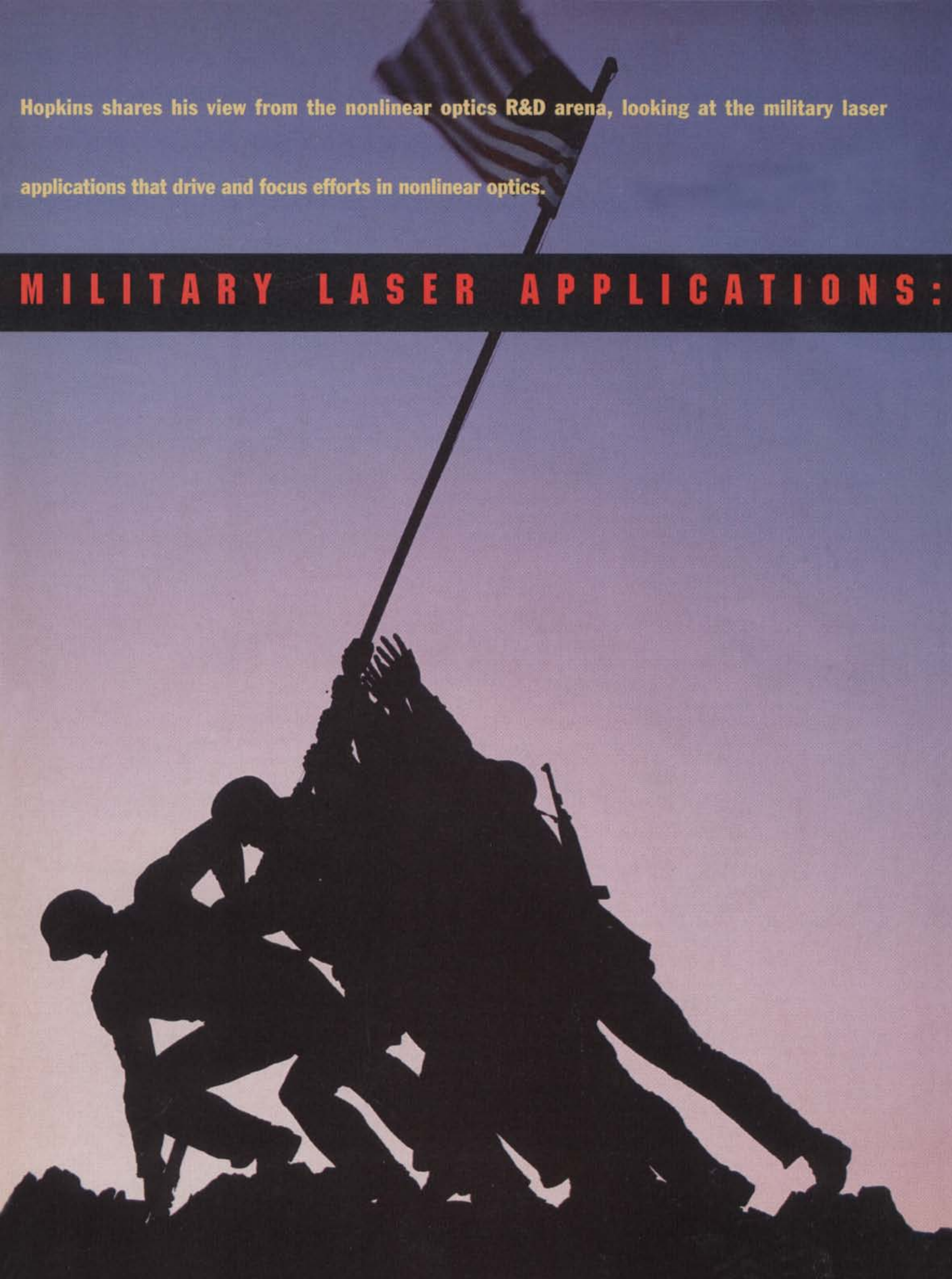
Hopkins shares his view from the nonlinear optics R&D arena, looking at the military laser applications that drive and focus efforts in nonlinear optics.

