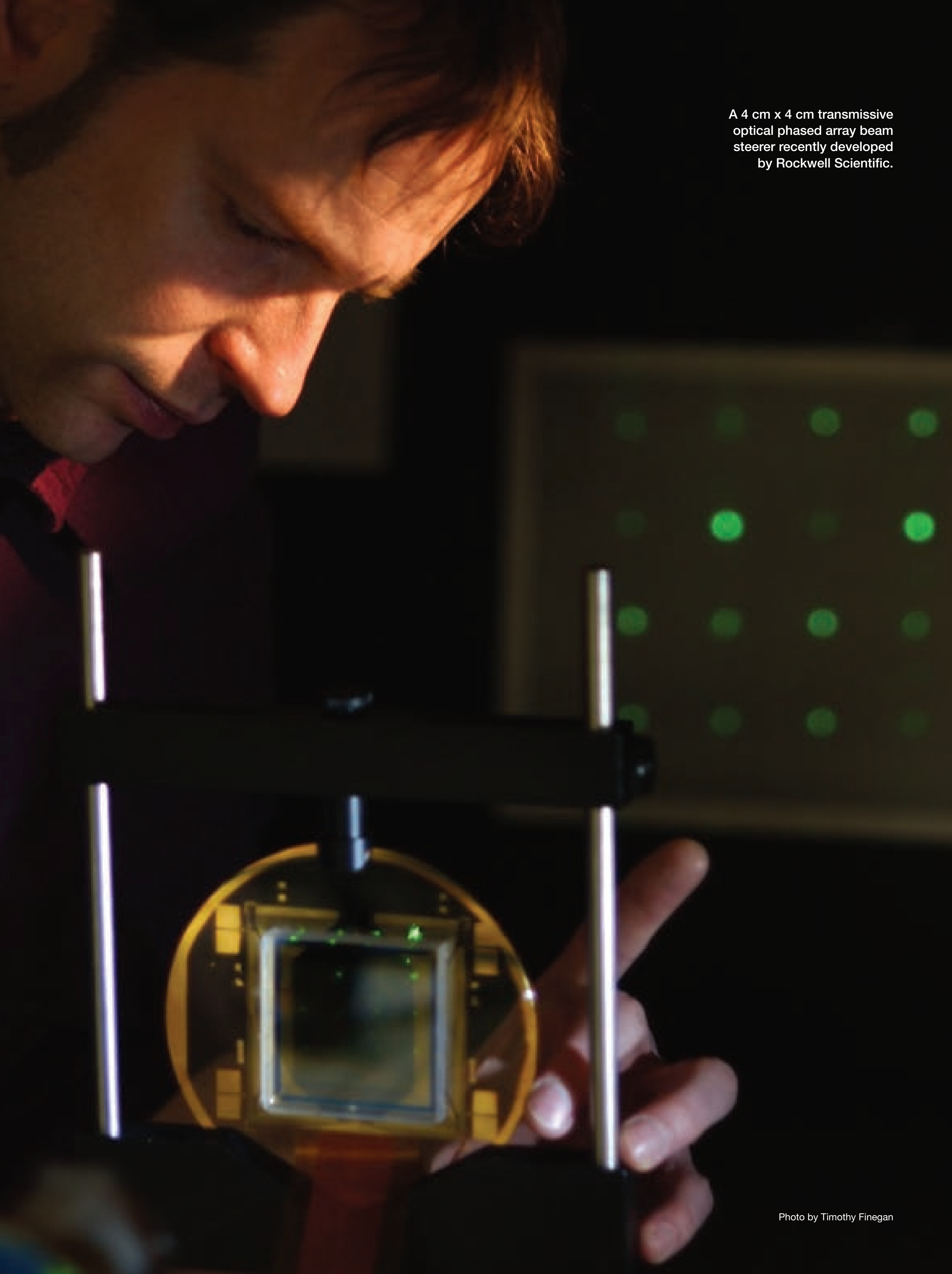

A 4 cm x 4 cm transmissive optical phased array beam steerer recently developed by Rockwell Scientific.

Photo by Timothy Finegan

Agile Nonmechanical Beam Steering

Paul F. McManamon

The day is coming when engineers will be able to replace mechanical complex gimbal and steering mirror assemblies in electro-optical systems with thin, conformal devices that either have no moving parts or only make use of micro-motion. These revolutionary devices for beam steering will allow rapid and highly precise random access stabilization and pointing.

