High-Throughput Continuous Beam Steering Using Rotating Polarization Gratings

Chulwoo Oh, *Student Member, IEEE*, Jihwan Kim, *Student Member, IEEE*, John Muth, *Member, IEEE*, Steve Serati, *Member, IEEE*, and Michael J. Escuti, *Member, IEEE*

***Abstract*—A new beam steering concept comprising independently rotating, inline polarization gratings (PGs) is experimentally demonstrated. The approach, which we term *Risley gratings*, achieves high steering throughput within a large field-of-regard (FOR) in a fashion similar to *Risley prisms*, composed of wedged prisms. However, because PGs are patterned in thin liquid crystal layers, they enable a system with far less thickness, weight, and beam walk-off. Furthermore, large apertures are feasible and wavelengths from visible to infrared can be chosen. Any direction within a solid angle defined by twice the diffraction angle of each PG can be addressed mechanically. Here we demonstrate a Risley grating system with a 62° FOR and 89%–92% transmittance at 1550-nm wavelength, using two PGs with 6-μm grating period.**

***Index Terms*—Beam steering, diffraction, polarization grating (PG), Risley prism.**

I. Introduction

PRECISION beam pointing is a requirement for optical systems where beam alignment and target tracking are required, such as free-space optical communications, countermeasure, laser weapons, and fiber-optic switches. As this context often demands compact, robust, and cost-effective devices for beam steering, *Risley prisms* [1], comprising two or more wedged prisms, have long been used for its high degree of accuracy and stability. Their utility, however, is often limited by small deflection angles and poor size scaling properties due to bulky prismatic elements where wide angles and modest/large apertures are required.

Here, we introduce an arrangement of two independently rotating, inline polarization gratings (PGs) [Fig. 1(a)] to achieve a remarkably efficient and compact beam steering device [Fig. 1(b)], which we term *Risley gratings*. The single-order diffraction, high efficiency, polarization behavior, and wide acceptance angle of the PGs [2], [3] (PGs) employed enable a unique opportunity for beam steering with high throughput and low sidelobes.

Manuscript received August 27, 2009; revised October 21, 2009; accepted November 07, 2009. First published December 01, 2009; current version published January 20, 2010. This work was supported by the National Science Foundation (Grant ECCS-0621906) and the U.S. Air Force Research Laboratory (Sensors Directorate).

C. Oh, J. Kim, J. Muth, and M. J. Escuti are with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695 USA (e-mail: coh@ncsu.edu; jkim15@ncsu.edu; muth@ncsu.edu; muth@unity.ncsu.edu; mjescuti@ncsu.edu).

S. Serati is with Boulder Nonlinear Systems Inc., Lafayette, CO 80026 USA (e-mail: sserati@bnonlinear.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2037155

