction is accompanied by rotation of the polarization state by 90º), we can achieve linear phase-to-intensity transformation even in the diffusion recording mode when linearly and elliptically polarized waves are mixed. The transformation occurs because the inherent π/2 phase difference between orthogonal components (x and y) of elliptically polarized wave is transferred into an interference term of the transmitted signal and diffracted reference waves [7].

In this relation the signal wave having speckled structure with random polarization at the fiber’s output is linearly polarized by means of a polarizer before entering the crystal. Linear polarization of a reference wave having Gaussian intensity distribution is transformed to an elliptical by using a quarter-wave plate. We considered two geometries of the hologram recording: transmission and reflection. In transmission geometry reference and object waves (with wave vectors \(k_R\) and \(k_O\), respectively) propagate in the same direction in the PR crystal at small angles to each other, while in reflection they are almost counter propagating (Figure 2). To observe efficient anisotropic diffraction from the reflection hologram, the grating vector \(K = k_R - k_O\) should be oriented along one of the principal crystallographic axes of the crystal. For the transmission geometry the anisotropic diffraction is the most pronounced if the interfering beams propagate at small angle in respect to the [T10]-axis while the grating vector \(K\) is parallel to the [110]-axis [8].

An insertion in figure 1 shows the experimental traces of the transducer excitation and photo-diode current proportional to the intensity of the signal wave after its mixing with the reference wave in PR crystal. One can see that the intensity modulation occurs at the same frequency as the modulation signal. This result confirms that the linear regime of phase demodulation is achieved in our system.
The holographic principle of beams combining allows us to successfully match different wavefronts of the reference and object beams, while adaptive properties of the dynamic hologram results in compensation of undesirable slow phase drifts caused by environmental changes.

We have used a solid state Nd:YAG laser generating at the wavelength of 1064 nm at which CdTe crystal possesses high photoconductivity. The laser coherence length is about 100 m, so we were able to use long enough fiber (19 m) as a signal arm of the interferometer without necessity of providing the same length for reference arm.

Figure 2. Transmission (left) and reflection (right) geometry of hologram recording.

3. Sensitivity and theoretical detection limit

The sensitivity of an adaptive interferometer is primarily defined by the wave-coupling constant, $\kappa$, which can be represented for the hologram recorded in the diffusion mode as [9]

$$\kappa = -\sqrt{2R} \frac{mn_0^3 n_{a1}}{\lambda} \frac{E_D}{1 + E_D/E_q} \quad \text{with} \quad E_D = \frac{2\pi k_B T}{\Lambda e} \quad \text{and} \quad E_q = \frac{e \cdot N_A \Lambda}{\varepsilon \varepsilon_0 2\pi},$$

where $n_0$ is the refractive index; $n_{a1}$ is electro-optical coefficient; $E_D$ is the diffusion electric field; $E_q$ is the saturation field; $e$ is the electron’s charge; $N_A$ is the concentration of the photorefractive centers; $\Lambda=2\pi/|K|$ is the spatial period of dynamic hologram; $R$ is the intensity ratio of the reference to the object beam in the input of the crystal; $k_B$ is the Boltzman’s constant; and $T$ is the temperature; $\varepsilon \varepsilon_0$ is a dielectric constant.

The larger $\kappa$, the higher sensitivity to small phase changes can be achieved. Therefore, one could expect increase of the sensitivity due to reduction of hologram spatial period for fixed material parameters of the crystal. The smallest $\Lambda$ can be achieved by switching from the transmission to the reflection geometry of the hologram recording (figure 2). However, this increase of $\kappa$ depends on the concentration of the photorefractive centers, $N_A$. Note that coupling constant in the reflection geometry may become even smaller than that in the transmission geometry if the concentration of the photorefractive centers is small ($N_A < 2 \times 10^{16}$ cm$^{-3}$ for CdTe with $n_0 = 2.85$) due to reduction of the saturation field $E_q$.

