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Wide dynamic range wavefront sensor using sub-wavelength grating array

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ABSTRACT

We propose a new zonal wavefront sensor with a very wide dynamic range. The proposed sensor uses a sub-wavelength grating array to subdivide the input wavefront and produce transmitted light spots on CCD. The wavefront tilts are calculated from the transmissions of a sub-wavelength grating array. The dynamic range and resolution of the proposed sensor are respectively decided by the grating parameters and the sub-unit size of the array. So these two performances of the sensor are independent of one another, which enables the realization of wide dynamic range and high resolution simultaneously. We introduce the principle of the sensor by both Rigorous Coupled Wave Analysis and Finite-Difference Time-Domain methods. A simulation is designed to validate our proposed method, and the measurement errors are analyzed. The sensor performs good sensitivity for wide incident angles, which is particularly suitable for spherical input wavefront.

1. Introduction

Wavefront sensing has many applications in industry, astronomy, physic and etc. It provides the means to measure the shape of an optical wavefront. There are many highly accurate wavefront sensing technologies, such as Shack–Hartmann wavefront sensor [1] (SHS), lateral shearing interferometer [2], point diffraction interferometer [3], etc. Among these techniques mentioned above, SHS has been widely used for its wide dynamic range, real-time measurement, and the relatively simple configuration [1,4]. It uses a lenslet array to subdivide the input wavefront and produces a set of foci, then gives signals by calculating the centroid positions of the foci. The sub-aperture size of the lenslet decides the dynamic range (the maximum measurable wavefront tilt angle) and resolution with a trade-off between them, which makes it difficult to simultaneously improve both of them [5]. To solve this problem, many ways have been invented, such as changing the structure of SHS [6–8] or designing special algorithm to extend the dynamic range [5,9], etc. However, this limitation of the performance improvement attributed to the trade-off will still exist, as long as the centroid positions of the foci are utilized as signals to detect the wavefront tilt.

On the other hand, the sub-wavelength structures have been used in many field as sensors [10], light filters [11] polarizing beam splitters [12], etc. For example, the grating can also be designed as a beam selector, which the reflection of the grating strongly depends on the incident angle [13]. The polarizing beam splitters in Ref. [12] is based on the form birefringence of a sub-wavelength grating in the quasi-static domain. It can achieve high extinction ratio with specific incident angle [12]. Surface Plasmon Resonance sensors can measure changes in the refractive index occurring at the surface of a metal film supporting a surface plasmon. The incident angle is an important parameter and sometimes need to be scanned during measurements [10]. The above examples show a common characteristic that sub-wavelength gratings can have a strong angular sensitivity, which is also the sensitivity of the wavefront tilt for plane wave incident. This provides a possibility to sense the wavefront tilt by the sub-wavelength grating.

In this paper we present a new zonal wavefront sensor, namely Sub-wavelength Grating Array wavefront Sensor (SGAS). The proposed sensor uses a sub-wavelength grating array to subdivide the input wavefront and produce transmitted light spots on CCD. It uses the wavefront subdividing method as that in SHS, but SGAS utilizes the light intensity instead of the centroid position of the spot to give signals. By measuring the transmissions of a sub-wavelength grating array, SGAS can provide the wavefront tilts of every sub-unit respectively. The dynamic range and resolution of SGAS are independent of one another, which enables the realization of wide dynamic range and high resolution simultaneously. The underlying idea of the sensor is based on that the transmissions of the sub-wavelength gratings depend on the input wavefront tilts for circular polarized input light. We introduce the

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principle of the proposed sensor. A simulation is designed for proving the performance and the measure errors during the simulation are analyzed. Finally, we discuss the characteristics and possible applications.

2. Transmission variation

Firstly, let us assume that a plane wave is incident on a sub-wavelength grating as illustrated in Fig. 1. For plane wave, the incident direction is vertical to the wavefront. So we can get the wavefront tilts by measuring the incident angles of the input plane wave. According to the Grating Equation [14], when $d < n\lambda/2$ (d is the grating period, n is the substrate material index, λ is the input light wavelength), there is only 0th order diffraction in the transmitted light. Under the above conditions, the transmission of the 0th order diffraction of the grating does not only depend on the grating parameters, such as the material, thickness of the film, the period, duty cycle of the grating, but also the light source conditions, such as the incident angles and polarization. This phenomenon provides an approach for relating the transmission of the grating to the incident beam angle by appropriately choosing the grating parameters and input polarization.

For sub-wavelength gratings, the transmissions with transverse electric (TE) and transverse magnetic (TM) polarization are quite different, which makes the transmission sensitive to the light polarization [12]. But we want that the transmission only has a sensitivity to the incident angle. So we consider circular polarized, which has both of TE and TM polarizations included, as the input light polarization. (The situations of natural light and linearly polarized light incident will be discussed in Section 5.).