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Traditionally, electro-optical (EO) systems steer using very complex and expensive mechanical systems. For microwave radars, on the other hand, phased array approaches that provide rapid random access steering without any moving parts have become widely available. EO systems will soon follow suit and provide random access beam, or field of view, steering with limited or no moving parts, leading to significantly increased capability and reliability at a lower cost.

We all know that a prism can steer light. The index of refraction in a prism is larger than that of air, so light travels more slowly within the prism. Light passing through a prism will also be tilted because the light moving through the thick end of the prism will be delayed compared to light traveling through the thin end.

Light could be steered by electronically writing a prism. The problem is that it is difficult to create an optical path difference (OPD) as large as would be required to write the full prism. For example, a 10-cm width aperture steering to 30 degrees would need a 5-cm OPD at the thick end of the prism.

For a single wavelength, however, we can take advantage of the fact that light is a sine wave. With sine waves, it does not matter if we have 0, 2π, 4π or $n\pi$ phase shift. From a phase point of view, they are all the same. We can therefore subtract 2π phase shift every time the phase reaches 2π, ending up with a sawtooth phase profile. The unfolded phase, which is called a modulo 2π phase profile, looks like a full prism and steers light in the same manner. However, it makes the beam steerer wavelength-dependent (dispersive).

We would like to be able to steer to large angles using this approach. Radar phased array apertures steer to greater than 45 degrees by modulating phase. The largest angle you can steer to results from the size of the smallest individually addressable phase element. An individual radiator has a beam divergence given at the half power points by:

$$\theta = \frac{1.08 * \lambda}{d} \quad , \qquad (1)$$

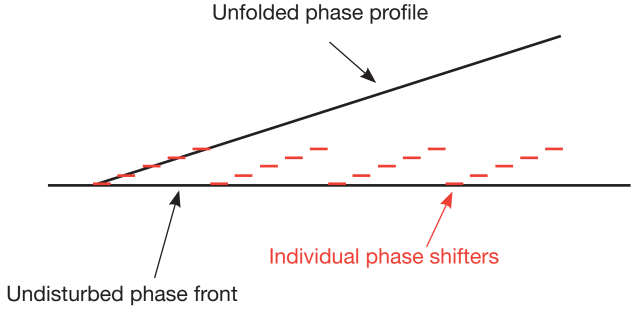
where θ = beam divergence, λ = wavelength of the electromagnetic radiation, and d = the width of the individual radiator. If the phase can be locked among many individual radiators, the beam will become narrower in angle proportional to the increase in the effective size of the radiator:

$$D = nd \, , \qquad (2)$$

where n is the number of individual radiators assembled to make the large radiator. The beam width will be reduced by substituting large D for small d in equation 1. By adjusting the phasing among the individual elements, the narrow beam can be steered under the envelope of the beamwidth from an individual radiator.

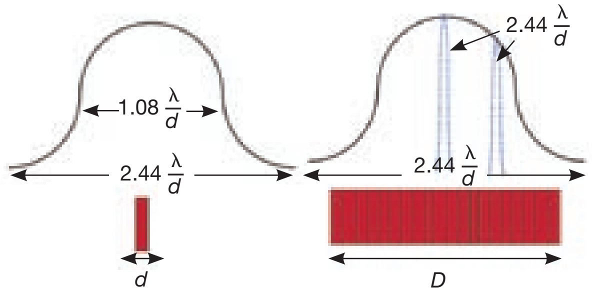
Phased array microwave radars steer to angles larger than 45 degrees. To do this, the radars use individual radiators that are at a half wavelength spacing or closer. From equation 1, if d equals one half of λ, then θ = 2.16 radians, or 124 degrees. This is the full beam width at the half power points. We could

[Modulo 2π Phase Shifting]

