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# Looking for a Light

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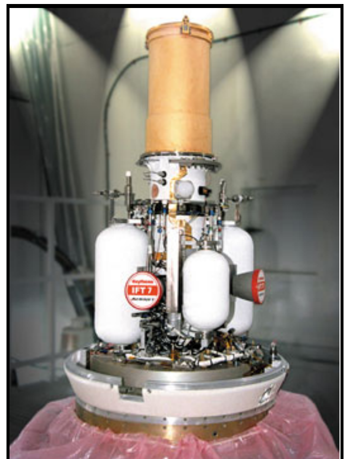
**Optical technologies offer the promise of a RF-free battlefield**

In the modern battlespace, when you emit, you die. When you communicate, you risk being intercepted, jammed, or shot down. Even if spectrum supremacy is achieved or presumed, there are other difficulties in a radio-frequency (RF) world. When you transfer real-time surveillance images, you run short of needed capacity. When you target potential enemies, you lack the resolution to differentiate friend from foe. For these reasons, the US Department of Defense (DoD) is spearheading a transformation in the electronic-defense arena in which optical signals will increasingly be used in air and space in the modern battlefield. The Pentagon is adding optical techniques to its arsenal in order to overcome the limitations of RF used in communications, radar, and other sensing equipment.


Raytheon was recently awarded a $38.6-million contract by the US Army to develop the laser-radar (LADAR) technology base for the next generation of interceptors for the Ballistic Missile Defense Organization. The Army's Advanced Discriminating LADAR Technology (ADLT) program has the goal of developing a range-resolved, Doppler-imaging LADAR sensor to enhance the ground-based midcourse defense segment's exoatmospheric kill vehicle (shown here) with additional discrimination capability.

Raytheon image

Driven by the need for new military and homeland-security capabilities above and beyond what RF solutions can offer, the US government is investing billions of dollars in the research, development, and deployment of optical solutions. Triggered by the emergence of new subsystems that combine coherent optical technology, integrated opto-electronics, and digital signal processing, the military and homeland-security forces can supplement and, in some cases, replace RF-based applications with greatly improved capabilities available only in the optical domain. The move to optical technologies will result in secure communications with virtually unlimited capacity, vast improvements in battlefield identification, higher resolution in both tracking and discrimination of targets, and remote sensing of airborne substances such as trace gases from explosives, rocket fuel, and other materials.

## RF Limitations

Since RF signals tend to propagate over a broad geographical area, they can be detected, intercepted, tracked, and, as a consequence, jammed by adversarial forces. For communications, the RF spectrum has limited capacity, both at the single-channel level and in the total number of channels that can be transmitted asimultaneously. For radar, RF has limitations in resolution, a key factor for tracking and discrimination.

In the area of communications, optical technology provides the answer for capacity-hungry applications like high-resolution imagery, live video feeds, broadband sensors, and more. To take advantage of optical technology's broadband capabilities, the US is implementing the Global Information Grid, a worldwide optical network that uses terrestrial and sub-oceanic fiber-optic transmission facilities, supplemented by optical links in free space and between satellites. The military has ongoing solicitations to deploy such optical-communications systems in air and space, enabling very high-speed transmission of intelligence, surveillance, reconnaissance, and battlefield information. For air-to-satellite applications, rates of 1 Gb/s (one-billion bits per second), with an objective of going to 10 Gb/s, are being requested. For satellite crosslinks, the need is for rates of 10 Gb/s, with an objective of going even faster. In the RF world, broadband transmission at these rates is not possible.

When measured by capacity per channel, optical communications provide a 1,000-fold increase over RF communications. For high-speed military communications through air and space, a RF channel typically transmits on the order of millions of bits per second (Mb/s), up to a maximum of hundreds of Mb/s. This limit in maximum data rate per channel restricts the type and quantity of information that can be conveyed. For example, high-capacity sensors and real-time imaging systems may exceed the capacity of a single RF channel. An optical-communications channel provides capacity of tens of Gb/s, more than enough to convey information from not just one but a multitude of the most capacity-hungry applications. As an example, a single optical channel operating at 10 Gb/s can transport a thousand HDTV signals simultaneously. The total usable bandwidth of the optical communications spectrum is on the order of 10,000 times higher than the total usable RF bandwidth.


