A Novel Device for Detecting the Polarization Direction of Linear Polarized Light Using Integrated Subwavelength Gratings and Photodetectors

Erli Chen, *Member, IEEE,* and Stephen Y. Chou, *Senior Member, IEEE*

***Abstract*— A solid-state device that can be used to detect the polarization direction of linear polarized light is proposed. The device consists of six transmission gratings with periods in the subwavelength region of the incident light and six photodetectors integrated separately underneath each grating. A variable, defined through the photocurrent ratios of the grating-photodetector pairs, shows a one-to-one correspondence with the angle between the electric vector of the incident linear polarized light and the orientation of the gratings' fingers, which is therefore used to determine the polarization direction. An angular resolution of 0.2° can be achieved.**

***Index Terms*— Linear polarization, metal grating, photodetector.**

I. Introduction

EVEN though linear-polarized light sources are everywhere, there is no solid-state device with which the polarization direction of the light can be determined conveniently. At present, the most frequently applied method to do this is to insert a polarizer and a photodetector (located behind the polarizer) into the beam under testing. The polarization direction of the light is then determined by rotating the polarizer until an angle, corresponding to a minimum (or maximum) output from the photodetector, is reached. Although simple, this method suffers from a low angular resolution ($>5°$), because the transmittance of a polarizer becomes insensitive to the polarizer's orientation when it is close to the minimum (maximum) transmission angle. In those circumstances that the polarization direction of linear polarized light has to be measured rather accurately, sophisticated instruments such as polarimeters have to be used. However, nearly all today's polarimeters contain rotating components [1], [2], which has greatly restricted their applications.

In this letter, we propose a solid-state electronic device—linear-polarization direction detector (LPDD)—that can detect the electric field (E-field) direction of linear polarized light. Compared to existing instruments, this device has significant advantages. First, the device only consists of micrometer-size transmission gratings and photodetectors; all of them can be integrated on the same chip within a diameter less than 0.1 mm using a process compatible with that of microelectronic devices. Second, no rotating parts and expensive components such as polarizers and retarders are used. Finally, since no rotation involved, the device's operation is simple and fast.

II. Device Design and Performance

To achieve a LPDD, a polarimetric element is essential. Previous studies have been shown that metal gratings have a strong polarization effect if their periods are less than the wavelength of the incident light [3]–[7]. Since gratings are compact, incident-angle insensitive, and, most importantly, easy to be integrated with electronic devices, it is not hard for us to chose them as the needed polarimetric elements.

Gratings were fabricated on 0.1-mm-thick fused-silica substrates using e-beam lithography. The fingers of the gratings were made of 20/30-nm-thick Ti–Au with width-to-spacing ratio close to 1:1. The areas of the gratings were $20 \times 26\ \mu\text{m}^2$. The polarimetry of the gratings was characterized with linear polarized light supplied by a He–Ne laser located behind a Glan–Laser prism polarizer (Newport). Gratings were mounted on a rotation stage with an angular resolution of 1°. A long-working-length objective focused the beam onto the gratings' surface within a diameter of approximately 15 μm. The transmitted light was then collected into a Si photodetector by a similar objective. A lock-in amplifier was used to collect the data. The transmittances of the gratings were measured as a function of the angles between the polarization of the light and the fingers of the gratings. Fig. 1 shows the polarization-dependent transmittances of the gratings with periods of 200, 400, and 600 nm, measured at the wavelength of 0.633 μm. The angle, θ, is defined as 0° when the light is S-polarized (i.e., the electric vector of the light is perpendicular to the gratings' fingers), and ±90° when it is P-polarized (i.e., the electric vector is parallel to the fingers). As shown in the figure, two factors affect the transmittance of a grating—the polarization direction and the gratings' period. For example, the transmittances of the 200- and 400-nm gratings reach their maximum values at 0° and minimum values at ±90°.

Manuscript received January 31, 1997; revised May 13, 1997. This work was supported in part by the National Science Foundation and U.S. Office of Naval Research.

