Polarization Gratings
for
Non-mechanical Beam Steering Applications

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Polarization Gratings for Non-mechanical Beam Steering Applications

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ABSTRACT

Over the last few years, Boulder Nonlinear Systems (BNS) and North Carolina State University (NCSU) have developed a new beam steering technique that uses a stack of thin liquid crystal polarization gratings (LCPGs) to efficiently and non-mechanically steer a beam over a large field-of-regard (FOR) in discrete steps. This technology has been successfully transferred to BNS through an exclusive license agreement, and a facility has been completed to enable commercial production of these devices. This paper describes the capabilities enabled by both the LCPGs and the successful transfer of this technology.

Keywords: non-mechanical, beam control, beam steering, imaging, remote sensing, conformal aperture

1. INTRODUCTION

Efficient, wide-area beam control is a critical capability for sensors and typically represents one of the primary constraints for active and passive sensing and imaging systems. In 2007, Boulder Nonlinear Systems (BNS) and North Carolina State University (NCSU) began a successful collaboration to develop liquid crystal polarization grating (LCPG) switches for non-mechanical, wide-angle beamsteering. LCPGs are thin birefringent films that steer light to one of two deflection angles, depending on the polarization handedness of the input light. Active devices also possess a third polarization independent 'off' state. An appropriate stack of LCPGs can create a wide-angle non-mechanical beam control system with significant improvements over mechanical systems in size, weight, and power (SWaP), beam agility, and pointing stability for future conformal aperture implementations of active transmitters and receivers. This work represents a success story for the SBIR program, with early advances developed as an Air Force SBIR program and progressing to the commercial capabilities currently offered by BNS. Manufacture of the patented devices has been successfully transferred to a dedicated cleanroom production facility at BNS to enable the technology to be exploited for a broad range of applications including active and passive remote sensing and imaging, as well as, manufacturing and bio/medical imaging and sensing.

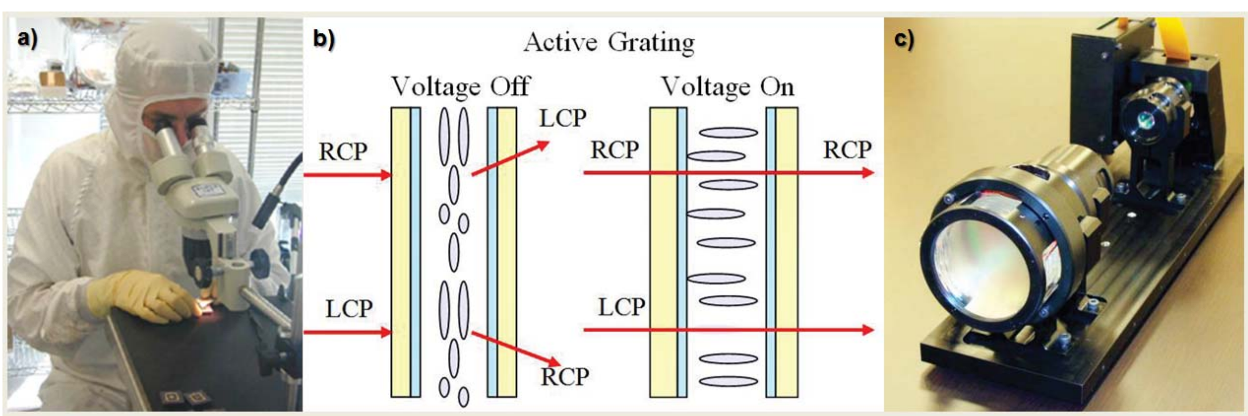

Figure 1. Efficient polarization gratings for non-mechanical beam control. The LCPGs for beam steering were co-developed by BNS and NCSU. a) Boulder Nonlinear Systems has successfully transferred the technology from NCSU to a dedicated cleanroom manufacturing facility at BNS in Lafayette, CO. b) A depiction of the active grating operation. Based on the handedness of the polarization, the beam is selectively steered to a particular direction, including a polarization independent 'off' state. c) An image of the steering unit successfully developed through an AFRL Phase 2 SBIR program, which is capable of continuously and non-mechanically steering a beam over an 80°×80° field-of-regard[1].

