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Paul F. McManamon

Jianru Shi

Philip J. Bos
Kent State University - Kent Campus, pbos@kent.edu

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Broadband optical phased-array beam steering

Paul F. McManamon
Wright-Patterson Air Force
Research Laboratory
Dayton, Ohio 45433-7304

Jianru Shi
Philip J. Bos
Kent State University
Liquid Crystal Institute
Kent, Ohio 44242-0001

Abstract. An array of phase retarders can be used as an optical phased array (OPA) to steer light [McManamon et al., *Proc. IEEE* 84(2), 268–298 (1996)]. The introduction of resets enables steering to larger angles without requiring an optical path difference (OPD) greater than one wavelength. These resets, however, are correct only at the design wavelength. The beam steerer is therefore very dispersive. It has been shown theoretically that resets of an integer multiple of the wavelength will make the beam steerer less dispersive [McManamon and Watson, *Proc. SPIE* 4369, 140–148 (2001)]. We offer the first experimental proof that resets of $n\lambda$ are less dispersive than resets of a single λ. We also show experimentally that the dispersion associated with fixed period resets does vary, but only within a fixed limit. Last, we show the equivalent of power shifting from one order to the next as larger resets move from being divisible by one integer times the nondesign wavelength toward being divisible by the next integer times the nondesign wavelength.
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Subject terms: spatial light modulators; optical phased arrays; nonmechanical beam steering; broadband beam steering.

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1 Grating Dispersion Analysis

An optical phased array (OPA) grating can steer[1] a wave component to its n'th diffraction order with high efficiency if the following phase condition is met:

$$\mathrm{OPD}(\lambda_d) = n\lambda_d, \tag{1}$$

where the design wavelength is denoted as λ_d. Resets are an integer multiple of the design wavelength.[2] The OPA grating is called an n'th order grating. For a nondesign wavelength λ, the optical path difference (OPD) of a reset is no longer an integer multiple of that wavelength. There is a fractional residue:

$$\mathrm{OPD}(\lambda) = m\lambda + \chi\lambda, \quad -0.5 \leqslant \chi \leqslant +0.5, \tag{2}$$

where m is the closest integer number to express the OPD of the reset in terms of the nondesign wavelength. Here $\chi\lambda$ is the fractional residue of the OPD. When the OPD is not an integer multiple of the wavelength, the reconstructed wavefront after exiting the grating does not align in phase. There is phase mismatch between wave segments exiting from neighboring period segments. The χ parameter characterizes the phase mismatch. When $\chi=0$, the wavefront segments are in phase. When $\chi=\pm 0.5$, the wavefront segments are mismatched by a half wavelength. Because all wave components experience the same OPD, neglecting material dispersion, we have

$$n\lambda_d = m\lambda + \chi\lambda. \tag{3}$$

We denote the period of the n'th order OPA grating by d_n. According to the grating equation, the steering angle of the design wave, denoted by α, is determined by

$$d_n \sin\alpha = n\lambda_d. \tag{4}$$

A nondesign wavelength can be steered to its m'th order rather than its n'th order. The steering angle of the nondesign wavelength, denoted by α', is determined by

$$d_n \sin\alpha' = m\lambda. \tag{5}$$

The angular dispersion of the nondesign wavelength with respect to the design wave is defined as $\delta\alpha \equiv \alpha' - \alpha$. If $\delta\alpha/\alpha \ll 1$, then $\delta(\sin\alpha) = \cos\alpha \times \delta\alpha$, and

$$\delta\alpha = \frac{\delta(\sin\alpha)}{\cos\alpha} = \frac{\sin\alpha' - \sin\alpha}{\cos\alpha} = \frac{m\lambda - n\lambda_d}{d_n\cos\alpha} = -\frac{\chi_n\lambda}{d_n\cos\alpha} \tag{6}$$

For a small steering angle, $\cos\alpha \approx 1$. Therefore:

$$\delta\alpha \approx -\frac{\chi_n\lambda}{d_n} \tag{7}$$

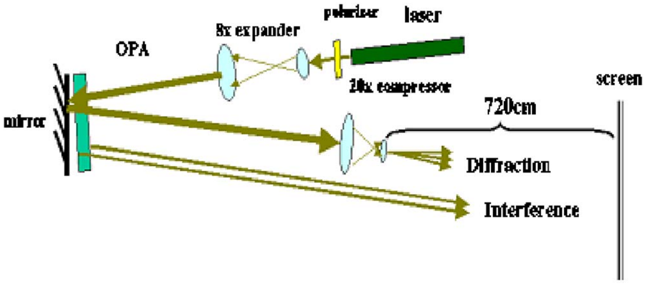

Fig. 1 Experiment setup.