MILITARY LASER APPLICATIONS:



PROVIDING FOCUS TO NONLINEAR OPTICS R&D

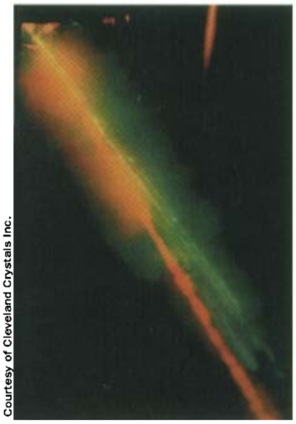
By F. Kenneth Hopkins

Nonlinear optics is having an increasingly significant impact on the performance of lasers and laser applications. The impact can be seen, for example, in the variety of improved second-harmonic generators (doubling the frequency of laser light) and optical parametric oscillators (converting laser light to longer wavelengths) that can be bought off-the-shelf today. The reasons for these revolutionary new products are twofold. First, many new or improved nonlinear optical (NLO) crystals have become commercially available during the past 10 years. These include the various chalcopyrite semiconductors such as zinc germanium diphosphide and silver gallium selenide, grey-track resistant potassium titanyl phosphate (KTP) and related compounds, borates such as beta-barium borate and lithium triborate, and quasi-phase matched structures such as periodically-poled lithium niobate (PPLN).[1] The second reason is the continued improvement of solid-state lasers, especially in regards to diode pumping.

NLO crystals serve four purposes in a laser system

- wavelength conversion—thereby offering new discrete wavelength lines and wavelength tunability over spectral ranges that are considerably broader than with dye lasers,
- optical amplification,
- electro-optic *Q*-switching for pulsed lasers, and
- optical phase conjugation for more ideal beam profiles and eventually for the coupling of laser beams.

Wavelength conversion is especially critical to numerous applications because it enables the construction of all solid-state laser sources at the specific wavelength or tunable-wavelength range required. For illustration, the fixed 1.064-μm wavelength light from a common Nd:YAG laser may be used with NLO crystals to first produce light at 355 nm and then tunable light through the visible spectral region (400–700 nm) as illustrated in Figure 1. The Nd:YAG laser technology may be purchased "off-the-shelf," and it provides excellent performance including high power.



Courtesy of Cleveland Crystals Inc.

Figure 1. Time exposure of an optical parametric oscillator tuned through the visible spectrum.

The ability to construct such versatile, all solid-state laser sources is significant because alternative laser sources using gases and dyes are relatively large and heavy and often have problems that stifle their use in exacting military systems, especially on air and spacecraft, as well as in commercial systems like medical applications. With a few exceptions, such as certain CO_2 lasers, chemical and gas lasers are typically problem prone due to hazardous laser gases or dyes, limited shelf and operational lifetimes, and the need for possibly unreliable laser media flow systems. Free electron lasers have also been suggested as competing wavelength-tunable laser

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sources, but these systems will probably only be viable for a few high-power laser applications due to their enormous weight, size, and cost.

Applications

What are the principal applications of lasers that have driven the development of NLO materials and devices? Medical diagnosis and treatment are probably the most consequential commercial applications. Wavelength-tunable laser sources based upon NLOs provide the many specific wavelengths required for various medical procedures such as cancer surgery using photoreactive agents, the removal of tattoos and birthmarks, and optical diagnostics by fluorescence or spectroscopic absorption. In addition, NLOs makes a single device for providing these wavelengths possible, an important virtue in today's budget-conscious medical environment. Additional important application areas include industrial processes requiring ultraviolet laser light (for example, precision machining, next-generation photolithography, rapid prototyping, and surface cleaning) and the many applications requiring eye-safe lasers.


Courtesy of Northrop Grumman Corp.

Figure 2. The Nemesis system protects aircraft from infrared-guided surface-to-air missiles.

During the past few decades, military applications have probably been the most important force in terms of advancing the technology, in the same way the military has been the primary driver for the development of many other young technologies. For example, the electronics harvest that has come from Silicon Valley "was the creation of U.S. Defense policy,"[2] the U.S. military supplied most of the funding for early laser research and development,[3] and "government funding has been absolutely crucial in the development of the semiconductor laser industry in the U.S."[4] Three categories of military applications will be discussed: laser weapons, laser radar, and information technology. Many additional military laser applications certainly exist, such as range finders and laser designators, but these have had a relatively minor influence on NLO R&D.

