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Novel optical accelerometer based on Fresnel diffractive micro lens

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ABSTRACT

This paper presents an innovative optical accelerometer based on an integration of a Fresnel diffractive micro lens with a reflecting membrane. The reflecting membrane mounted on an inertial mass is placed parallel behind the diffractive micro lens. The light intensity at the conjugate position of an applied monochromatic point source is highly sensitive to the displacement of the membrane. The working principle is specifically discussed. In addition, this sensor makes use of a quad beam structure to allow the flat displacement of the inertial mass. Mechanical simulations using finite element method show the designed structure has a wide range of operation. A prototype accelerometer has been successfully developed. Dynamic tests indicate that the accelerometer has promising performance. This accelerometer can be fabricated using microelectromechanical systems (MEMS) technology, with relatively few process steps, so it is suitable for batch production. By optimizing structural designs, it can be a competitive candidate for a number of application fields ranging from vibration monitoring to inertial navigation.

1. Introduction

Accelerometers have been widely used for monitoring vibration and are conventionally based on capacitive or piezoelectric principles [1,2]. Such conventional sensors have limited applications in radioactive, harsh, or highly explosive environments, because they are susceptible to electromagnetic fields. Optical accelerometers are suitable to be placed where strong electromagnetic fields are applied, because of their immunity to electromagnetic interference (EMI).

In previous reported work, the state-of-the-art optical accelerometers can be classified using intensity-based, photoelastic, interferometric and wavelength-encoded modulation. The principle of intensity-based sensors is to modify the power of a lightwave as a function of the magnitude to be measured [3–6]. They are easy to setup, reliable and low cost, but the main drawback is the sensitivity to external disturbance. Photoelastic sensors are based on the photoelastic effect that many noncrystalline transparent materials which are ordinarily optically isotropic become anisotropic and display optical characteristics similar to crystals when they are stressed [7]. Usually, this type of sensor is not easy to setup as temperature dependence and stress distribution easily influence its measurement accuracy. Wavelength-encoded sensors using fiber Bragg gratings (FBG) [8,9], have the advantage of not being directly affected by extraneous optical power changes. Nevertheless, they require a complex signal demodulation system. Interferometric sensors based on Mach–Zehnder, Michelson, and Fabry–Perot configurations provide the highest sensitivity in vibration sensing [10–14]. Among them the most attractive is the Fabry–Perot sensors, because of their easy implementation, low size and robustness. Nieva et al. [15] presented a Fabry–Perot vibration sensor where the cavity is formed between a substrate and a cantilever beam. The relative deflection of the cantilever beam with respect to the substrate due to the external vibration changes the received light intensity. This design shows promising results, but the main disadvantage is that without lenses or a collimated source, only a small fraction of the source power will reach the detector.

Taking into account the advantages and drawbacks of these configurations, this paper presents a new optical accelerometer that mainly consists of a Fresnel diffractive micro lens and a reflecting membrane [16]. The sensing principle is described in detail. Moreover, a quad beam structure composed by an inertial mass sustained by four beams is analyzed and implemented to permit the flat displacement of the mass [17]. Finally, vibration test of a fabricated prototype accelerometer is carried out to prove the sensing principle.

2. Sensing principle

2.1. Optical sensing

The key element of the accelerometer consists of a Fresnel diffractive micro lens and a reflecting membrane as shown in Fig. 1. The Fresnel diffractive micro lens is made of a metallic pattern on a glass substrate which consists of a set of alternating opaque

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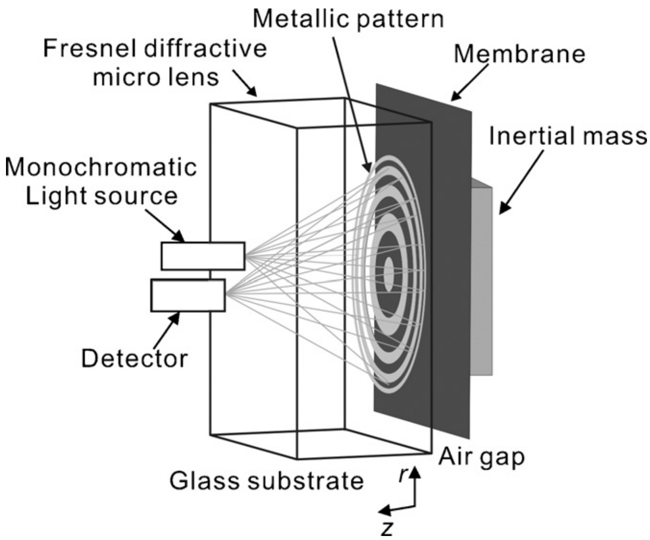

Fig. 1. Schematic of the proposed accelerometer.

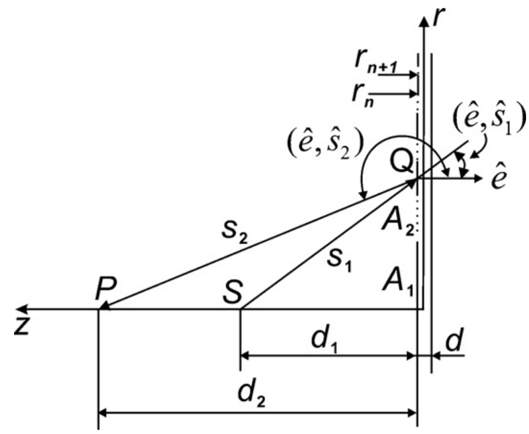

Fig. 2. Simplified geometry for calculation of the interferometric light intensity in cylindrical coordinates where S and P denote the point source and the detector, respectively. $s_1 = |SQ|$ and $s_2 = |QP|$. A_1 and A_2 are the reflection coefficient of the opaque and transparent zones, respectively.

