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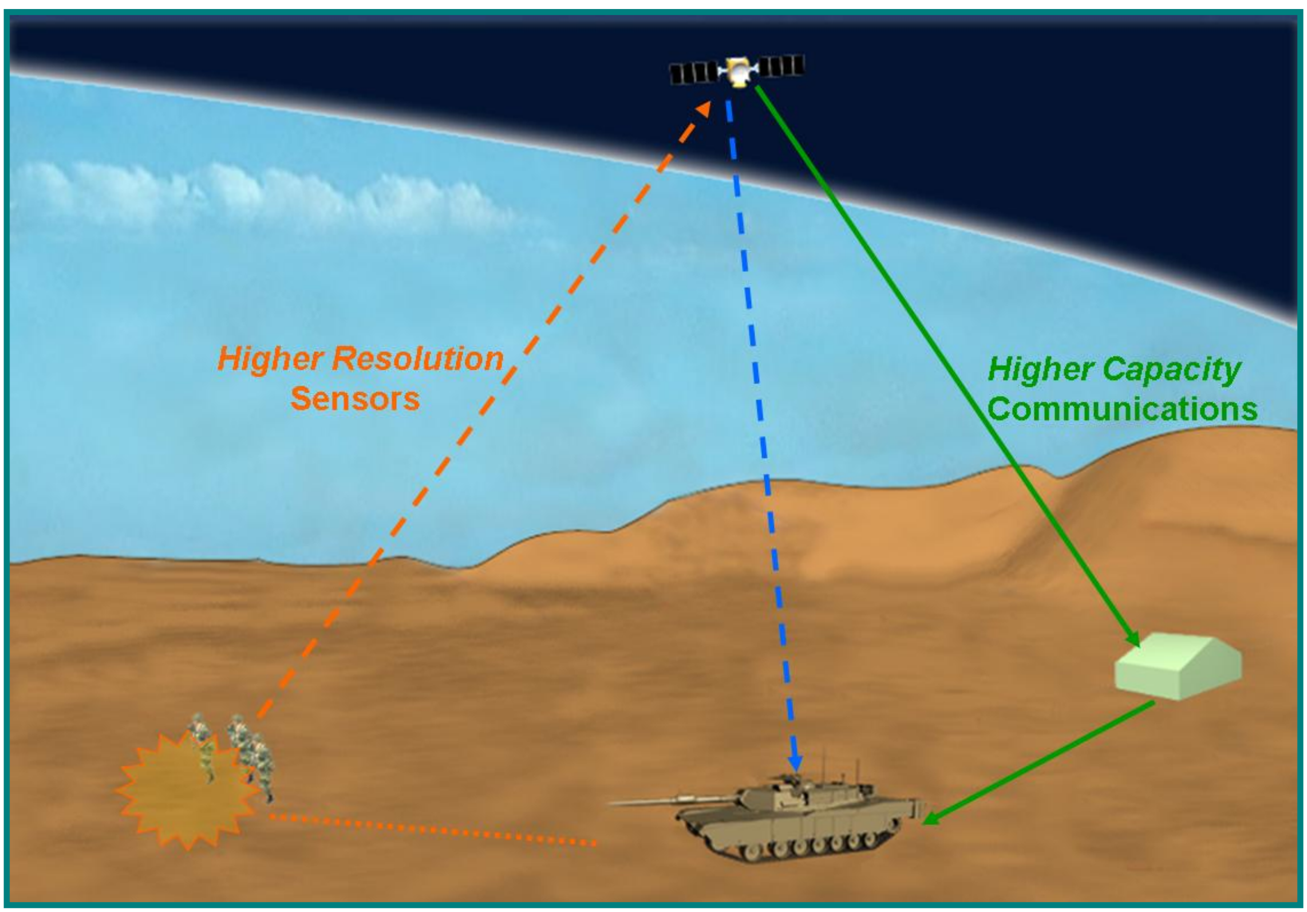
The RF Frontier and Beyond

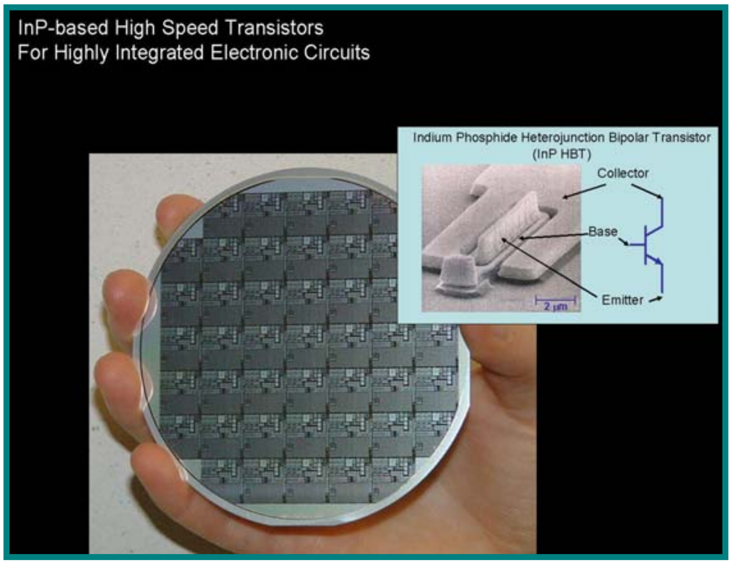
Around the Microsystems Technology Office (MTO), one of our themes is "smaller is better." I agree. But for me, smaller is better because "smaller is faster," and I contend that "faster is better."

