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Design of harmonic oscillator for MOEMS three-component acceleration seismic geophone

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Abstract: The harmonic oscillator of three-component acceleration seismic geophone based on photoelastic effect is designed by the methods of inertia force perpendicular to the harmonic oscillator and differential detection technology. In terms of dual M-Z interferometer of three-component acceleration seismic geophone, equal division of optical power and single-mode transmission of light are the bases of correct acceleration detection. The structure of M-Z interferometer is introduced. The optical field transmission of dual M-Z interferometer in three-component acceleration seismic geophone is simulated by the waveguide optics simulation software OptiBPM v9.0, and the optical field transmission graph of dual M-Z interferometer is obtained. The simulation result shows that when the light emitted from the laser passes through the dual M-Z interferometer, the optical field peak values of 1/4 branch waveguides all achieve 0.52, and the splitting ratio is 1:1:1:1. The equal division of optical power is realized, and the harmonic oscillator designed meets the demand of proper acceleration detection of three-component acceleration seismic geophone.

Key words: fiber and waveguide optics; harmonic oscillator; M-Z interferometer; photoelastic effect; three-component

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MOEMS 三分量加速度地震检波器简谐振子设计

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摘 要： 采用惯性力与简谐振子相垂直及差动检测技术的方法，设计基于光弹效应的三分量加速度地震检波器简谐振子。对于简谐振子中的双 M-Z 干涉仪而言，光功率的均分和光的单模传输是实现正确检测加速度的基础。介绍了 M-Z 干涉仪的结构和工作原理。用波导光学模拟软件 OptiBPM v9.0 对双 M-Z 干涉仪光场传输进行仿真，得到双 M-Z 干涉仪的光场传输图。从仿真结果可以看出，从激光器 LD 发出的光经过双 M-Z 干涉仪后， 1/4 分支波导的光场峰值都达到了 0.52 ，分光比达到了 1:1:1:1 ，实现了光功率的均分，设计的简谐振子满足三分量加速度地震检波器实现正确检测加速度的要求。

关键词： 纤维与波导光学；简谐振子； M-Z 干涉仪；光弹效应；三分量

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1 Introduction

The appearance of three-component acceleration seismic geophone is to replace the conventional geophone that can only accept the single longitudinal wave. It accepts three-component seismic information in the mean time and carries out high resolution and high signal to noise ratio multi-wave seismic exploration[1]. At present, the structures of three-component acceleration seismic geophones existing and under study at home and abroad can be divided into two categories: XYZ-coordinate orthogonal three-component geophone and 54.74° symmetric orthogonal three-component geophone. The traditional vertical geophone is used as core body by the above two types of geophones, which will cause serious crosstalk between the poles, too large volume, construction difficulties and other shortcomings when they are used for three-component exploration.

Because the cross-axis sensitivity of the majority of three-component acceleration seismic geophones used to seismic exploration is high, measurement accuracy of each axial acceleration is reduced. And they can't carry out accurate exploration under complex geologic environment due to their poor performance stability and inadequate width[2,3]. At the same time, their application ranges are limited because of their large volume and vulnerable to electromagtic interference. To solve the above problems, the main research direction is to reduce the coupling interference between each component, increase the integration degree of geophone, lower distortion of each component's signal based on maintaining stable performance, realize high sensitivity output in a wide seismic frequency range and obtain smooth amplitude corresponding curve.

In order to form the active waveguide devices of the optical sensing and optical information processing system structural components, the method of inputting signals from the exterior should be adopted to modulate the waveguide light transmitting in the film. Modulations of the waveguide light can be divided into amplitude modulation, phase modulation, polarization wave plane rotation, moving optical frequency and optical path switching. The light modulation method of dual M-Z interferometer designed is phase modulation. Changes in external acceleration are detected by detecting changes in optical phase in the dual M-Z interferometer.

2 Design of harmonic oscillator of MOEMS three-component acceleration seismic geophone

Micro-opto-electro-mechanical system(MOEMS) is the integration of integrated optics and micro-electro-mechanical system(MEMS) technology. The mass produced by MEMS technology and the optical waveguide produced by lithography technology are the major components of seismic geophone. The crystal deforms under the influence of the outside world, causing refractive index changes in the crystal, and this phenomenon is known as the photoelastic effect of crystal. Compared with other types of acceleration seismic geophones, the acceleration seismic geophone based on the photoelastic effect has the following advantages[3]: wide frequency band, wide dynamic range, simple and compact structure, and good overload stability.