2. BACKGROUND

In 2007, BNS began a successful collaboration with North Carolina State University (Prof. Michael Escuti) to develop transmissive, liquid crystal polarization grating (LCPG) switches for non-mechanical wide-angle beamsteering. Manufacture of the patented devices has been successfully transferred to BNS with an exclusive license arrangement and the construction of a dedicated cleanroom production facility. Passive LCPGs are thin birefringent films that steer light to one of two deflection angles, depending on the polarization handedness of the input light (see Figure 2). Including electrically variable waveplates in the stack enables switching operation for arbitrary polarizations. LCPGs are similar to traditional diffraction gratings utilizing a periodic structure to steer light, however, they use polarization modulation instead of pure phase or amplitude modulation, resulting in high first-order efficiencies exceeding 99.8%. The high efficiency and compact size makes LCPG's a natural candidate for coherent beamsteering[3] and active and passive image scanning systems. Although passive LCPGs have been in development since 2005, it has only been recently that active LCPGs have been available[2]. When an active LCPG is switched on, its grating structure disappears, resulting in a crucial third undeflected and unpolarized light path. Because each element in a stack can be switched off, added, or subtracted from the net deflection, a relatively small stack can provide a large set of deflection angles, enabling a wide range of angles in two dimensions to be achieved with a small number of stack elements. High quality, large aperture gratings have been demonstrated with large steer angles for wavelengths from visible to MWIR. These devices are optically efficient, rugged, and capable of being placed on remote platforms, where size, weight and power (SWaP) can represent a significant system constraint.

Combining these devices with a spatial light modulator (SLM) allows even greater flexibility in both fine beam control and wavefront correction. An SLM is a device that modulates light according to a fixed spatial (pixel) pattern. SLMs have an expanding role in several optical areas where light control on a pixel-by-pixel basis is critical for optimum system performance. SLMs are typically used to control incident light in amplitude-only, phase-only or the combination (phase-amplitude). BNS manufactures and sells liquid crystal based Spatial Light Modulators for a variety of applications that are based on liquid crystal on silicon (LCoS) technology, provide high speed phase or amplitude modulation, and operate with high optical efficiency (see Figure 3). The first devices were developed in 1990 and the first commercial LCOS SLM (a sub-millisecond analog device) won the 1994 Photonics Spectra Circle of Excellence Award. BNS manufactures both one and two-dimensional SLMs covering a range of sizes (up to 4 inch aperture) and resolutions. BNS has delivered both transmissive and high-efficiency reflective devices. In the last 5 years, BNS has been actively transitioning liquid crystal (LC) devices from the visible, near-visible and near infrared (NIR) to the short wave infrared (SWIR), mid-wave infrared (MWIR) and long wave infrared (LWIR). To date, BNS has delivered SWIR and MWIR SLMs that operate at 200 frames per second (fps).

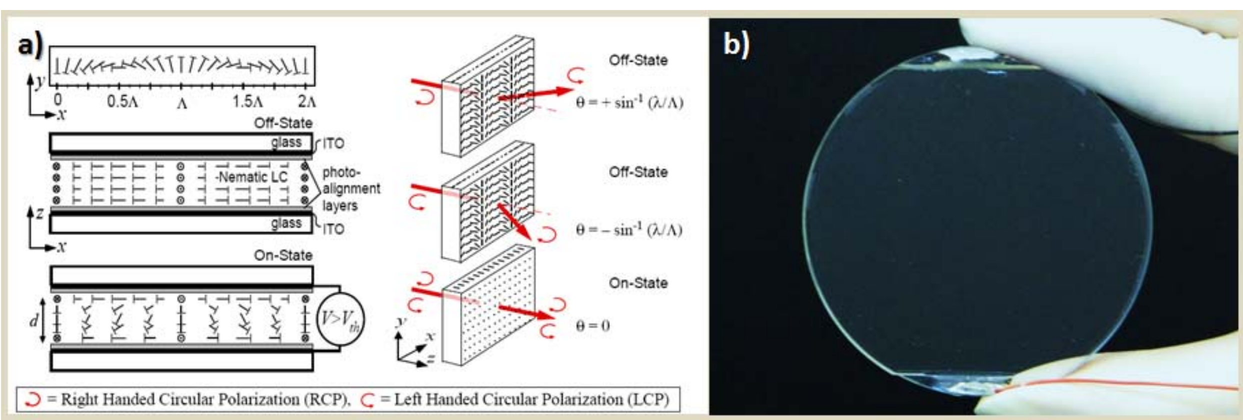

Figure 2. Polarization grating switch overview. a) Switchable LCPGs can switch between three different steering states. A stack of several PGs enables wide field-of-view beam control. Including electrically variable waveplates in the stack allows operation with arbitrary polarization states. b) A picture of a polarization grating switch used for wide angle beam steering. These devices were used to demonstrate 112°×112° beam steering with a single 50 mm conformal aperture. The production facility at BNS is now operational for manufacturing both active and passive LCPG switches to address a wide range of system configurations.