Further we will investigate dependency of the sensitivity on the space period. Usual way of estimating performance of an adaptive interferometer is to compare its sensitivity with that of the classical homodyne interferometer free of optical losses [6, 10]. It is well known that the classical interferometer adjusted to the quadrature condition allows measurements of the smallest phase change. Therefore, the ratio of the minimal detectable phase change measured by an adaptive interferometer (when the signal is equal to the noise, signal-to-noise ratio $\text{SNR} = 1$) and the classical homodyne detection limit characterizes interferometer’s sensitivity. Such a comparison is usually done in conditions when inevitable shot noise of the photodetector is much larger than all other noises of the measuring system (noise of laser, electronics etc.). Under these conditions, the signal-to-noise ratio can be expressed as [11]:

$$\text{SNR} = \frac{\Delta P_S}{Q\sqrt{P_S}} \quad \text{with} \quad Q = \sqrt{\frac{4 \Delta f \hbar \nu}{\eta}},$$

where $P_S$ is the power of non-modulated object beam received by the photo-detector; $\Delta P_S$ is the variation of object beam power caused by the phase modulation; $\eta$ is the quantum efficiency of the
photo-detector; $h\nu$ is the photon’s energy; and $\Delta f$ is the frequency bandwidth of the detection electronics. In the classical lossless interferometer under the quadrature conditions one can find that $P_S = 2P'_0$ and $\Delta P_S = 2P'_0\phi$ for small phase variations ($\phi \ll 1$), where $P'_0$ is the power of the object beam, which is equal to that of the reference beam. The classical homodyne detection limit, $\phi_{\text{lim}}^C$, can be now found from equation 2 by equalizing $\text{SNR}$ to the unity:

$$\phi_{\text{lim}}^C = \frac{Q}{\sqrt{2P'_0}}. \quad (3)$$

Signal-to-noise ratio of an adaptive interferometer $\text{SNR}_A$ can be experimentally estimated by use of equation 2 if the photo-detector's current is directly proportional to the optical power. We can represent the relative detection limit using equation 3 as following

$$\delta_{\text{rel}} = \frac{\phi_{\text{lim}}^d}{\phi_{\text{lim}}^C} = \frac{\text{SNR}_C}{\text{SNR}_A} = \frac{\sqrt{2P'_0P_S}}{\Delta P_S} \phi. \quad (4)$$

Here $P_S$ is the mean light power received by the photo-detector and $P'_0$ is the power of the input object beam in the classical interferometer. All losses of the object light beam in the way between the input of the interferometer and photo-detector have to be taken into account. Optical losses from the passive optical elements can be significantly reduced by applying antireflection coating. The largest optical losses are caused by optical absorption in the photorefractive crystal that allows us readily recalculate the input power of the adaptive interferometer: $P_S = P_0 \exp(-\alpha L)$ Considering situation when the object beam power in classical interferometer, $P'_0$, is equal to the power of object beam entered to the crystal in adaptive interferometer, $P_0$, we can obtain expression for the relative detection limit:

$$\delta_{\text{rel}} = \sqrt{2} \exp \left( \frac{\alpha L}{2} \right) \frac{P_S}{\Delta P_S} \phi. \quad (5)$$

Here $\Delta P_S/P_S$ is just the modulation depth of photo-detector current, which modulation was caused by transient phase shift $\phi$. $\alpha$ is the absorption coefficient of the crystal, and $L$ is the crystal thickness. After measuring all these parameters, the relative detection limit is calculated from equation 5.

Comparison of the adaptive interferometer sensitivity in different geometries (reflection and transmission) was done by measuring the relative detection limit $\delta_{\text{rel}}$ as a function of the holographic grating period $\Lambda$, which determines the coupling constant in accordance to equation 1. For measurements $\delta_{\text{rel}}$ we apply sinusoidal voltage to piezo-electric cylinder to introduce into the object beam phase modulation $\phi$ with peak-to-peak amplitude of 0.2 radians. This phase modulation results in the modulation of the photo-detector current at the same frequency. The ratio of the peak-to-peak current modulation and its mean level is equal to $\Delta P_S/P_S$ With measured sample absorption $\alpha$ and thickness $L$, we calculate $\delta_{\text{rel}}$ from equation 5. Dependencies of the relative detection limit on the spatial period for two CdTe:V crystals are shown in figure 3. In transmission geometry the grating period was varied from 5.2 to 0.8 $\mu$m by changing the angle between interacting beams from 12 to 89 degrees, respectively. However, in the reflection geometry (when the grating period reaches its minimum) we were not able to change $\Lambda$ in significantly wide range, and hence only one experimental point (at $\Lambda = 0.19 \mu$m) corresponding to the reflection hologram is shown in figure 3 for both samples.

