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LIGHT PRESSURE DETECTION BY TWO-WAVE MIXING IN THE PHOTOREFRACTIVE $BaTiO_3$: Co CRYSTAL

The paper studies the high-sensitive detection of light radiation pressure using an adaptive interferometer based on photorefractive 45°-cut $BaTiO_3$: Co crystal. For small phase modulation measurement the authors employed a polarization filtering, which ensured the linear regime of signal detection in the photorefractive crystal with nonlocal response. It was demonstrated that the proposed method of light pressure measurement could be used as a broadband photodetector. It was experimentally found that the sensitivity was 2 μW in the wavelength range from 488 to 1600 nm.

ADAPTIVE HOLOGRAFIC INTERFEROMETER, LIGHT PRESSURE, TWO-WAVE MIXING, PHOTOREFRACTIVE CRYSTAL, HIGH-SENSITIVE DETECTION, BROADBAND PHOTODETECTOR.

Introduction

It is well known that light exerts pressure on an illuminated object that is a result of the momentum transfer from photons to the object, which reflects, absorbs, or refracts the light [1]. Even though light pressure is negligible in common practice, nowadays it has numerous applications ranging from manipulation on biological particles and nanotechnology up to cooling and trapping atoms [1—3].

In this paper we consider a high-sensitive detection of light pressure using an adaptive holographic interferometer based on photorefractive 45°-cut $BaTiO_3$: Co crystal. In our experiment, the light pressure causes a displacement of a reflecting membrane, and this response is measured by the adaptive interferometer. We demonstrate that the device based on light pressure measurement can be used as a broadband achromatic photodetector with linear response.

Adaptive Interferometer with Linear Phase Demodulation

In our experiments we measured the increased vibrations of a reflecting membrane caused by the pressure of light being amplitude-modulated. An adaptive interferometer with photorefractive crystal is well known as a simple and efficient configuration for measuring small vibrations [4]. In most industrial applications the fast response time of the photorefractive crystal is needed and many efforts were made to develop the setups with photorefractive semiconductors and sillenite crystals, which have the fastest response time. However, these crystals have low electro-optic coefficients, which results in weak two-beam coupling even with external field enhancement of the photorefractive effect. In our experiments with highly reflective membrane the major factor leading to the loss of light should be the weak coupling, or, in the other words, the low reflectivity of the photorefractive grating. Thus to achieve high light efficiency and as a result maximum sensitivity we have to choose a crystal with high reflectivity even at the expense of response time. For our experiments we selected 45°-cut $BaTiO_3$, which provides one of the strongest grating reflectivity without resorting to an externally applied electric field [5, 6]. While the absence of the electric field is an appreciable advantage in itself, in this case the diffusion mechanism of the photorefractive grating recording is dominant. As a consequence the photorefractive grating is $\pi/2$-phase shifted with respect to the interference pattern. The signal and the reference waves are in phase in the exit of the crystal, and it results in the weak quadratic detection of the signal wave phase modulation. To provide high-sensitive linear detection we employed a photorefractive interferometer with different polarizations of

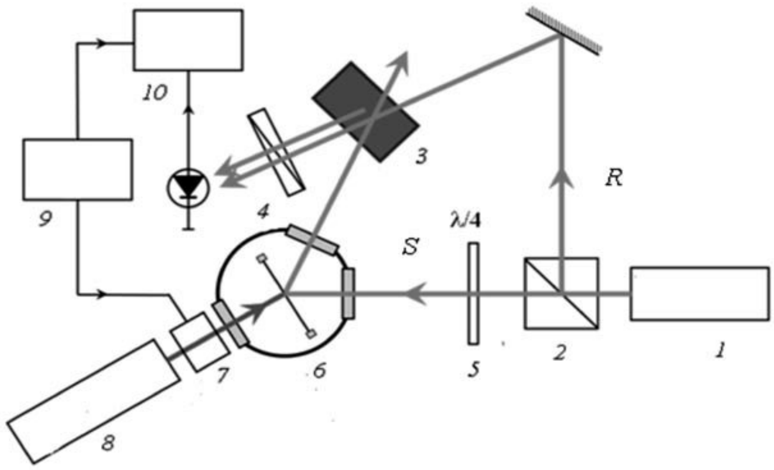

Fig. 1. Experimental setup:
1 – Nd : YAG laser (λ = 532 nm), *2* – beam splitter, *3* – $BaTiO_3$: Co crystal, *4* – polarizer, *5* – λ/4 retarder, *6* – vacuum chamber with reflective membrane, *7* – intensity modulator, *8* – laser (λ = 488, 632, 1600 nm), *9* – function generator, *10* – lock-in amplifier; *R*, *S* – the reference and the signal beams, respectively

the interfering waves and polarization filtering [7, 8].