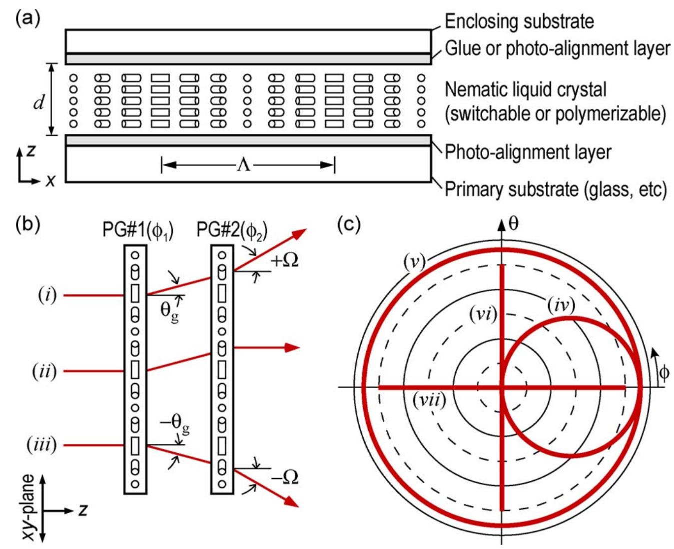

Fig. 1. Efficient, wide-angle steering with Risley gratings, based on rotating, inline, PGs: (a) side-view of single PG, showing LC director profile; (b) steering with two inline PGs with orientations $\{\phi_1, \phi_2\}$ having values of (i) $\{0°, 180°\}$, (ii) $\{0°, 0°\}$, and (iii) $\{180°, 0°\}$; and (c) continuous scanning patterns as orientations are varied as (iv) $\{\phi, 0°\}$, (v) $\{\phi + 180°, \phi\}$, (vi) $\{\phi - 90°, -\phi + 90°\}$, and (vii) $\{\phi, -\phi + 180°\}$.

While previous approaches for wide-angle steering with liquid crystal (LC) phase gratings (e.g., [4]) have been studied, in practice their performance has been severely limited by modest deflection angles, low system-level throughout, and significant sidelobe leakage. Two recent efforts studied PG-based, nonmechanical steering in two approaches: continuous fine- [5] and discrete wide-angle [6] steering. Both had high efficiency and low leakage, but they necessarily involve transparent electrodes that may manifest significant absorption for some applications. While recent studies in polarization-insensitive displays [7] and imaging [8] also employed stacked PGs with relative orientations, the implications for pure beam steering of this arrangement was not realized or discussed.

Since the two PGs can be formed in thin LC layers and they are scalable to large areas (easily many cm^2) without increasing their thickness, the Risley grating approach provides dramatic aspect ratio improvement as compared to Risley prisms. A further feature is that our arrangement can be tailored to operate at nearly any wavelength from visible to midwave-infrared.

We will describe the construction and operational principles of this beam steering device based on PGs and demonstrate Risley gratings that perform continuous steering of a laser beam (at 1550 nm) with the maximum deflection angle of $\pm 31°$ and up to 92% throughput. We characterize the experimental steering behavior, and describe the output angle of the steered beam using the direction cosine space method.

II. Background

In general [2], [3], PGs are diffractive elements composed of periodic profiles of optical anisotropy, and as such, often manifest unique behavior. Here, we use "circular"-type PGs [2], defined by a spiraling, constant-magnitude, uniaxial birefringence [Fig. 1(a)]. Remarkably, this PG exhibits some of the best properties of both the thin (Raman–Nath) and thick (Bragg) grating regimes, including 100% theoretical efficiency into a single diffraction order and a wide acceptance angle. As long as the parameter $\rho = 2\lambda^2/\bar{n}\Delta n\Lambda^2 \ll 1$, the first-order efficiency can be accurately approximated [2] as follows:

$$\eta_{\pm 1} = \frac{1 \mp S_3'}{2} \sin^2\left(\frac{\pi \Delta n d}{\lambda}\right) \qquad (1)$$

where Δn is the birefringence, $\bar{n}$ is the average index, d is the grating thickness, Λ is the grating period, λ is the wavelength, and $S_3' = S_3/S_0$ is the normalized Stokes parameter describing polarization ellipticity of the incident light. Note that a single first-order efficiency can indeed be 100% when $\Delta n d = \lambda/2$ and when circularly polarized light (i.e., $S_3' = \pm 1$) is incident. Note further that first-order diffracted light will have the reverse handedness of the input, and is always circularly polarized regardless of the input. The first-order diffraction angle θ_g is determined by the classic grating equation: $\sin\theta_g = \lambda/\Lambda$ at normal incidence.

III. Operation Principles

Efficient and compact beam steering devices are possible by arranging two independently rotating PGs inline [Fig. 1(b)]. The principle of operation is described as follows. A circularly polarized, collimated, narrowband beam is normally incident on the first PG. With theoretically 100% efficiency, this light is redirected into the polar angle θ_g with an azimuthal direction set by the azimuth angle ϕ_1 of the first PG. The second PG then receives this beam, and redirects it again with a nonlinear dependence on its diffraction angle θ_g and azimuth angle ϕ_2. We illustrate elemental steering curves (lines and circles) in Fig. 1(c), where the relative and absolute PG azimuth angles are scanned throughout their range.