Raw speed, derived from advanced electronic and optical devices, translates into radio frequency (RF) systems with increased bandwidth and dynamic range. These are key parameters that will enable our military communications and surveillance systems of the 21st century. Taming the expanding RF frontier is one of our primary missions at DARPA. Why? Because if we do tame it, we will be able to detect anything, from anywhere, at anytime, and globally share this information in real-time with high reliability and security.

As MTO continues to develop faster electronics and photonics, higher capacity communication systems and higher resolution sensor systems will be realized.

For example, MTO has developed some of the world's fastest electronic transistors. These compound semiconductor-based devices operate up to 500 GHz, which is more than 100 times faster than the best available PCs. These devices are small, but more important, they are fast! If we consider a typical RF antenna system, this increased electronic speed translates into increased





performance front-end amplifiers; faster analog-to-digital and digital-to-analog converters linking the RF and digital worlds; and higher throughput back-end digital signal processors.

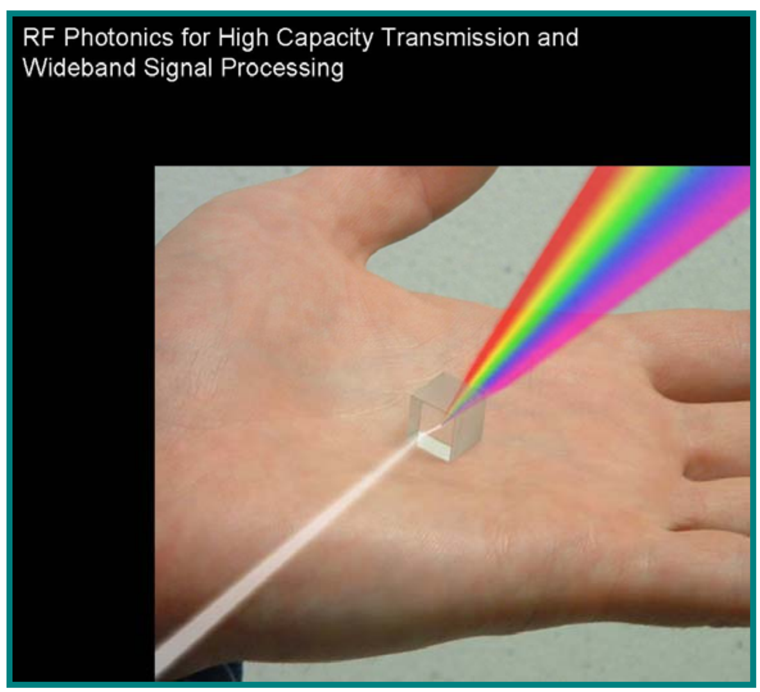
MTO is also developing photonic crystal technology that has the potential to capture and resolve many terahertz of bandwidth using novel nonlinear optical materials and techniques. Coupled with high-speed laser modulation and detection techniques, this technology can provide real-time snapshots of the entire RF environment from 2 MHz through 100 GHz all within only one of many available parallel channels.

These electronic and photonic technologies are opening up high-frequency antenna system opportunities the military is anxious to exploit. Millimeter-wave and submillimeter imaging systems that can see through walls and RF and free-space optical communication links that can securely pass 100s of Gigabits per second of information throughout the theatre. These components change the game.

Although impressive as stand alone technologies, by coupling high-speed electronics with wideband photonics, we will soon be able to simultaneously harness and process millions and millions of MHz of bandwidth. Imagine simultaneously broadcasting and receiving more than a million different high definition television channels over air!

Photonics is ideal for transporting and preprocessing enormous volumes of RF bandwidth and data, while electronics is best-suited for finer resolution processing, storage, and display. As high-speed electronic capabilities continue to improve, more and more optical bandwidth can be channeled to back-end electronic processors. The optical portion of the EM spectrum can provide an endless reservoir of RF bandwidth to draw from. The challenge is getting electronics and photonics to work together and concurrently exploit the advantages that each technology has to offer.