In order to utilize the grating for sensing technique, the variation of the transmission of the grating need to be continuous and regular in certain range. When the period of the grating $\Lambda > 250$ nm, the transmission may become too sensitive to the incident angle, because the transmission is easy to be effected by Surface Plasmon Resonance phenomenon or un-0th order diffraction. So we choose grating period $\Lambda < 250$ nm when $\lambda = 632.8$ nm. For the convenience of manufacturing, the aspect ratio should be less than 2 and grating fill factor is chosen between (0.4–0.6). In the choice of film materials, we choose the materials which have been experimentally test and show good angular sensitivity [17,18]. For example, a silver nanowire grating with the properties of wide-incident-angle polarization and color filtering is presented in Refs. [18]. According to the above, we choose many sets of probable parameters to calculate their transmissions. After comparing the numerical calculating results, we find that, with some sets of parameters of the sub-wavelength grating, the variation of the transmission of the grating can be continuous and regular (Fig. 2). SGAS is based on this phenomenon. In order to increase the reliability, both of Rigorous Coupled Wave Analysis (RCWA) and Finite-Difference Time-Domain method (FDTD) are applied for analysis. The parameters which can realize the above phenomenon are not unique. The examples of the useful parameters for calculation are listed in Table 1.

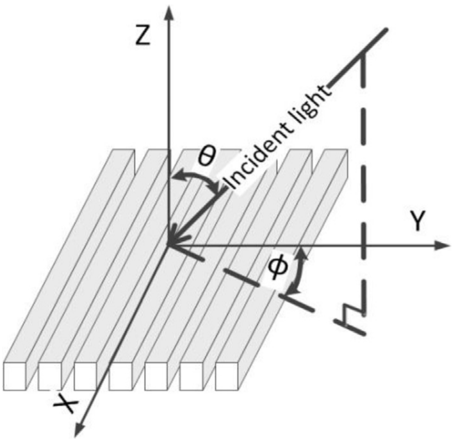

Fig. 1. θ is the angle with respect to the z-axis. φ is the angle rotated about the z-axis in a right-hand context. The beam direction is vertical to the wavefront plane.

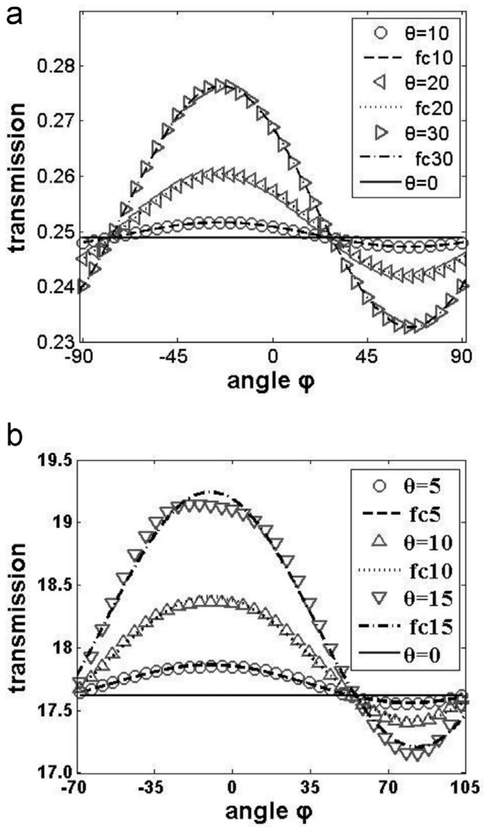

Fig. 2. (a) Transmission of the grating depends on the incident light angle. The calculation results come from RCWA. Lines (dashed curve and solid curve) are fit curves to the corresponding data. (b) Transmission of the grating depends on the incident light angle. The calculation results come from FDTD. Lines (dashed curve and solid curve) are fit curves to the corresponding data.

Fig. 2a and b respectively shows the calculation results and the well fitted curve from RCWA and FDTD. We can see that when θ is invariable and φ changes continuously, the transmission would change periodically. All the fit curves can be expressed as a sine function:

$$T = a_0 + a_1 \sin(2\varphi + a_2) \tag{1}$$

where T is the transmission of the grating. a_0 is the mean value of the corresponding curve. a_1 is the amplitude of the sinusoid fit curve. Fig. 3 shows the responses of a_1 (when a_0 has been normalized to 10,000) to the angle θ. Both results from RCWA

Table 1
The useful parameters for calculation.

Input light source	Wavelength Polarization	632.8 nm Circular
Grating	Film material Film thickness Period Grating fill factor (Ag/whole) Substrate material	Silver (Ag) 70 nm 200 nm 0.6 Glass (SiO_2)