An EPIC Partnership for Earth Science: Collaboration Between NASA and Industry to Develop Photonic Integrated Circuit Instrumentation

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Scientific progress has often proved most lucrative at the intersection of multiple disciplines. Similarly, significant technical innovation can occur when there is overlap among industries. Here, we'll envision one aspect of the progress that can be achieved when the techniques of solid-state photonics are combined with the fabrication methods of the semiconductor industry to build tools to help answer questions in Earth Science.

There is a vibrant community of researchers in academia and industry that are developing photonic integrated circuits (PICs), which are devices that manipulate photons in the way that standard electronics manipulate electrons. The application space for PICs is at least as large and diverse as it is for conventional electronics, and the PIC devices can be of comparable physical size. PICs perform various complicated signal processing operations. They can contain optical components such as detectors, modulators, and interferometers. Interestingly, they can perform these manipulations on photons that are collected from the ambient environment. In other words, they can be used as remote sensors, where the information content of the collected signal encodes the history of where the photons have been and what they have encountered. Indeed, a PIC device can host lenslets, micromirrors, spectrometers, and detectors – a complete scientific instrument – on a wafer.

With meticulous control of photons in PICs, usually at visible-to-infrared wavelengths, it is possible to perform the complicated tasks that radio telescopes perform on centimeter (or longer) scale waves. For decades, radio-astronomers have been building multi-dish arrays that are separated by distances up to several kilometers. Signals from separate dishes are combined to achieve the imaging performance (or angular resolution) of a monolithic optic that is as big as the largest dish separation. A handful of small, distributed, radio dishes can achieve exquisite imaging performance without requiring a focal length that is comparable to their baseline separation. Imagine the shape of a typical telescope or camera lens, which has a focal length that is often longer than the primary optic is wide. Radio arrays don't look like this. A kilometer-sized radio array doesn't need to place a detector or focusing optic somewhere a kilometer up in the sky. The radio array can generate images while all the dishes are located flat on the ground. Translated into the realm of PICs, this means that a PIC instrument can achieve the optical performance of a lens or mirror that is the size of the wafer, but without the need for a bulky telescope.

Eliminating the focusing optics decreases the size and weight of the instrument, which decreases the cost of putting an instrument in orbit. A PIC instrument also removes the need to assemble, align, hold in place, and test those optics, which further reduces the instrument cost. After developing the design and fabrication methodology, duplicate instruments can be lithographically manufactured at essentially the cost of materials. The potential for scaling up the production of wafers makes PIC instrumentation an excellent candidate for missions that require multiple sensors.

One application in remote sensing that significantly benefits from a multi-sensor approach is aerosol measurement. This is because the key diagnostic of the size, shape, and composition of particles is how they scatter light. The more angles at which the scattering from aerosol is measured the more robustly the sizes and shapes of the particles are constrained. It is also possible to measure the light that is scattered in different directions simultaneously if there are multiple sensors. The synchronized observations mean that the particle measurement is specific to a short instant in time. Such observations can capture the properties of aerosol in situations where they are rapidly changing. Identifying the size and composition of aerosol is important for many fields of study, such as urban air pollution, investigations of wildfire smoke, and the radiative balance of the atmosphere in climate forecasts.

The Earth-observing PIC (EPIC) Multispectral Aerosol Polarimeter (MAP) mission was developed at the Lockheed Martin Advanced Technology Center (ATC) to investigate the properties of aerosol from a constellation of orbiting PIC sensors. Each sensor in the EPIC MAP constellation is a tiny imaging polarimeter that is sensitive to multiple wavelength bands from the visible through the infrared. Light is collected by pairs of millimeter-sized lenslets that couple the light into the circuit on the wafer. Waveguides then route the light through structures that separate the photons by wavelength, before combining them in two arms of an interferometer on the chip. Each pair of lenslets on the PIC is analogous to a pair of radio dishes and serve as a baseline for the imager. The performance specifications for ground sampling distance and revisit times are ambitiously set in the EPIC MAP mission to significantly exceed the requirements for objectives that are detailed by the scientific community in the 2017 Earth Science Decadal Survey. Although EPIC MAP is currently planned as a constellation of 3U cubesats where each payload is on a dedicated satellite, the sensors could also be hosted payloads on a commercial constellation. Both the number of geographic locations that are covered simultaneously, and the frequency of revisit times, will scale with the size of the constellation. The details of the observations are determined by the specific science needs of the mission and the EPIC MAP observing strategy is optimized for those objectives.

The NASA Earth Science Technology Office (ESTO) has partnered with ATC to develop and test the PIC instrumentation that is fundamental to the EPIC MAP mission. The close collaboration between ESTO and ATC is important for overcoming the unique technical challenges of PIC instrument development for Earth Science. The ATC partnership with ESTO expands on the recent collaborations between LM and NASA in Heliophysics (e.g., the IRIS mission) and Astronomy (e.g., NIRCAM on JWST). The partnership between ATC and ESTO leverages complementary resources. For example, the process of proposal peer review that is supported by ESTO provides valuable feedback to the scientists at ATC. Panel reviews and NASA program management provide guidance and interpretation of the most relevant and interesting Earth Science applications. NASA ESTO leverages a network of scientists throughout academia that work on technology development for Earth Science. This feedback to ATC scientists helps to guide roadmaps that are used to define the direction of development and to narrow the parameter space of Earth Science instrument performance objectives.

As an industry partner, LM ATC invests in the infrastructure and institutional knowledge of the PIC fabrication process, which supports multiple customers and applications. The heritage of fabrication and optimization from different programs is knowledge that is not often available in the peer-reviewed literature. The scientific and technical expertise at ATC, along with in-house tooling in our PIC fabrication facility, allows for a rapid design-fabricate-test cycle for PIC instruments and components. This lowers the cost and increases the pace of development. For PIC instruments, it is often easier to design the components of a novel instrument than it is to fabricate them to predicted performance measures. A significant investment of effort is often needed for component optimization and the improvement in overall instrument efficiency. LM ATC has invested in both the tooling and the knowledge needed for PIC development and optimization, which supports building scientific instrumentation.

The EPIC MAP mission showcases how the collaboration between industry and NASA can drive rapid technology development for Earth Science. Leveraging the overlap in complementary interests and expertise in the ESTO collaboration with ATC is like finding the overlap between different scientific disciplines or between different industries. The partnership has the potential to drive both rapid innovation and significant scientific progress. The new paradigm in instrumentation enables the development of low-cost observing platforms that can reshape how we measure the environment and what new questions we can hope to answer. The future of remote sensing may indeed be EPIC.