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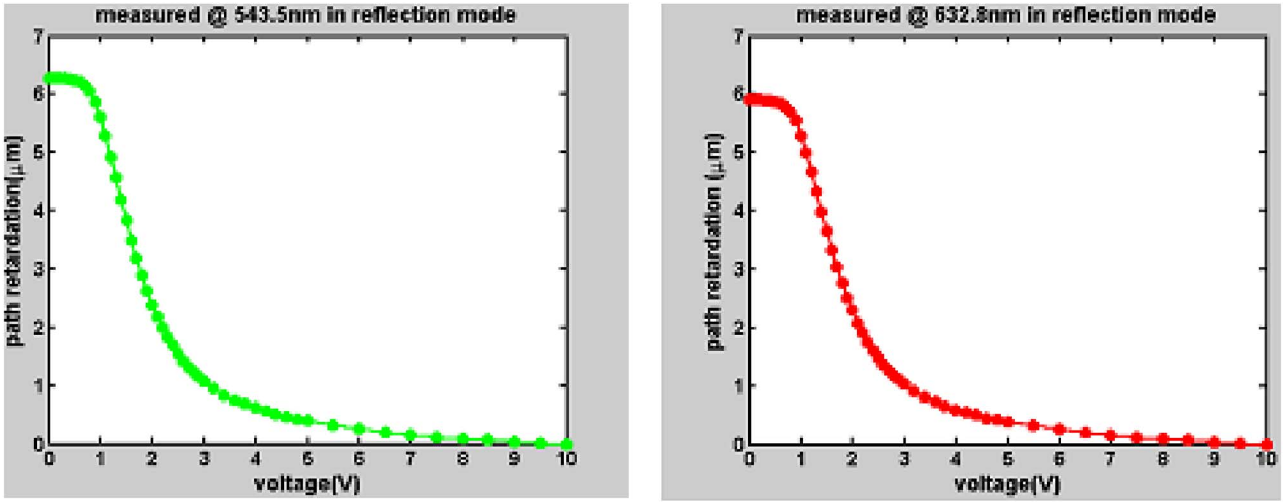

Fig. 2 Path retardation versus voltage for both wavelengths.

2 Grating Dispersion Experiment

Kent State has a fabricated a 96-element liquid crystal device with a pitch of 100 μm. Each electrode is 97 μm wide, with a 3-μm gap between electrodes. It is useful to operate in the visible to obtain many wavelengths within the OPD, enabling the use of many orders of beam steering. The liquid crystal used is BL036 (T_{NI}=95 deg, k_1=13.7, k_2=27.5, k_3=16.4, $\Delta\varepsilon$=16.4) with a birefringence of 0.267 at 589 nm. The liquid crystal cell gap is approximately 10 μm. The OPD for each wavelength used can be seen later in Fig. 3. The OPD is high enough to enable 10th-order steering at red, 0.6328 μm, and almost 12th-order at green, 0.5435 μm. Figure 1 shows the experimental setup. The reflected light from the OPA cell is compressed 20 times to make it easier to see the far-field diffraction pattern. This compression is done so the far field is reached in a shorter distance as well, and as so the angular pattern is larger and easier to see. Experimentally measured angles, as seen later in Figs. 5, 6, 8, and 9, are 20× larger then given by Eq. (4) due to this angular magnification.

In this experiment, traditional nematic liquid crystals are used. Making thicker liquid crystal layers slows up a traditional liquid crystal by the square of the increase in thickness. This makes the experimental device used for this experiment slow, but it does not matter for this experiment. The development of sheared liquid crystals[3] has provided the possibility of making thick and rapid liquid crystal devices suitable for taking advantage of the multiple-order approach discussed in this paper. We did not use sheared liquid crystals for this experiment, since so far they have been developed for the mid-IR region, and have more scattering in the visible than desired. The advent of sheared liquid crystal technology, however, may make the approach discussed in this paper applicable to practical beam-steering devices.

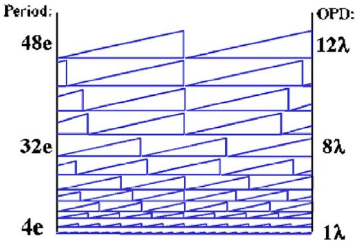

Fig. 3 Phase profiles used for steering to a constant angle with multiple orders.