E. Chen was with the Nanostructure Laboratory, Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455 USA. He is now with NRW 110, Seagate Technology, Inc., Bloomington, MN 55435 USA.

S. Y. Chou is with the Nanostructure Laboratory, Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455 USA.

Publisher Item Identifier S 1041-1135(97)06432-X.

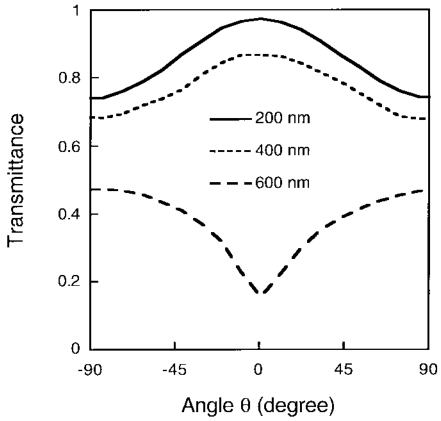

Fig. 1. Measured transmittances of the gratings with 200-, 400-, and 600-nm periods. The angle is defined as 0° when the polarization (E-field) of the light is perpendicular to the grating's fingers, and ±90° when they are parallel.

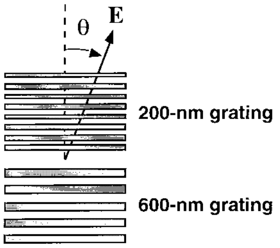

Fig. 2. The configuration of a grating-photodetector pair. The periods of the two gratings are 200 and 600 nm and each grating has a photodetector underneath it.

Nevertheless, the angles corresponding to the maximum and minimum transmittances of the 600-nm grating are exactly reversed. This phenomenon is caused by the excitations of surface modes when one of the grating's propagating orders becomes grazing [8]. As a result, transmittance of the S-polarization changes sharply. In fact, it reaches a maximum when the period of the grating is much smaller than the light wavelength and a minimum when the period equals to the light wavelength (Rayleigh's anomaly). On the other hand, the transmittance of the P-polarization remains almost the same since the grazing mode of this polarization is suppressed in a shallow grating. The overall effect of the S- and P-polarizations is that a grating favors the transmission of the S-polarized light if its period is much smaller than the light wavelength; it favors that of the P-polarized light if its period is close to the wavelength.

Fig. 1 clearly indicates that the transmittance of a grating has a one-to-one correspondence with the polarization angle θ, provided that θ is either in the I–III or II–VI quadrant. This feature provides an unique property for determining the polarization angle. For example, if mount a grating onto the surface of a photodetector, the photocurrent of the detector will be proportional to the transmittance of the grating, and therefore will have the same one-to-one correspondence with the polarization angle. However, the polarization angle cannot be completely determined by the photocurrent of the photodetector since it is also proportional to the incident optical power. This problem can be solved by separately integrating two gratings onto the surfaces of two photodetectors (Fig. 2). If the two gratings are integrated so closely such that they encounter the same optical intensity under an illumination, the photocurrent *ratio* of the two photodetectors will be independent of the incident optical power. On the other hand, it will still have a one-to-one correspondence with the polarization angle if the periods of the gratings are different. In fact, the polarization-dependency of the photocurrent ratio will be stronger than that of any grating's transmittance if two gratings with reversed maximum-transmittance-angles are used, for example, the 200- and 600-nm gratings.

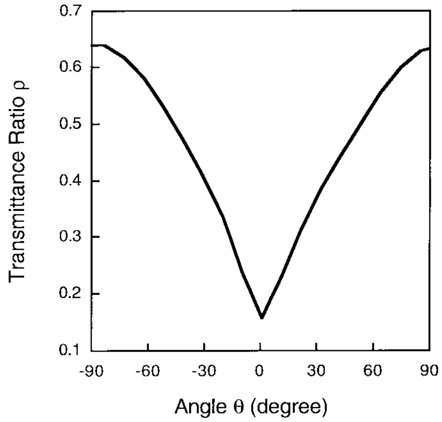

Fig. 3. The photocurrent ratio of the grating-photodetector pair shown in Fig. 2. The ratio is independent of the incident optical power and also has one-to-one correspondence with the polarization angle provided that it is either in the I–III or II–IV quadrant.