We have tested few photorefractive crystals of CdTe:V which were grown in CNRS-Bordeaux Institute of Condensed Matter Chemistry by using modified Bridgman technique. Samples have similar size ($L = 6 \text{ mm}$) and absorption ($\alpha = 1.7 – 2.0 \text{ cm}^{-1}$).

One can see from figure 3 that the slope of the dependence $\delta_{\text{rel}}(\Lambda)$ is different for two samples in the transmission geometry ($\Lambda > 0.8 \mu$m). Only two parameters ($r_{41}$ and $N_A$) may affect the slope of $\delta_{\text{rel}}(\Lambda)$ in the diffusion mode of holographic recording. Since difference of the electro-optic constant $r_{41}$ is hardly possible for crystals of the same content, we conclude that the reason of different slope is...
different concentration, \( N_\text{A} \), of photorefractive centers in these samples: BR-4Z-05 has higher concentration of the centers than BL-07-B1. Note that \( \delta_{\text{rel}} \) decreases in both samples when we switching from transmission to reflection geometry. However, the value of \( \delta_{\text{rel}} \) decreasing (or coupling increasing) is much larger for the BR-4Z-05 sample that also relates with higher concentration of the photorefractive centers due to stronger influence of the saturation field on the coupling constant at smaller \( \Lambda \) (see equation 1). Therefore, concentration of photorefractive centers has to be high enough for efficient beam coupling in the reflection geometry.

As seen in figure 3 the best sensitivity was obtained for the BR-4Z-05 sample in the reflection geometry: the sensitivity of the interferometer using dynamic hologram recorded in photorefractive crystal without any external electrical field and any polarization filtering is only 5.7 times smaller than the sensitivity of classical lossless interferometer, which is non-adaptive. It corresponds to the minimal detectable transient phase excursion of \( \phi^\text{lim}_\Delta = \phi^\text{lim}_C \sqrt{P_0/\Delta f} = \delta_{\text{rel}} \phi^\text{lim}_C \sqrt{P_0/\Delta f} = 1.9 \times 10^{-9} \text{ rad} \sqrt{\text{W/Hz}} \) (for \( \lambda = 1064 \text{ nm}, \eta = 0.8 \)) which is reduced to optical power and frequency bandwidth.

4. Noise and real detection limit
In order to estimate the interferometer sensitivity in previous section we supposed that all noises except for inevitable shot noise of photodetector are eliminated (or at least less then shot noise). It is clear that this situation is ideal. Actually there are a number of significant noise sources in real interferometer. These are laser noise, detection electronics noise, thermal noise of photodetector etc. Therefore the minimal detectable value \( \phi^\text{lim}_\Delta \) obtained in section 3 is a theoretical limit of measuring capability of the interferometer.

At the same time it has been found that most significant noise occurs due to modulating a polarization state of modes guided through the multimode fiber. As a result total polarization state of output wave is changed too. As we use the polarizer after the fiber (see figure 1) the modulation of polarization is transformed to the intensity modulation, which is also registered by photodetector. However this signal is very unstable – its amplitude slowly drifts during measurement. Such behavior is caused by temperature affecting on the polarization of light wave modes as well.