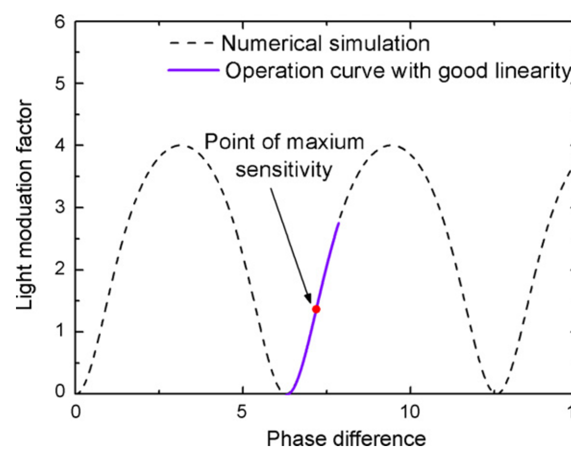

Fig. 3. Theoretical curve of M.

and transparent rings. The reflecting membrane is placed parallel behind the diffractive lens. When a monochromatic point source is applied in front of the diffractive lens, the total back-reflected interferometric light is highly sensitive to the position of the membrane. The theoretical analysis of the optical sensing principle is discussed as follows.

For calculation simplicity, the on-axis point source and detector arrangement is used shown in Fig. 2 where the point source S and the detector P are both assumed to be placed on the central axis of the diffractive lens. d_1 and d_2 are distances of S and P from the diffractive lens, respectively. Assuming that the complex amplitude of the light source is $U(S)$, the total light disturbance $U(P)$ at the detector is given by [18]

$$U(P) = -\frac{i}{2\lambda}\iint_{\sigma} U(S)A(r,d) \times \frac{\exp(i(2\pi/\lambda)(s_1+s_2))}{s_1 s_2}[\cos(\hat{e},\hat{s}_1) - \cos(\hat{e},\hat{s}_2)]d\sigma \approx -\frac{2\pi i}{d_1 d_2 \lambda}\exp\left(i\frac{2\pi}{\lambda}(d_1+d_2)\right)U(S) \times \int_0^R A(r,d)\exp\left(i\frac{\pi r^2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)\right) rdr \quad (1)$$

where $\hat{e}$ denotes the unit vector normal to the diffractive lens, $\hat{s}_1$ and $\hat{s}_2$ denote the unit vector of SQ and QP, respectively, $d\sigma$ is the area element at Q, λ is the wavelength of the light source, R is radius of the border of the diffractive lens, $A(r, d)$ is the complex aperture function dependent on the radii of the Fresnel zones and the air gap thickness d between the diffractive lens and the reflecting membrane, and the Fresnel approximation $s_1 \approx d_1 + r^2/2d_1$, $s_2 \approx d_2 + r^2/2d_2$, and $\cos(\hat{e},\hat{s}_1) - \cos(\hat{e},\hat{s}_2)/2 \approx 1$ is used to reach the last expression. The total disturbance at P is obtained by summing all the Fresnel zones (as assumed to be $2N$)

$$U(P) = -\frac{2\pi i}{d_1 d_2 \lambda}\exp\left(i\frac{2\pi}{\lambda}(d_1+d_2)\right)U(S)\sum_{n=0}^{N-1}\left[A_1\int_{r_{2n}}^{r_{2n+1}}\exp\left(i\frac{\pi r^2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)\right)rdr + A_2(d)\int_{r_{2n+1}}^{r_{2n+2}}\exp\left(i\frac{\pi r^2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)\right)rdr\right] \quad (2)$$

where r_n is the radius of the nth Fresnel zone border given by

$$\sqrt{r_n^2 + d_0^2} - d_0 = \frac{n\lambda}{2} \quad (3)$$

d_0 is the primary focal length of the diffractive lens [19]. For the Fresnel approximation, $r_n \approx \sqrt{n\lambda d_0}$. A_1 is the reflection coefficient of the metal coating on the substrate while $A_2(d)$ is the reflection coefficient of the substrate/air gap/membrane system [20]. If d_1 and d_2 satisfy the conjugate relation

$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{d_0} \quad (4)$$

Eq. (2) then becomes

$$U(P) = -N\frac{2d_0}{d_1 d_2}\exp\left(i\frac{2\pi}{\lambda}(d_1+d_2)\right)U(S)\left(1 + \frac{\rho - \exp(i\delta)}{1 - \rho\exp(i\delta)}\right) \quad (5)$$

where ρ is the reflection coefficient of the glass–air interface and $\delta = (4\pi/\lambda)d$ is the phase difference induced by the air gap. This expression is obtained by assuming that both the metal and membrane are perfectly reflecting. The light intensity at P then can be written by

$$I = I_0 CM \quad (6)$$