SAND2012-3268 C

SAND2012-3268C

Development of Photonic Crystal Based Large Format IR Scene Projection Technology

J. A. Wilson[1], B. Burckel[2], J. Caulfield[1],
S. Cogan[3], M. Massie[3], R. Rapp[4], R. Rose[4], D. Snyder[4]

[1]Cyan Systems, Santa Barbara, CA
[2]Sandia National Laboratory, Albuquerque, NM
[3]Nova Teledyne, Solvang, CA
[4]U.S. Air Force AFRL/RWGG , Eglin AFB, FL

ABSTRACT

We report demonstration of prototype Photonic Crystal (PhC) based IR emitters for use in large format IR scene projectors. This approach will support FOVs well over 20 degrees while simulating very high resolution scenes with response time faster than 5 msec. The spectral capability offers true target fidelity for both high temperature regions, approaching 3000K targets against low temperature backgrounds and precise spectral bandwidth and band placement. Single or multiple simultaneous spectral bands can be readily represented giving an unprecedented ability to test emerging generations of multi spectral sensor systems. Spectral bands can be simulated with emission form any combination of SWIR, MWIR and LWIR spectral regions. Mini arrays with up to four different spectral bands have been fabricated. The technology of the emitter is discussed as well as the driver electronic chip and the use of state of the art wafer bonding to assemble the final projector chip. The method of wafer bonding enables emitters of very large format to be fabricated with high yield. The PhC chip is compatible with production in commercial MEMS foundries. These photonic crystals are fabricated from refractory materials to provide high radiance and long device lifetime and require less electrical power to achieve high operating temperature. Cyan is teamed with Sandia National Laboratories, to develop photonics crystals designed for realistic scene projection systems and with Nova sensors to utilize their advanced Read-In Integrated Circuit (RIIC). The program is supported by the Missile Defense Agency's Extremely Large IRSP program.

Keywords: Infrared Scene Projector (IRSP), Photonics Crystal (PhC), Metamaterials, MEMS Foundry, Extremely Large IRSP (ELIRSP), Tungsten, Read In Integrated Circuit (RIIC)

1. INTRODUCTION

Modern Infrared Focal Plane Arrays (IRFPA) have been developed with very high dynamic range and multiband versions are being deployed in fielded systems. Field testing of these advanced sensors can be very challenging, time consuming, and expensive. There is a need to develop advanced scene projection technology to operate both in laboratory testing and validation of fielded units immediately prior to mission use. A new approach based on PhC emitters promises to enable scene projectors with unprecedented fidelity to real world scenarios. Photonic crystals are a class of metamaterials that derive their properties primarily from their structure rather than the material used. Metamaterials offer a capability to engineer structures for desired properties rather than the frequently futile search for natural materials with those properties. The structure used here employs Tungsten PhCs fabricated in a "log pile" arrangement, shown on the right in Figure 1, using the MEMs foundry at Sandia National Laboratories (SNL). Use of Tungsten offers several important advantages, including high operating temperature, structural rigidity and stability, long component lifetime and a broad compatibility to generic foundries.