This noise can be reduced by using optical fiber with bigger core due to statistical averaging of each mode contribution to the output signal. Figure 4 shows dependency noise-to-signal ratio (NSR) as a function of phase modulation amplitude for two sizes of fiber core: 50 and 550 \( \mu \text{m} \). One can see that 11-fold increase of the core size has led to 5-fold reduction of noise level. As a result the real detection limit has been also 5-fold reduced and amounted to \( 81.1 \times 10^{-10} \text{ rad} \sqrt{\text{W/Hz}} \) which is just one order less then theoretical limit \( \phi^\text{lim}_\Delta \). At the same time a dynamic range has been extended from 17 to 30 dB. Obtained sensitivity of the interferometer allowed reliable broadband (\( \Delta f = 50 \text{ MHz} \)) measurement of fiber elongation in the range from 0.09 to 113 nm providing only 10 mW of the object.
beam’s power. At the same time it is possible to reduce minimal detectable elongation down to 1.2 pm in case of relatively narrow bandwidth $\Delta f = 10$ kHz.

If the fiber is tightly connected to an object under investigating and the fiber elongation is caused by an object deformation, then we can detect an ultra small deformation in the range from 0.0001 to 11 $\mu$ε providing the fiber’s sensitive part length of only 1 cm.

Figure 4. Noise-to-signal ratio vs. phase modulation amplitude for two values of fiber core size (50 and 550 $\mu$m) and two frequencies of phase modulation: 1 kHz (left) and 10 kHz (right).

5. Frequency response
As known, any adaptive interferometer based on dynamic holograms operates as a high-pass filter [iv]. It is clearly seen from figure 5 in which we show dependence of the modulation amplitude of photodetector’s current on the modulation frequency for both samples. These measurements were carried out by applying to the piezo-ceramic sinusoidal voltage at different frequency with such amplitude as to keep the peak-to-peak phase modulation of the light beam emerged from the multimode fiber at the level of 0.2 radians for any frequency. Intensities of the coupling beams were the same while measuring both samples: $I_{REF} = 37.8$ W/cm$^2$ and $I_{OBJ} = 2.4$ W/cm$^2$. We define the cut-off frequency, $f_{cut}$, of our interferometer as the frequency at which the interferometer response drops down to the half of the saturation value at high frequencies. The cut-off frequency of the adaptive interferometer is inversely proportional to the response time, $\tau_R$, of the photorefractive crystal [5]: $f_{cut} = (2\pi\tau_R)^{-1}$. One can see that more sensitive sample (BR-4Z-05) has slower response $f_{cut} = 180$ Hz ($\tau_R = 0.9$ ms) in contrast with less sensitive but faster BL-07-B1 sample: $f_{cut} = 750$ Hz and $\tau_R = 0.2$ ms. It is well known that cut-off frequency can be increased by increasing total light intensity of interacting beams [8]. By reducing size of both reference and object beams down to 0.6 mm, we increase the intensity to 67.2 W/cm$^2$ and 3.9 W/cm$^2$ for the reference and object beams, respectively. In accordance with Eq.10, we measured higher cut-off frequency: 300 Hz for BR-4Z-05 sample and to 1250 Hz for BL-07-B1 sample. It is worth noting that cut-off frequency higher than 1 kHz is required for industrial online applications, where either object surface is fast moving or efficient noise rejection at frequency 50/60 Hz is desirable.

Figure 5. Frequency response of the adaptive interferometer based on diffusion reflection hologram recorded in CdTe:V crystal. Circles are related to the sample BR-4Z-05, squares – to the sample BL-07-B1. Total light intensity of ~ 40 W/cm$^2$. 
6. Discussion
As one can see from figure 3, the sensitivity of adaptive interferometer can be essentially improved by switching from transmission to reflection geometry (i.e. by reducing the space period, \( \Lambda \)) if the concentration of photorefractive centers, \( N_a \), is high enough. In the reflection geometry we have got 4.5-fold increase of the sensitivity for BR-4Z-05 sample and 1.5-fold increase for BL-07-B1 sample compare to the best sensitivity obtained in transmission geometry. In the transmission geometry, diminishing of the spatial period \( \Lambda \) is always accompanied by decreased overlapping of the reference and object beams (i.e. by decreasing of the interaction length). This decrease becomes even more pronounced for small diameters of the interacting beams. Note that diminishing of the beam diameter is the direct way to increase the intensity of the interacting beams and consequently, to increase the cut-off frequency. Moreover, the minimum \( \Lambda \) achievable in the transmission geometry is limited by the refraction index of the crystal, which is quite high for CdTe crystal: \( n_0 = 2.85 \) at \( \lambda = 1064 \) nm resulting in the minimal \( \Lambda \) of about 0.8 \( \mu \)m. In contrast in the reflection geometry one can readily achieve perfect overlapping even for interacting beams of small diameter.

