Six-channel adaptive fiber-optic interferometry system for nano-metrology

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Six-channel adaptive interferometer based on dynamic holograms multiplexing in photorefractive CdTe:V crystal is developed. The geometry of wave mixing in the crystal which precludes a cross-talk between channels is found out. The key feature of the proposed interferometer system is the orthogonal geometry of wave mixing in photorefractive crystal where depolarized light waves can be used in measurement channels without any polarization filtering. This reduces both optical losses and noise level in the measurement system. The interferometer is characterized by high sensitivity per a channel which allows a broadband (1 MHz) detection of vibration with the amplitude below 0.1 nm. Moreover high cut-off frequency, 0.7 kHz, achieved in CdTe crystal at light intensity makes possible to perform the measurement of ultra-small vibrations in quite unstable (e.g. industrial) environment.

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NOMENCLATURE

DH = dynamic hologram
PRC = photorefractive crystal
RDL, δ_{rel} = relative detection limit

1. Introduction

As known, interferometric systems are very sensitivity measurement tools capable to detect small quantities, e.g. objects displacements less than 1Å [1]. However owing to high sensitivity interferometric systems becomes open to influence of environment which is usually quite unstable (temperature drift, accidental mechanical impacts, etc.). As a result, it becomes very difficult or even impossible to use interferometry systems out of laboratory. In its turn, use of dynamic holograms recorded in photorefractive crystal (PRC) makes interferometer measurement systems adaptive to slow temporal changes of environment providing its stabile operation [2].

At the same time, there are a number of practical applications where several simultaneous measurements are required [3]. Thereby a development of multichannel adaptive system is an actual problem. Since a dynamic hologram (DH) is a key element of an adaptive interferometer, DHs multiplexing in single PRC is a way for solution of the problem. Attempts for development of multichannel adaptive interferometer on the basis of such approach were undertaken in papers [4-6]. In the work [4] independency of channels operation was achieved by mutual incoherence of light waves recorded DHs in PRC. In the work [5] channels separation in PRC was achieved by creating conditions at which main holograms and cross-holograms had different spatial orientation while an external electric dc-field applied to PRC has provided selective enhancement of only main holograms. The method of DHs spectral multiplexing in which holograms recorded in PRC by light waves with different but close wavelengths has been proposed in the work [6]. Here, signals from different channels were demultiplexed by means of narrowband spectral filters. Necessity of using strong electrical field is common drawback of all above-listed schemes. It is involve number of technical difficulties (electric field screening, crystal overheating, etc.) [7]. Moreover, in the last scheme, the number of channels is limited by PRC spectral sensitivity and spectrum width of used light source.

In this work we proposed a novel scheme of dynamic holograms multiplexing in PRC which provides a cross-talk free multichannel adaptive interferometer. The multiplexing approach does not require application of external electric field to a photorefractive crystal neither use of spectral techniques. Six-channel fiber-optical adaptive interferometric measurement system is realized on the base of proposed scheme. Both a cross-talk level between channels and DHs multiplexing capacity were studied.

2. Principle of dynamic hologram multiplexing

Key element of the adaptive interferometer is a dynamic hologram recorded in PRC of cubic symmetry (groups of 23 and 43*m*) in diffusion mode without applying external electric fields to

PRC. The orthogonal geometry of waves mixing in which an object and reference beams propagate in PRC in mutually orthogonal directions is used [8].

Fig.1 illustrates a principle of two orthogonal holograms multiplexing. Two object waves S_1 and S_2 propagate in PRC at small angle to its principal crystallographic axis, [001]. In its turn, single common reference wave R propagates orthogonally to the object waves along another principal axis, [100].