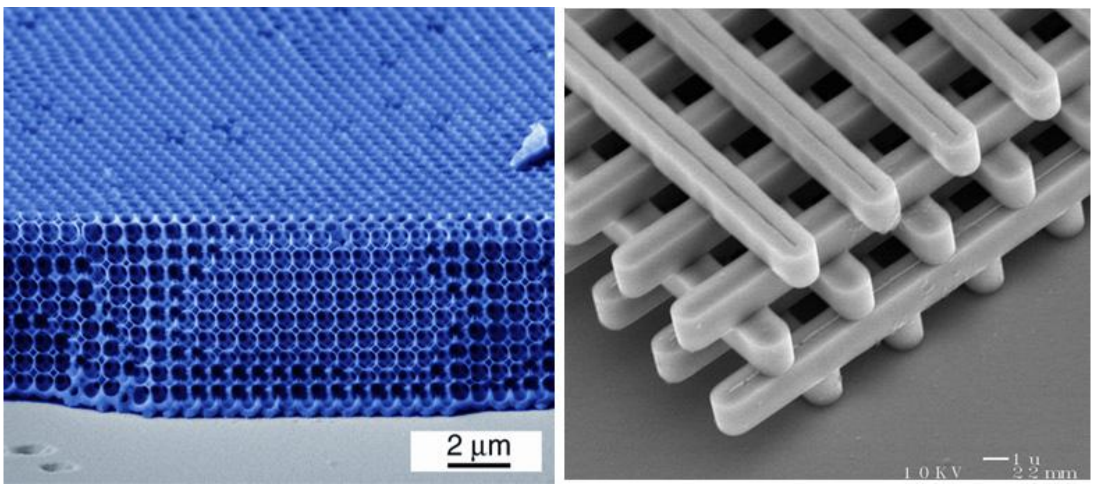


Figure 1. Two of the many candidate structures available for use as PhC emitters.

2. OVERVIEW OF PHOTONIC BANDGAP MATERIALS

Structures that exhibit photonic bandgaps are composed of dielectric components formed with periodicity in one, two or three dimensions. Depending on the scale of the periodicity and the size of the dielectric components the optical analog of an electronic band structure can be tailored which will allow or prevent propagation of specific wavelengths.[1] The width and placement of the allowed and forbidden bands is determined by the geometry of the specific design.[2] Lord Rayleigh was the first to note that light reflection is inherent in materials that possessed a periodic variation in the index of refraction.[3]

In order to design the photonic crystal structure for scene projectors, Sandia Laboratory has developed a finite element solution to the 3-dimensional Maxwell's equation using a periodic index of refraction in all 3 dimensions. This simulation is known as the Rigorous Coupled Wave Analysis (RCWA) and is used obtain key optical properties of the PhC lattice: reflection (R), transmission (T) and absorption (α). Using this set of equations we can optimize the photonic bandgap to allow IR emission bands of arbitrary width, precisely matching real world signatures, while suppressing unseen out-of-band energy.[4]

Multiband Photonic Crystal Design and Optimization Process

The RCWA simulation is shown schematically in **Error! Reference source not found.**. Key steps in the design process are:

- IR emission is first calculated assuming a black body heating source.
- A generic algorithm is used to find the optimal lattice parameters that maximize emitter efficiency in the band of interest.
- Candidate structures emission profiles outside the band of interest are retained and revaluated using Maxwell's equations scaling law via the sliding window objective function.

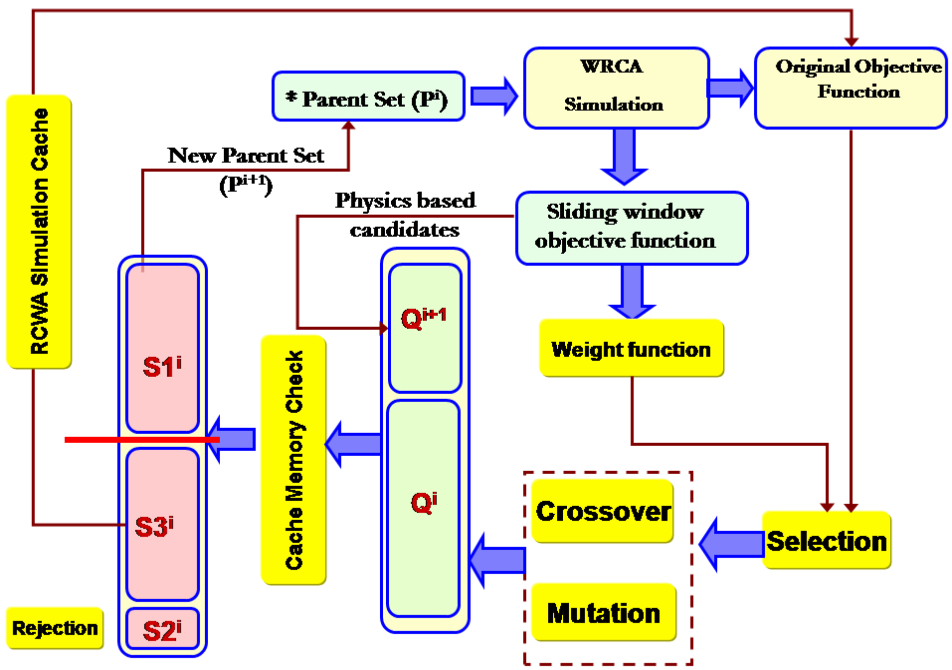


Figure 2. Sandia's Rigorous Coupled Wave Analysis used for PhC Optimization.