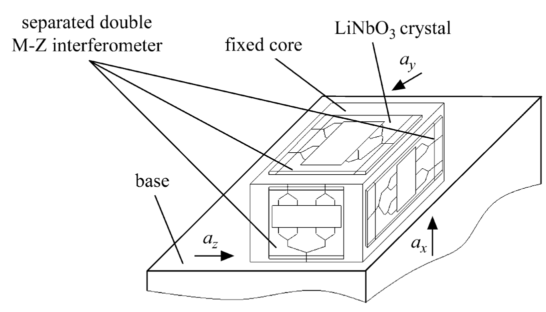


Fig.1 Schematic diagram of the structure of MOEMS three-component acceleration seismic geophone

The harmonic oscillator of three-component acceleration seismic geophone consists of three separate dual M-Z interferometers produced on three mutually perpendicular surfaces of a Z-cut Y-propagation $LiNbO_3$

crystal. Three-component harmonic oscillator is the sensitive element, which is composed of three M-Z interferometer chips arranged along X,Y,Z three directions, and its structure is shown in Fig.1. Three polarized light with mutually perpendicular vibration directions respectively inputs along the X,Y,Z directions. Thus, $LiNbO_3$ crystal is both the sensitive unit and the sensitivity unit, which reduces the volume of the whole harmonic oscillator[4~6].

Light emitted from laser respectively enters three M-Z interferometer chips in three beams. When the base is affected by the acceleration in any direction, due to the photoelastic effect, three M-Z interferometer chips respectively sense components (a_x, a_y, a_z) in X, Y, Z three directions of acceleration a. Changes in components of the acceleration are converted into optical phase changes. Then they are transmitted through the optical fiber to the outside processor for differential treatment. At last, the relationship between the voltage and acceleration to be detected is gotten after treatment to complete acceleration detection[6].

Let the acceleration a_k act on the mass associated with the waveguide. Then acceleration can be decomposed into a_x, a_y, a_z in three directions along the coordinate axis. Because the volume of waveguide is very small compared to the mass, it can be regarded as equivalent to a_x, a_y, a_z three-component accelerations directly and evenly acting on the three cross sections of the waveguides, i.e., A_1, A_2, A_3 planes. Given the stresses of the three planes be $\sigma_1, \sigma_2, \sigma_3$ respectively, the areas of the three planes are S_1, S_2, S_3 respectively, and the quality of mass is m. Then[6]

$$\sigma_1 = \frac{m(a_x + g)}{2S_1}, \quad \sigma_2 = \frac{ma_y}{2S_2}, \quad \sigma_3 = \frac{ma_z}{2S_3}. \tag{1}$$

3 M-Z interferometer

3.1 Structure of M-Z interferometer

The structure of M-Z interferometer is shown in Fig.2[7]. G_1 and G_2 are two parallel plane glass plates with semi-reflecting surface A_1 and A_2 respectively. M_1 and M_2 are two plane mirrors. Four reflecting surfaces are usually organized into nearly parallel, and their centers are respectively located on the four angles of a parallelogram. The typical size of the long side of the parallelogram is 1∼2 m. The light source S is placed on the focus of the lens L_1. Suppose that S is a monochromatic point light source. After the emitted optical wave is collimated by L_1, it inputs on the semi-reflective surface A_1. The wave surfaces of the plane optical wave which are projected and reflected by A_1, and reflected by M_1 and M_2 are respectively W_1 and W_2. Then under normal circumstances, the virtual image W_1' that W_1 is relative to A_2 and W_2 are inclined to each other, and forms an air gap. Parallel equidistant straight line interference fringes will be formed on W_2 (imaginary intersection at P point of W_2 of two emitting light is drawn in Fig.2). The direction of stripes is parallel to the edge of wedge of air wedge formed by W_2 and W_1'. When W_2 deforms because of some physical reasons(such as making W_2 pass through the air studied), the interference patterns are no longer parallel equidistant lines. Then the changes in response physical quantities can be measured from the changes in interfere images(for example, the refractive index or density of the studied area)[8].

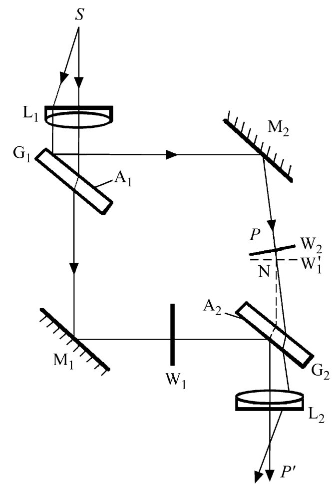


Fig.2 Schematic diagram of structure of M-Z interferometer

3.2 Working principle of M-Z interferometer

M-Z interferometer modulates the intensity of interference light through the phase differences between the signal arm and reference arm, and its structure is shown in Fig.3[6,9,10].

