Non-contact Optical Measurement of High-frequency Nanometer Vibration

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We present a non-contact and high accuracy interferometeric technique for detecting high-frequency nanometer vibrations. The measuring system which is based on the principles of dynamic hologram in photorefractive crystal can work on the homodyne condition without external electric field applied to the crystal. Crystal BSO is used and equivalent to an adaptive beam splitter. The diffracted reference beam having matched wavefront with the test beam, and it permits to operate perfect homodyne detection on highly speckled beams. Furthermore, any low frequency modulation in the interfering beams such as those caused by noise from ambient vibration or slow motion of the object will be compensated for by the crystal. The factors that affect diffraction efficiency have been investigated such as intensity ratio of the reference beam and the test beam, the angle between the above two beams. The experimental results on the sample of piezoelectric ceramic with different vibration frequencies are presented.

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1. Introduction

Vibration measurement has found wide ranging applications both in industry and academic research, such as process monitoring, laser ultrasonic nondestructive detection and materials characterization. Laser interferometers have been used for years[1-7]. Originally, homodyne or heterodyne interferometers can not operate effectively with the speckled beam from the rough surface. The signal to noise will decrease significantly. Moreover, the interferometers have to be aligned very accurately to get larger étendue. The Fabry-pérot interferometer has a large étendue to collect light efficiently. However, the device is quite large, adding complexity and cost.

Recently, some new types of interferometers with various photorefractive crystals have been developed and were used to detect the broadband nanometer vibration[8-11]. Unlike the conventional interferometers, these interferometers can process the speckled signal wavefront scattered from the rough surface because of the photorefractive effect. Furthermore, any low frequency modulation in the interfering beams such as those caused by noise from ambient vibration or slow motion of the object will be compensated by the crystals.

In this paper, the interferometer based on the principles of dynamic holography in photorefractive crystal and homodyne detection is described. Crystal $Bi_{12}SiO_{20}$ (BSO) is used and equivalent to an adaptive beam splitter. It permits to operate perfect homodyne detection on speckled beams. A quarter-wave plate is used in the reference beam path to fulfill the condition of in-quadrature and to provide the linear and sensitive homodyne detection. The factors that affect diffraction efficiency of dynamic hologram in BSO crystal have been investigated. The optimal condition for vibration detection is obtained. The experimental results on the sample of piezoelectric ceramic with different vibration frequencies are presented.

2. Theoretical Background

A test beam which is phase modulated at φ(t) due to the vibration and a reference beam interferes within a photorefractive crystal as shown in Fig.1. A dynamic hologram is then recorded in the crystal.

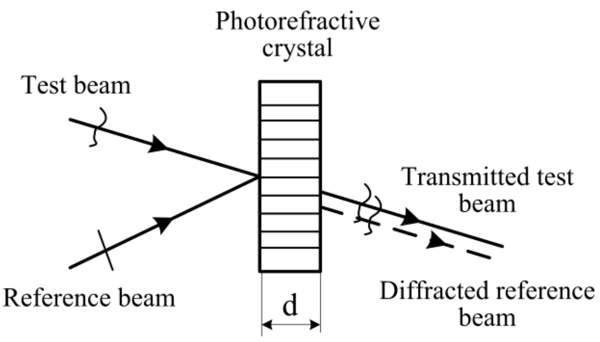


Fig. 1 Schematic Diagram of the photorefractive beam combiner

The test beam amplitude can be expressed as $E(0,t)=E(0,0)e^{i\varphi(t)}$. The amplitude of diffracted reference beam by the dynamic hologram can be written as[12]:

$$E_R = e^{-\frac{\alpha d}{2}} E(0,0)(e^{\gamma d} - 1) \tag{1}$$

Where α is the optical absorption coefficient of the crystal, d is the crystal thickness, γ is the photorefractive gain as $\gamma = \gamma' + i\gamma''$.

The transmitted test beam amplitude is :

$$E_T = e^{-\frac{\alpha d}{2}} E(0,0) e^{i\varphi(t)} \tag{2}$$

At the exit of the crystal, the amplitude of combined beam is:

$$E(d,t) = e^{-\frac{\alpha d}{2}} E(0,0)\left[(e^{\gamma d} - 1) + e^{i\varphi(t)}\right] \tag{3}$$

The intensity on the photodetector is:

$$I = e^{-\alpha d} I_0 \left[e^{2\gamma' d} + 2e^{\gamma' d} \sin(\gamma'' d)\varphi(t)\right] \tag{4}$$

When the vibration displacement is u(t), and when the test beam is back scattered from the vibrating surface, the phase modulation is:

$$\varphi(t) = \frac{4\pi}{\lambda} u(t) \tag{5}$$

The output signal from detector is directly proportional to the vibration displacement. The signal to noise ratio is:

$$SNR = \frac{4\pi u}{\lambda} \sqrt{\frac{2\eta I_0}{h\nu \Delta f}} e^{-\frac{\alpha d}{2}} \sin(\gamma'' d) \tag{6}$$

where Δf is the detection bandwidth, $h\nu$ is the photo energy, u is the RMS displacement, and η is the detector quantum efficiency.