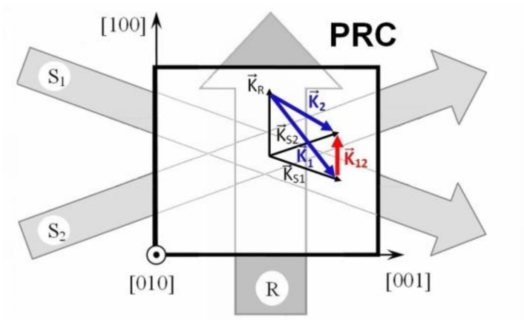

Fig.1 Geometry of orthogonal holograms multiplexing

The pair of waves S_1-R forms the main hologram with grating vector K_1 (associated with the first demodulation channel). The pair of waves S_2-R forms the second main hologram with grating K_2 (the second demodulation channel). At the same time an interference of the object waves S_1 and S_2 leads to appearance of holographic grating K_{12} which may be interpreted as a cross hologram. The interaction of any pair of waves at dynamic hologram recorded in diffusion mode (without external electric field) in a non-gyrotropic photorefractive crystal of cubic symmetry can be described by the simplified system of vectorial coupled-wave equations [9, 10]:

$$\begin{cases} \dfrac{\partial}{\partial l_1}\mathbf{A}_1 = -m\kappa_D \hat{\mathbf{H}}_2 \mathbf{A}_2, \\ \dfrac{\partial}{\partial l_2}\mathbf{A}_2 = m^* \kappa_D \hat{\mathbf{H}}_1 \mathbf{A}_1, \end{cases} , \tag{1}$$

where $\mathbf{A_1}$ and $\mathbf{A_2}$ are vectorial amplitudes of mixed waves; m is a half-contrast of the interference pattern; κ_D is wave-coupling constant which depends on material parameters of PRC and wavelength; l_1 and l_2 are directions of the interacting waves propagation, which are different in general. Tensor $\hat{\mathbf{H}}$ is a 2x2 coupling matrix whose components are obtained from the normalized tensor $\hat{\Delta}^K$ of dielectric-permittivity changes caused by the holographic grating space-charge electric field as following [9]:

$$H_{ps} = \langle p | \hat{\Delta}^K | s \rangle, \tag{2}$$

where $\langle p|$ and $\langle s|$ are vectors which form the basis where the amplitudes of mixed are determined.

By using Eq.(2), the coupling matrix for pair of object and reference waves interacting in the geometry depicted in Fig.1 will be found as

$$\hat{\mathbf{H}} = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 \end{pmatrix}. \tag{3}$$

Non-zero elements of the matrix $\hat{\mathbf{H}}$ indicate a presence of coupling between the object and the reference waves. Moreover, as seen, the couple matrix has zero components of at main diagonal. This means that light diffraction from DH recorded in this geometry is anisotropic. Such diffraction is required for realization of linear mode of object wave phase demodulation at DH [11]. In addition ti this requirement it is necessary to provide at least one of the mixed waves with elliptical polarization (another wave can be linearly polarized).

In the same way, one can show from Eq.(2) that the coupling matrix for pair of two object waves is zero:

$$\hat{\mathbf{H}} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}. \tag{4}$$

Thus, in the multiplexing geometry based on vectorial wave-mixing in cubic PRC (Fig. 1), there is no interaction between two object waves. In other words, dynamic hologram multiplexing does not lead to appearance of cross-talk between channels. It opens opportunity for building of highly-effective adaptive measurement system with a large number of channels. At the same time other sources of crosstalk could appear in the real system besides interaction in PRC. So, an experimental verification is needed.

Furthermore, a mutual influence of light fields from different channels in PRC can reduce a contrast of interference pattern in a channel. According to Eq.(1) This can results in diminishing of the interferometer sensitivity in the channel and as a sequence will determine DH multiplexing limit. Thus, in this work, we studied how strong this mutual influence and what the limit is.

3. The system architecture

A six-channel fiber-optical adaptive interferometer based on proposed principle of multiplexing orthogonal dynamic holograms in PRC is developed and its performance is studied. The scheme of interferometer is presented in Fig.2,a.

