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Sensitivity of transverse shift inside a double-grating Talbot interferometer

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ABSTRACT

We study the Talbot interferometry with an additional mask grating located behind the diffraction grating. The self-imaging so-called, Talbot carpet, can be very sensitive to an external perturbation. We here show the measurement and the optimization of sensitivity of transverse shift of one of the two gratings inside Talbot interferometer as a function of grating constant and opening fraction of the grating itself. The results show that the sensitivity of the transverse shift is increased dramatically at smaller grating constants while no effect for different opening fractions. A sensor of our simple scheme can be suggested as an excellent inertial sensing applications such as displacement sensor, spectrometer, and vibration sensor.

1. Introduction

Inspired by a versatile utility of the optical near-field effect, namely Talbot effect, which was discovered since 1836 [1], several studies and applications have been carried on. When a diffraction grating is illuminated by a collimated light will generate a periodic interference pattern which has the periodicity similar to the grating itself if the observed screen located at a certain distance behind the grating so called Talbot length (L_T) [2–4].

The Talbot effect has been used broadly in many fields. In light optics, the Talbot effect was used for making surface profiles [5,6], for measuring temperature profiles [7,8], for displacement sensors [9], and also high contrast X-ray imaging [10,11]. In quantum optics, the Talbot effect has been used to study quantum mechanics, i.e. superposition principle with electron [12], atom in space domain [13], atom in time domain [14], as well as molecules [15,16].

Here, we study the transverse shift of one of the two gratings in a double-grating Talbot interferometer. The transverse shift of the grating over an interferogram makes the modulated intensity behind the grating and is very sensitive to an external perturbation. We also have demonstrated our idea with mechanical gratings act as an amplitude grating. The sensitivity of the setup will be optimized presently with the grating parameters, i.e. grating constant or period (d), and opening fraction (f). The sensitivity in the scale of nanometer will be obtained in our scheme. The Talbot effect with a double-grating scheme will be recommended as an inertial sensing application in the impressive range, even though it is simple, and low-cost.

2. Theory and method

Here, we explain briefly the Talbot effect. The detail of theory is shown elsewhere [4]. Assuming a plane wave with the wave number k propagating along z axis falls onto a diffraction grating at $z = 0$ (Fig. 1). The grating has the periodic modulation in the x direction so the incident wave can be represented by $\psi = \exp(ik_\theta x)$, where $k_\theta = k\sin\theta$ is

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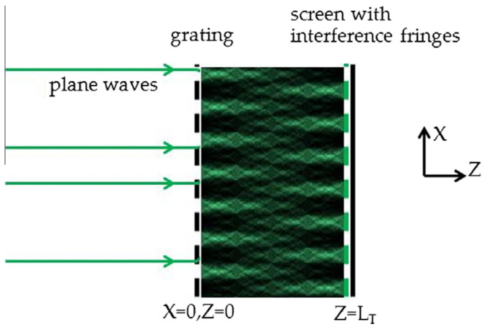

Fig. 1. The Talbot effect with a diffraction grating. The fine structure is an optical carpet which illustrates the understanding of interference patterns in the Talbot interferometry.

the projection of the incident wave vector onto the x-axis. While the time dependence in the wave function can be omitted in case of static grating. Behind the grating at $z = 0$ the wave will be transformed by the grating to be,

$$\psi(x, z = +0) = T(x)\exp\{ik_\theta x\}. \tag{1}$$

Here, the grating transmission function $T(x)$ is given by

$$T(x) = \sum_n A_n \exp\{i2\pi nx/d\}, \tag{2}$$

where d is the grating period and A_n represents the components of the Fourier decomposition of the periodic for the grating. For grating with an opening fraction f (the ratio between the slit width and the grating period) the Fourier components are given by

$$A_n = \frac{\sin(n\pi f)}{n\pi}, \tag{3}$$

where $n = 0, \pm1, \pm2, \ldots$. When the wave propagates for a distance z behind the grating it acquires an additional phase $\exp\{i\sqrt{k^2 - k_\perp^2}z\}$, where $k_\perp = k_\theta + nk_d$ is the wave vector parallel to the x-axis. With the paraxial approximation ($k \gg k_\perp$) and $\theta = 0$ for the Talbot effect, the wave function is reduced to