Laser weapons

The U.S. military, viewing the laser as "the biggest breakthrough in the weapons area since the atomic bomb,"[5] has pursued laser development for a number of applications. However, the primary attraction of the laser has historically been the promise of directed energy beam weapons.[3] Laser weapons may be grouped as either high- (P_{avg} > 1 kw) or low-power (P_{avg} < 1 kw). In general, NLOs is only pertinent during the foreseeable future to low-power weapons because current NLO materials cannot provide both the efficiency and power handling capability required for aircraft-, ship-, or tank-based systems. Low-power laser weapons have been pursued operating in both the visible and the infrared spectral regions.

Dazzling

Visible lasers have been used for countering pilots, soldiers, or sailors by dazzling, or flash blinding, (along with the potential for permanently blinding them).[6] Flash blindness is an effect we have all experienced in mild forms—such as when we flip on the bathroom light during the night after our eyes have already adjusted to the dark. Numerous reports indicate that dazzling systems have been pursued for a number of years. For example, "the British had reportedly used a 'laser dazzle sight' to 'flash blind' Argentinean pilots in the Falkland Islands in 1982. Similar uses of laser devices to blind or visually impair combatants have been reported in Vietnam, Afghanistan, and in the Iran-Iraq war."[7] The British weapon was described as an argon ion laser fitted with a sighting telescope with a power range between 10–100 W.[8] In a more recent example, on April 4, 1997 a Russian ship sailing in U.S. coastal waters near Seattle, Wash. reportedly irradiated a Canadian helicopter with a red-colored laser. The two men aboard the Canadian helicopter experienced short-lived "laser burns" to their eyes.[9] In addition, the U.S. Army developed a laser rifle capable of temporarily disabling enemy personnel without inflicting permanent injury.[10] However, efforts in this area of systems development appear to have dwindled because of an international agreement signed in Vienna on Oct. 6, 1995, although the treaty solely addresses laser blinding weapons.

Concerning the characteristics of these systems, laser 'dazzle' weapons are designed ideally to operate with a power level significantly below the maximum permissible exposure limit without hazardous effect or adverse biological changes in the eye or skin, and with a mode of operation being either continuous-wave or near-continuous-wave to prevent permanent eye injury.[11] The purpose for NLO in these systems is to provide the most effective dazzling wavelengths from solid-state lasers (green for day-time vision and blue for night-time vision), and ultimately to provide wavelength tunability that cannot easily be blocked with conventional laser goggles.

IRCM

Infrared laser sources are key to the infrared countermeasure (IRCM) systems used to defend aircraft, ships, and other military vehicles through a technique that confuses heat seeking missiles by injecting false signals into the missile's guidance electronics.[12] Ultimately, these systems will replace chaff and flares for more effective protection by actively tracking and "jamming" the missile's infrared guidance system.[13] According to the USAF's Maj. Gen. Richard Paul, the most pressing need for IRCM "is the protection of large aircraft. That's where we believe the immediate threat is and where we have the highest vulnerability. In a nutshell, we need to protect large aircraft against shoulder-mounted missiles. We would eventually like to extend the capability into smaller IRCM packages for fighter-size aircraft, as well."[14] These needs translate into a market "greater than $500 million for military aircraft alone."[15]

The key word for these systems is "jamming"—in contrast with "damaging"—which means that the laser power levels required are considerably lower than for the high-power weapons. Specifically, average laser power levels required in the mid-IR spectral region are somewhere around 15–40 W according to the open literature.[16] The required laser wavelengths can easily be determined by considering the emission spectra of a jet aircraft after the emitted light passes through the absorbing atmosphere to the missile's photodetectors and the detectivity of the many possible photodetectors being used in the missiles' guidance systems, information commonly reported in the literature.[17] These wavelengths can only be produced with the required power by NLOs. As was also true for "dazzling" systems previously discussed, the potential use of spectral filters may make necessary the use of laser sources with wavelength tunability (that is, optical parametric oscillators), which cannot easily be blocked. Someday, NLOs may additionally provide laser beam steering and Q-switching for these systems.

