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Six-channel adaptive fibre-optic interferometer

R.V. Romashko, M.N. Bezruk, A.A. Kamshilin, Yu.N. Kulchin

Abstract. **We have proposed and analysed a scheme for the multiplexing of orthogonal dynamic holograms in photorefractive crystals which ensures almost zero cross talk between the holographic channels upon phase demodulation. A six-channel adaptive fibre-optic interferometer was built, and the detection limit for small phase fluctuations in the channels of the interferometer was determined to be 2.1×10^{-8} rad $W^{1/2}$ $Hz^{-1/2}$. The channel multiplexing capacity of the interferometer was estimated. The formation of 70 channels such that their optical fields completely overlap in the crystal reduces the relative detection limit in the working channel by just 10 %. We found conditions under which the maximum cross talk between the channels was within the intrinsic noise level in the channels (–47 dB).**

Keywords: *photorefractive crystal, dynamic hologram, adaptive interferometer, multiplexing.*

1. Introduction

Interferometer measurement systems are known to possess high sensitivity and can thus be used to detect very small physical quantities, e.g. vibration amplitudes of the order of a fraction of an angstrom [1]. At the same time, because of their high sensitivity, interferometry systems are rather susceptible to external influences, such as temperature and atmospheric pressure fluctuations and accidental mechanical impacts, which limits the use of such systems under nonlaboratory conditions.

One way to solve this problem is to use dynamic holograms (DHs) recorded in a photorefractive crystal (PRC), which make the interferometry system adaptive, i.e. capable of adjusting to uncontrolled changes in external factors and remaining operative under real conditions [2,3]. This approach, referred to as adaptive interferometry, was pioneered by Hall et al. [2] and has since been further developed and successfully employed [3–9].

There are a number of practical applications that require simultaneous measurements of several physical quantities. In particular, these include simultaneous monitoring of parameters of a large number of objects, extended objects and physical fields [10–12]. Solving such problems requires a large number of sensors combined into multichannel measurement systems. This approach has generated wide interest in the development of multichannel adaptive interferometers.

Since a DH is a key element of adaptive interferometers, a natural approach is to multiplex the set of DHs being formed in a single PRC. Attempts to create multichannel adaptive interferometers using this approach were reported, e.g., in Refs [13–15]. Kulchin et al. [13] achieved independent operation of channels by using mutually incoherent light beams to form holograms that were multiplexed in a PRC. Fomitchov et al. [14] achieved multiplexing by creating conditions under which the main holograms and cross-holograms had different spatial orientations in the crystal, and an external electric field applied to the crystal in a certain way ensured selective enhancement of the main holograms. Qiao et al. [15] proposed a method for wavelength-division multiplexing of DHs, in which holograms were formed in a PRC by light beams slightly differing in wavelength and the signals from different channels were demultiplexed using narrow-band spectral filters. A drawback common to the above methods is that a high external electric field must be applied to the PRC, which entails a number of technical problems (shielding effect, overheating of the crystal and others) [16,17]. Moreover, in the methods that employ wavelength-division multiplexing, the number of channels is limited by the spectral sensitivity of the PRC and the spectral width of the light source.

Preliminary experimental data demonstrate that, when an orthogonal geometry is used, DH multiplexing in one PRC is possible without the above difficulties [18].

This paper presents a theoretical analysis of DH multiplexing in an orthogonal geometry. We demonstrate that such vectorial wave coupling geometry in a PRC enables cross talk to be almost completely suppressed. The proposed geometry has been used to build a six-channel adaptive fibre-optic interferometer measurement system, and its performance has been assessed.

2. Orthogonal geometry of DH multiplexing

To form DHs in a PRC, an orthogonal geometry is used in which signal and reference beams propagate through a PRC of cubic symmetry in mutually perpendicular directions [19]. This geometry ensures the most effective implementation of linear phase demodulation mode for depolarised light [20], characteristic, in particular, of multimode optical fibres that can be used as sensors.

The operation of a multichannel interferometry system relies on the multiplexing of a set of orthogonal DHs: N signal beams interact with a common reference beam in a PRC.