$$\psi(x, z) = \sum_n A_n \exp\left\{ink_d x - \frac{in^2\pi z}{L_T}\right\}, \tag{4}$$

where $k_d = 2\pi/d$ and $L_T = d^2/\lambda$ is the Talbot length. An optical carpet according to the Talbot effect can be simulated with Eq. (4) (Fig. 2). In order to study the transverse shift over the interferogram, we replace the screen shown in Fig. 1 by a second grating as a mask grating and a photodiode for intensity detection behind the mask. Therefore, the corresponding intensity $I(x, z) = \psi^*(x, z)\psi(x, z)$ with the mask can be expressed as

$$I(x, z) = \sum_{n,m} M(x - \delta)A_n A_m \times \exp\left\{i(n - m)k_d x - i\frac{(n^2 - m^2)\pi z}{L_T}\right\}. \tag{5}$$

The function $M(x)$ is the step function corresponding to the mask,

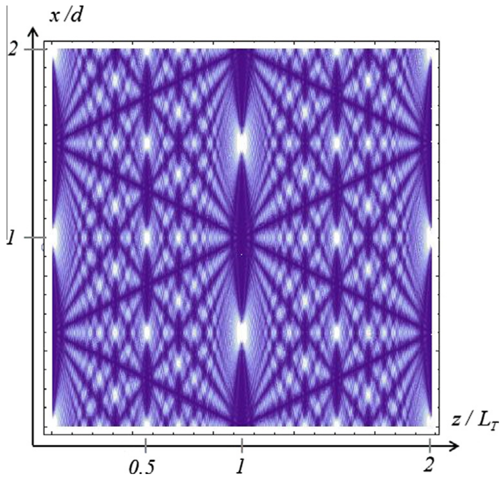

Fig. 2. Theoretical simulation of intensity of optical carpet according to Eq. (4): the grating period is 50 μm, the opening fraction is 0.1.

$$M(x) = \begin{cases} 1 & ; jd - \frac{fd}{2} < x < jd + \frac{fd}{2} \\ 0 & ; \text{otherwise} \end{cases}, \tag{6}$$

where $j = 0, \pm1, \pm2, \ldots$ and δ is the transverse shift between the two gratings.

3. Experiment

We demonstrate our idea with the 5 mW green diode laser ($\lambda = 532$ nm) as a coherent source which is expanded by an optical telescope to a diameter of 20 mm, and then illuminated a diffraction grating and downstream positioned a second grating which is similar to the first one acting as a mask grating. The telescope is used to expand the laser beam in order to cover the whole grating which makes a clean shape of the Talbot image [17]. The two-grating system (chromium on glass, Edmund Optics Inc., $d = 200$ μm, $f = 0.5$) is separated with a distance of one Talbot length. The mask grating is placed above the first translation stage (MTS50/M-Z8E, resolution 1.6 μm, Thorlabs) and the second translation stage (MTS25/M-Z8E, Thorlabs) in order to move longitudinally in the z-axis, and transversely in the x-axis, respectively (Fig. 3). Behind the mask grating we place a beamsplitter to split the light into two detections, i.e. a CCD and a photodiode. The CCD camera (DCU223C, Thorlabs) is first used to set the distance between the two gratings by looking at the image behind these two gratings. The rotation grating holders (LCRM2/M, Thorlabs) are helped to align both gratings parallel to each other. The intensity behind the mask grating is recorded with the photodiode (PM120D, resolution 1 nW, Thorlabs) and the data are sent through an interfacing card (NI USB6009) to the computer. It had been shown that a two-gratings configuration can cancel out the Talbot effect; therefore the intensity distribution behind the mask is nearly independent of the distance [18]. The mask grating is scanned transversely with a step of 5 μm for one grating period of 200 μm and the intensity behind this mask grating is measured with each step.