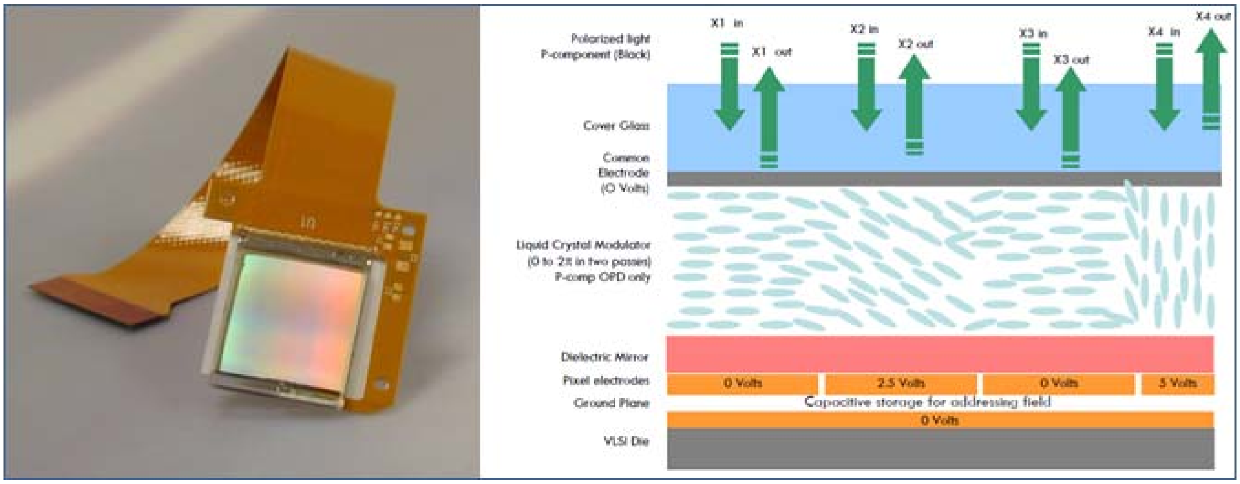

Figure 3. Spatial Light Modulator overview. The BNS reflective SLMs are based on liquid crystal on silicon (LCoS) technology, provide high speed phase and/or amplitude modulation, and operate with high optical efficiency. In the last 5 years, BNS has been actively transitioning liquid crystal (LC) devices from the visible, near-visible and near infrared (NIR) to the short wave infrared (SWIR), mid-wave infrared (MWIR) and long wave infrared (LWIR). To date, BNS has delivered SWIR and MWIR SLMs that operate at 200 frames per second (fps).

3. TECHNOLOGY TRANSFER & MANUFACTURING CAPABILITY

Because of the strong, positive response to the prototype systems developed using this technology, and the significant potential for other application areas, BNS has made a substantial investment in commercializing the LCPG technology. This investment includes a dedicated cleanroom facility (see Figure 4), manufacturing equipment, and training for the manufacturing personnel. The additional cleanroom augments our existing facilities for the on-site manufacture of commercial spatial light modulators. In the last 5 years, BNS has been actively transitioning liquid crystal (LC) devices from the visible, near-visible and near infrared (NIR) to the short wave infrared (SWIR), mid-wave infrared (MWIR) and long wave infrared (LWIR). BNS has worked with NCSU to fabricate visible, NIR and MWIR LCPGs, and will continue to advance these capabilities with the new facility.

Figure 4. Boulder Nonlinear Systems LCPG cleanroom manufacturing facilities. BNS has made a significant internal investment in order to create a dedicated manufacturing facility to commercialize the LCPG technology. The high efficiency of the devices combined with low-SWaP will enable advances in several areas requiring compact, high efficiency beam/light control. Applications include active and passive imaging, remote sensing, manufacturing, and bio/medical imaging and sensing.