R.V. Romashko, Yu.N. Kulchin Far Eastern Federal University, ul. Sukhanova 8, 690950 Vladivostok, Russia; Institute for Automation and Control Processes, Far Eastern Branch, Russian Academy of Sciences, ul. Radio 5, 690041 Vladivostok, Russia; e-mail: romashko@iacp.dvo.ru, director@iacp.dvo.ru;
M.N. Bezruk Institute for Automation and Control Processes, Far Eastern Branch, Russian Academy of Sciences, ul. Radio 5, 690041 Vladivostok, Russia; e-mail: bezmisha@list.ru;
A.A. Kamshilin University of Eastern Finland, Yliopistonranta 1, P.O. Box 1627, FI-70211 Kuopio, Finland; e-mail: kamshiline@uku.fi

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Figure 1 illustrates the $N = 2$ case. Two signal waves, S_1 and S_2, propagate through a PRC at small angles, θ_1 and θ_2, to the principal crystallographic axis [001], completely overlapping one another in the crystal. A common reference wave, R, propagates in the [100] direction, normal to the signal waves.

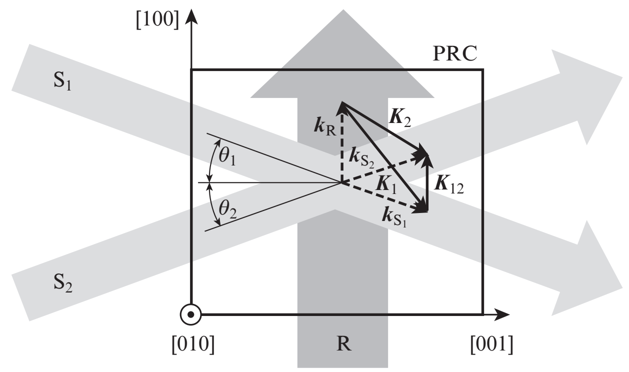

Figure 1. Geometry of DH multiplexing in a PRC.

The waves S_1 and R form one main holographic grating with a vector $\boldsymbol{K}_1$ (the first demodulation channel), and the waves S_2 and R form the other main holographic grating with a vector $\boldsymbol{K}_2$ (the second demodulation channel). Interference of the signal waves S_1 and S_2 may in turn produce a cross grating with a vector $\boldsymbol{K}_{12}$. Interaction of waves on such a grating, if it will be formed, will lead to coupling of the signals of the corresponding channels and cross talk.

As seen in Fig. 1, the vectors of the main holograms, $\boldsymbol{K}_1$ and $\boldsymbol{K}_2$, are almost parallel to the [001] axis, whereas the vector of the cross hologram, $\boldsymbol{K}_{12}$, is normal to it. This distinction determines the nature of the interaction between waves in the crystal and, as shown below, makes it possible to ensure multiplex recording of a set of holograms free of cross talk.

The interaction of two waves in a nongyrotropic PRC of cubic symmetry can be described by the equation of coupled waves [19]:

$$\frac{\partial}{\partial l_1}\boldsymbol{A}_1 = -m\kappa_{\mathrm{d}}\hat{H}_2\boldsymbol{A}_2, \quad \frac{\partial}{\partial l_2}\boldsymbol{A}_2 = -m^*\kappa_{\mathrm{d}}\hat{H}_1\boldsymbol{A}_1, \tag{1}$$

where $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ are the vector amplitudes of the coupled waves; m is the contrast of the interference pattern formed by the two waves; $\kappa_{\mathrm{d}} = \pi n_0^3 r_{41} k_{\mathrm{B}} TK/(\lambda e)$ is the coupling parameter for waves on a diffusion holographic grating, which is determined by the refractive index of the PRC n_0, the electro-optical coefficient r_{41}, wavelength λ, the Boltzmann constant k_{B}, temperature T and the magnitude of the holographic grating vector, K; l_1 and l_2 are the coordinates measured in the propagation direction of the waves $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ in the PRC, which may in general differ; and $\hat{H}$ is the wave coupling matrix, whose components depend on the directions of the unit vectors $\langle p|$ and $\langle s|$ of the orthogonal basis that defines the plane of oscillations of the electric field of the light wave in the principal crystallographic axes [20, 21]:

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

where $\hat{K}$ is the tensor of the dielectric permittivity change induced by the electric field of the space charge. Its components depend on the direction of the holographic grating vector ($\boldsymbol{K}_1$, $\boldsymbol{K}_2$ or $\boldsymbol{K}_{12}$, see Fig. 1) [19].