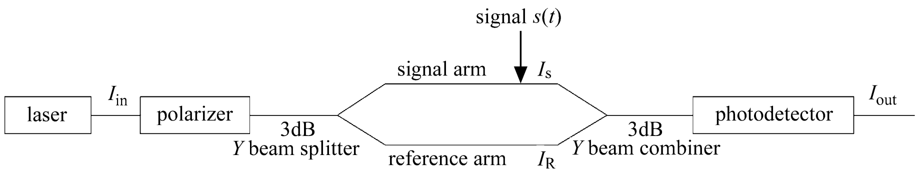


Fig.3 Working principal diagram of M-Z interferometer

Light emitted from the laser goes into 3 dB Y-branch beam splitter after it is polarized by the polarizer, and light is divided equally into the signal arm and reference arm. Let the initial phase of the incident light from laser be φ_0, then

$$E_{\mathrm{m}} = A\exp(\mathrm{i}\omega t + \varphi_0). \tag{2}$$

Let the phase change of signal light I_{s} caused by signal $s(t)$ be φ_1, then

$$E_{\mathrm{s}} = \frac{A}{\sqrt{2}}\exp(\mathrm{i}\omega t + \varphi_1),\ E_{\mathrm{R}} = \frac{A}{\sqrt{2}}\exp(\mathrm{i}\omega t + \varphi_0). \tag{3}$$

Then the output light intensity is

$$I_{\mathrm{out}} = \left|\frac{A}{\sqrt{2}}\exp(\mathrm{i}\omega t + \varphi_1) + \frac{A}{\sqrt{2}}\exp(\mathrm{i}\omega t + \varphi_0)\right|^2 = A^2\cos^2\left(\frac{\varphi_1 - \varphi_0}{2}\right) = I_{\mathrm{in}}\cos^2\left(\frac{\Delta\varphi}{2}\right). \tag{4}$$

So the light intensity of emitting interference light is modulated by the signal $s(t)$.

4 Simulation of optical field transmission in dual M-Z interferometer

$LiNbO_3$ crystal produced by Ping Guang Group in Jiaozuo is used as the optical waveguide material of harmonic oscillator in three-component acceleration seismic geophone. Proton exchange technology is utilized to produce the strip optical waveguide in the $LiNbO_3$ substrate. Finite difference beam propagation method (FD-BPM) is adopted to set the parameters of the dual M-Z interferometer, as shown in Table 1.

Table 1 Parameters table of dual M-Z interferometer

Type of waveguide	S-Bend Sine
Waveguide width (μm)	6.0
Waveguide depth (μm)	2.0
Angle of 1/2 branch	1.15°
Angle of 1/4 branch	1.55°
Refractive index of waveguide core (μm)	1.50
Refractive index of waveguide cladding (μm)	1.49
Wavelength of input light (μm)	1.55
Mode-field distribution (μm)	modal
Polarization state (μm)	TE
Operator	Pade (1,1)
Step length	1.55
Boundary condition	TBC
Calculation method	FD-BPM

Waveguide optics simulation software OptiBPM v9.0 is adopted to carry out two-dimensional simulation of optical field transmission in the dual M-Z interferometer to get the optical field simulation graph, which is shown in Fig.4. It can be seen from Fig.4 that the optical field peak values of 1/4 branch waveguides all reach 0.52, and the splitting ratio is 1:1:1:1. The light intensity of light emitted from laser LD is equally divided into 1/4 after splitting by the two branches and entering into the four branches.