Since the angle relationship is nonlinear, it is often convenient to introduce the direction-cosine space [9] where diffraction at an arbitrary incident angle can be described by simple, linear vector representations as shown in Fig. 2. The direction cosines of the steered beam are given by

$$\alpha = \sin\theta_g(\cos\phi_1 - \cos\phi_2) \qquad (2a)$$

$$\beta = \sin\theta_g(\sin\phi_1 - \sin\phi_2) \qquad (2b)$$

$$\gamma = \sqrt{1 - \alpha^2 - \beta^2}. \qquad (2c)$$

By definition, $\alpha^2 + \beta^2 \leq 1$. The net azimuth and polar angles of the transmitted beam can be determined from (2) as

$$\phi = \tan^{-1}(\beta/\alpha) \qquad (3a)$$

$$\theta = \cos^{-1}(\gamma). \qquad (3b)$$

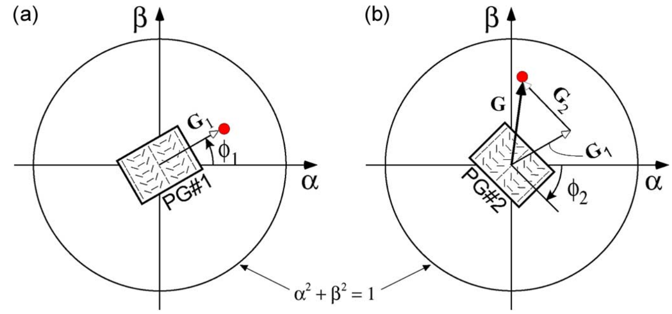

Fig. 2. Vector representations of PG diffraction in direction-cosine space: (a) the first PG diffraction $\mathbf{G}_1$; (b) the second PG diffraction $\mathbf{G}_2$. The final direction can be expressed as a simple vector sum $\mathbf{G} = \mathbf{G}_1 + \mathbf{G}_2$.

The maximum steering angle is defined as $\Omega = \sin^{-1}(2\lambda/\Lambda)$, and the device can point a beam to any angle within a $\pm\Omega$ cone [see Fig. 1(b)], with a field-of-regard $(\text{FOR}) = 2\,\Omega$. Chromatic dispersion follows typical diffractive dispersion.

The speed and precision of this approach depend primarily on the mechanical mounts employed. We would expect the scanning speed of motorized mounts to exceed that of the Risley prisms due to the substantially reduced mass and volume of the optical elements.

IV. Fabrication and Results

We assembled a Risley grating beam steering system with 62° FOR at 1550 nm using a pair of PGs, each with $\theta_g = 15°$ ($\Lambda = 6\ \mu$m) and 1-cm^2 aperture. Two PGs were mounted in separate rotation stages, manually controlled, to independently set their grating orientations.

The defect-free PGs were formed as LC cells, using polarization holography and photo-alignment materials, as described elsewhere [10], [11]. A linear-photopolymerizable polymer (LPP) (ROP-103/2CP, from Rolic) and nematic LC (LCMS-102 [12], from Boulder Nonlinear Systems, $\Delta n = 0.31$ at 1550 nm) were utilized. The individual PGs exhibit nearly ideal PG diffraction as (1) with >98% first-order efficiency, with no observable higher orders or scattering. Note that an LC with high birefringence is crucial to achieve low-leakage and low-scateering PGs with a large diffraction angle. Both air/glass interfaces on each PG [Fig. 1(a)] were treated with anti-reflection coatings to reduce reflection losses.

Fig. 3 shows images of the steered beam (from an infrared (IR) laser with circular polarization) directed onto a planar screen, showing a variety of simple scans (lines and circles) within the entire FOR. These correspond to the curves indicated in Fig. 1(c), validating (3). Each image is a superposition of individual pictures taken of the beam at various angles on a fluorescent infrared viewing-card in a dark room.