The liquid crystals used do not have an identical index of refraction at the two wavelengths chosen. To correct for the difference in index of refraction at the two wavelengths it is necessary to measure the relative index and compensate during the experiments. Figure 2 shows the retardance for each wavelength. We can see that there is more retardance at the green wavelength. The cell also had nonuniformities in one direction. Fortunately, the nonuniformities

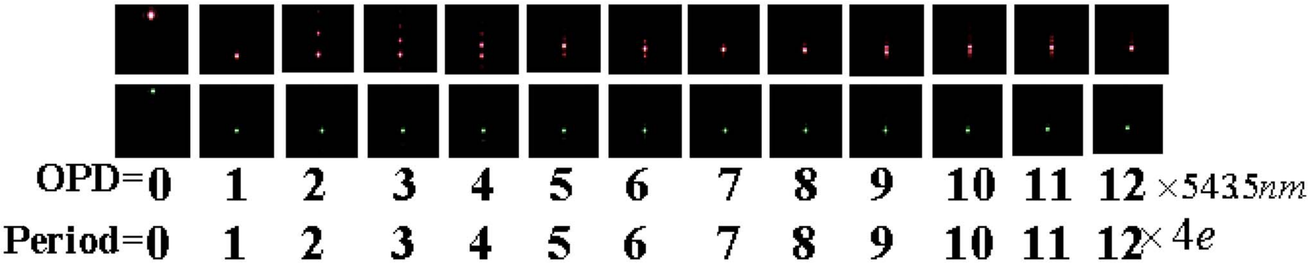

Fig. 4 Pictures of steered beams at the green design wavelength and the red, nondesign, wavelength.

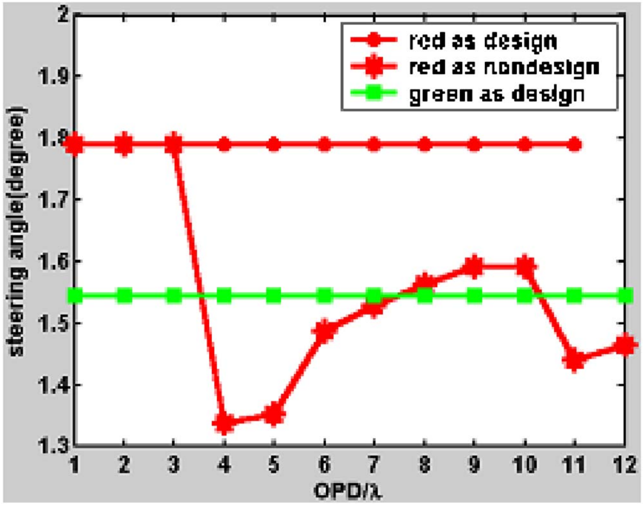

Fig. 5 Steering angle for first to twelvth-order grating with a constant design steering angle.

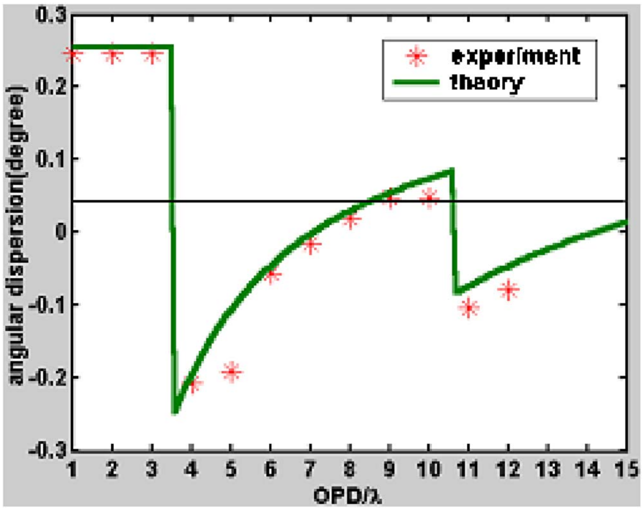

Fig. 6 Comparison with theory regarding the angular dispersion.

were in the direction cross wise to the electrodes, so these nonuniformities were compensated across the cell by varying the voltage on each electrode.

