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All-dielectric metasurface-based roll-angle sensor

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ABSTRACT

We propose and demonstrate an all-dielectric metasurface-based roll-angle sensor, in which the roll angle is translated into the change of polarization state of the probe light. A circular polarization beam splitter is designed and fabricated to split the probe light into right-circularly polarized and left-circularly polarized light beams, whose intensities are then collected to estimate the roll angle. The experimental results show that the developed roll-angle sensor has a measurement resolution of 0.1° and a measurement range of 30°. The all-dielectric metasurface-based design promises to substantially reduce the size of the roll-angle sensor and is expected to gain wide applications especially on space-limited occasions.

1. Introduction

Roll angle, as one of the six degrees of freedom (forward/backward, up/down, left/right, roll, pitch, yaw), defines a rotation around the longitudinal axis. Combined with other degrees of freedom, it can completely determine the location of an object in a three-dimensional space. As such, roll angle can, for example, directly impact the performances of the general robot [1] and the product quality of computer-aided manufacturing [2]. In addition, it also plays a crucial role in various applications, such as space docking [3] and Abbe-error correcting [4]. Therefore, accurate, reliable, remote and compact measurement of roll angle is of significant interest. Among the various methods, optical methods have currently become a major method for roll-angle measurement due to the advantages of non-contact, high-sensitivity and flexibility of design. Although many optical devices have been reported, it remains challenging to measure roll angle in contrast to the measurement of other two angular displacements (yaw and pitch), since the roll-angular displacement is perpendicular to the optical axis of the probe beam and is usually difficult to be sensed by the probe beam [5,6]. According to the specific response signals, at present, the roll-angle measurement can be realized by translating the change of roll angle into either phase difference of two probe beams (interference technique [6–9]), or position shift (geometry technique [10–12]) or polarization change (polarization technique [13–15]) of a probe beam. Among these techniques, the polarization technique can provide a high sensitivity in a relatively large measurement range [13,15], and is, thereby adopted in our development of the roll-angle sensor. It is also noted that current roll-angle sensors based on the above techniques typically consist of bulk optical components, which result in a complicated system with a large size and restrict their use on some space-limited occasions.

In this work, we report the first development of a metasurface-based roll-angle sensor that has a potential ultracompact size. Metasurface is an artificial planar structure that enables control of phase, amplitude, and polarization of light in a sub-wavelength distance [16–19]. Through spatially arranging the scatters with a sub-wavelength center-to-center distance and different structural dimensions, it can realize various optical components possessing the same functions as bulk optical components, such as lens [20,21], polarizer [22,23], deflector [24], waveplate [25,26], and also some exotic phenomena unrealizable with traditional bulk optical components, such as cloaking [27]. In addition, different from a conventional bulk optical component that only possesses a single function, a metasurface-based planar optical component can simultaneously realize multiple distinct functions, which will substantially simplify the integration and miniaturization of optical devices. For example, by realizing functions of polarization

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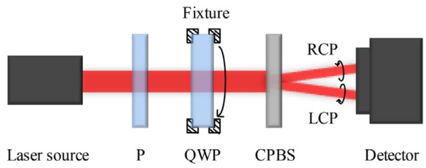

Fig. 1. Optical schematic of the roll-angle sensor, which consists of a laser source, a linear polarizer (P), a quarter-wave plate (QWP) fixed with a rotating component under test, a circular polarization beam splitter (CPBS) and a detector.

selection and beam deflecting with a single metasurface, Pors et al. proposed a polarimeter and experimentally demonstrated the simultaneous determination of the four Stokes parameters [28]. Khorasaninejad et al. only employed a camera and a metalens that incorporates functions of a polarizer, deflector and lens to realize a compact device for multispectral chiral imaging [29]. In these applications, metasurface exhibits its advantages in design flexibility and potential compactness. In recent years, metasurface that completely consists of dielectric materials (all-dielectric metasurface) attracts lots of attention [20,24,25,29,30]. Compared with other metasurfaces comprised of metal and dielectric materials (such as plasmonic metasurface [21–23,26–28]), all-dielectric metasurface makes light manipulation more efficient and integration with other devices accessible [31,32], since it enables simultaneous control of electric and magnetic components of light and is also compatible with existing semiconductor processes. Considering its inherent advantages and ability in polarization control, all-dielectric metasurface promises to realize roll-angle measurement and substantially reduce the size of current roll-angle sensors, especially those based on the polarization technique, and is thereby employed in this work.