The scheme of the holographic interferometer, which provides counter-propagating two-wave mixing in the photorefractive crystal, is shown in Fig. 1. The photorefractive crystal, $BaTiO_3$: Co, has cobalt concentration of approximately 0.01 mol. % and the length of 4 mm along the grating wave vector. The angle between the interfering beams was 170°. A frequency-doubled Nd : YAG laser (λ = 532 nm) was used as a light source for the interferometer. The reference beam *R* has horizontal polarization, while the signal beam *S* is elliptically polarized. The quarter-wave retarder, which controls the signal beam polarization, introduces a phase shift between vertical and horizontal polarization components. The photorefractive grating is recorded by the interference pattern of the horizontal component of the signal beam and the reference beam. Only light with extraordinary polarization is reflected by the grating due to the great difference between effective electro-optic coefficients for ordinary and extraordinary waves [6]. In our experimental setup the light with vertical polarization is reflected, and therefore the reference beam passes the crystal without reflection by the grating, and this feature increases the interferometer efficiency.

The complex vectorial amplitudes of the signal and reference waves, which enter the crystal through the opposite facets, are given by

$$S = S_0 \begin{bmatrix} (1-i)\sin\theta\cos\theta \\ \sin^2\theta + i\cos^2\theta \end{bmatrix} e^{i\varphi(t)},$$

$$R = R_0 \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \qquad (1)$$

where S_0 and R_0 are the scalar amplitudes of the signal and reference, respectively; θ is the angular position of the quarter-wave retarder; $\varphi(t)$ is the phase modulation of the signal wave caused by the reflective membrane vibration.

The reference wave has vertical polarization; therefore the horizontal *x* component of the signal wave does not take part in the photorefractive grating build-up process. The grating recorded by the *y* component reflects the horizontal *x* component of the signal wave. The quarter wave plate changes the phase between the *x* and *y* components of the signal wave that allows the adjustment of the phase difference between the reflected signal wave and the reference one. Eq. (1) shows that the reference wave transmitted through the crystal is in phase with the reflected wave when the angular position of the retarder θ = 45°. In this case the configuration shown in Fig. 1 provides high-sensitive linear detection of the fast phase modulation of the signal wave. The polarization

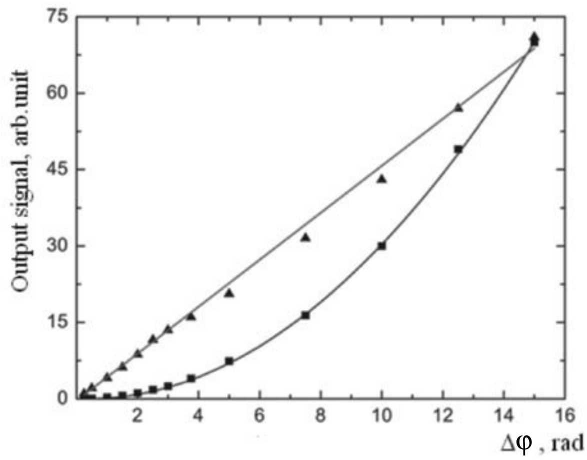

Fig. 2. An amplitude of the output signal versus the amplitude of signal wave phase modulation, Δφ, measured with (▲) and without (■) the quarter wave retarder.
Solid curves are the best linear and parabolic fits of the experimental data

analyzer in front of the photodetector mixes the vertically polarized reference wave and the reflected signal one, which has horizontal polarization. The light intensity behind the polarization analyzer is

$$I(t) = PS_0^2 \sin^2 \alpha + TR_0 \cos^2 \alpha + + \frac{1}{4}\sqrt{PT} S_0 R_0 \sin 2\alpha \sin \varphi(t), \quad (2)$$

where P is intensity reflectance of the photorefractive grating, T is transmittance of the crystal, and α is an angle that transmission axis of the polarization analyzer makes with the x axis.

Obviously, the interferometer has the highest sensitivity when α = 45° and the amplitude of the intensity modulation is

$$\Delta I(t) = \frac{1}{4}\sqrt{PT} S_0 R_0 \sin \varphi(t). \quad (3)$$

Our experiments have confirmed that the proposed configuration of the interferometer allows linear detection of the phase modulation. We observed only the first harmonic of the signal when the quarter-wave plate was installed and aligned in the optimal position. Without the phase retarder, when the signal and reference wave had the same polarization, only the second harmonic was observed and the output signal dependence on the phase modulation amplitude was quadratic. The results of those experiments (see Fig. 2) reveal a significant advantage in output signal of the «linearized» interferometer when a small phase modulation is detected. In that experiment the vacuum chamber with reflective membrane was replaced by a piezo-driven mirror. We used this result as an interferometer calibration to determine the membrane displacement in the measurements of light pressure.

We found experimentally the optimal positions of the quarter wave plate and the polarization analyzer, and that measure yielded the maximum sensitivity of the interferometer. The result obtained differs from the 45°-position predicted theoretically by approximately 20°. The measurements of the grating reflectance as a function of the polarization angle show that maximum value is also observed with our crystal sample when the polarization differs from the vertical one by 20°. Apparently, these discrepancies we can explain by the difference between the considered 45° crystal cut and the crystallographic orientation of our $BaTiO_3$: Co sample, which has been cut close to 30°.

