My current research portfolio consists of work ranging from nanoscale electro-optic modulators to 40 square meter hybrid solar energy systems. A common theme that cuts across this 10 order of magnitude change in length scale is the coupling of fundamental optical materials and device physics to emerging applications with significant impact. The Photonic Materials and Device Lab (PMDL) is constantly seeking out new optical materials and photonic device innovations that can impact a broad range of applications, ranging from information technology, to renewable energy, to infrared optics. We now provide a summary of some of our current research programs.

**FOCUS**

Our ARPA-E FOCUS program has the goal of improving the usefulness of solar energy to power companies by combining photovoltaic electricity production with concentrated solar power heat production as seen in the schematic. The program is led by Sharp Laboratories of America, a COS Industrial Affiliate, and our group has been responsible for optical design and characterization. The picture shows former graduate student Byron Cocilovo (now Dr. Cocilovo and soon to be working at Apple) characterizing a segment of the optical system. A critical part of the system is an optimized hyperbolic dichroic mirror that sits near the focus of the parabolic reflectors, with the job of sending the 500-850nm light down to concentrated PV cell units while allowing the rest of the light to pass through to the heat tube. The mirror was designed to optimize photovoltaic energy output over the full year in Tucson, accounting for key aspects such as balancing the separate photovoltaic cells. This work was recently published in *Applied Optics* (A. Miles et al., *Applied Optics* 55, 1849 (2016)). A full scale prototype of the system is currently under construction on a site owned by the UA College of Agricultures and Life Sciences (CALS) just west of I-10.
MOSAIC
Our ARPA-E MOSAIC program is focused on creating more efficient (> 30%) solar panels by combining standard silicon panels for diffuse light collection (labeled as 1-Sun sheet in the figure below) and high efficiency concentrated photovoltaic arrays for the direct sunlight (known as direct normal insolation or DNI). Key optical design elements include a cylindrical lens concentrator in one direction and a waveguide sheet concentrator in the other direction as shown in the schematic. This work is also done under subcontract to Sharp Laboratories of America and started in January 2016.

Schematic showing basic approach to a high efficiency solar panel

Athermal Optical Add-drop Multiplexers
Silicon photonics is a major technology development in integrated optics, where the goal is to take the substantial manufacturing knowledge that exists for processing silicon for electronics and apply it to making integrated optical devices. There are many major corporations, start-up companies, and universities dedicated to realizing this vision and many products are now in the market place. One of the difficulties with silicon as an integrated photonic material is that it has a fairly high thermo-optic coefficient, meaning that its refractive index changes significantly as the temperature is changed. Ordinarily this problem is solved by providing temperature control for the chip, so that its performance doesn’t change as the ambient temperature drifts. However, in electrical power hungry data center environments, this is not a viable option. We have developed an approach for making silicon photonics less dependent on temperature, by replacing the standard silicon dioxide top cladding with a sol-gel material that has similar refractive index but a large and negative thermo-optic coefficient. This material essentially compensates the effect in silicon leading to much less temperature sensitivity for an optical add-drop multiplexer as shown in the figure (S. Namnabat et al., OFC 2016, paper Tu2F.3). We have recently achieved practically complete athermality in these devices as will be reported in a forthcoming manuscript.
Electro-optic Modulators

Our work on electro-optic modulators now spans from high speed low insertion devices with optimized fabrication processes for RF photonics applications to novel plasmonic modulators only 30 microns in length. All processes required to both fabricate and package EO polymer modulators have been modified to improve manufacturability. The figures below show a 40GHz EO polymer modulator at an intermediate step in the fabrication process as well the process by which fiber ferrules are pigtailed to the EO polymer modulator chips. State-of-the-art EO
polymers are being used, with material figures of merit for high speed modulators many times bigger than those of lithium niobate (R. Himmelhuber et al., Sensors 15, 18239 (2015)). Plasmonic modulators take advantage of the subwavelength waveguides possible with plasmonic confinement to make ultracompact devices as shown in the images shown below.

![Silicon taper entering plasmonic waveguide region – initial silicon width is ~ 400nm](image1)

![Complete modulator with wirebonds made to the gold electrodes](image2)

**Infrared Optical Polymers**

Despite tremendous advances in optical materials for the ultraviolet, visible and near-infrared over the last few decades, relatively little progress has been made in developing materials for the mid-wave infrared (MWIR; 3 – 5 micron wavelength) and the long-wave infrared (LWIR; 8-12 micron wavelength). We have recently collaborated with Dr. Jeff Pyun’s group in UA’s Chemistry and Biochemistry department to demonstrate the first optical polymers that can be suitable for MWIR applications. This is achieved by the development of a sulfur-based copolymer material that has relatively low hydrogen content, leading to reduced absorption from C-H vibrations. The materials can be molded into lenses and windows; the figure shows imaging at 1550nm (grey picture) as well as transmission through a window in the 3-5 micron region (labeled as “e”). Picture “d” shows what is seen through a conventional optical polymer, PMMA, through an identical thickness of material. These exciting results have garnered attention from major corporations, resulted in
one issued US patent thus far (US 9,206,218) and led to several publications (J. Griebel et al., *Advanced Materials* 26, 3014 (2014) and J. Griebel et al., *ACS Macro Letters* 4, 862 (2015)).

**Diatom Photonics**

There has been recent interest in the development of new microscale devices with mesoscale to nanoscale features for a variety of applications including use in biosensors, solar cells, batteries, detectors, and photonic and plasmonic devices. Current methods of fabrication of such devices tend to rely on 2D photolithography or chemical etching, and while these techniques can be very precise and reliable for 2D patterns, they are not well-suited to producing complex 3D structures. Diatoms, a type of single-celled photosynthetic algae, offer an alternate route to the production of micro and nano-structured materials. Diatoms produce rigid cell walls (called frustules) made of amorphous silica with a wide variety of species-dependent shapes and features. Of particular interest is the fact that in many species, these frustules have periodic holes, or pores, ranging in size from tens of nanometers to a few microns; the figure to the right shows a scanning electron micrograph of a *Coscinodiscus wailesii* diatom shells at various resolutions. With on the order of $10^5$ unique diatom species, there are many frustule shapes to investigate as potentially interesting photonic devices. The first figure below shows our use *C. wailesii* frustules as a tunable filter for a bright white light supercontinuum source. The diffraction from the diatoms periodic structure determines what color will dominate in the transmitted light (K. Kieu et al., *Optics Express* 22, 15992 (2014)).
Surface enhanced Raman scattering (SERS) can occur when a rough or patterned surface is coated with a plasmonic metal, such as silver or gold. The development of SERS substrates is an active area of research and usually involves the use of lithography or various etching processes. The periodic structure of holes in diatom frustules makes it possible to observe strong SERS when a silver coated *C. wailesi* frustule is coated with the benchmark Raman scattering molecule thiophenol as shown in the figure below, where the top spectrum is for thiophenol on a planar silver film (mostly noise) and the bottom spectrum is for thiophenol on a diatom frustule coated with silver (clear thiophenol peaks). The signal is enhanced by at least a factor of 300 for the diatom SERS substrates (manuscript in revision).