3. Experiments

3.1 Experimental Setup

The scheme of homodyne laser vibration measuring system using photorefractive crystal BSO without external electric field is presented in Fig 2. The beam from a single longitudinal mode Nd:YAG laser with wavelength of 532nm and power of 150mW, is divided into two beams which are reference beam and test beam. A half-wave plate is used together with polarizing beamsplitter(PBS) to vary the power ratio between the two beams. The test beam passes through a quarter-wave plate and is focused on the target. The back scattered light whose phase contains the vibration information from the target is collected by the lens with large aperture and passes through the quarter-wave plate once again to change the polarization state. The scattered test beam interferes with the reference beam on the crystal BSO which is the size of 5×5×5mm and (110) cut. A dynamic grating is formed inside the crystal. Simultaneously, the diffracted reference beam is generated and interferes on the photodetector with the partial scattered beam transmitted directly through the crystal. Time based signals of photocurrent which is proportional to the vibration displacement of the target are recorded by a digital oscilloscope with storage capabilities or a data acquisition of NI USB-5322. Another quarter-wave plate is used in the reference beam path to improve the measuring sensitivity in the condition of non electric field on the crystal.

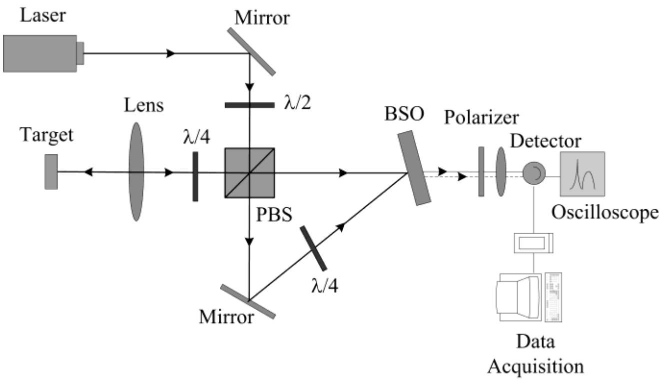


Fig. 2 Schematic of experimental setup

3.2 Experimental results

3.2.1 Parameter Optimization

The factors that affect diffraction efficiency of dynamic hologram in BSO crystal have been investigated including the intensity ratio of the test beam and the reference beam, the angle between these two beams to acquire the maximum diffracted reference beam and the optimal interference on the photodetector. Fig. 3 shows the results. The optimal parameters are following: the reference beam power is 25mW, the test beam power is 5mW, and the convergence angle is 32°. Under this optimal condition, the signal on the photodector is amplified by 20%, from 2.6mW to 3.1mW. The amplification of the test beam is given by Fig.4. When reference beam is blocked, only transmitted test beam signal can be observed. After the reference beam is opened, the amplified signal including diffracted reference signal and transmitted test signal is observed.