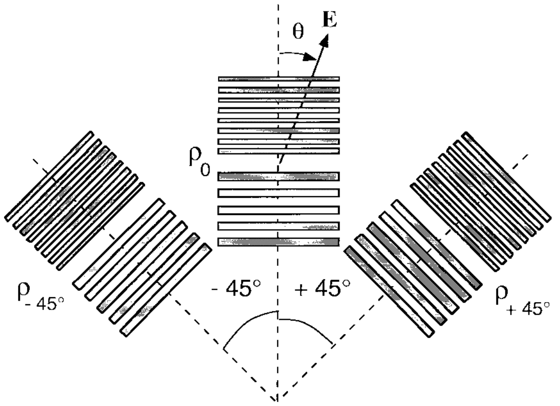

Fig. 4. The final structure of the device. Three grating-photodetector pairs are integrated on the same substrate.

The photocurrent ratio of the 200/600 grating-photodetector pair, $\rho = I_{600}/I_{200}$, is shown in Fig. 3. As expected, it changes more rapidly with the polarization angle than does the transmittance of a grating. Furthermore, we have also found that the photocurrent ratio remains a constant at each polarization angle even if the incident optical power varies by several orders of magnitude.

However, the photocurrent ratio does not tell whether the angle is in the I–III or II–IV quadrant. This problem can be solved by integrating the original grating-photodetector pair with two identical, but ±45° rotated pairs (Fig. 4). The photocurrent ratios of these pairs, i.e., $\rho_{+45°}$ and $\rho_{-45°}$ as

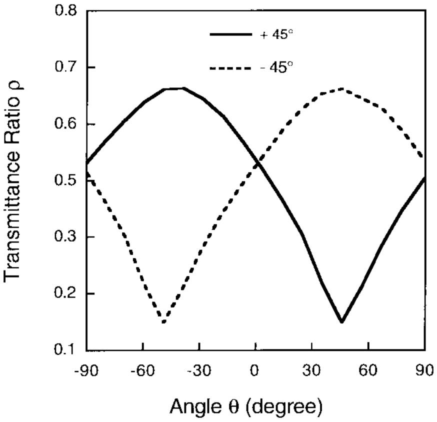

Fig. 5. The transmittance ratios of the $+45°$ and $-45°$ rotated grating-photodetector pairs.

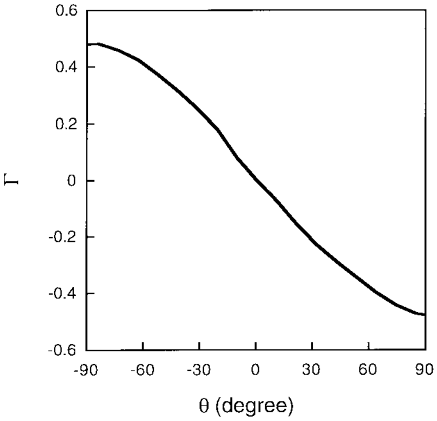

Fig. 6. Γ as a function of the polarization angle, θ. It is a monotonic function of the angle in all quadrants.

shown in Fig. 5, are shifted ±45°, respectively, from that of the original pair on the θ-axis. Knowing $\rho_{+45°}$ and $\rho_{-45°}$, a new variable, Γ, can then be defined as

$$\Gamma = \frac{\rho_{+45°} - \rho_{-45°}}{|\rho_{+45°} - \rho_{-45°}|}(\rho_0 - \min(\rho_0)) \tag{1}$$

where ρ_0 is the photocurrent ratio of the original pair. As shown in Fig. 6, Γ is a monotonic function of the polarization angle in all quadrants. Therefore, any polarization angle is uniquely determined by a Γ value. Moreover, all numerical operations needed for calculating ρ and Γ can be realized electronically by using circuits ether integrated on the same chip with the device or installed in an external meter. The calibration curve, Fig. 6, can be stored in an EPROM.