After selection of the photonic lattice parameters for a given waveband, the RCWA was run on sample spectra in key IR bands. Estimations performed suggest that PhC radiant power efficiencies can be as much as 73 % more efficient than a blackbody at wavelengths in the 3-5 μm and the 8-12 μm range.

Simulation performed to date have also shown a forward radiative profile that is significantly more forward directional than a Lambertian radiator. This forward angular radiation profile minimizes wasted heat to the dewar walls over that typical for Lambertian radiators. Due to the selective band emission of a PhC, a higher radiance in the desired bands than can be achieved compared to a standard blackbody radiator at the same input power level.

There are numerous benefits that can be exploited via these preferred spectral and angular emission actions, including but not limited to; 1) increased in-band radiative efficiency, 2) lower sidelobe radiance, allowing reduced RIIC drive current, 3) reduction in inter-dewar wasted heat, lowering the cooling requirements, and potentially simplifying the projector dewar design.

3. THERMAL/RADIATIVE PERFORMANCE PREDICTIONS

Optimization of a PhC based scene projector emitter to operate at high output fluxes while still delivering quick response time involves balancing the thermal and electrical conductivity and capacitance. To accomplish this we have developed a finite-difference model that solves the heat equation with both radiative and conductive losses to the surroundings based on component geometry and materials chosen. The expression governing the thermal behavior of the XTEMPS pixels for the case of excitation by Joule heating is shown in Figure 3. A schematic of the physical setup described by the equations is shown in Figure 4.

$$C_{th}\frac{dT_E}{dt} = I_E^{\,2} R_E - 2\sigma_{PhC} A \varepsilon_{PhC} (T_E^{\,4} - T_S^{\,4}) - Gleg\,(T_E - T_S)$$

$$T_E = \int \frac{I_E^{\,2} R_E}{C_{th}}\,dt - \int \frac{2\sigma_{PhC} A \varepsilon_{PhC} (T_E^{\,4} - T_S^{\,4})}{C_{th}}\,dt - \int \frac{Gleg\,(T_E - T_S)}{C_{th}}\,dt$$

Applied Power Heating **Radiated Heat** **Conducted Heat**

Figure 3. Heat flow equation used to simulate and optimize XTEMPS performance parameters.

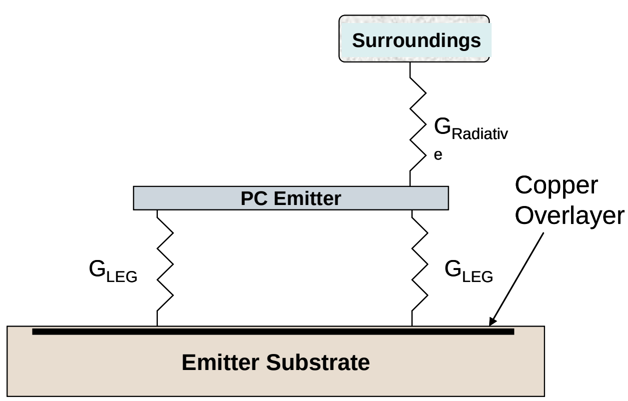


Figure 4. Simple schematic shows how heat is dissipated through both radiation and conduction. The radiative term goes as ~T^4 .

From the heat flow equation above one can determine rise and fall times and approximate them with exponentials. These equations are non-linear and transcendental in nature, and can be solved iteratively. The equations shows that radiative loss will go as T^4 and conductive as T, which means that at lower temperatures, more power can be expected to be dissipated thru conduction.

With PhCs operating at high temperatures, the radiative decay dominates over the thermal time constant set by the mechanical leg conductance and thermal mass. Small leg conductance can be advantageous in retaining heat and boosting output flux.

Note that the time constants above are based upon the conductive time constants. In reality, the radiative dominance of heat loss at higher temperature serves to lower the effective time constant. A dynamic simulator to solve the heat flow equation based on these parameters was developed for XTEMPS.