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Two major IRCM system development programs are underway. First, the Nemesis IRCM system being developed by an international team led by Northrop Grumman, will be the first system fielded, initially by the U.K. Ministry of Defense and the U.S. Special Operations Command.[18] The system, shown in Figure 2, uses arc-lamp jamming sources with a planned upgrade to laser sources.[19] Second, the Advanced Threat Infrared Countermeasures (ATIRCM) system under development at Sanders; a Lockheed-Martin Company, is a laser based system.[20] Both systems use an open-loop approach.[21] Future systems may use a closed-loop approach in which the system "first bounces laser energy off the seeker and analyzes the returned echo to determine the type of IR missile. Then the system selects a laser modulation that is most effective in countering that particular type of seeker."[22]

Laser radar

Another broad application category is laser radar, a 25+ year old technology that goes by a number of other names such as lidar (light detection and ranging) and ladar (laser detection and ranging). Even though laser radar was one of the first applications conceived for lasers, limited availability of solid-state laser sources slowed progress of the technology until recently. Laser radar is used for wind profile characterization, target acquisition, tracking and pointing, and remote sensing of chemical and biological agents. Ground-based and air-borne wind-profiling systems typically only require monochromatic light that can be readily produced with existing solid-state laser technology, sometimes requiring shifting to eye-safe wavelengths.

Acquisition, tracking, and pointing

Regarding target acquisition, tracking, and pointing, laser radar provides higher accuracy and more precise resolution than microwave radar since it operates at a much shorter wavelength. In addition, it is typically appropriate for shorter ranges in the atmosphere than microwave radar due to greater optical absorption and scattering. These characteristics thus make laser radar more suitable for such missions as low-altitude flight, which requires the detection and avoidance of obstacles such as power transmission lines along with the ability to perform terrain following.[23] Additional military areas are in space, beyond the earth's absorbing atmosphere, (*e.g.*, rocket plume imaging), underwater for sensing using blue laser light (*e.g.*, detecting mines), and for applications where electromagnetic signals must be minimized (such as near sensitive electronics). Laser radar has been used by the non-defense sector in a number of industries such as mapping the contour of land, construction, ship-building, metal, and police traffic monitoring. The future offers many more potential applications including mobile-robot navigation, collision avoidance systems for automobiles, surface modeling, medical imaging and prosthetics, custom apparel design, surveillance, and the detection of fish in the ocean.

Many laser wavelengths are available for target acquisition, tracking, and pointing with Nd:YAG at $\lambda = 1.064$ µm and CO_2 with several wavelengths between 9 and 11 µm being the most commonly used. However, many future systems will require eye safe wavelengths beyond 1.5 µm, in the region where solid-state lasers are rather limited. The conversion of 1.064 µm from Nd:YAG with an NLO crystal is a reasonable solution and also makes wavelength tunability feasible, which may be required for object identification achieved by analyzing the objects' reflection at various wavelengths or for imaging in high-clutter environments.[24]

Remote sensing

The remote sensing of chemicals and biological agents appears to be the most active R&D area of the three laser radar application areas. Two techniques are used for remote sensing. The first, referred to as differential absorption lidar (DIAL), measures the absorption spectra of molecules. For the simplest case of sensing a single, distinct chemical, two laser wavelengths are required. One wavelength (λ_{ON}) is within a high-absorptive spectral region of the chemical being detected, and the other (λ_{OFF}) is within a low-absorptive region. The two beams of laser light are directed together at the site being examined. The difference between the two absorption cross sections gives an approximate measure of the concentration of the chemical being sensed. It should be emphasized that the wavelength, λ_{ON}, is usually chosen with great precision so that the absorption by the chemical in question is very high, while the absorption of other chemicals present is small. For example, mustard gas has a very distinct absorption peak at a wavelength of 8.24 μm.[25] In addition, as more chemicals with overlapping spectra are present, the analysis naturally becomes more complex, and data at additional wavelengths is needed. *(Editor's Note: Analysis of chemicals will be discussed in greater detail in the April issue of* OPN.*)*

Sandy Shaeffer/MAI

Figure 3. Military exercise responding to simulated nerve gas release in Washington, D.C. on April 30, 1997.

The second remote sensing technique is time-resolved fluorescence spectroscopy in which a UV laser beam excites the chemical being sensed and the newly emitted light at the chemical's characteristic wavelengths gives a direct measure of the chemical's concentration. This technique has been pursued for the detection of biological agents since "bacteria, viruses, and many bacterial toxins, as well as all known nutrient media for biological agents (all of which contain such proteins) have been shown to have strong UV fluorescence spectra."[23] As more chemicals or biological agents with overlapping spectra are present, emission spectra at additional UV wavelengths are often required to deconvolute the data. In most instances, DIAL is the preferred technique because it is generally more sensitive, the key infrared spectra of the chemicals being analyzed by DIAL often aligns with the atmospheric windows (primarily the 3–5 μm and 8–12.5 μm bands and secondarily the 1.55–1.75 μm and 2.0–2.4 μm bands) for longer range detection capability, and potentially dangerous UV light need not be projected.

