# Multi-channel adaptive interferometry system

Roman Romashko[1,a], Yuri Kulchin[1,b], Salvatore Di Girolamo[2,c], and Alexei Kamshilin[2,d]

[1] Institute Automation and Control Processes, FEB RAS, 5, Radio str., Vladivostok, Russia
[2] University of Kuopio, P.O. Box 1627, FIN-70211, Kuopio, Finland
[a] romar@delphin.marine.su, [b] kulchin@iacp.dvo.ru,
[c] girolamo@messi.uku.fi, [d] alexei.kamshilin@uku.fi

## Abstract

Multichannel adaptive interferometer based on multiplexing dynamic reflection holograms in a photorefractive crystal of cubic symmetry is proposed. Efficiency of hologram multiplexing is theoretically and experimentally studied. It is shown that for used recording geometry a crosstalk between channels does not exceeds inherent noise of single channel in wide angular range, while sensitivity depletion in one channel is insignificant for large number of channels.

**Keywords**: Photorefractive crystal, dynamic hologram multiplexing, adaptive interferometer, multi-channel system

## 1. Introduction

A usage of dynamic photorefractive (PR) holograms in optical and fiber-optical measurement systems make them adaptive, i.e. capable to operate in unstable environment and reliably detect ultra-small physical quantities (vibrations, deformations, alternative force fields etc.) [1]. At the same time a development of multidimensional measurement systems consisted of high number of sensor channels, requires appropriate number of photorefractive crystals as well as reference optical beams for recording a set of holograms. This leads to undesirable complexification of the measurement system. One of possible way for solving this problem is multiplexing of several dynamic holograms in a single photorefractive crystal.

In this paper we propose technique for dynamic reflection holograms multiplexing in a photorefractive crystal of cubic symmetry and study possibility of development a multichannel measurement system on this base.

## 2. Holograms multiplexing geometry

Scheme of hologram multiplexing in PR crystal of cubic symmetry (point groups 23 and $\bar{4}3\text{m}$) is shown in Fig. 1. Two signal waves propagate in the crystal along its principal axis [001], where they and are mixed with one common reference wave which propagates towards to them. All waves are mutually coherent, so then they produce interference patterns and, as possible sequence, dynamic holograms [2], which could be generally of one of two types. The first type is a main hologram formed by pair of two beams – signal and reference, while the second type is a cross-hologram formed by two signal beams. Main holograms form channels, while cross holograms lead to appearance of cross-talk between channels.

Operation of single channel was studied in details in works [1, 3]. It was shown that detection limit $\delta_{\text{lim}}$ achievable in the adaptive interferometer based on dynamic reflection hologram recorded in CdTe crystal can be as low as $4.4\times10^{-9}\,\text{rad}\sqrt{\text{W/Hz}}$. However multiple recording of hologram the holograms can affect on this limit due to two main reasons: (i) reduction of sensitivity in single channel and (ii) increase of noise in the channel due to appearance of cross-talk between channels. These parameters define an efficiency of dynamic holograms multiplexing and, consequently, performance of multi-channel system.

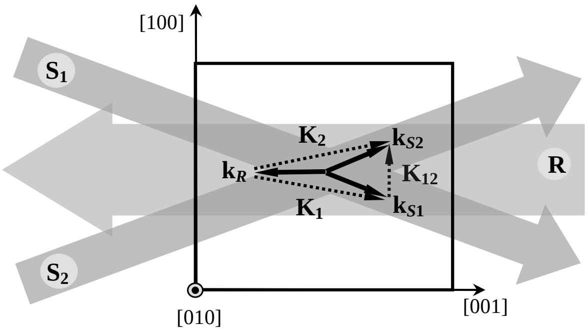

Fig. 1. A geometry of reflection holograms multiplexing in PR crystal: $R$ – reference beam; $S_1, S_2$ – signal beams; $\vec{k}_R, \vec{k}_{S1}, \vec{k}_{S2}$ are their wave vectors, respectively; $\vec{K}_1, \vec{K}_2$ – wave vectors of main holograms; $\vec{K}_{12}$ – wave vector of cross-hologram.