4. MULTISPECTRAL PIXEL FABRICATION

Test structures constituting a Design of Experiments (DOE) matrix containing hundreds of different pixel, array, and thermal leg geometries were fabricated to explore the design parameter space to identify robust unit cell designs and to empirically identify dependencies of heater impedance on structural details. Figure 5 illustrates the design of one of a single candidate pixel on the test structure. The top seven layers are the W bars of the photonic crystal while the lower two layers represent a serpentine heater (tan) and electrically insulating (blue) layers. This is an example of a thermally heated PhC emitter. W is the material of choice[5] for this approach to high temperature operation due to it's compatibility with existing MEMS foundry processes and it's ability to provide long operational life time at emitter temperatures around 2000K.

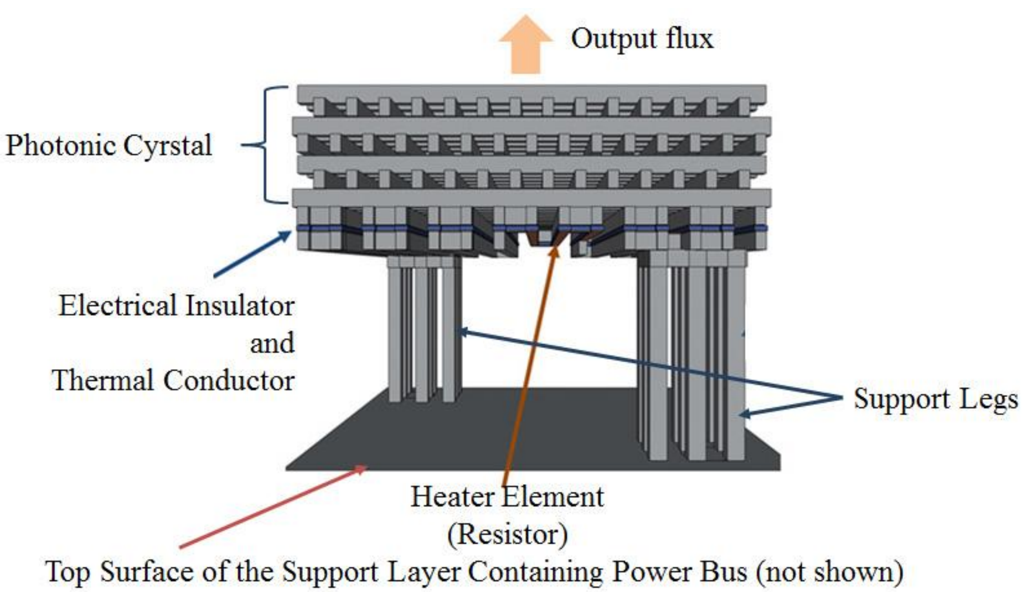


Figure 5. Schematic representation of the structure of a single unit cell supported by two electrically conductive legs.

Figure 6 shows micro photos of a single color (left) and a dual band (right) 16 x 16 element mini-array. The dual band array achieves two color operation from spatially adjacent single color unit cells. Each unit cell in any array (single or two color) is individually addressed and driven. Each array shown exhibited 100% structural yield.

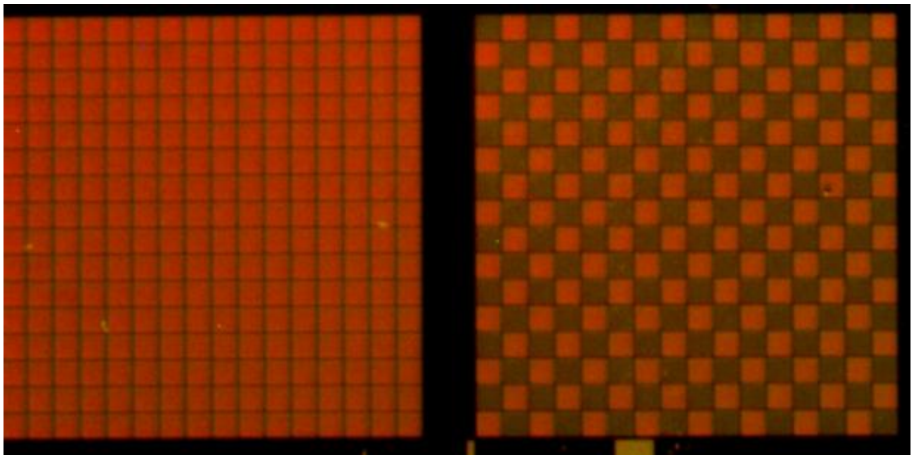


Figure 6. Single Color and Multicolor Photonic Crystal Mini Array showing excellent structural yield.