It can be shown using Eqn (2) that, for any pair of waves interacting in the geometry represented in Fig. 1, the coupling matrix has the form

$$\hat{H} = \begin{pmatrix} 0 & h \\ h & 0 \end{pmatrix}, \tag{3}$$

where $h = \cos\beta$ (β is the angle between the holographic grating vector and the principal crystallographic axis [001]). Note that the diagonal elements of the coupling matrix being zero attests to anisotropic diffraction from the DH in the geometry under consideration. As shown by Kamshilin and Grachev [22], this enables linear phase demodulation of a signal wave on a DH.

When the cross hologram vector $\boldsymbol{K}_{12}$ is normal to the [001] axis ($\beta = 90°$), the coupling matrix $\hat{H}$ is zero. This means that there is no coupling between the two signal waves, and hence there is no cross talk between the channels. At $\beta \neq 90°$, the elements of the coupling matrix $\hat{H}$ are not identically zero, and there is coupling between the two signal waves. As follows from (1) and (3), its efficiency is determined by the product of the wavenumber K and element h of the coupling matrix: $\chi = Kh$ (the parameter χ can be taken as a quantitative measure of coupling efficiency).

It is worth noting that both K and h are determined by the propagation directions of the interacting waves. It can be shown from geometric considerations (Fig. 1) that, for a reference wave normal to the [001] axis and a signal wave, the parameter $\chi_1 = K_1 h_1$ is determined by angle θ_1:

$$\chi_1 = k\cos\theta_1, \tag{4}$$

where $k = 2\pi n_0/\lambda$. For two signal waves, we have

$$\chi_{12} = k(\cos\theta_1 - \cos\theta_2). \tag{5}$$

It is seen from (5) that, when the angles θ_1 and θ_2, at which signal waves propagate in a PRC, are identical (e.g. both are equal to zero), there is no interaction between the waves ($\chi_{12} = 0$). For $\theta_1 \neq \theta_2$, there is cross talk, which increases with increasing difference between θ_1 and θ_2. Given that χ_1 determines the signal and that χ_{12} determines cross stalk, the cross talk level in the first channel can be estimated as

$$X = \chi_{12}/\chi_1 = 1 - (\cos\theta_2/\cos\theta_1). \tag{6}$$

It is seen from (6) that the cross talk increases with increasing difference between the angles at which the signal waves propagate. Consider a system where the wave S_1 propagates in a crystal along the crystallographic axis [001] ($\theta_1 = 0$) and the wave S_2 propagates at the maximum possible angle, $\theta_2 = \theta_{\max}$, which is determined by the total internal reflection angle: $\theta_{\max} = \arctan(n_0^{-1})$ (the angle of incidence on the input face of the crystal is 90°). For a CdTe crystal ($n_0 = 2.85$), we obtain $\theta_{\max} = 20.5°$. Under such conditions, the cross talk X is 6.7%. Clearly, such situation does not occur in practice because signal beams are directed to a PRC at angles much less than 90°.

It can be shown using (5) and (6) that, when the maximum cross talk is set at the level of –46 dB (which corresponds to the intrinsic noise in the channels), signal waves can propagate in the PRC at angles within 6° to the [001] axis. Accordingly, the beam can be launched into the crystal at angles of up to 16.5° relative to the input face.

It should be noted that the above theoretical analysis considers beams that completely overlap in the PRC. If the beams overlap only partially, this will further reduce the cross talk.

Thus, the proposed geometry has great potential from the viewpoint of building multichannel adaptive interferometry systems because it offers the possibility of precluding or minimising the cross talk between the multiplexed channels formed by signal beams (including completely overlapping beams) that propagate through a PRC in a rather wide angular range.