Continuous beam steering was confirmed within ±31°. A ~92% throughput (ie, transmittance) was observed, defined as $T = P_{\text{out}}/P_{\text{in}}$, where P_{in} and P_{out} are powers of the incident and steered beams, respectively. We also measured the diffraction efficiency, a normalization that removes the effect of the substrates, defined as $\eta = P_{\text{out}}/P_{\text{tot}}$, where P_{tot} is the total transmitted power into the exit hemisphere. Fig. 4(a) shows both transmittance and efficiency of the steered beam. This shows

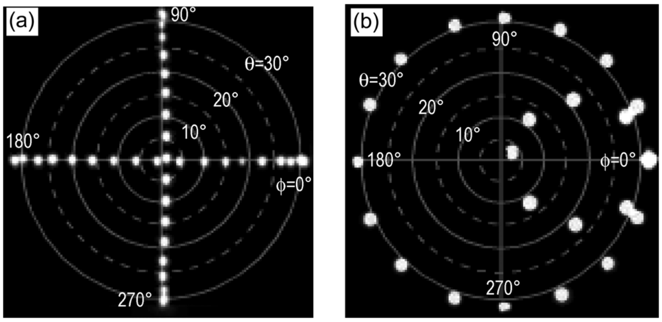

Fig. 3. Demonstration of Risley grating beam steering with a 62° FOR at 1550-nm wavelength. Note that individual pictures of the steered beam incident on an IR sensitive detecting screen were captured and superimposed.

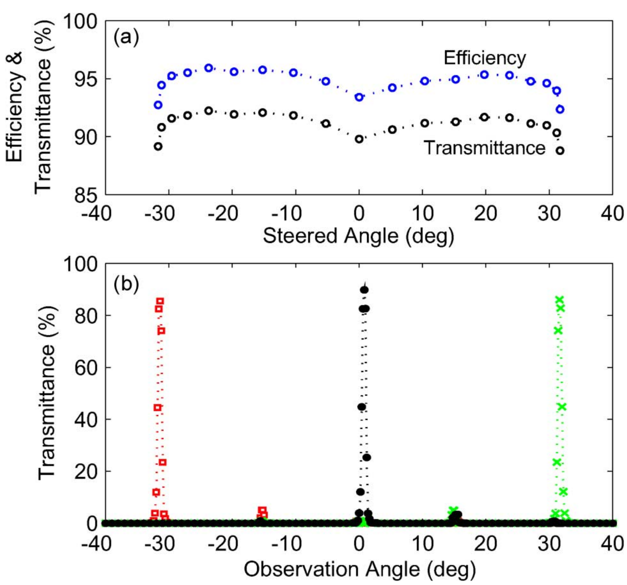

Fig. 4. High throughput from 92% to 89% of Risley gratings: (a) transmittance and efficiency of the steered beam across the FOR; (b) normalized power (transmittance) observed across the FOR $\pm 40^\circ$ for three steering angles.

high transmittance (from 92% to 89%), with some dependence on the steering angle.

We measured the reflectance (loss) of each of the four AR coatings to be $\sim$1%. The remaining loss is due to leakage into sidelobes, as shown in Fig. 4(b) where we show the fraction of transmitted power observed when the PGs were fixed. In all cases, the sidelobe leakage (in the range of 1% to 6%) occurred at angles that were multiples of θ_g. This leakage relates to the oblique incidence on the second PG, and likely can be reduced by the use of higher birefringence LC and additional retardation compensation films.

Limited by our measurement error, we measured <0.5% absorption and scattering. However, LC absorption in this IR region is low (typically <0.01% at 1550 nm [13]), and we conclude that scattering dominated. Reflection losses can be improved via enhanced index-matched substrates.