The angular resolution of the device is determined by its angular sensitivity, $d\Gamma/d\theta$, and the relative error in measuring the photocurrent ratio. The sensitivity of the device, calculated from Fig. 6, is equal to 0.01 degree^{-1} at 0°. The relative error in measuring Γ has been found to be 0.2%. Therefore an angular resolution of 0.2° can be achieved. The experimental errors are mainly caused by the noises from the light source and the photodetectors. In our experiment, the photocurrents of the detectors are measured individually. By integrating an electronic divider with each grating-photodetector pair, simultaneous photocurrent measurement and ratio-taking are possible, which will effectively suppress the common modes of the noise and therefore improve the angular resolution of the device. It should also be remarked that different LPDD's may be needed at different light wavelengths since the polarimetry of a grating depends strongly on the wavelength. However, for a small wavelength variation, a simple calibration should be enough to keep the device functional.

In application, a LPDD can be designed as an optical head such that it can be easily inserted into and then removed out from a beam. Since the photodetectors inside a LPDD can also be used to detect the incident optical power, this head can therefore be applied as a power head with capability of polarization-direction detection. Additionally, a two-dimensional (2-D) array of LPDD can be used to map the polarization state of the light with varied cross-section polarizations, for example, the circular-tangential polarized light [9].

Finally, a simplifed version of the LPDD with a lower resolution is to use the four photodetectors; three of them with gratings and 45° apart and the fourth one without a grating (for calibrating light intensity).

III. CONCLUSION

We have proposed, for the first time, a monolithic device for detecting the polarization direction of linear-polarized light. An angular resolution of 0.2° is predicted. The device consists of only subwavelength metal gratings integrated with photodetectors, no rotating parts exist. A variable, defined through photocurrent ratios of the detectors, shows a one-to-one correspondence with the polarization angle of the linear-polarized incident light, which is, therefore, used to determine the polarization direction. Compared to other instruments, this device is compact, simple, fast and cost-effective, which make it an ideal element for optoelectronics and optical integrated circuits.

REFERENCES

[1] D. Clarke and J. F. Grainger, *Polarized Light and Optical Measurement*. New York: Pergamon, 1971.
[2] K. Serkowski, *Planet, Stars and Nebulae Studied with Photopolarimetry*. Tucson, AZ: Univ. Arizona Press, 1977.
[3] G. R. Bird and M. J. Parrish, "The wire grid as a near-infrared polarizer," *J. Opt. Soc. Amer.*, vol. 50, pp. 886–891, 1960.
[4] J. P. Auton, "Infrared transmission polarizers by photolithography," *Appl. Opt.*, vol. 6, pp. 1023–1027, 1967.
[5] H. Brauninger, H. Kraus, H. Dangschat, K. P. Beuermann, P. Predehl, and J. Trumper, "Fabrication of transmission gratings for use in cosmic X-ray and XUV astronomy," *Appl. Opt.*, vol. 18, pp. 3502–3505, 1979.
[6] G. J. Sonek, D. K. Wagner, and J. M. Ballantyne, "Ultraviolet grating polarizers," *J. Vac. Sci. Technol.*, vol. 19, pp. 921–923, 1981.
[7] H. Lochbihler, E. Polnau, and P. Predehl, "Polarimetry of transmission gratings," *Appl. Opt.*, vol. 34, pp. 5725–5731, 1995.
[8] A. Hessel and A. A. Oliner, "A new theory of Wood's anomalies on optical gratings," *Appl. Opt.*, vol. 4, pp. 1275–1297, 1965.
[9] J. Asada and S. Nishiwaki, "Optical element converting linear polarization into circular-tangential polarization," *Appl. Opt.*, vol. 34, pp. 4768–4771, 1995.