At the same time, it is worth pointing out that an overlap of the optical fields of signal beams in the PRC, inevitable in the multiplexing geometry under consideration, will reduce the contrast m of the interference fields that form holograms and, as a consequence, will reduce the signals in the channels [as follows from the system of Eqns (1)]. In the context of building a multichannel interferometer, a reduction in contrast leads to sensitivity loss in the channels of the system. As shown below, the degree of sensitivity loss, in turn, places a limit on channel multiplexing in a single PRC.

3. Experimental configuration

The proposed geometry for multiplexing orthogonal DHs was used to build a six-channel adaptive fibre-optic interferometer (AFOI), and its operation was studied experimentally. Figure 2a shows a schematic of the AFOI.

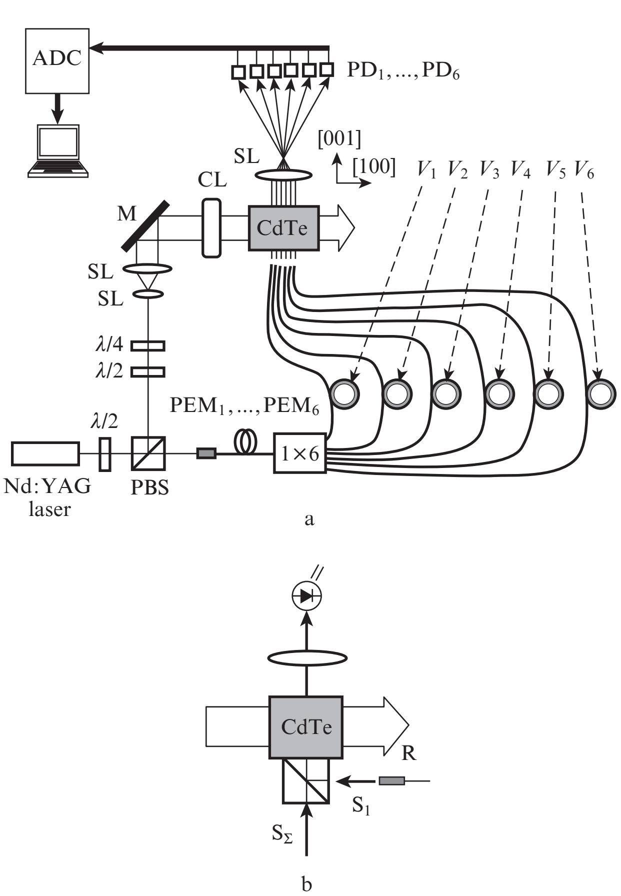

Figure 2. (a) Schematic of the AFOI and (b) modified configuration for assessing the hologram multiplexing limit: (λ/2, λ/4) half- and quarter-wave plates, (PBS) polarisation beam splitter, (SL) spherical lens, (CL) cylindrical lens, (M) mirror, (PEM_i) piezoelectric modulator, (PD_i) photodetector, (ADC) analogue-to-digital converter.

The output of a cw Nd:YAG laser is divided into two beams by a polarisation beam splitter. One beam (reference) is passed through a CdTe crystal along its crystallographic axis [100]. The other beam is further split by a 1×6 fibre coupler into six signal beams identical in power, which are coupled into six multimode fibres (MMFs). Each MMF acts as a sensing element in the respective channel of the measurement system. The response of the ith element to a measurand is simulated by the piezoelectric modulator PEM_i: the sinusoidal voltage V_i applied to it modulates the phase of the ith signal wave. The signal beams from the MMFs are sent to a PRC along its principal crystallographic axis [001], at right angle to the reference beam.

It is worth pointing out that effective interaction between waves in the crystal is only possible at certain polarisations of the waves. In most instances, polarisation filters are needed for this purpose [21]. At the same time, a DH formed in an orthogonal geometry possesses polarisation selectivity [20], which allows one to eliminate polarisers from the optical path of the signal beams. As a consequence, the interferometer configuration considerably simplifies: the output end faces of the fibres can be merely butted against the input face of the PRC, obviating the need for focusing lenses. Thus, the orthogonal geometry for DH formation ensures the most effective channel multiplexing: the number of channels is only limited by the dimensions of the crystal and the fibre packing density.

