Laser Radar Development

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ABSTRACT

This paper discusses the trends in laser radar development. Applications include reconnaissance and targeting from airborne and spaceborne platforms. A multifunction airborne sensor system, which includes a laser radar function with many modes, is defined. A multidiscriminant space borne laser radar is also described and its feasibility is assessed. A number proposed and existing Air Force programs to develop laser radar technology are described.

KEY WORDS

Sensing, affordable sensing, multifunction sensing, multifunction EO, multidiscriminant sensing, modular sensors, laser radar, ladar, lidar, and multidiscriminant laser radar

1. INTRODUCTION

Two major objectives are discussed. One is a multifunction system for aircraft application. Modern aerospace vehicles must perform a large number of sensing functions, but to fit within modernization budgets they must do it at very low cost. A modular, multifunction, open architecture, sensing system required of EO systems on a combat aircraft is discussed. Multiple aperture modules will be used, and one or more systems modules will encompass common components. The other thrust is a multidiscriminant laser radar for space based applications. A number of space based laser radar applications are discussed. These include target identification, target designation, wind sensing, and gas cloud identification. Laser communications is briefly discussed since it is an easy additional function to add to laser radar. Laser radar development efforts that will enable these thrusts are also discussed.

2. TECHNOLOGY EFFORTS THAT SUPPORT MULTIFUNCTION AND MULTIDISCRIMIANT LASER RADAR SYSTEMS

The Air Force Research Laboratory is developing laser radar systems based upon 2 different laser types. One is a solid state Raman shifted laser that uses NdYag as its initial laser. [1] The other is a system based upon a 2 μm laser radar. The Nd Yag based system has both a 1.064 μm designator mode and can generate 1.56 μm radiation using Raman shifting with a solid state material. The system to be delivered will generate approximately 400 mj at 1.56 μm or 700 mj of light at 1.064 μm. The 1.56 μm energy can be used for a snapshot imaging sensor system. One disadvantage of this laser system is that we will pay over $200,000. for the diodes to pump such a laser. This laser is however ideal for a 1.5 μm direct detection snapshot laser radar, such as we will use in the Enhanced Recognition And Sensing laser Radar ,ERASER, program. This laser is also an ideal pump for a direct detection mid IR OPO system, which we plan on developing in the medium term. Solid State Raman shifted lasers have excellent beam quality, which makes pumping an OPO very favorable. For a multidsicriminant laser radar we may also wish to have a coherent mode for vibration detection and for wind sensing. At least two groups have shown narrow linewidth seeded operation of solid state Raman shifted lasers, so it should be possible to use such a laser radar in a coherent mode.[2] This is however very immature technology. The other potential basis for a multidsicriminat laser radar is a 2 μm laser. This can be done in a number of ways, but at this time the preferred approach appears to be 804 μm diodes pumping a 1.93 μm ThYag, which in turn pumps a 2.128 μm HoYag laser. The last wavelength is chosen so we can double it and provide a designator function.[3]

One real advantage of such a system is that it will have an 8 or 10 msec upper state lifetime compared to 200 μsec for NdYag. This means a dramatic reduction in the required cost of diodes for low rep rate sensors. It will be necessary to buy CW diodes rather than quasi CW diodes, and they are somewhat more expensive per peak watt, but are more reliable. Even with the somewhat higher cost per peak watt the diode costs should be an order of magnitiude lower than diode cost associated with a NdYag system. This makes the assumption that it is possible to have enough gain in this laser to achieve the pulse width and energy desired for a designator, and for other applications. If it is not possible then a NdYag amplifier might still be required, in which case the positive cost impact would be much reduced.

Another enabling technology that I want to briefly discuss is optical phased arrays. Figure 1 shows sketch of an optical phased array.[4] This array deflects one dimension at a time. Because of this it will require simple addressing. It has the potential to achieve costs not much more than those associated with displays found in notebook computers.