## 3. Crosstalk

Mixing of any two coherent waves with complex amplitudes $\vec{A}$ and $\vec{B}$ in PR crystal in diffusion regime (without application of external electric field to crystal) is described by system of coupled-waves equations [4]:

$$\begin{cases} \frac{\partial}{\partial z}\vec{A} = \kappa\widehat{\mathbf{H}}\vec{B} \\ \pm\frac{\partial}{\partial z}\vec{B} = -\kappa\widehat{\mathbf{H}}\vec{A} \end{cases}, \tag{1}$$

where $\kappa$ is coupling constants defined by material parameters of the crystal and space-charge field generated in it by mixed waves interference [5]. Left side of the second equation is positive if mixed waves propagate in same direction in crystal (transmission geometry of recording) while it is negative if waves propagate in opposite directions (reflection geometry).

$\widehat{\mathbf{H}}$ is $2\times2$ coupling matrix which define character of waves interaction at the dynamic hologram which they create. The elements of matrix $\widehat{\mathbf{H}}$ depends on the relative orientation of holographic grating's wave vector and polarization components of light field in crystallographic axes [4]. On can show that for main holograms, which wave vectors $\vec{K}_1$ and $\vec{K}_2$ are almost parallel to axis [001], the coupling matrix will have non-diagonal unit elements: $\widehat{\mathbf{H}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. That means that there is coupling between waves recorded such the hologram – between signal and reference wave.

In contrast, for two signal waves which are recording the cross-hologram, all elements of the coupling matrix are equal to zero $\widehat{\mathbf{H}} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$, if the grating vector of such cross-hologram $\vec{K}_{12}$ is strictly perpendicular to axis [001]. It means that in this case there is no coupling between to signal waves, and then there is no crosstalk between channels related with these waves.

However the coupling can appears if orthogonality of the vector $\vec{K}_{12}$ to axis [001] is violated. Such coupling will leads to occurrence of crosstalk between channels, which level (noise to signal ratio) can be estimated by following equation:

$$C \approx \frac{|\sin\phi|}{2}h, \tag{2}$$

where $\phi$ is an angle between vector $\vec{K}_{12}$ and direction perpendicular to axis [001]; $h \leq 1$ is a factor taking into account a degree of beams overlapping inside crystal.

The dependency $C(\phi)$ is shown in Fig. 2 together with experimental data. As one can see a violation of orthogonality to axis [001] leads to appearance cross-talk. However the cross-talk level is below a self-noise level in a channel or slightly exceeds it in a wide angular range of cross-hologram's grating vector deviation, making easy a creation of a large number of channels without visible increase of noise level in a channel.

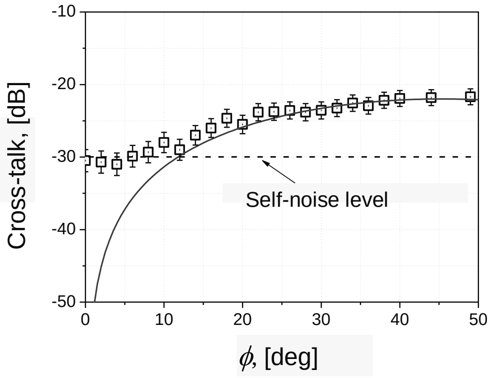

Fig. 2. Crosstalk as a function of angle between cross-hologram's grating vector and direction perpendicular to axis [001]. Horizontal line represents the level of channel's internal noise.