Figure 7 shows a schematic of the mask layer used to define the lateral length of the leads from the support legs to the heater contacts. Lead length is used to fine tune the balance of thermal and electrical impedance and therefore response time.

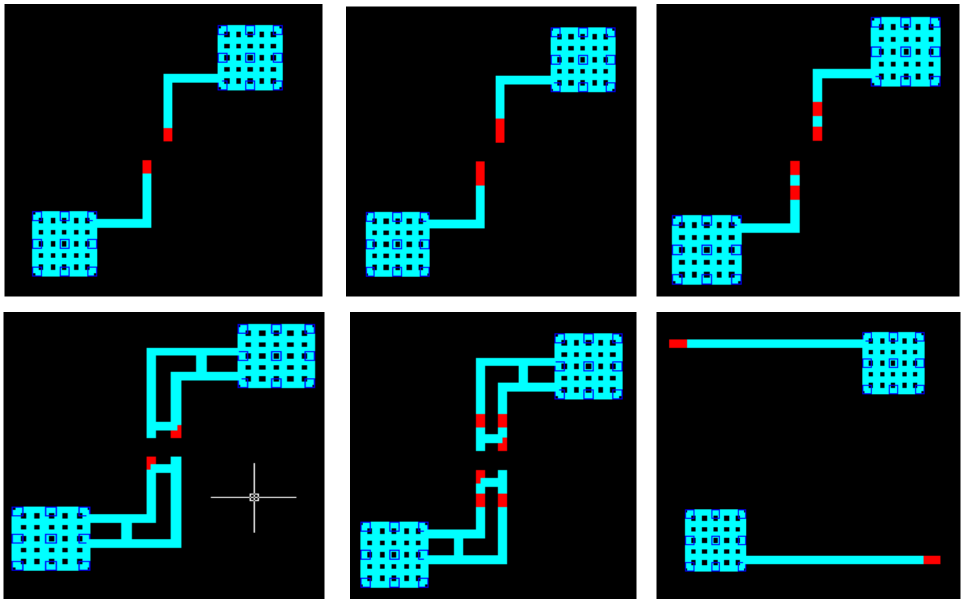
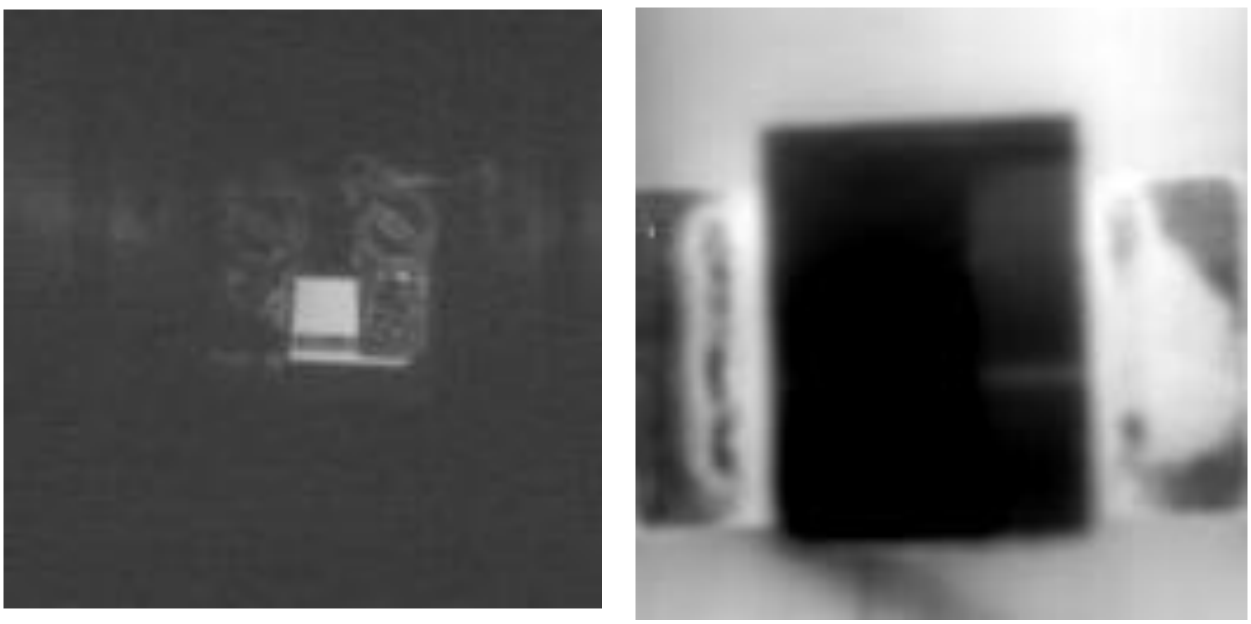


Figure 7. Design of experiments on varying leg structures to optimize PhC performance.