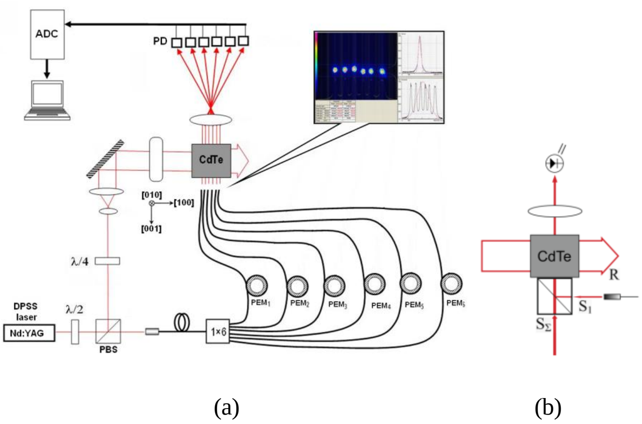

Fig. 2 (a) Experimental scheme of six-channel adaptive interferometer: PBS is a polarization beam splitter; ADC is analog-to-digital converter; PEM is a piezoelectric modulator. (b) Modification of the scheme for studying of DH multiplexing limit

CW light radiation from Nd:YAG laser is divided by polarization beam splitter and half-wave plate on two light beams in ratio 7:2. The first beam – reference – (P_R = 700 mW) was formed by cylindrical lens and directed by means of mirror into photorefractive crystal, CdTe:V, along its principal crystallographic axis [100]. The second beam is additionally sub-divided by means of fiber-optical 1×6-splitter into six equal object light beams which were coupled in six multimode optical fibers (62,5 μm core diameter, NA = 0,22). Each multimode fiber acts as a channel sensitive element of the multichannel system. Measurand interaction on i-th sensor was imitated by means of piezoelectric modulators PEM_i (Fig.2,a). AC-voltage U_i applied PEMs resulted in phase modulation in *i*-th object wave. Then, all object waves were directed to PRC along its crystallographic axis [001], orthogonally to the reference wave.

It is worse to note that following conditions should be fulfilled for realization of linear mode of phase demodulation in adaptive interferometer based on diffusion photorefractive hologram: light diffraction should be of the anisotropic character; one of the waves must have elliptical polarization, while another wave must have linear polarization [10, 11]. As it was shown above used geometry of wave mixing supports anisotropic diffraction of light. According to the next requirement, the reference wave was elliptically polarized by means of quarter-wave plate (see Fig.2,a). Considering the last requirement, it should to note that dynamic hologram recorded in orthogonal geometry has the polarization selectivity. It allows one not to use polarizing filters to select desired linear polarization from arbitrary polarized (or depolarized) object wave (like specked wave emerged from multimode fiber). Absence of polarizing filters allowed one to put the input ends of optical fibers very close to the entrance face of PRC (distance less than 1 mm). As a result a diameter of the object beam was amounted (without using focusing lenses) just to 0,7±0.1 mm (see inset in Fig. 2,a), while distance between centers of beams was 1,0±0.1 mm. Thus the beams were spatially separated in a bulk of crystal providing completely independent operation of holographic channels. The lens installed behind the crystal provided focusing light from each fiber to the corresponding photodetector.

It is worse to note that high cut-off frequency, 0.7 kHz, achieved in CdTe crystal at light intensity of 140 mW/mm² makes possible to perform the measurement of ultra-small vibrations in quite unstable (e.g. industrial) environment.

4. Cross-talk

Ac-voltage applied to the piezoelectric modulators has provided the phase modulation in each channel with equal amplitudes 0,7 rad at different frequencies: $f_1 = 20{,}5$ kHz; $f_2 = 16{,}0$ kHz; $f_3 = 12{,}0$ kHz; $f_4 = 9{,}0$ kHz; $f_5 = 5{,}5$ kHz; $f_6 = 2{,}0$ kHz. The oscilloscope traces of the photodetector currents which represent demodulation signals in each channel are shown in Fig. 3 together with their Fourier spectra.