## 4. Sensitivity reduction

One of key parameter which defines sensitivity of an adaptive interferometer based on dynamic hologram recorded in PR crystal is the coupling constant $\kappa$ (see Eq.(1)) which is proportional to a contrast of interference pattern produced inside crystal by signal and reference beams [2, 5]. At the same time holograms multiplexing implies mixing several signal beams with single reference one. This leads to unavoidable overlap of light field of selected signal wave with additional waves, and, as a result, to reduction of interference pattern contrast for selected hologram:

$$m = \frac{2\sqrt{I_R I_S}}{I_R + I_S + \sum_i I_i h_i}, \tag{3}$$

where $I_R$, $I_S$, $I_i$ are intensities of the reference, selected signal and $i$-th additional signal waves, respectively; $i \in [0, N]$, $N$ is a number of additional signal waves (or number of multiplexed holograms); $h_i$ is a factor taking into account a degree of overlapping selected signal beam with $i$-th additional one inside crystal.

Reduction of $\kappa$ caused be decrease of $m$ leads to reduction of waves coupling by means of the dynamic hologram and consequently to depletion of sensitivity in a channel. At the same time such depletion can be minimized by proper focusing of light beams and reducing overlap factor $h_i$. One can show that for crystal of 6 mm length and light beam's diameter of 1 mm, average overlap factor amounts 0,5. In this case up to 15 channels can be formed in the single crystal with just 50%-depletion of the sensitivity in one channel (Fig. 3).

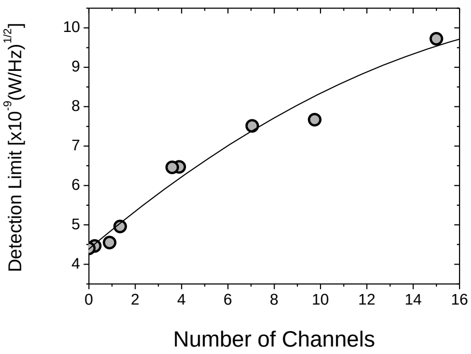

Fig. 3. Dependency of absolute detection limit in one channel on the number of additional channels formed in a crystal.

Figure 4 demonstrates an operation of two-channel measurement system which simultaneously detects vibrations at different frequencies in two separated areas. As one can see there is no visible crosstalk between channels.


(a) (b)

Fig. 4. Snapshots of oscilloscope traces which demonstrate an operation of two-channel adaptive measurement system: first channel (a), second channel (b). Trace on a top is a detected signal, while bottom trace represents a modulation signal which excites vibration with amplitude of 10 nm.

## 5. Conclusion

In this paper we proposed the geometry of dynamic hologram multiplexing in photorefractive crystal of cubic symmetry without application of any external field. This geometry provides an extremely low crosstalk between channels related with multiplexed holograms in wide angular range for input signal beams. Moreover, insignificant depletion of one-channel sensitivity in proposed geometry make possible developing highly efficient adaptive multi-channel measurement system.

## 6. Acknowledgments

This work was supported by Russian Foundation for Fundamental Research (grant 07-02-91015) and Academy of Finland (project No. 118487).

## References

1. S. Di Girolamo, A.A. Kamshilin, R.V. Romashko, Y.N. Kulchin, and J.-C. Launay. *Opt. Express.* 2007, vol. 15, p. 545.
2. M.P. Petrov, S.I. Stepanov, and A.V. Khomenko. *Photorefractive Crystals in Coherent Optical Systems.* Springer-Verlag, Berlin. 1991.
3. S. Di Girolamo, A.A. Kamshilin, R.V. Romashko, Y.N. Kulchin, and J.-C. Launay. *Opt. Lett.* 2007, vol. 32, p. 1821.
4. B.I. Sturman, E.V. Podivilov, K.H. Ringhofer, E. Shamonina, V.P. Kamenov, E. Nippolainen, V.V. Prokofiev, and A.A. Kamshilin. *Phys. Rev. E.* 1999, vol. 60, p. 3332.
5. L. Solymar, D.J. Webb, and A. Grunnet-Jepsen. *The Physics and Applications of Photorefractive Materials.* Oxford University Press. 1996.