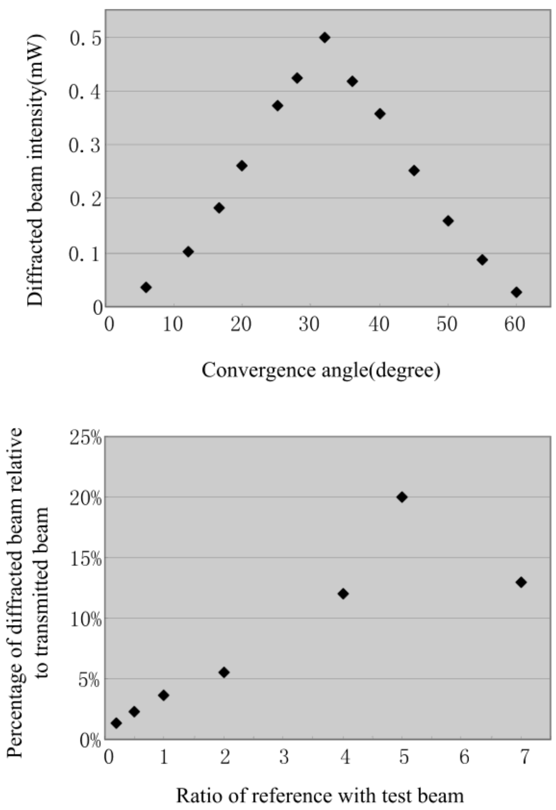


Fig. 3 The optimization results

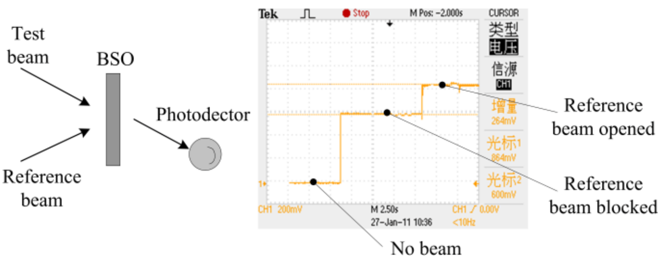
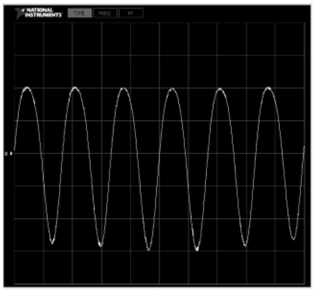


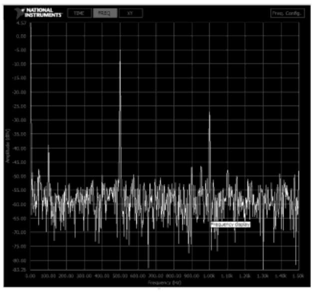
Fig. 4 Amplification of the test signal

3.1.2 Vibration Detection

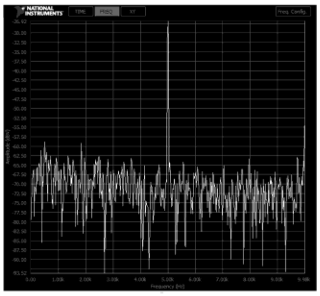
A piezoelectric ceramic is used as the target. By applying sinusoidal voltage of 2.5V on it, the displacements in the order of nanometers with frequencies from 500Hz to 90kHz are generated. The time-based vibrating signal is measured and the spectral signal is gotten by FFT using Labview. The results are shown in Fig.5. It can be seen that the detected frequency exactly corresponds to the predetermined frequency。The signal amplitude decreases along with the frequency increase. The voltage on the piezoelectric ceramic was adjusted to higher, the higher frequency will be detected. The detection technique is reliable and can be used for measurement of brandbond nanometer vibration.



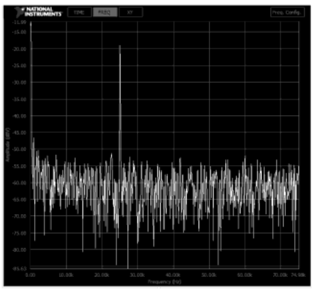
(a) Time based signal



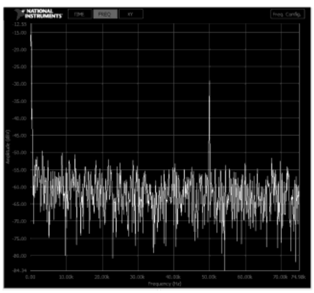
(b) Spectral signal (predetermined frequency of 500Hz



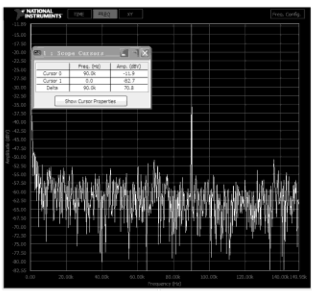
(c) 5kHz



(d) 25Hz



(e) 50kHz



(f) 90kHz

Fig. 4 Measurement results of a piezoelectric ceramic with different vibration frequency

4. Conclusions

This paper presents a vibration measuring system based on the photorefractive crystal BSO. The dynamic hologram formed by the interference between reference beam and test beam encoding the vibration information is recorded into the crystal. The diffracted reference beam has the matched wavefront with the test beam which is useful to detect the seriously speckled beam from the rough surface. A quarter-wave plate is applied in the reference beam path to obtain the maximum measuring sensitivity. The homodyne detect without external electric field onto the BSO can be conducted. The factors that affect diffraction efficiency have been investigated and the optimal measurement condition is obtained. The vibrations of the piezoelectric ceramic with frequencies from 500Hz to 90kHz have been reliably detected.

ACKNOWLEDGEMENT

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