4. DEVICE CAPABILITIES & APPLICATIONS

Existing systems have demonstrated beam/light control over a 112°×112° field-of-view for visible and SWIR from a single aperture. These demonstrations have been for both coherent beams and imaging. Therefore, the technology is applicable to all passive and active optical sensing systems. Some of the demonstrated system parameters include:

- Low scattering losses(< 0.5% per element)
- High overall diffraction efficiency (>99% per element)
- Clear apertures exceeding 5 cm (current manufacturing process supports > 15 cm)
- Non-mechanical steering over a 112°×112° field-of-regard with sub milliradian (mrad) precision
- Application to incoherent, non-collimated beams (for imaging applications)
- Power consumption less than 4 mW per element (full system draws < 0.5 W)
- Demonstration of systems from visible to SWIR (LCPGs demonstrated from visible to MWIR)

The LCPGs (see Figure 5) have been successfully implemented in several steering systems providing precision, wide-angle beam control for active and passive systems with a conformal aperture. Each element consumes ~4 mW, and the entire wide-angle beam control system consumes < 0.5 W. In each case, the complete package weighed ~0.5 kg. The compact package offered the size, weight, and power (SWaP), beam agility, and pointing stability improvements needed for future conformal aperture implementations for active and passive transmitters and receivers. This is in contrast to the requirements of a typical gimbal that is constrained by inertia, bulky, power-hungry, slow, and does not provide random access within a scene. For example, an 8 inch gimbal would typically be > 20 kg and use > 300 W (this is for the gimbal only and excludes the control electronics) to achieve a full scale deflection time > 400 milliseconds. The demonstrated non-mechanical architectures have a coarse steerer mass of ~0.5 kg using ~0.5 W to provide a full scale deflection time of < 10 milliseconds. This represents an order of magnitude improvement in weight, two orders of magnitude improvement in performance, and three orders of magnitude improvement in power while providing additional capabilities with a conformal aperture. Potential future applications (see examples in Figure 6 through Figure 9) include any platform requiring low-SWaP, high-performance beam control (*e.g.*, unmanned aerial vehicle (UAV) defense, bomber defense, High Energy Laser (HEL) strike, and long-range target identification). Additional uses for the technology include beam control for manufacturing, communications, and automotive applications.

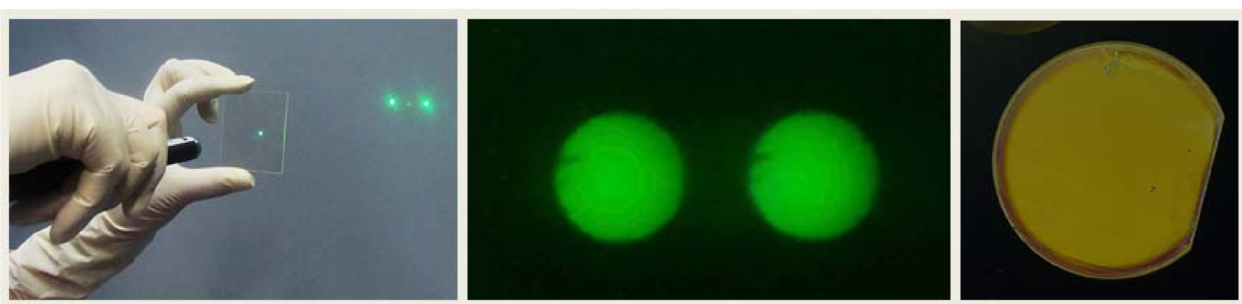

Figure 5. Manufacturing capabilities. LCPG devices can be manufactured on a variety of substrates exceeding 15cm diameter with the existing facilities and equipment. On-site capabilities include both active and passive LCPGs. Device wavefront quality is typically limited by the substrate.