5. CHARACTERIZATION TEST STRUCTURES

The in-band emission and out-of-band rejection properties of the type of PhC selected as the program baseline was demonstrated early in the program as shown in Figure 8. Here two sections of PhC differing in spacing and size of the W bars are viewed with an MWIR sensitive camera. On the left the PhC is being heated by passing a current through the substrate causing emission in the sensitive band of the camera. The PhC viewed on the right has an allowed emission band that is outside that of the camera. In this case the scene shows a film resistor suspended behind and insulated from the PhC. The film resistor is heated by a current and emits as a gray body. The PhC does no allow photons in the sensitive band of the camera to propagate through. The heated film resistor can be seen glowing on either side of the dark PhC. This demonstration was made using macroscopic section of PhC a few mm on a side.



Emission from PhC in camera band — Blocking gray body emission in camera band

Figure 8. Out-of-band blocking and in-band emission of MWIR is demonstrated for the logpile type of PhC.

Dewar test of wire bonded PhC unit cell

Actual emitter unit cells on the scale of 50μm were incorporated into the DOE to optimize specific design features and different fabrication processes. One of these DOE chips is shown in Figure 9. Two rows of devices are wire bonded to carrier pads for dewar testing.

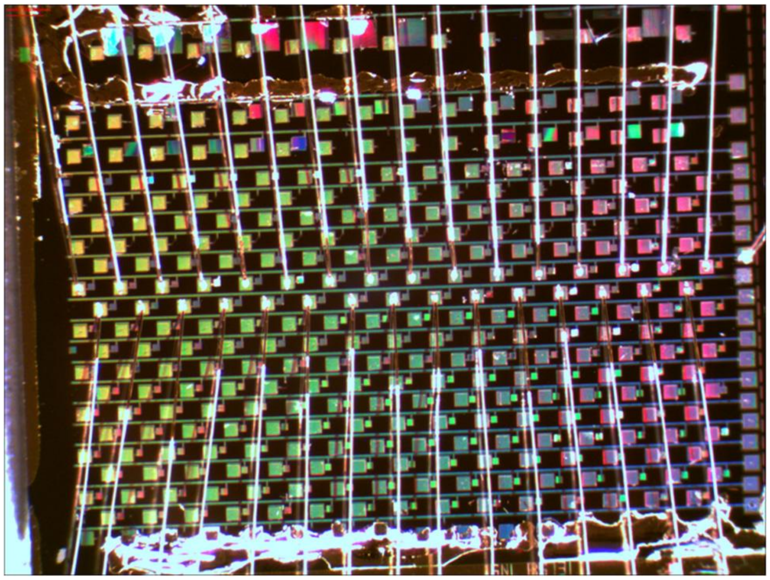


Figure 9. Microscope photo of a DOE test chip showing the 0.7 mil Au leads bonded to two rows of candidate devices.

Both rows of unit cells have PhC emitters designed to emit in band 3 (4.45 to 4.95 μm) of four possible bands, but have different supporting leg structures. Spectral measurements to determine detailed spectral performance are in progress at Sandia NL. As a result of this DOE lot and a subsequent process tuning lot a baseline design for the first full array demonstration has been selected and masks for a fully operational MWIR-LWIR two color 256x256 array are being laid out.

Individual unit cells were driven directly by a power supply outside the dewar while emission was monitored with an MWIR sensitive camera. A single frame from the AVI file of one of these devices is shown in Figure 10.

Figure 10. A single frame from an AVI file showing emission from a single 50 x 50 μm^2 photonic emitter tuned to an MWIR band.

These DOE unit cells do not have optimum impedance and required higher current to operate than will be the case for optimized arrays being run by a RIIC. Current supplied to the device shown in Figure 9 was varied to over 500mA before one of the 0.7 mil lead lines melted. The frame shown is at about 75 mA.