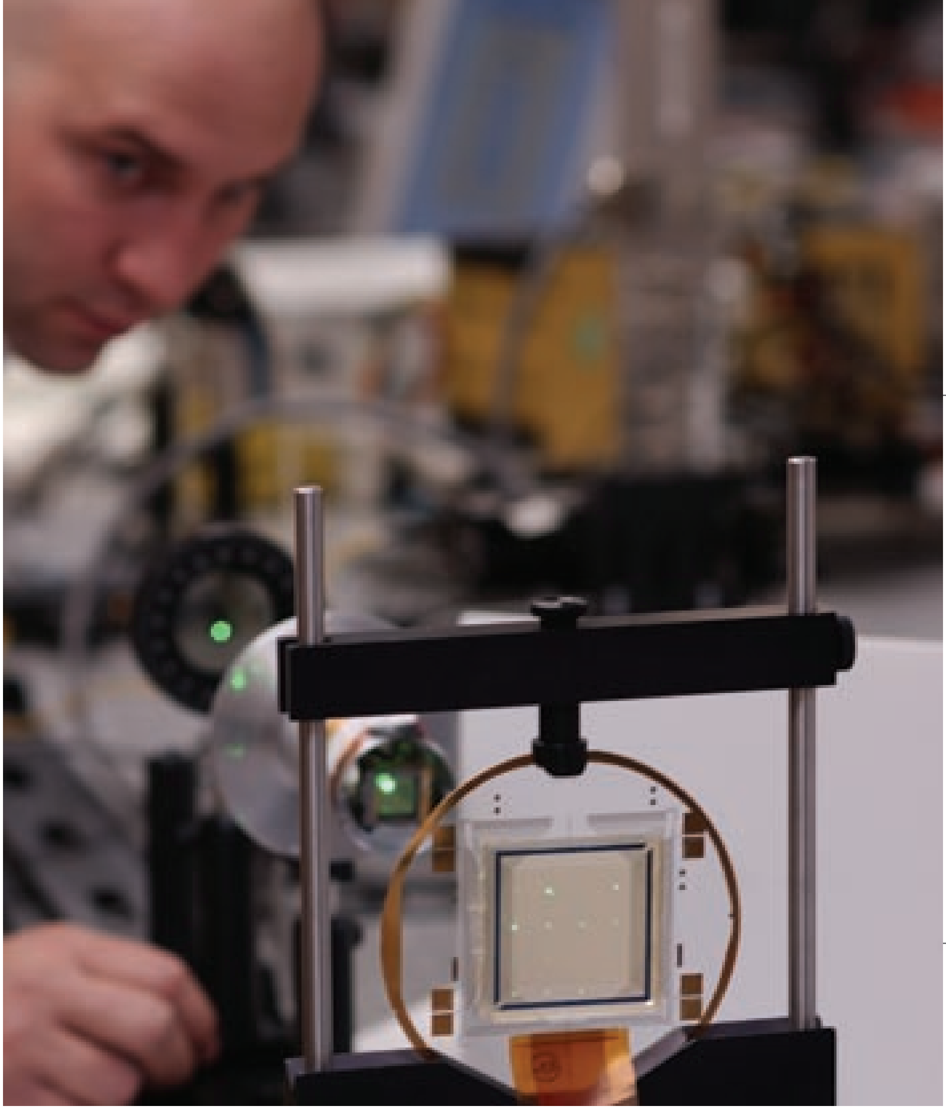


A sawtooth phase profile with a triangular unfolded phase profile is used to create beam steering.

[The Envelope Under Which Beam Steering Occurs]



λ = wavelength of the electromagnetic radiation; d = the width of the individual radiator; $D = dn$, where n is the number of individual radiators assembled to make the large radiator.



Timothy Finegan

By imposing an electric field, it is possible to change the index of refraction of a liquid crystal for light of a given polarization.

steer plus or minus 60 degrees and still be above the half power point, neglecting the cosine factor loss in the projected area of the aperture.

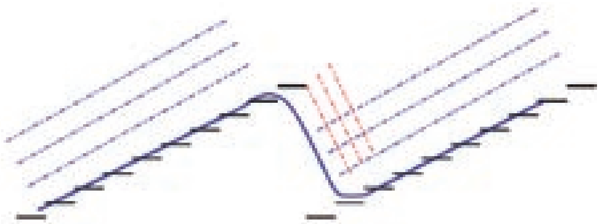
Liquid crystal spatial light modulators can be used to create individual radiators with a phase we can modulate. However, half wavelength spacing is currently not possible for these liquid crystal-based devices. The problem is fringing fields. Liquid crystals are birefringent due to the orientation of long molecular chains.

By imposing an electric field, it is possible to change the index of refraction of a liquid crystal for light of a given polarization. We can write the sawtooth phase profile discussed earlier by using a series of small electrodes across from a ground plane, with a liquid crystal medium in between. The electrodes can be made at half wavelength spacing, so it would seem that we should be able to steer to very large angles, just like phased array radar.

The figure on the right shows the difficulty. Fringing fields make it impossible to impose a voltage that stays only between the small electrodes. Rather, voltage expands outward to each side of the small electrode. As a rule of thumb, the narrowest voltage region above an electrode is about the thickness of the liquid crystal layer between the electrode and the conducting sheet.