Lockheed Martin is developing the Low Cost Autonomous Attack System (LOCAAS) smart submunition (inset right) for the US Air Force and Army. Target aimpoint and warhead mode are automatically determined by the LADAR seeker, which has greater resolution than a radar seeker and no RF emissions. The top image of the above series indicates range, while the middle shows the intensity of the image. The actual photograph showing what the LADAR seeker was viewing is shown at the bottom. This is an example of how optical technology is being applied to overcome the disadvantages of a RF-based application.

Lockheed Martin photos

In the area of target tracking and basic discrimination, the use of optical technologies also offers benefits over conventional RF radar. In the optical world, laser-detection-and-ranging (LADAR) systems use the same principle as radar except that they transmit and detect light frequencies instead of RF. Some of the transmitted light is reflected back to the LADAR receiver, where it is analyzed for changes in signal properties that enable the range, velocity, and direction of the target to be determined.

LADAR systems are in widespread use today and vary in their complexity and application. Ranging LADAR is used to determine the range to the target by measuring the time taken for the light to travel to the target and back. When combined with three-dimensional computer modeling, for instance, ranging LADAR will allow UAVs and robotic vehicles to navigate safely through unknown terrain. Doppler LADAR is used to measure the velocity of a target. When the transmitted light hits a target moving towards or away from the LADAR system, the frequency of the light reflected off the target will be changed, creating a Doppler shift. If the target is moving away from the LADAR, the return light will have a lower frequency. If the target is moving towards the LADAR, the return light will be at a higher frequency. Furthermore, the target can also be atmospheric in nature, such as dust and aerosol particles that are carried by the wind, enabling remote measurement of wind velocity to be made.

LADAR provides a large increase in resolution over RF-based radar. Optical frequencies are five to eight orders of magnitude higher than those of RF. Since image resolution is proportional to the wavelength of the electro-magnetic radiation used, the higher frequencies and shorter wavelengths of optical signals produce greater resolution in the detection of range, velocity, direction, and shape of the object of interest.

As shown, optical communications and LADAR systems offer vast improvements over RF systems. Yet even more dramatic breakthroughs in performance and capabilities are gained by using programmable transmitters and programmable, coherent, optical receivers employing digital signal processing. The performance of optical-communications systems is greatly improved by providing added security against eavesdroppers, increasing resistance to jamming, expanding capacity, and increasing link margins. The performance of LADAR and other sensing systems are improved through higher resolution, and their field of application can be expanded. Coherent detection lends itself to the use of the advanced modulation techniques, enabling increased capacity and more efficient use of the optical spectrum.

Conventional optical communications transmitters modulate the intensity of light to encode information. Using On-Off-Keying, each timeslot conveys one bit of information. The laser is turned on to convey a

"1" bit or turned off to convey a "0" bit. Using conventional direct detection, the light detectors at the receiver respond to the intensity of the received light in order to differentiate between a "1" and a "0."

Transmitters used in coherent communications systems make use of the most modern modulation schemes that use the phase of light to encode the information. As an optical signal propagates, its phase oscillates between 0 and 360 degrees. By controlling the phase of the optical field, the information is encoded in each given timeslot. For example, in quadrature-phase-shift keying (QPSK), the transmitted information is encoded as one of four possible phases of the signal, corresponding to two bits of information in each timeslot. In differential QPSK (DQPSK), the information is encoded in the relative changes of the phase. In both cases, communications capacity is doubled compared to on-off-keying. Quadrature-amplitude modulation (QAM) can further increase capacity by encoding even more bits into each timeslot by controlling both the phase and the intensity of the light. In addition, each of the two orthogonal polarization states of the light signal can be separately modulated, further doubling communications capacity.

## The Optical Advantage

With coherent detection, used for both optical communications and LADAR, the received optical signal is demodulated by mixing it with a local oscillator that is close in optical frequency and locked in phase to the transmitter. Coherent detection provides a linear transformation of the optical signal to the electrical domain, downconverting the signal's carrier frequency from hundreds of trillions of cycles per second (terahertz) to baseband. This has key advantages. First, the receiver is inherently frequency selective, since the local oscillator frequency can be changed to detect signals in specific parts of the optical spectrum and electronically filter out others — without the use of optical filters. Second, the mixing of the received signal with the local oscillator boosts the power of the received signal, thereby increasing receiver sensitivity, requiring less transmitted power, and improving link margins. Third, this maintains the phase and polarization information of the original signal, which, after sampling, enables decoding and processing using advanced digital signal-processing techniques.