As it was shown in section 3 the best sensitivity was obtained for the BR-4Z-05 sample in the reflection geometry: sensitivity of the interferometer using dynamic hologram recorded in photorefractive crystal without any external electrical field and any polarization filtering is only 5.7 times smaller than sensitivity of classical lossless interferometer. Such for adaptive interferometers: more sensitive photorefractive beam combiners were reported [6, 7, 10, 12]. However, in all cases either DC [6, 10] or AC [7, 12] electric field was applied to the crystal. Application of DC electric field requires uniform illumination of the inter-electrodes space. Otherwise, the electric field screening leads to diminishing of the beam coupling. Anyway, hologram recording under DC-field by light beams of high intensity is hardly possible in fast semiconductors due to the crystal overheating that limits the cut-off frequency. Recording of dynamic hologram under AC-field allows overcoming the field-screening problem but it is achieved because of application of high-voltage at the frequency much higher than \( f_{cut} \) that requires use of expensive power source and generates significant noise. Proposed technique of vectorial wave mixing via reflection-type dynamic hologram recorded in the diffusion mode is very simple in its implementation and provides good combination of the sensitivity and response time. Interacting beams in the reflection geometry can be tightly focused for increasing the light intensity inside the crystal, which results in increasing of the cut-off frequency without significant reduction of the interaction length owing to almost collinear beams propagation. Consequently, high cut-off frequency can be achieved even with relatively low-power laser. In our experiments, diminishing of the beam diameter from 0.8 mm down to 0.6 mm results in significant increase of the cut-off frequency, while the interferometer sensitivity was reduced only by \( \sim 18\% \) in the reflection geometry (the relative detection limit was increased from 5.7 to 7 for BR-4Z-05 sample, and from 10 to 11.3 for BL-07-B1 sample). This small diminishing of the sensitivity may be explained by not optimal focal length of the lenses used for focusing the interacting beams into the crystal.

In order to overcome this problem we have developed an optimal geometry of launching light into the crystal [13]. Relations which define parameters of the optical system (focal length and geometrical arrangement of lenses and crystal) as functions of the crystal parameters (thickness and refractive index) were obtained. Using these relations we found optimal configuration of the optical setup in which two narrow and weakly diverged optical beams are completely overlapped inside the crystal providing maximal density of optical power and consequently high cutoff frequency without diminishing the hologram efficiency. In this geometry total power of light used for hologram recording can be reduced to 3 mW to obtain light intensity of \( \sim 30 \) W/cm2 which is enough to record fast photorefractive hologram with response time of \( \sim 0.2 \) ms.

7. Conclusion
We have developed a highly sensitive and fast-adaptive interferometer based on a dynamic hologram recorded in semiconductor photorefractive crystal and multimode optical fiber as a sensor. High sensitivity of the adaptive interferometer approaches the sensitivity of the classical lossless non-
adaptive interferometer which allows for the detection of ultra-small displacements (0.1 nm) or deformations ($10^{-4}$ µε) while adaptive properties of dynamic hologram eliminate all low-frequency unwanted influences. The hologram is recorded without applying any external electric field to the crystal. At the same time sufficiently high cut-off frequencies at relatively low intensities have been achieved due to the fast response of the semiconductor crystal CdTe. Additionally optimal geometry of beam focusing allowed for a significant reduction of total light power. All of these simplifies the measuring system and reduces its energy consumption.

Thus the adaptive interferometer fiber-optic measuring system developed in the present work holds much promise for long-term monitoring of ultra-small vibrations and dynamic deformations in industrial environment.

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