Imagine software-defined optical radios, similar to the Joint Tactical Radio System (JTRS) at 2 GHz today, but now with terahertz of available channel bandwidth that can seamlessly transport voice, video, and data through mobile networks, treating bandwidth as a true commodity. In this scenario, real-time access to entire libraries of intelligence data would be at our decision-makers' fingertips. Data more detailed than ever before imagined. Realizing this vision means overcoming daunting



challenges in component development, especially on the optical side.

To put things into perspective, today's optical communication techniques are at the Marconi stage of development as compared to RF communications. How do we begin to bridge the gap?

A key challenge is developing photonic components and techniques that exploit absolute phase and frequency for information processing and transmission. Today's optical transmission and processing systems rely largely on incoherent technologies and energy-based detection that require very little frequency and phase stability. The RF and wireless communities routinely exploit precise phase and frequency information, and practically take it for granted; this was not always the case.

To unleash the full bandwidth potential of optics and provide seamless handoff with RF technology, the optical phase and frequency must be tamed in a similar manner as RF phase and frequency was tamed throughout the 20th century. Taming the RF phase and frequency dramatically changed the way we fight battles and affected our everyday lives with fascinating wireless technologies.

We will bridge the RF and optical gap by mastering coherent optical techniques. This is easier said than done, since optical signals are 10,000 times higher in frequency than typical RF signals, and 10,000 times more difficult to control. Truly a challenge appropriate for the 21st century and for DARPA.

There is enormous room for component innovation in the temporal and frequency stability of optical signals and the phase-locked processing and filtering of these signals. Subhertz linewidth laser oscillators with absolute frequency references and fast tunable optical-filtering technologies are essential to realize this vision. Higher speed electronics will complement this development and ease the optical component challenges and requirements. The result will be hybrid optical/RF sensing and processing systems that will satisfy military bandwidth demands well into the future.

How do we get there from here? As a reference, let me baseline our current high-speed electronics and RF photonics activities within the office.

On the electronics side, we have exceeded 500-GHz device speeds and believe that electronic transistors operating to 1000 GHz will be available in the foreseeable future. The acoustic community has long exploited GHz electronics and processors by trading speed for performance. The RF community can begin to exploit terhertz electronics and processors the same way. Using negative feedback techniques, one can trade speed for linearity in terhertz-grade transistors to enable lower frequency RF amplifiers with greater than 100 times improvement in dynamic range. One hundred times greater linearity might not sound important, but imagine an airborne platform that can operate in the presence of strong interference and detect signals 200 or more kilometers deeper into hostile territory. Or an RF network that can communicate up to four times the capacity as before within the same constrained bandwidth. This is dramatic.

On the photonics side, devices with 100-GHz modulation bandwidths are being developed. Remember, a 100-GHz bandwidth channel is only 0.1 percent of the optical carrier, which is extremely narrowband in relative terms. Building on these channels, parallel optical processors that can crunch the equivalent of 20 Teraflops of information in real-time are also under development. That is the equivalent computing power of 10,000 PCs. Wideband optical modulation and parallel processing are key enablers.

These are good starts to achieving the vision outlined, but a lot of work remains.

New electronic materials, fabrication, and devices are essential to further improve high-frequency transistor and RF circuit performance. Compound semiconductor materials, particularly the III-V compounds such as indium phosphide (InP) and gallium nitride (GaN) figure to play an increasing role in meeting high-end military performance levels.

Parallel with continued electronic device development, we need to move forward in advanced photonic techniques for transmitting and processing signals from DC-to-daylight. We must develop new photonic materials and devices that provide for efficient optical phase, frequency and amplitude modulation well into the terahertz region. Moving toward vector modulation and demodulation, away from traditional scalar optical modems, is imperative. Coherent optical technologies for producing ultra-high-Q tunable filters, resonators, and oscillators are required. Nanophotonic and bandgap engineered semiconductor structures and crystals are guaranteed to be a large part of the optical solution.

For both electronics and photonics, making smaller widgets will be the key to making them faster. Scalable fabrication techniques and heterogeneous integration approaches will certainly be part of the equation.

Most important is finding compatible device processes and interfaces for merging high-speed electronics with wideband photonics in integrated microsystems unleashing bandwidth and processing power like we have never seen before. The key is finding ways to exploit the inherent advantages of electrons, the processing workhorse, and photons, the bandwidth enabler. Building stronger technical solutions that can adapt in real-time to its environment by including contributions from both of these technologies is my vision for the future.

As our electronic and photonic devices continue to improve, the challenge is to get them to coherently work together to produce capabilities that match 21st century defense needs. Sensing and communicating at further distances with greater clarity and capacity are paradigm changing capabilities. If we are successful in marrying these fast device technologies, I believe we are on target to revolutionize warfare well into this century.

This is only a glimpse of how MTO is working towards generation-after-next RF and optical systems. We want to hear your ideas in these areas as we work to solve some of our important national problems. Always remember, “smaller is faster,” and “faster is better.”