The inherent advantages of coherent detection enable critical new capabilities not available with conventional communications and LADAR systems. Coherent optical technology offers enhanced security and resistance to jamming for transport of sensitive intelligence, surveillance, and reconnaissance information. Data encryption and user authentication are the major communications-security (COMSEC) approaches used in today's communications networks. While these methods provide an efficient means to secure the sensitive information, they do not prevent a hostile opponent from jamming the signal or eavesdropping and storing the data. Increasing computation power and efficient algorithms may enable the eventual deciphering of this maliciously collected data. Thus, as adversaries become more sophisticated, there is a growing and urgent need to provide additional security at the optical-transport layer for communications in air and space. In order to avoid interception and jamming, optical systems can use frequency and polarization hopping. Using a secret key to synchronize the transmitter and receiver, the optical carrier frequency and polarization can be changed thousands of times a second across hundreds of usable channels over a broad spectrum, preventing an adversary from intercepting or jamming the transmissions. The coherent receiver with its inherent frequency selectivity lends itself to this implementation.

Coherent techniques and digital processing can also improve capabilities for target discrimination, battlefield identification, and remote sensing systems. Coherent LADAR, already in use today, measures target range and velocity with greater sensitivity than conventional LADAR, since coherent detection preserves the phase information of the reflected photons. Like in communications, the linear transformation to baseband, combined with digitization, enables the employment of digital signal-processing techniques, such as polarization recovery and spectral analysis, to further enhance the performance of LADAR.

Coherent detection and digital processing enable a new class of laser Doppler vibrometers. The vibrometer can be used to measure the vibration of a target's surface by illuminating a target with multiple beams of light from slightly different directions, then measuring the tangential micro-Doppler shift. The range of future applications for coherent laser Doppler vibrometry is broad. For missile defense, it can be used to discriminate between an actual warhead and similarly shaped decoys that vibrate in a different manner. For battlefield identification, it can be mounted on a missile to discriminate between the vibrational signature of an enemy tank versus a friendly tank prior to arming and detonating, preventing friendly-fire incidents. For combat operations, it can be used to remotely determine the presence of trace gasses commonly found around explosives and rocket fuel, without putting soldiers into harm's way.

Above and beyond the use of coherent detection, LADARs and vibrometers can be further improved by employing programmable optical transmitters. By using linear modulators capable of modulating the optical field with required information, like the ones used for QPSK or QAM modulation, LADAR transmitters can create a multitude of LADAR signals with tailored waveforms to further increase their resolution and applicability. They can operate in multiple modes such as frequency-chirped, pulse-compression, and optically synthesized pulses. Furthermore, their waveforms can be adapted digitally based on operational needs.

Pop smoke! One of the fundamental dsadvantages of optical technologies is that clouds, fog, smoke, sandstorms, and physical structures can obscure the laser signals, modifying the light's characteristics or hindering its passage through a combination of absorption, scattering, and reflection. Atmospheric turbulence can also hinder the propagation of laser signals, causing scintillation, which results from the spatial variation in a light beam's wavefront phase. One remedy for optical communications through air or space is to assure alternate transmission paths by using a mesh network of nodes on the surface, in the air, and in space. Here, machinegunners of the US 22nd Marine Expeditionary Unit train in smoky battlefield conditions.

USMC photo

## The Dawn of Light

While there are many benefits of using optical signals, there are also limitations for which remedies are emerging. Optical signals propagate through air and space as a modulated, narrow beam of laser light, typically requiring a line of sight between transmitter and receiver. Clouds, fog, smoke, sandstorms, and physical structures can obscure the laser signals, modifying the light's characteristics or hindering its passage through a combination of absorption, scattering, and reflection. Atmospheric turbulence can also hinder the propagation of laser signals, causing scintillation, which results from the spatial variation in a light beam's wavefront phase. Such turbulence is caused by wind and temperature gradients that create pockets of air with rapidly varying densities, resulting in fast-changing indices of optical refraction. These air pockets act like lenses with time-varying properties and can lead to distortions of the optical beam's wavefront phase.

One remedy for optical communications through air or space is to assure alternate transmission paths by using a mesh network of nodes on the surface, in the air, and in space. Another solution for communications and LADAR is the use of higher power and various wavelengths to further mitigate some of these effects.

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