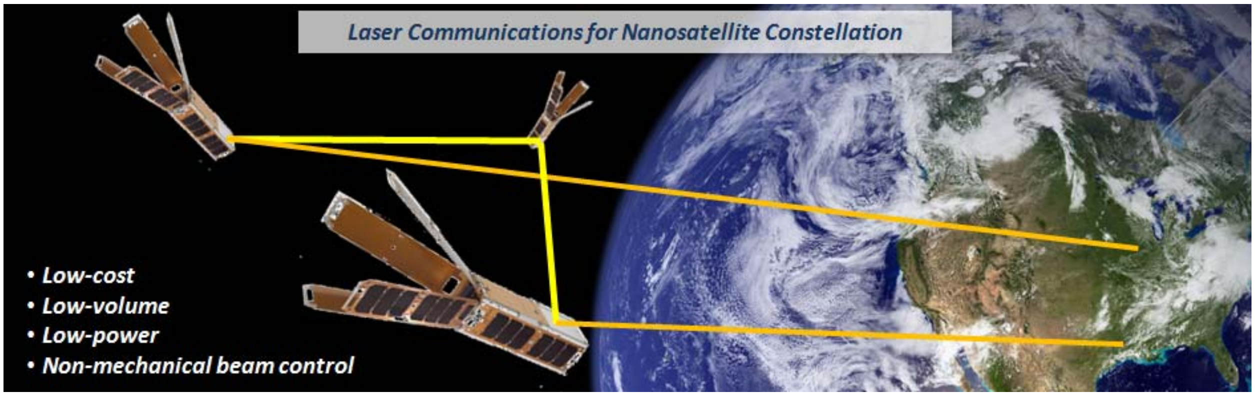

Figure 6. Low-SwaP beam control for optical communications. The extremely low-SWaP of the LCPG devices can provide precision beam control over a wide-field-of-regard.

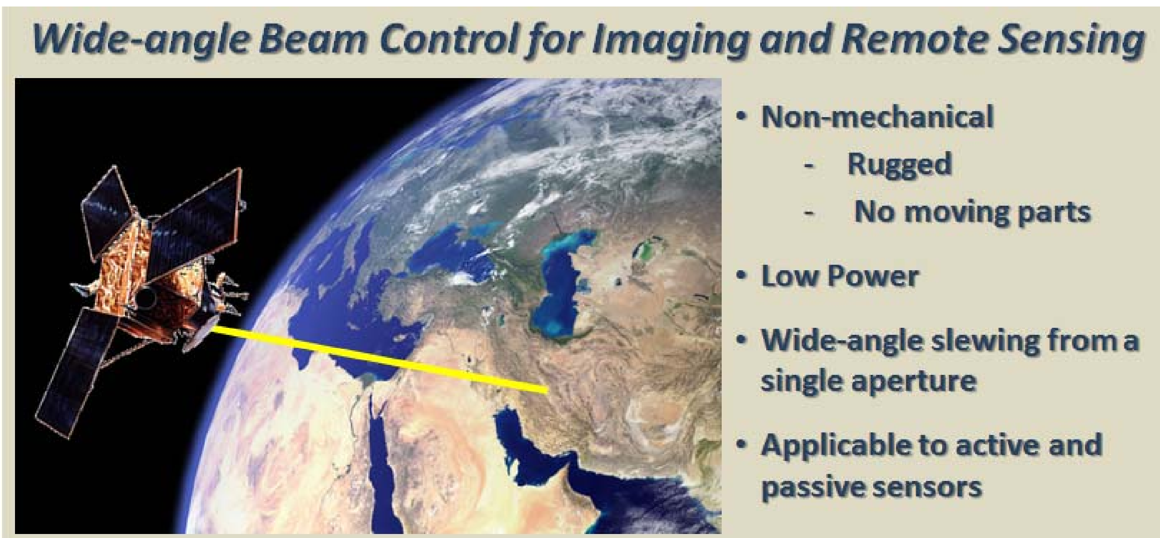

Figure 7. Long-range precision beam control. The rugged, non-mechanical beam control system provides significant advantages for SWaP constrained environments requiring large slew angles.