If we assume a birefringence of 0.2, the liquid crystal layer must be 5λ thick to create a one-λ phase delay. Using equation 1, the full width half power point of the envelope can be calculated to be 12 degrees, so we can steer out to 6 degrees in either direction at the half power points. For a reflective liquid crystal approach, the thickness of the liquid crystal layer could be half as much, thus doubling the allowed steering angle.

[Actual Phase Profile Compared To Imposed Voltage Profile]



Fringing fields make it impossible to impose a voltage that stays only between the small electrodes. Rather, voltage expands outward to each side of the small electrode.

Beam steering techniques

Two techniques are currently being used for wide angle beam steering: holographic glass and birefringent prisms. In the holographic glass approach, multiple holograms are angularly multiplexed in a single piece of glass. The holograms produce large angle deflections. A liquid crystal beam steerer before the glass selects which hologram is addressed, resulting in the desired large angle of deflection. Many layers of holographic glass can be used.

For example, we could use eight holograms in each direction, azimuth and elevation. If each hologram steers to angles separated by five degrees, then we have a total field of regard of 40 degrees, broken up into eight zones of five degrees each. Doubling the field of regard to 80 degrees would require doubling the number of holographic gratings. Filling each zone requires the use of a second azimuth and elevation liquid crystal beam steerer after the holographic glass.

Raytheon has pursued this approach and demonstrated continuous beam steering over a field of regard greater than 45 degrees. It would be possible to use this technique to steer both polarizations of light if all of the elements in the beam steerer were doubled.

However, loss can be significant due to all of the required elements. Right now, the largest diameter holographic glass available is about 3.5 cm in diameter.

A second approach to wide angle beam steering is to use birefringent prisms. This technique also starts with an azimuth/elevation liquid crystal beam steerer for small to moderate angle beam steering. Larger angles are reached using a set of binary birefringent prisms. One polarization sees the prism deflecting the beam in one direction, while the other sees the prism deflecting it the other way.

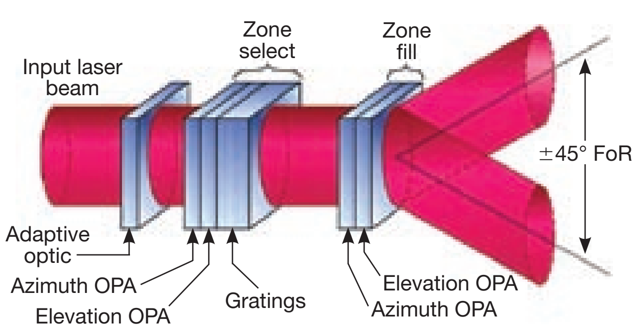
Binary beam steering can be accomplished by rotating polarization between prism layers. A liquid crystal layer can be used to rotate polarization immediately before each birefringent prism. Multiple prisms at factors of two in angular deflection allow for large angle beam steering.

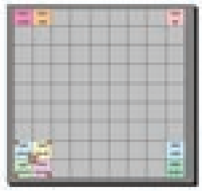
For example, once again taking the case of a 40-degree field of regard continuous beam steerer, birefringent prisms would be needed for 2.5 degrees, 5 degrees and 10 degrees to steer over the field of regard. If the desired field of regard was 80 degrees, a 20-degree steering prism would be needed. Rockwell Scientific is pursuing the birefringent prism approach for wide angle steering. The company has demonstrated steering out to plus or minus 20 degrees using this approach.

A difficulty with birefringent prism wide angle beam steering is that the prisms will get very thick as one approaches large angles. If a person were to use a birefringent material with a 0.2 birefringence and a 5-cm diameter aperture, a 20-degree beam steerer would require a prism thickness of more than 8 cm. This thickness level causes problems with beam walk-off—meaning the beam can hit the side wall because it is steered and remains in a long tunnel.

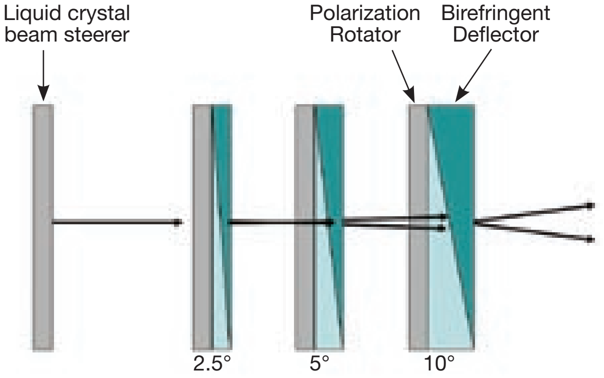
To compensate for beam walk-off, a thick aperture must expand as the beam travels from the entrance of the aperture to the exit. Currently, the largest birefringent prisms range from 1 cm to about 5 cm, depending on the material used; prisms made from higher birefringence materials are available in smaller sizes.