Note that the beam divergence at the output of the MMFs (NA = 0.22) is 13°. The fibres were normal to the input face of the crystal to within 3°. With the beam refraction in the crystal taken into account, the beams propagated along the crystal at an angle within $\pm6°$ to the [001] axis. According to Eqn (6), the maximum cross talk level for this angle is –46 dB.

4. Cross talk evaluation

To study the cross talk between the AFOI channels, these were phase-modulated at the same amplitude (0.7 rad) and different frequencies (20.5, 16, 12.5, 9, 5.5 and 2 kHz). Figure 3 shows oscilloscope traces of the photodetector currents (demodulation signals in the channels) and their Fourier spectra. It can be seen that the spectrum of each channel contains, in addition to the strong peak at its working frequency, weaker components at the frequencies of the other channels. The Fourier spectrum of the signal in the first channel is shown in greater detail in Fig. 4. As seen, the average cross talk level is –25 dB (at the frequency of the third channel).

It follows from the data in Figs 3 and 4 that the cross talk exceeds the calculated cross talk form the interaction between the signal beams in the PRC. Therefore, the cross talk is contributed by other sources, whose nature must be established. The additional cross talk between the channels may be due to light scattering by inhomogeneities in the PRC, so that the light from one channel finds its way to the photodetectors of the neighbouring channels. Another possible cause is the modulation of the intensity of the common reference beam used for DH multiplexing in the PRC. In addition, cross talk may be caused by light reflection from the end faces of the MMFs back into the fibre coupler, where the light is redistributed over the channels.

To assess the contribution of the above sources to the overall cross talk, we successively measured the demodulation signal in each channel while blocking the light from the other channels, in which phase modulation was maintained (the light was blocked in front of the crystal). It was found that the