We used one wavelength as the design wavelength, and measured beam steering at both the design wavelength and an alternate wavelength. Resets were always a multiple of the design wavelength. The N'th-order grating period is denoted by d_N. Dispersion was expected and measured for the nondesign wavelength. Three experiments were conducted. In the first experiment, the order and period of resets were varied such that the design steering angle remained constant. This experiment showed dispersion decreased for constant angular steering when the order was increased. For the first experiment, the smallest number of elements in the reset period was 4. Ideally it is desirable to keep the smallest number of elements in a period to 8 or more in order to maintain high steering efficiency, but we could steer to higher orders if the first order of experiment we used 4 elements within a period. In the second experiment, the period of the resets was held constant at 48 electrodes while the order was varied. This was done to determine whether the maximum dispersion associated with constant period resets is also constant. The last experiment showed energy moving from one order to the next. This experiment was equivalent to the mismatch in phase between periods being varied for the nondesign wavelength.

In experiment 1 the beam is steered to the 1st through the 12th orders, starting with no steering, or the zeroth order. The period is proportional to the grating order m. Period is calculated by

$$d_m = 4md, \tag{8}$$

where m is the order, d is the electrode width, and d_m is the period. The period between resets varies from 4 electrodes to 48 electrodes. In the case with the largest reset values, we have two phase ramps across the 96 electrode optical phased array. Because the OPD of the reset divided by the period stays constant the design steering angle is also constant. Figure 3 shows the phase profiles used to create the various orders. The picture at the far left in Fig. 4 shows the unsteered beam. The red, nondesign wavelength, is on top. Figure 5 shows the measured steering angles, assuming the steered angle is associated with the brightest spot. Looking at the case with green as the design wavelength, we can see that for the first three orders, the red wavelength is steered to the angle it would have been steered to if red was the design wavelength, assuming the brightest beam is used to measure position. We can see, however, that at orders 2 and 3 there are two separate beams. At the fourth order, we see the brightest position is now the higher of two spots, so it appears as though there is a sudden jump in the steering position. What really has happened is a different position

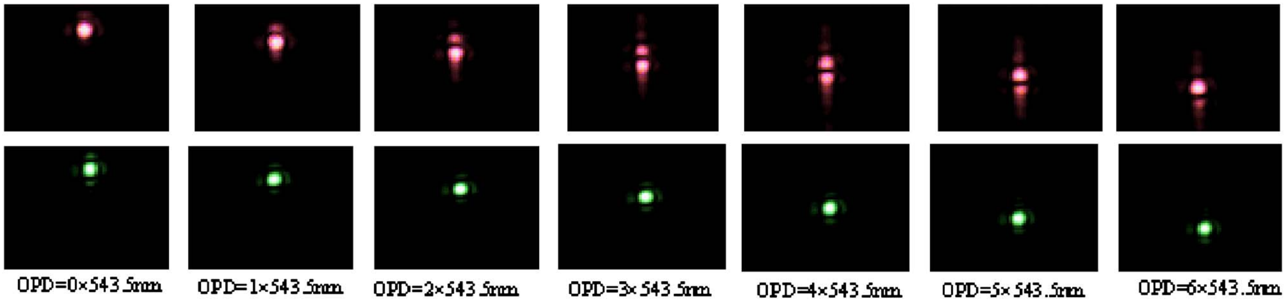

Fig. 7 Steering green design wavelength and red nondesign, with constant period and varying order.

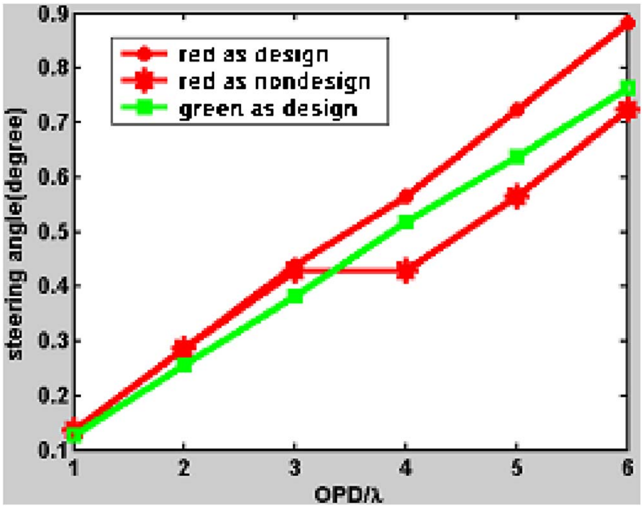

Fig. 8 Steering from the first- to the sixth-order grating with fixed period.