The remote sensing of chemicals and biological agents has rapidly growing importance for both military and commercial applications. The Gulf War particularly heightened concern in the military about the threat of chemical and biological warfare and about the need to detect these agents from a distance. The war emphasized that almost any country is technically capable of deploying these outlawed agents.[26] It also made evident that existing chemical detection techniques are often unreliable as illustrated by various instances such as one in which the tear gas CS was incorrectly identified to be the nerve gas, sarin.[27] In addition, fear of terrorist use of these agents is intense as illustrated in Figure 3[28] and as highlighted by the Army's training program for 120 U.S. cities on what "to do when the first biological or chemical attack occurs."[29]

The most discussed civilian application of remote sensing is pollution monitoring that may be performed either by looking down from satellites onto the earth or by projecting laser beams from hand-held, aircraft-mounted, or truck-mounted DIAL units. Among the many chemicals detected by this technique are H_2O, CO_2, CO, CH_4, O_3, NH_3, $CHCl_3$, and SO_2. Additional applications of DIAL include natural gas detection, petroleum exploration, and pipeline monitoring.

Information technology

Information technology is enormously important for both military and commercial applications, and NLO-enhanced lasers have the potential to impact on the specific areas of data storage, communications, and displays. Since the 1982 introduction of the CD, optical data storage has been growing in importance because of the much greater information density that it provides over magnetic storage. The storage density of planar optical storage systems like CDs, is inversely proportional to the square of the wavelength of light. Therefore, systems using shorter wavelengths have much higher storage densities. Consequently, numerous research projects have been pursued during the past 15 years seeking inexpensive second harmonic generators (SHGs) for diode lasers. Today, one company has plans to market a high-density digital videodisk using a SHG with PPLN as the NLO material. Unfortunately for the NLO researchers, diode-laser technology is progressing quickly, and short wavelength, blue/violet-emitting laser diodes have been demonstrated with operational lifetimes that are rapidly increasing. InGaN-based multi-quantum-well-structure laser diodes, for example, have demonstrated emission at 417 nm.[30] Therefore, the potential for NLO having a long-term impact on 2-D optical memory during the future is questionable. 3-D storage schemes have also been pursued with even higher levels of data storage capacity. Some of these concepts, offering the possibility of parallel accessibility to the stored data, require wavelength-tunable laser sources with narrow and precisely-tuned spectral output.

The uses of NLO-enhanced laser systems have been discussed in the past for various optical communication systems such as communication with submerged submarines. Blue-green laser light transmits well in sea water, and laser-based communication systems inherently cannot be easily jammed or intercepted because laser beams are directional. Several NLO efforts have pursued the development of blue-green laser sources during the 1980s primarily for this application, but these efforts have stopped because the idea of using optics for submarine communications has been deemed too expensive during a time of shrinking defense budgets.[31]

An additional information technology area affected by NLO-enhanced laser sources is projection displays. The military has need for dynamic infrared scene generators for testing systems and components such as target recognition algorithms. In these scene generators, NLOs provide a means to convert the light from existing lasers to the various wavelengths needed in the infrared. NLOs also afford a way to wavelength shift a scene, composed in the visible or near infrared, directly into the mid- or far-IR spectral regions.[32] Commercially, laser-based projectors for theater audiences are under development. In these systems, NLO crystals allow laser beams to be generated with the ideal wavelengths (red at 605±5 nm, green at 530±10 nm, and blue at 470±10 nm) for optimum color perception.[33]

The future

Military applications will continue to drive NLO technology during the coming years. The remote detection of chemical and biological agents by either lidar or other techniques is an area that particularly appears to be growing in interest as discussed earlier. However, due to the maturing of NLO technology and to shrinking military budgets, commercial applications will most likely soon become the primary influence for NLOs, overtaking military needs. This coming transition should be recognized in part as a triumph for the military's researchers and contractors in helping to advance NLOs during the past decades.

Acknowledgment

Thanks to Patrick Hemenger for help and encouragement in writing this article.

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