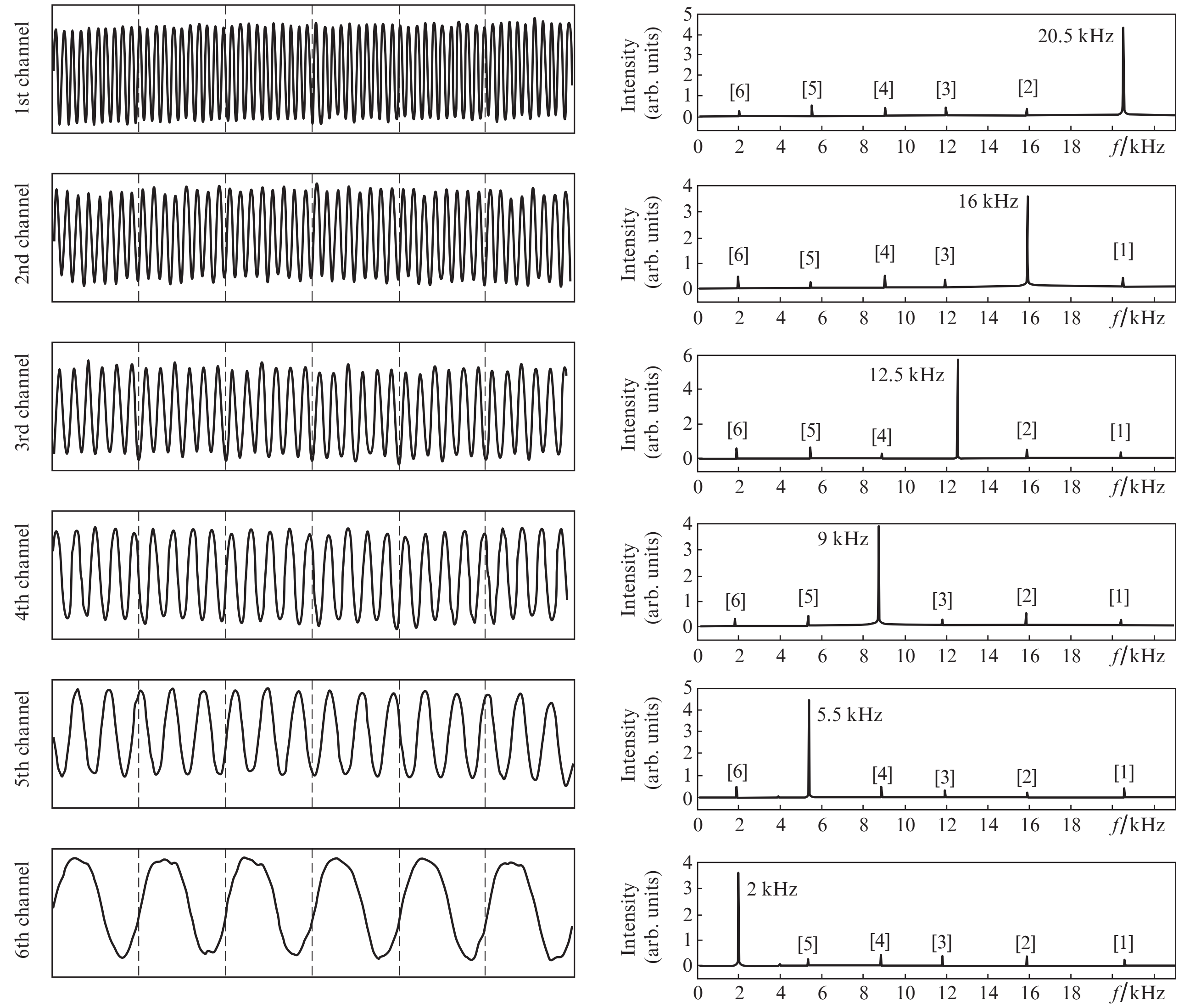

Figure 3. Oscilloscope traces of the demodulation signals in the channels of the six-channel AFOI (left panel) and their Fourier spectra (right panel). The numbers in square brackets specify the channels responsible for the cross talk.

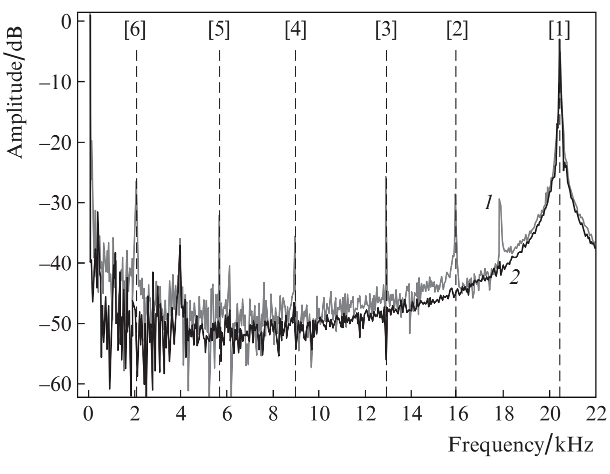

Figure 4. Fourier spectrum of the demodulation signal in the first channel (*1*) before and (*2*) after immersion oil was applied to the end faces of the fibres. The numbers in square brackets specify the channels.

cross talk level in all the channels remained unchanged. Thus, neither the light scattering by inhomogeneities of the PRC nor the intensity modulation of the common reference beam makes any significant contribution to the overall cross talk.

To assess the contribution of the light reflection from the end faces of the MMFs, the faces were covered with immersion oil ($n = 1.516$), which reduced the cross talk by an order of magnitude: the highest value was no greater than −47 dB of the main demodulation signal in the channel. The average cross talk was about −50 dB, which approaches the calculated value. The effectiveness of the approach in question is illustrated by Fig. 4, which demonstrates that the cross talk in the spectrum of the signal dropped to below the intrinsic noise level in the channel.

5. Sensitivity of the multichannel AFOI and multiplexing capacity

We assessed the AFOI sensitivity, which was quantified by the relative detection limit (RDL): the ratio of the minimum phase modulation depth detectable by the adaptive interferometer to that detectable by a classic homodyne interferometer, $\delta = \varphi_a/\varphi_c$ (where $\varphi_c = 1.5\times10^{-9}$ rad $W^{1/2}$ $Hz^{-1.2}$). Using the results presented in Fig. 3 and previous findings [23], we calculated the RDL for each channel. The average RDL was found to be 14 ± 1, which corresponds to an absolute detection limit $\varphi_a = 2.1\times10^{-8}$ rad $W^{1/2}$ $Hz^{-1/2}$. At an input beam power of 1 mW and wavelength of 1064 nm, an interferometer with such sensitivity can detect vibration amplitudes of down to 1.7 Å in a frequency range as broad as 10 MHz [1].