An Achromatic Photodetector Based on Light Pressure Measurement

As a detector of light pressure we used a thin flexible highly reflective membrane placed in a vacuum chamber. The air pressure in the chamber was about 5 N/m². The membrane

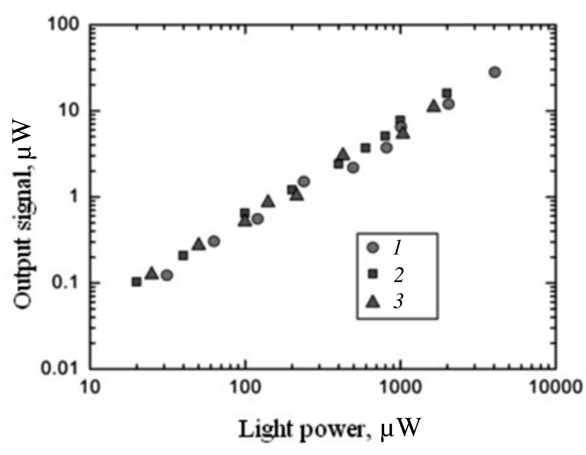

Fig. 3. An amplitude of the output signal as a function of the incident light power for three different wavelengths λ:
1 – 488 nm, *2* – 633 nm, *3* – 1600 nm

was composed of a 5 μm-thick nitrocellulose substrate coated with an 0.12 μm-thick aluminum reflective layer. The measured reflectivity of the membrane was 85–95 % in the wavelength range of 0.4–1.6 μm. The membrane was illuminated through the right-side windows of the vacuum chamber by the green CW light (see Fig. 1) that made possible to detect fast membrane displacement interferometrically. The laser beam causing this displacement entered the chamber from the left. It showed a periodical intensity modulation that resulted in increased vibrations of the membrane with amplitude depending linearly on the incident light intensity. As a source of the incident light we used lasers of three different wavelengths: 488, 633, and 1600 nm. The experimental results are presented in Fig. 3, where we show the photodetector amplitude as a function of the incident light intensity. The response of the photodetector is highly linear and achromatic. The measured signal-to-noise ratio at the incident light power of 20 μW was about 10. Thus we estimated the sensitivity of the photodetector as 2 μW taking it as a noise-equivalent power. It is of note that in the experiments with the vacuum chamber the noise level was nearly 30 times as high as that in the experiments with the calibration using piezo-driven mirror. Apparently, the increase in noise is associated with membrane imperfections that scatter the signal wave. Therefore, the improvement of the membrane quality should allow reaching the sensitivities in excess of 1 μW.

Conclusion

In order to measure the light pressure we propose a new configuration of the adaptive photorefractive interferometer with highly efficient 45°-cut $BaTiO_3$: Co crystal. In this setup the two orthogonal linear polarization components of the signal wave play different roles. One of them builds up the photorefractive grating interfering with the reference wave inside the crystal but does not contribute to the output signal of the interferometer. The other component is reflected by the photorefractive grating and is mixed with the reference wave by the polarizer, which yields the output signal. The phase shift between two polarization components is controlled by the phase retarder that allows the linear phase demodulation using the crystal with nonlocal, local or mixed photorefractive response. We have applied this interferometer for measurements of light pressure. It was experimentally found that the sensitivity was 2 μW over a wide spectral range. Our experimental results make possible to suggest a new type of the photodetectors based on the interferometric measurement of the light pressure.

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Петров В.М., Хоменко А.В., Криницкий Я.А., Гарсиа А.М. ДЕТЕКТИРОВАНИЕ ДАВЛЕНИЯ СВЕТА ПОСРЕДСТВОМ ДВУХВОЛНОВОГО СМЕШЕНИЯ В ФОТОРЕФРАКТИВНОМ КРИСТАЛЛЕ $BaTiO_3$: Co.

Сообщается о высокочувствительном детектировании давления светового излучения с использованием адаптивного интерферометра на основе фоторефрактивного кристалла $BaTiO_3$:Co со срезом 45°. Для измерений с небольшой фазовой модуляцией была использована поляризационная фильтрация, которая обеспечивает линейный режим детектирования сигнала в фоторефрактивном кристалле с нелокальным откликом. Показано, что разработанный инструмент для измерения давления света можно использовать в качестве широкополосного фотодетектора. Экспериментально установлено, что чувствительность составляет 2 мкВт в диапазоне длин волн 488 – 1600 нм.
АДАПТИВНЫЙ ГОЛОГРАФИЧЕСКИЙ ИНТЕРФЕРОМЕТР, ДАВЛЕНИЕ СВЕТА, ДВУХВОЛНОВОЕ СМЕШЕНИЕ, ФОТОРЕФРАКТИВНЫЙ КРИСТАЛЛ, ВЫСОКОЧУВСТВИТЕЛЬНОЕ ДЕТЕКТИРОВАНИЕ, ШИРОКОПОЛОСНЫЙ ФОТОДЕТЕКТОР.

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