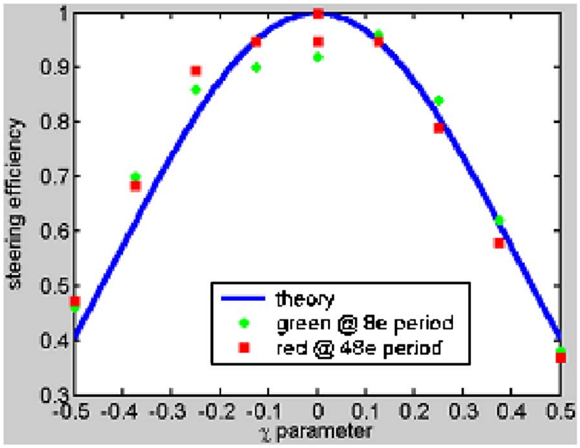

Fig. 10 Steering efficiency measurement.

has become the brightest position. Total spread in beam positions is obviously less as we progress to higher orders. This is consistent with the previously described theory. Figure 5 plots the position of the brightest spot, referred to as the steering angle. The design wavelength only has one spot while the nondesign wavelength has multiple spots due to dispersion, with the multiple spots closer together at higher orders. Figure 6 plots angular dispersion versus order, including both theory and experiment. For Fig. 6 the angular dispersion plotted is the difference between the brightest red spot and the design steering angle for the green design wavelength.

In experiment 2, the beam is steered to orders 1 through 6, while keeping the period between resets constant. A period between resets of 48 electrodes was utilized while increasing the order, and the steering angle, to six different angles. Because the period is fixed at 48 electrodes, the steering angles are proportional to the grating orders while operating at the design wave. At nondesign wavelengths, the beam will split into two or more beams. The energy distribution will vary at different orders. In Fig. 7 the green laser is taken as the design wavelength and the red laser as the nondesign wavelength. The red, nondesign wavelength is on top in Fig. 7. Increasing angular deflection is shown for the design wavelength. Increasing angular deflection is also shown for the nondesign wavelength, although dispersion can be seen in the figures. Looking at the spread in beams for the nondesign wavelength it appears there is not much change in beam spread, or dispersion, as a function of order. Figure 8 shows the steering angle variation for the design and nondesign wavelengths, again using the assumption that the steered angle is the brightest spot. We can see that the brightest spot is steered at low orders the same as if red was the design wavelength. At higher orders, the brightest spot moves below the angle for green design wavelength. Dispersion limits remain constant as order changes, but the angle that the nondesign wavelength is steered to varies from one side of the design angle to the other (see Fig. 9).

In experiment 3, we increase the OPD of the resets from zero to one wave by one-eighth wave steps. We measured the diffraction efficiency of the zeroth order and the first order. This is equivalent to the case where the nondesign wavelength moves from one order to the next. For this experiment the energy flows from one order to the next

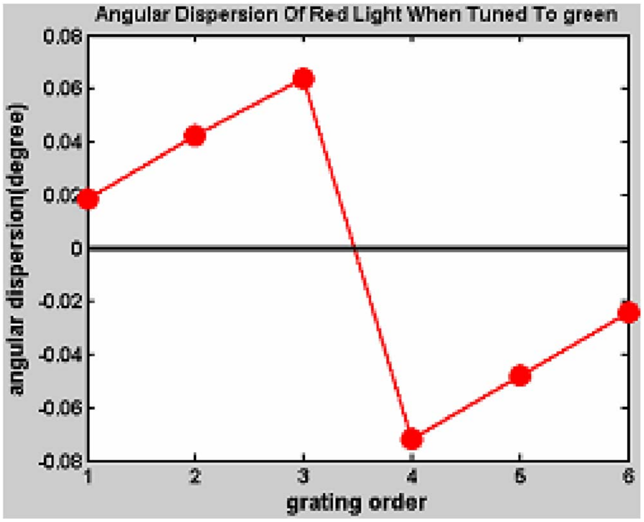

Fig. 9 Angular dispersion versus order for constant reset period.