[Wide Angle Steering Approaches]





In the holographic glass approach, multiple holograms are angularly multiplexed in a single piece of glass, producing large angle deflections. A liquid crystal beam steerer selects which hologram is addressed, resulting in the desired large angle of deflection.



Steering using birefringent prisms. An azimuth/elevation liquid crystal beam steerer is used for small to moderate angle beam steering. Larger angles are reached using a set of binary birefringent prisms. The number of components shown would need to be doubled to steer in both dimensions.

> Nonmechanical beam steering will become available for active, laser-based, EO systems before it is used for passive EO sensors.

As mentioned earlier, the use of modulo 2π beam steering creates a dispersive system. This will be sufficient for most laser radar or laser communications applications. Even broadband laser communications require a very small fractional bandwidth.

For steering a wavelength other than the design wavelength, the steering angle is given by:

$$\theta = \theta_0 \frac{\lambda}{\lambda_0} \quad , \qquad (3)$$

where θ is the actual steering angle, λ is the wavelength of light steered, θ_0 is the steering angle at the design wavelength and λ_0 is the design wavelength. A 2.5-GHz-wide laser communications signal would only have a fractional bandwidth of about 1.3×10^{-5}, so the angular spread from that bandwidth would be minimal.

However, if the goal is to steer broadly separated laser lines, or to steer passive sensors, then dispersion becomes a significant issue. The wavelength range of visible light is from 0.4 to 0.7 µm—a significant fractional bandwidth. Passive infrared sensors are often from 3 to 5 µm in wavelength, or from 8 to 11 µm. Both would result in very broadly steered beams using this approach without any dispersion compensation.

Reducing dispersion

We have investigated two basic approaches for significantly reducing dispersion. The first is to increase the size of the resets, which are used to reduce the required amount of OPD. The effective phase is the same after subtracting 2π phase as it was before the subtraction. When the wavelength differs from the design wavelength, each reset results in a phase discontinuity.

If instead of a 2π reset we have a 200π reset, the design wavelength does not need to be far off before the new wavelength will divide into the 100 design wavelength optical path difference by either 99 or 101 times, again causing a smooth unfolded phase profile. This is the reason why larger resets result in better dispersion properties.

To use modulo 200π resets, however, you must be capable of producing much larger OPDs. Research out of Kent State suggests that this can be accomplished by using sheared liquid crystals while maintaining switching speed. Disadvantages to this approach would be increased voltage requirements and absorption. Higher voltage is needed to maintain the same E field as the liquid crystal layer becomes thicker. Prior to the Kent State breakthrough, liquid crystal switching became slower as the square of the thickness.

A second approach to mitigating dispersion caused by resets is to combine beam steering with a telescope that has a magnification of dispersion that exactly cancels the dispersion resulting from the beam steering. This is a very unusual telescope, using a Fourier transform lens to maintain a constant back focal distance while varying the focal length of the lens with wavelength.

We are investigating using this approach to mitigate beam steering dispersion. We have fabricated one device along these lines, but it was very long and only lessened dispersion over a relatively narrow bandwidth in the visible region.

Future outlook

The steering devices that are available at present are small, expensive and steer over relatively narrow angles. In the not-so-far-off future, however, we will be able to steer optical systems randomly and rapidly with no moving parts. We will design devices to steer laser beams first, and then develop the ability to steer passive sensors. Conformal, nonmechanical steering of optical systems is within our grasp.

Initially, narrowband nonmechanical beam steering will become available. Broadband beam steering will take more time to develop. Thus, nonmechanical beam steering will become available for active, laser-based, EO systems before it is used for passive EO sensors. Also, passive EO sensors really tend to use both polarizations; for active EO systems, on the other hand, designers have more control over the polarization.

Over the long run, engineers should be able to use the inherent dispersion of optical phased array devices to enhance passive multispectral sensors. Currently, the main obstacle to using the dispersion is the variation of dispersion that occurs with the steering angle. ▲

[Paul McManamon is the 2006 president of SPIE and chief scientist in the Sensors Directorate at the U.S. Air Force Research Laboratory.]

[References and Resources]

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