Increasing the number of channels increases the number of light beams that are coupled into the PRC and in general can intersect the working beam. Clearly, the effect of extra channels will be determined by the overlap of the optical fields involved and will be strongest for extra beams completely overlapping the working beam. This situation – the worst from the viewpoint of cross talk – occurs when all the extra beams propagate within a common numerical aperture, which is equivalent to launching one beam into the crystal. This approach was used to experimentally assess the influence of the number of multiplexed channels on the sensitivity of the working channel. To this end, the experimental setup was modified as indicated in Fig. 2b. An extra, Gaussian beam parallel to the working beam was launched into the PRC. Its intensity was equal to the sum intensity of all the extra channels. The working (test) channel was formed by 1 mW of optical power from an MMF. The working and extra beams had the same diameter (1 mm) and completely overlapped in the crystal. The power of the extra signal beam was varied by a set of neutral filters in the range 0–150 mW, which was equivalent to the formation of 150 extra channels. The measurements were made at three reference beam powers: 2.4, 20 and 320 mW. Figure 5 shows the measured RDL of the working channel as a function of the total equivalent power of the extra channels.

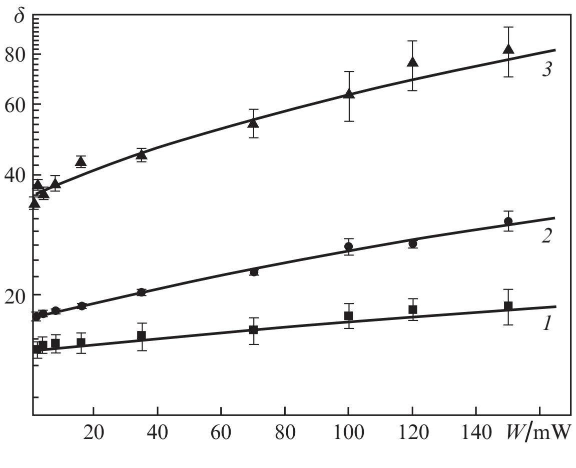

Figure 5. RDL in an individual channel as a function of the total equivalent power of extra channels, W, at ratios of the reference and signal beam powers of (1) 320:1, (2) 20:1 and (3) 2.4:1. The solid lines represent calculation results and the points represent the experimental data.

Note first of all that the lowest RDL, corresponding to the highest sensitivity of the interferometer, can be reached at the largest ratio of the reference and signal beam powers (320:1). If only one channel is operative, the RDL is 14, which correlates with the above data. With increasing extra beam power, the sensitivity of the working channel drops and, accordingly, the RDL increases, but only slightly. For example, when light equivalent to 70 extra channels is launched into the crystal, the RDL increases by just 10%. It is worth noting that, in this case, the worst situation occurs: the beams from the extra channels completely overlap both each other and the working beam.

Also shown in Fig. 5 are the RDLs evaluated by numerically solving Eqn (1) with allowance for the fact that the contrast of the interference pattern in a channel decreases with an increase in the number of channels. The calculation results are seen to be in rather good agreement with the experimental data. This lends support to the fact that the main cause of the reduction in the sensitivity of the AFOI channels is the decrease in the contrast of the interference field that forms the hologram.

6. Conclusions

We have proposed and analysed a new DH multiplexing geometry which ensures almost zero cross talk. This geometry was used to build a six-channel adaptive fibre-optic interferometry system. Experimental data demonstrate that cross talk in the interferometer is mainly due to the light reflection from the end faces of the fibres. Covering their end faces with immersion oil reduced the cross talk to at most –47 dB of the main signal in the channel, which was within the intrinsic noise level in the channel. The detection limit in the channels of the interferometry system was determined to be 2.1×10^{-8} rad $W^{1/2}$ $Hz^{-1/2}$. The multiplexing capacity has been estimated from experimental data. With an increase in the number of channels, the detection limit increases, but only slightly. The formation of 70 channels such that their optical fields completely overlap reduces the RDL in the working channel by just 10%.

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