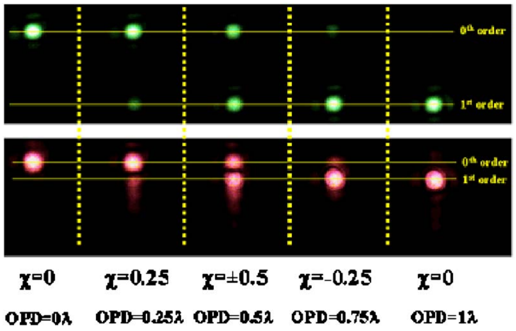

Fig. 11 Diffraction patterns when steering beam between the zeroth order and the first order.

order, and the diffraction angles vary discontinuously. The efficiency is plotted versus the χ parameter in Fig. 10. We have $\chi=0$ when OPD=0, $\chi=1/8$ when OPD=1/8 λ, etc. The steering efficiency is measured both with the green laser at an eight-electrode period and red laser at the 48-electrode period. In both cases, the efficiency plot follows the expected curve, as shown in Fig. 10. The efficiency is the ratio of peak intensity with respect to that of the zero OPD. The Fourier analysis gives the diffraction efficiency as

$$\eta = \sin c^2 \chi = \left(\frac{\sin \chi\pi}{\chi\pi}\right)^2. \tag{9}$$

This equation provides the theoretical efficiency shown in Fig. 10.

While we were only looking at χ for values of n between 0 and 1, it is equivalent to changing from n to order $n+1$, based on the definition of χ. Figure 11 shows the diffraction patterns of the green laser with an eight-electrode reset spacing in the top picture and the red laser with a 48-electrode reset spacing, as a function of χ. The horizontal lines indicate the zeroth order, or no steering, and the first-order position. When $\chi=0$ the beam stays in the zeroth order. When $\chi=\pm 0.5$ the beam is approximately split half and half between the two orders. When the beam totally moves to the first order, χ goes back to zero again. In between, the diffracted beam is split between the orders with different weight. This weight ratio is determined by the χ parameter.

3 Conclusions

This paper showed experimentally that when resets are an integer number of times the design wavelength we have less maximum dispersion then when resets are one design wavelength in magnitude. The decrease in maximum dispersion is inversely proportional to the size of the reset. This proves a previously published hypothesis.[2] Making thicker liquid crystal layers, and increasing maximum available OPD, becomes therefore a method of making an optical phased array beam steerer less dispersive. Second, the maximum dispersion depends on the period of the resets. With a constant reset period we have a variation in dispersion about the design angle, but the maximum dispersion is set by the reset period. This is fully consistent with the first conclusion. Larger resets, for a constant angle steering, result in a larger period between resets. Last, the angular dispersion of an OPA is proportional to the phase mismatch fraction.

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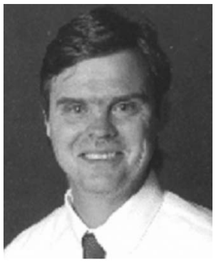
Paul F. McManamon received his PhD in physics from the Ohio State University in 1977. He has been with Wright-Patterson Air Force Base since 1968, joining Wright laboratory in 1979. His PhD was in laser physics. His primary work at the laboratory has been in electro-optical sensors. He was primary author a paper entitled "Optical Phased Array Technology," which received the IEEE W.R.J. Baker award for the best paper in any IEEE refereed journal or transaction. Recently he has emphasized laser radar sensors more than passive IR/electro-optic (EO) sensors, but has research interests in both areas. He acted as chief scientist for the Avionics Directorate of Wright Lab for over $2\frac{1}{2}$ years. He is currently senior scientist for infrared sensors, in the Sensors Directorate of the Air Force Research Laboratory. He is a Fellow of SPIE, the Military Sensing Symposia, and of the Air Force Research Laboratory. He is the 2005 vice president of SPIE and will be the 2006 president of SPIE.

Jainru Shi received his BS degree in 1991 from Hebei Normal University, China, his MS degree in liquid crystal physics in 1994 from Hebei University of Technology, Tianjin, China, and his PhD degree in liquid crystal applications in 2004 from the Liquid Crystal Institute, Kent State University, Ohio. From 1994 to 1999 he was a liquid crystal and optical sensor researcher with Hebei University of Technology, Tainjin, China. From 1999 to 2001 he was researcher with the National Science Foundation (NSF) Advanced Liquid Crystalline Optical Material Program at the Liquid Crystal Institute. Since 2001 he has been a researcher with the Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA) Electro-optical Beam Steering Program, BosLab, at the Liquid Crystal Institute. Shi received the 2003 and 2004 SPIE Scholarship Awards in Optical Science and Engineering and he holds one patent.



Philip J. Bos received his PhD degree in physics from Kent State University in 1978. After 1 year as a research fellow at the Liquid Crystal Institute at Kent State he joined Tektronix Laboratories in the Display Research Department. In 1994 he returned to the Liquid Crystal Institute, where he is currently an associate director and a professor of chemical physics. He currently has several projects in the area of applications of liquid crystals. He has over 100 publications and holds 20 patents.