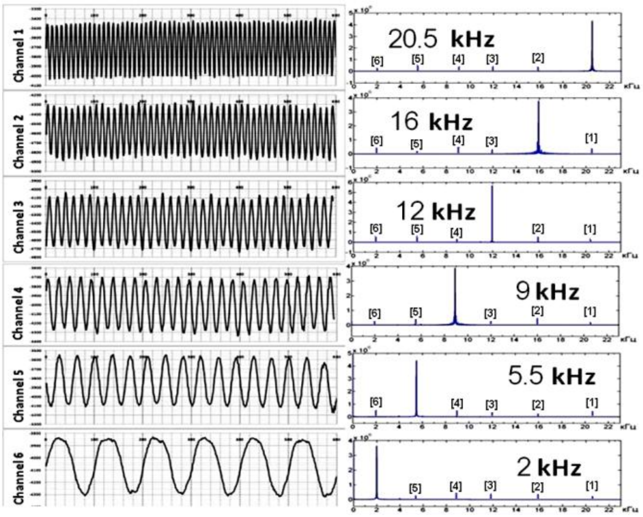

Fig.3 Demodulation signals in each channel of multichannel adaptive interferometer (left) and their Fourier spectra (right): [1] - [6] denote channels No.

As seen from Fig.3 the signal in each channel contains the components at frequencies of other channels in addition to main frequency. This means that there is a cross-talk between channels in the system. The experimentally measured level of the cross-talk reaches in maximum 7,5% of channel primary signal. The following reasons for this crosstalk can be considered as a most probable: (i) scattering of optical radiation by inhomogeneities in the PRC so that the radiation from one channel get into neighboring photodetectors; (ii) intensity modulation of a common reference beam originated in one channel is transferred to other object beams (or other channels); (iii) light waves reflection from the output ends of optical fibers back into the fiber splitter where they redistributed again through all channels.

In order to estimate a contribution of these potential sources to the overall cross-talk the demodulation signals were sequentially measured in each channel while other channels having phase modulation were optically blocked. It was found out that level of cross-talk in all channels has not changed up to accuracy of measurement error. Thus, the scattering of optical radiation on inhomogeneities in the PRC, as well as intensity modulation of the reference beam do not contribute significantly to the overall cross-talk.

For the estimation of a contribution of light reflected from the ends of optical fibers the last were covered by immersion oil, which reduced a reflection coefficient from 4% to 0,5%. As a result, the cross-talk level was decreased by one order of magnitude: maximum value of the noise did not exceed 1% of a channel primary signal. The changes in a signal Fourier spectrum for the first channel shown in Fig. 4 illustrate an effect of immersion oil application.

Thus it was found out that biggest contribution to a cross-talk between channels is related with light reflection from the ends of optical fibers. This effect can be additionally reduced by using optical fibers with tapered ends, as well as, by using fiber-optic splitters of better quality.

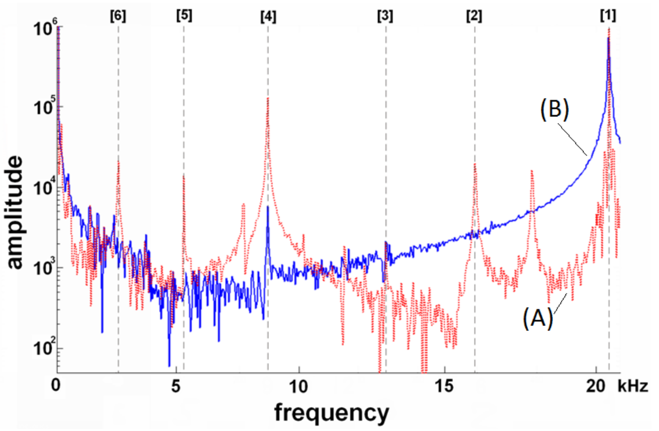

Fig.4 Fourier spectrum of demodulation signal of the first channel at without (A) and with (B) application of immersion oil to optical fibers ends

5. Multiplexing capacity

Performance of the multichannel adaptive interferometer from viewpoint of its sensitivity per a channel was studied in this work. A relative detection limit (RDL), which is ration between minimal detectable phase modulation in adaptive interferometer to the same one in a classical interferometer, was selected as a criterion of sensitivity [11]. RDL can be experimentally found as following

$$\delta_{rel} = \exp\left(\frac{\alpha L}{2}\right)\frac{P_{D0}}{\Delta P_D}\Phi, \tag{5}$$

where Φ is an amplitude of object wave phase modulation (Φ = 0,7 rad); α, L are absorption coefficient and crystal thickness, respectively (α = 2,0 cm^{-1}; L = 6,0 mm); P_{D0}, ΔP_D are the object wave average power and its modulation amplitude recorded by the photodetector, respectively.