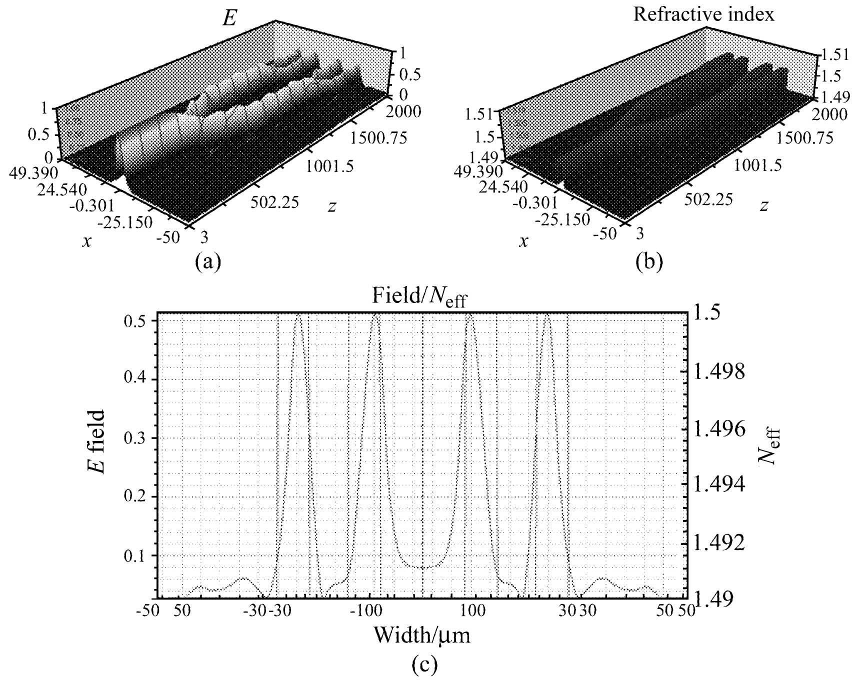
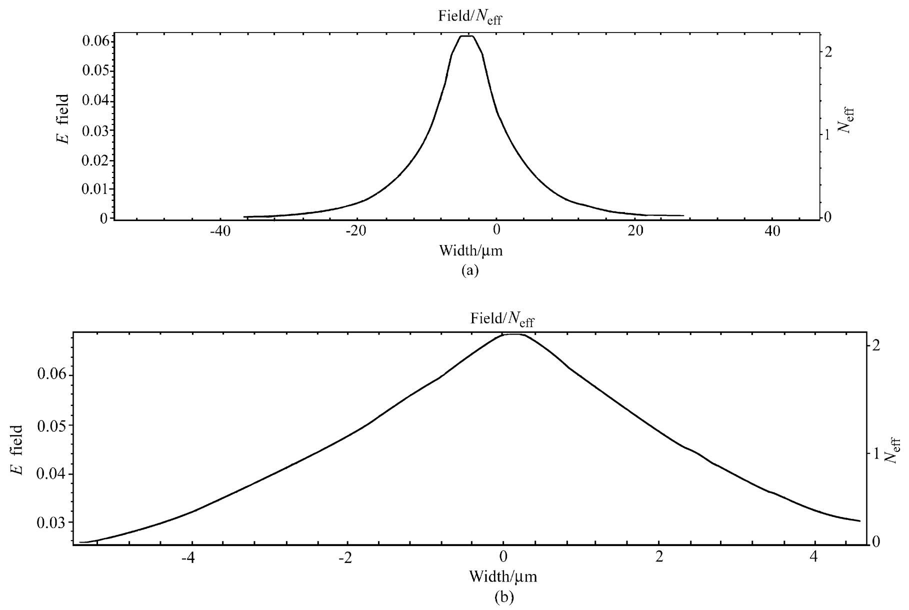


Fig.4 2D isotropic simulation graph (a) Optical field, (b) Refractive index, (c) Cut view

Three-dimensional simulation of optical field transmission in the dual M-Z interferometer is carried out by OptiBPM v9.0, as shown in Fig.5.



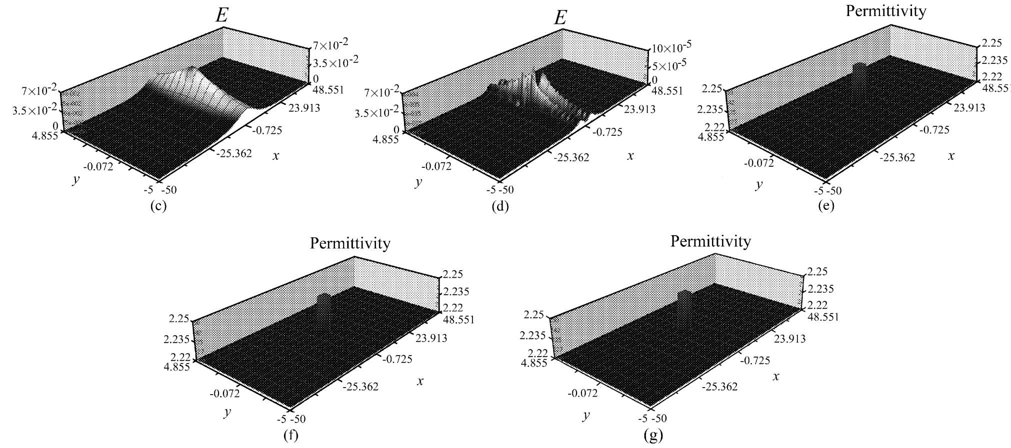


Fig.5　3D anisotropic simulation graph (a) X-Z Ex vs eps XX, (b) Y-Z Ex vs eps XX, (c) Ex-XY, (d) Ey-XY, (e) eps XX-XY, (f) eps YY-XY, (g) eps ZZ-XY

5 Conclusion

MOEMS three-component acceleration seismic geophone based on photoelastic effect converts optical phase changes into light intensity changes, and the detection of acceleration is achieved by detecting the light intensity in the dual M-Z interferometer. The method of FD-BPM is adopted to set the structure parameters of dual M-Z interferometer in the harmonic oscillator and the simulation is carried out. The simulation result shows that the light intensity is equally divided by 1/4. It achieves a relatively satisfactory result. The harmonic oscillator designed meets the system requirement of MOEMS three-component acceleration seismic geophone.

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