The camera used has a wide sensitivity band of 3 to 5 μm, while the emitter is designed to operate in a much narrower band. The XTEMPS emitter was recorded at over 11,000 counts before the wire bond failed. Based on calibration curves of Figure 11, it is estimated that the effective emission temperature of this very non optimum unit cell is about 800 K. Optimized unit cells using this basic design are projected to operate at real temperature approaching 2,000 K and will simulate targets of 3,000 K.

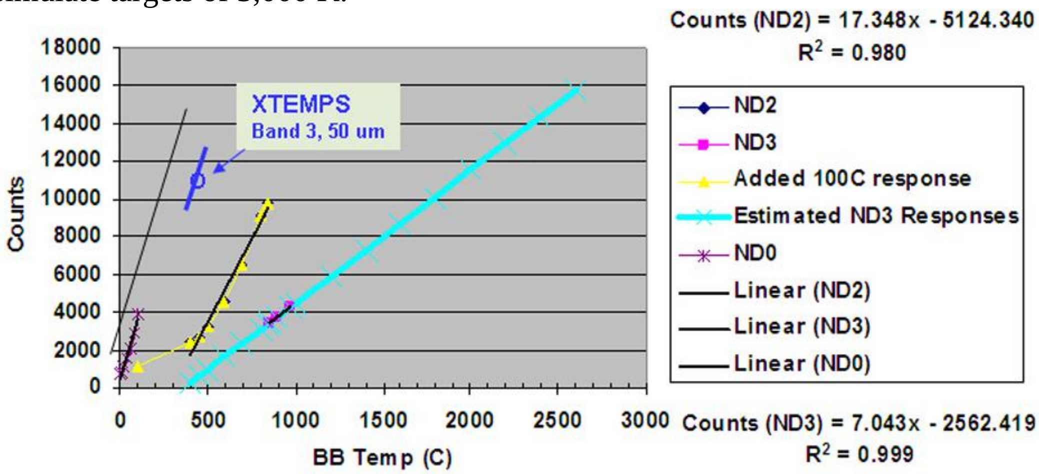


Figure 11. PhC measurement and calibration curve converting MWIR camera counts to effective emission temperature.

Fabrication of two color 256x256 format emitter demonstration array wafers has been completed. A single wafer is shown in Figure 12.

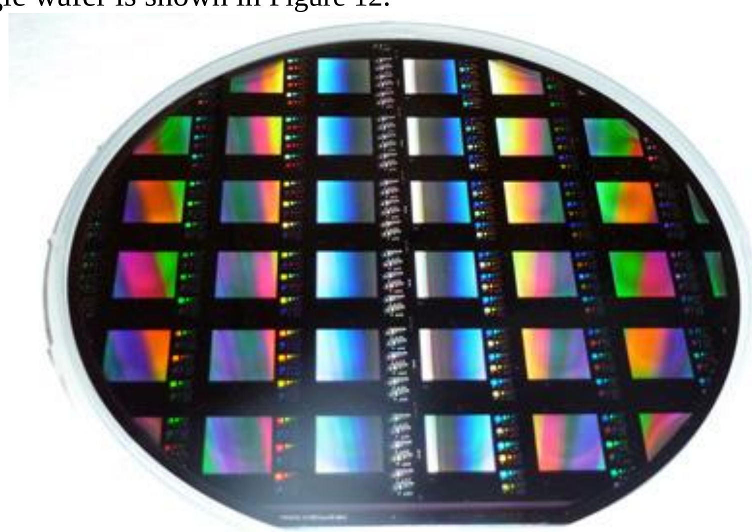


Figure 12. Completed wafer of 256x256 two color emitter arrays prior to dicing and wafer bonding to the RIIC.

Wafer dicing and bonding to the RIIC are in progress. Close up SEM images of unit cells for each of the two MWIR spectral band sis shown in Figure 13. Note the spacing difference in the two unit cells. The closer spacing seen on the left emits the shorter MWIR band while the coarser spacing on the right, the longer. The height of the two unit cells was kept the same to ease processing As a result the longer wavelength unit cell is slightly non optimum, but close enough to demonstrate the dual band emission.