The remainder of this paper is organized as follows. In Section 2, we first introduce the employed principle in the roll-angle measurement. Then, we present details in the design of a key component of the proposed roll-angle sensor, namely a circular polarization beam splitter (CPBS) or a circular polarization beam-splitting lens (CPBL). Afterwards, the theoretical performance of the proposed roll-angle sensor, including the measurement range, linearity and sensitivity, is predicted through simulation. Section 3 presents the experimental details, including the fabrication of the key component, the sensor setup, and the sensor calibration, to demonstrate the feasibility and potential of the proposed all-dielectric roll-angle sensor. Some concluding remarks are finally drawn in Section 4.

2. Principle and design

2.1. Operating principle

Fig. 1 shows the schematic diagram of the proposed roll-angle sensor, which is comprised of a laser source, a linear polarizer (P), a quarter-wave plate (QWP), a metasurface-based CPBS and a detector. The light from the laser source first passes through P and then the QWP. Acting as a sensing component, the QWP is fixed with a rotating component under test and translates the rotation into the change of polarization state. The polarized light after the QWP is perpendicularly incident upon the CPBS and then is split into two sub-beams with a left- and right-circular polarization states, respectively. The intensities of the two sub-beams are ultimately collected by the detector.

In the Stokes-Mueller formalism, the Stokes vectors associated with the two sub-beams can be represented by

$$\boldsymbol{S'}_m = \mathbf{M}_{\mathrm{CPBS},m}\mathbf{R}\left(-\theta'\right)\mathbf{M}_{\mathrm{QWP}}\mathbf{R}\left(\theta'\right)\boldsymbol{S}, \tag{1a}$$

$$\mathbf{R}\left(\theta'\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta' & \sin 2\theta' & 0 \\ 0 & -\sin 2\theta' & \cos 2\theta' & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1b}$$

$$\mathbf{M}_{\mathrm{QWP}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & \sin\delta \\ 0 & 0 & -\sin\delta & \cos\delta \end{bmatrix}, \tag{1c}$$

$$\mathbf{M}_{\mathrm{CPBS},m} = \begin{bmatrix} 1 & 0 & 0 & m \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -m & 0 & 0 & -1 \end{bmatrix}, \tag{1d}$$

where m = +1 and –1, which denote the right-circularly polarized (RCP) and left-circularly polarized (LCP) light, respectively; $\boldsymbol{S} = I_0[1, 1, 0, 0]^{\mathrm{T}}$ is the Stokes vector of light passing through P, with the superscript "T" denoting the transpose and I_0 indicating the intensity of light passing through P; $\mathbf{R}(\cdot)$, $\mathbf{M}_{\mathrm{QWP}}$ and $\mathbf{M}_{\mathrm{CPBS}}$ are the Mueller matrices for coordinate rotation, QWP and CPBS, respectively; δ is the retardance of QWP and equals to 90° in theory; $\theta' = \theta + \theta_0$, and θ_0 is the initial angle of the fast axis of QWP with respect to the transmission axis of P and is set to 0° in theoretical analysis, θ is the change of the angle of the fast axis of QWP and also signifies the roll angle of the rotating component under test; and $\boldsymbol{S'}_m$ is the Stokes vector of RCP or LCP light passing through the CPBS. According to Eq. (1), the intensity of RCP or LCP light passing through the CPBS can be obtained as follows

$$I_m = I_0\left(1 + m\sin 2\theta\right), \tag{2}$$

which corresponds to the first element of the Stokes vector $\boldsymbol{S'}_m$. With Eq. (2), we can estimate the roll angle by

$$\hat{\theta} = \frac{1}{2}\arcsin\left(\frac{I_{+1} - I_{-1}}{I_{+1} + I_{-1}}\right), \tag{3}$$

where $\hat{\theta}$ is the estimation of the actual roll angle θ.

Compared with other polarization-based roll-angle sensors [13–15], the unique feature of the proposed roll-angle sensor is the metasurface-based CPBS. As mentioned above, the CPBS could split an incident beam into two circularly polarized beams, while conventional polarization-based roll-angle sensors typically adopt linear polarization beam splitters (LPBSs) that split an incident beam into two linearly polarized beams. More importantly, the metasurface-based design could make the proposed roll-angle sensor much more compact than the conventional polarization-based roll-angle sensors, since the metasurface-based CPBS could be integrated into the detector. It is noted that there also exists the metasurface-based linear polarization beam splitters in the literatures [33,34]; however, we should point out that the metasurface-based CPBS has more merits than the metasurface-based LPBS in terms of both their designs and performances, since the required phase in the metasurface-based CPBS can be accurately realized by simply rotating the direction of the scatters according to the Pancharatnam-Berry phase [35,36].

2.2. CPBL design

As shown in Fig. 1, the proposed roll-angle sensor is comprised of three parts. The first part is an emitter consisting of a laser source and a linear polarizer, which generates linearly polarized incident light. The second part is a modulator consisting of a QWP and a fixture, which couples the rotation of the QWP into the change of the polarization state of emerging light. The third part is an analyzer