RDL for each channel was calculated with using Eq.(5) from the experimental data shown in Fig.3. Its value was amounted to 15 ± 1 per a channel. The interferometer possessing such RLD is capable to provide a broadband (1 MHz) detection of (e.g.) vibration with the amplitude below 0,1 nm [11]. The differences in δ_{rel} figures are apparently related with non-uniformity of PRC electro-optic parameters in its bulk.

It is worse to note that light beams forming the channels do not mutually overlap in the crystal. However, if the number of channels increases the light fields of different channels could start overlapping. This may additionally have a negative effect on the sensitivity of the channels of the system. Therefore, in the work the performance of particular channel when it completely overlap with rest channel' beams was studied by measuring the channel RDL. For this purpose, the experimental setup has been modified in accordance with Fig. 2,b. The tested (working) channel was formed by light coming from the optical fiber. Other channels were simulated by entering an additional light beam which has the same diameter with working beam and completely overlapped with it in the crystal. Power of working object beam was 1 mW. Power of the additional beam was varied by means of neutral filters in the range from 1 to 150 mW so that allowed to simulate a formation of up to 150 additional channels. Power of the reference beam was set to 2,4 mW, 20 mW or 320 mW.

Experimentally obtained dependence of the relative detection limit on the total number of multiplexed channels is shown in Fig. 5. As seen, the smallest RDL achieved at the maximum power value of the reference beam.

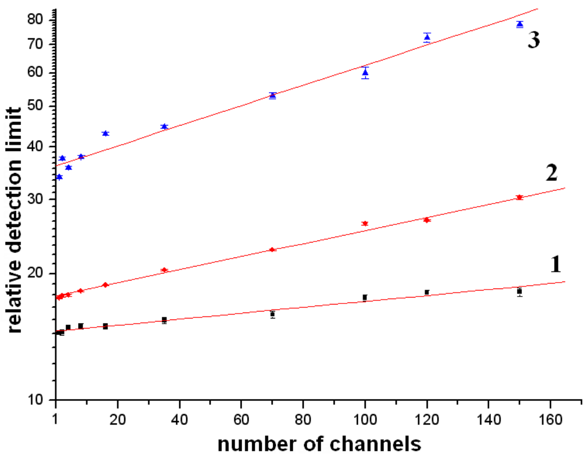

Fig. 5 Relative detection limit in a channel as function of total number of multiplexed channels experimentally obtained at different ratio of reference-to-object beams power: (1) – 320:1; (2) – 20:1; (3) – 2,4:1

The data presented in Fig.5 allows one to estimate the multiplexing capacity in the proposed scheme. Thus, in case of admittance of 10% worsening sensitivity of the interferometer in a channel (i.e. increase of RDL by 10%), up to 70 demodulation holographic channels can be created in a single PRC. Note that optical fields of these channels could be completely overlapped.

5. Conclusions

In this work a novel scheme of orthogonal dynamic holograms multiplexing in a photorefractive crystal which preclude appearance of a cross-talk was proposed. Based on this scheme a six-channel fiber-optic adaptive interferometric system was developed and its performance was studied. It was shown that biggest contribution to a cross-talk between channels in the system is related with quality of fiber-optical components while a multi-wave mixing in a photorefractive crystal do not produce any significant cross-talk which level do not exceed 1%. The system is characterized by high sensitivity per a channel (minimal relative detection limit is 15±1) and has high potential for increasing a number of channels. It is experimentally shown that up to 70 channels can be created while the sensitivity in a channel will be reduced only by 10%.

The multichannel system developed can be used for detection of ultra-small physical quantities (sub-nanometer vibration, deformation, translation, etc.) simultaneously in several points, for detection of ultra-weak distributed physical fields (acoustic, hydroacoustic, gravitation, etc.)

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