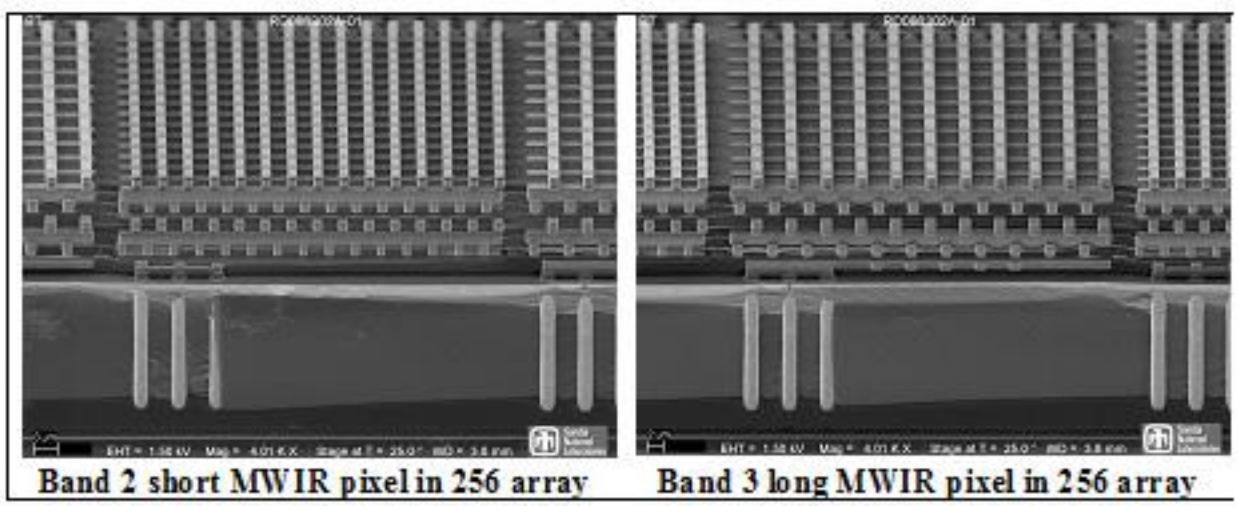


Figure 13. Close up of unit cells for each of the two MWIR bands.

6. SUMMARY

Cyan Systems and its team members have demonstrated Photonic Crystal based unit cells suitable for use in multispectral emitter arrays. Design and composition of the unit cell makes it capable of high temperature operation simulating targets with effective emission temperatures between 2000 and 3000K. By varying PhC subcomponent spacing in three dimensions the emission band can be tuned with regard to spectral band location and width. This tenability makes PhC emitters uniquely suited to high fidelity simulation of real target signatures. Single arrays tuned for up to four different spectral bands have been fabricated of candidate unit cell structures. Development of this multispectral scene projection technology will provide capability for enhanced simulation of the complex active and passive multispectral IR scenarios that represent modern sensor systems.

7. ACKNOWLEDGEMENTS

The authors appreciate the support of the Air Force Research Laboratory Munitions Directorate, Eglin AFB, Florida.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

8. REFERENCES

[1] R. B. Lamott, “Analysis and Application of the Bidirectional Reflectance Distribution Function of Photonic Crystals,” Masters Thesis, Air Force Institute of Technology, Dayton, OH, 2009.

[2] S. G. Johnson and J. D. Joannopoulos, “Introduction to Photonic Crystals: Bloch’s Theorem, Band Diagrams, and Gaps (But No Defects)”, MIT Tutorial on Photonic Crystals, February 2003.

[3] J. W. Strutt, (Lord Rayleigh), “On the Maintenance of Vibrations by Forces of Double Frequency, and on the Propagation of Waves Through a Medium Endowed with a Periodic Structure,” Phil. Mag., S.5, vol.24, no.147, August 1887, pp.145-59

[4] I. El-Kady, Zhi-Yuan Li, and K. M. Ho, An analytical model expansion method applied to 3D layers-by-layer metallic photonic crystals. Photonic and Electromagnetic Crystal Structures (PECS-IV) Conference Proceedings: Molding the flow of light on a chip, P126 (2002).

[5] V. Shklover, L. Braginsky, et al., "High-Temperature Photonic Structures. Thermal Barrier Coatings, Infrared Sources and Other Applications," Journal of Computational and Theoretical Nanoscience, vol. 5, no. 5, p. 862–893, 2008.