While this data was acquired at 1550 nm with $\sim$5 W/cm^2 intensity without degradation over many hours, we have also conducted preliminary tests with similar PGs at 1064 nm at $\sim$2 kW/cm^2 intensity without damage. We expect that the power handling limit in the Risley grating approach (with no electrodes and <0.01% LC absorption) should be much higher than that of any electrically controlled LC device (with electrodes having at best 0.2% absorption each).

V. Summary

We demonstrated that two rotating, inline PGs are a highly efficient beam steering device, with an ultracompact and lightweight form factor. The prototype continuously steers within 62° FOR, and manifests a transmittance as high as 92% into the steered direction, with sidelobe leakage on the order of a few percent. We employed PGs (with $\Lambda = 6$ μm and $\theta_g = 15^\circ$ at 1550-nm wavelength) formed in LC layers (a few μm thick). These thin-plate elements can be formed at almost arbitrarily large areas without increasing the thickness or beam walk-off. Larger steering angles, further loss reduction, and implementation at other wavelengths are expected via further optimization of substrates and PG materials.

References

[1] P. J. Bos, H. Garcia, and V. Sergan, "Wide-angle achromatic prism beam steering for infrared countermeasures and imaging applications: Solving the singularity problem in the two-prism design," *Opt. Eng.*, vol. 46, no. 11, p. 113001, 2007.

[2] C. Oh and M. J. Escuti, "Numerical analysis of polarization gratings using the finite-difference time-domain method," *Phys. Rev. A*, vol. 76, p. 043815, 2007.

[3] J. Tervo and J. Turunen, "Paraxial-domain diffractive elements with 100% efficieincy based on polarization gratings," *Opt. Lett.*, vol. 25, pp. 785–786, 2000.

[4] X. Wang, D. Wilson, R. Muller, P. Maker, and D. Psaltis, "Liquid-crystal blazed-grating beam deflector," *Appl. Opt.*, vol. 39, pp. 6545–6555, 2000.

[5] L. Shi, P. McManamon, and P. Bos, "Liquid crystal optical phase plate with a variable in-plane gradient," *J. Appl. Phys.*, vol. 104, p. 033109, 2008.

[6] J. Kim, C. Oh, M. J. Escuti, L. Hosting, and S. Serati, "Wide-angle, nonmechanical beam steering using thin liquid crystal polarization gratings," *Proc. SPIE*, vol. 7093, p. 709302, 2008.

[7] C. Oh, R. K. Komanduri, B. L. Conover, and M. J. Escuti, "Polarization-independent modulation using standard liquid crystal microdisplays and polymer polarization gratings," *IDRC Digest*, vol. 28, pp. 298–301, 2008.

[8] S. R. Nersisyan, N. V. Tabiryan, L. Hoke, D. M. Steeves, and B. Kimball, "Polarization insensitive imaging through polarization gratings," *Opt. Express*, vol. 17, pp. 1817–1830, 2009.

[9] J. E. Harvey and C. L. Vernold, "Description of diffraction grating behavior in direction cosine space," *Appl. Opt.*, vol. 37, pp. 8158–8160, 1998.

[10] G. P. Crawford, J. N. Eakin, M. D. Radcliffe, A. Callan-Jones, and R. A. Pelcovits, "Liquid-crystal diffraction gratings using polarization holography alignment techniques," *J. Appl. Phys.*, vol. 98, p. 123102, 2005.

[11] M. J. Escuti and W. M. Jones, "Polarization-independent switching with high contrast from a liquid crystal polarization grating," in *SID Sym. Digest*, 2006, vol. 37, pp. 1443–1446.

[12] S. Gauza, J. Li, S. T. Wu, A. Spaldo, R. Dabrowski, Y. N. Tzeng, and K. L. Cheng, "High birefringence and high resistivity isothiocyanate-based nematic liquid crystal mixture," *Liq. Cryst.*, vol. 32, pp. 1077–1085, 2005.

[13] S. T. Wu, "Absorption measurements of liquid crystals in the ultraviolet, visible, and infrared," *J. Appl. Phys.*, vol. 84, pp. 4462–4465, 1998.