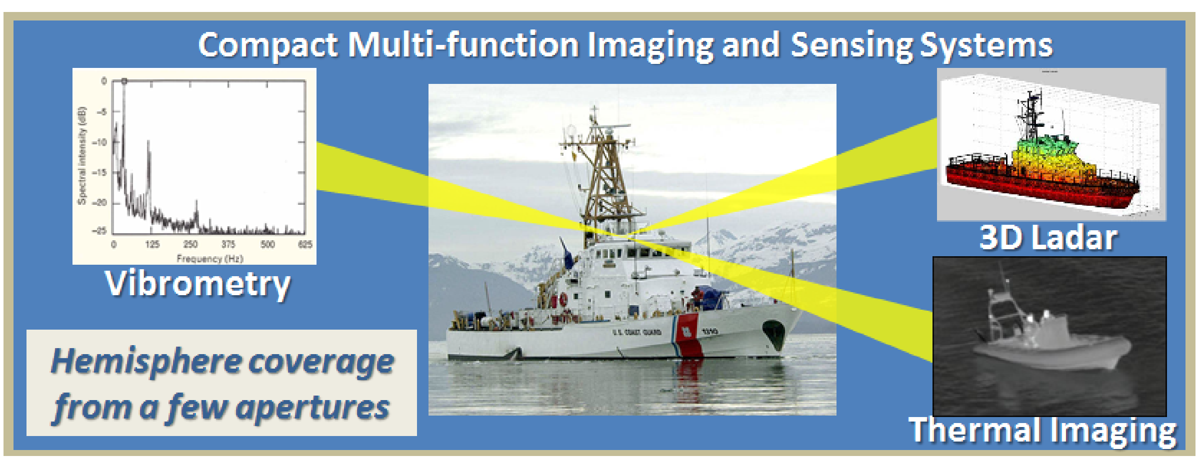

Figure 8. Wide-area coverage, multi-function imaging and sensing applications. The compact, non-mechanical light/beam control applies to multi-function sensors and imagers. The wide field-of-regard from a single aperture means that only a few apertures are required to cover a full hemisphere.

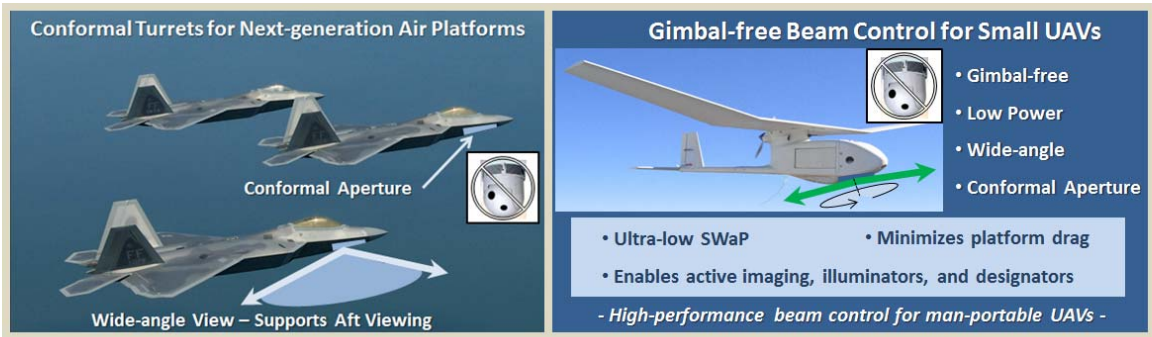

Figure 9. Gimbal-free beam control for air platforms. The low-SWaP and conformal aperture capabilities are applicable to UAVs and next-generation air platforms where mechanical gimbals are impractical.

5. FUTURE WORK

Now that the non-mechanical beam control technology has been successfully transferred and a production facility has been completed at BNS, the next step is to improve the capabilities and device yield, while decreasing manufacturing time. Materials are being explored to efficiently apply the capability to a broader range of wavelengths from UV to LWIR. For the current devices, the wavefront quality is determined primarily by the substrate. Future work will address methods of minimizing the required substrate thickness. Additional efforts are addressing system losses including scatter and index matching over broad wavelengths. Another item that will be addressed is increasing the aperture size beyond 15 cm and incorporating component alignment registration during manufacture.

6. SUMMARY

Boulder Nonlinear Systems (BNS) and North Carolina State University (NCSU) have successfully commercialized an important capability for compact, efficient, non-mechanical beam/light control. Efficient, wide-area beam control is a critical capability for sensors and typically represents one of the primary constraints for active and passive sensing and imaging systems. This work represents a success story for the SBIR program and will allow wide-scale implementation of the LCPG technology for active and passive systems. The LCPG technology enables an efficient, high-performance beam control system to be integrated into a low-SWaP package. The resulting system can address a wide field-of-regard (>100°×100°) with a single conformal aperture. A dedicated cleanroom manufacturing facility has been built, the staff has been trained, and an exclusive license arrangement has been executed. Devices can be manufactured from visible to MWIR with high efficiency (>99% per element) and clear apertures exceeding 5 cm (facility supports > 15 cm). The beam control systems support both collimated and non-collimated beams (for imaging applications), and exhibit very low power consumption with less than 4 mW per element (full systems consume < 0.5 W).

7. ACKNOWLEDGMENTS

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