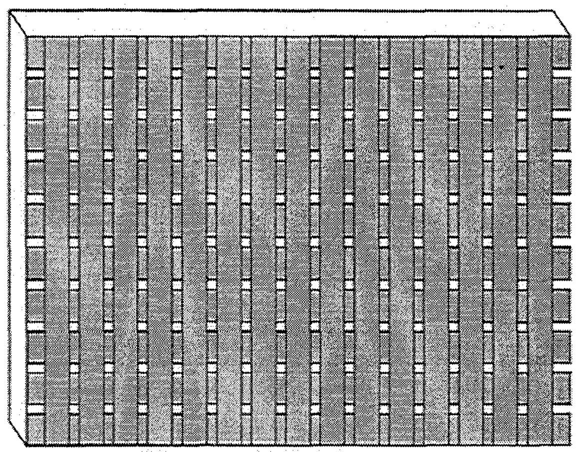

Figure 1: Optical Phased Array

Currently pointing and tracking devices are very expensive, and are difficult to make with high pointing accuracy. Optical phased arrays also will provide random access beam pointing such as associated with microwave phased array radar.

Receiver development includes a number of approaches to provide snapshot array capability. We started on this so a low rep rate, direct detection, laser radar could be made that is very similar to a laser designator. In addition snapshot imaginf greatly relieves pointing stability requirements, so it can lower cost of a laser radar system. Two dimensional receivers (angle / angle) are easy. It is simply a gated TV. We have an effort joint with the Army to develop photocathodes that are sensitive at the eyesafe 1.5 μm wavelength. We also are interested in extending this receiver capability out to about 5 μm, preferably without a cooler, so we can have laser radar sensors that can use the wavelength dimension for target discrimination and so we can use the mid IR wavelengths for improved atmospheric transmission. At most we would like to use a TE cooler rather than a full refrigerator. We also are interested in achieving a 32 x 32 array capable of providing range read out as well as the angular resolution. We have a couple SBIR efforts in this area to provide this capability at multiple wavelengths.[5] In addition we have an effort to provide a 10 x 10 coherent receiver array in the 2 μm region, where we have been doing more coherent laser radar receiver work.

3. MULTIFUNCTION AIRCRAFT BASED EO SYSTEM

Figure 2 shows an aircraft-based view of the Multifunction Identify, Strike, and Survive Integrated Optical Nodules, MISSIONs, concept, an aircraft based multifunction EO sensor system.[6] Wherever possible common components are placed in an environmentally benign region of the aircraft, and shared among the various apertures. Desired functions are re-examined to see if they can be accomplished in affordable ways that maximize use of common components and identical components while striving for reasonable systems simplicity. Complete azimuth coverage is envisioned as well as adequate elevation coverage (possibly on the order of –45 degrees to +15 degrees, although full elevation coverage is desirable). Multiple aperture modules are used, and one or more systems module will encompass common components. A single systems module could be sufficient, but for battle damage resistance, and possibly for space availability reasons, it may be necessary to have more than one systems module. In a concept demonstration, a single systems module is sufficient. When implementing the MISSIONs concept it is important to design it as a portion of a modular, multifunction, open aperture, avionics suite. This will allow maximum use of any synergy or affordability opportunities between EO systems and other avionics functions, such as a multifunction RF system. Certainly some processing functions can be shared, as well as a high-speed digital data bus. Some analog functions can probably be shared. The MISSIONs system should include all functions that can affordably be accomplished with EO / IR systems. Candidate functions are: 1.) Air to ground target acquisition and identification at ranges in excess of 20 Km (for tank size mobile targets such as a Russian T –72); 2.) Target designation against air to ground targets, even if the MISSIONs equipped aircraft turns for home after the target is acquired and the weapon is released; 3.) Hand-off to Global Positioning System , GPS, based munitions, or combination GPS / seeker based munitions; 4.) Air to air target acquisition and identification at ranges in excess of 60 Km (for the infrared signature of an F-16 size target without any plume); 5.) Very high probability of infrared missile countermeasure against all A/A and A/G threats, to include modern threats that have anti-flare discrimination circuitry and imaging seekers;

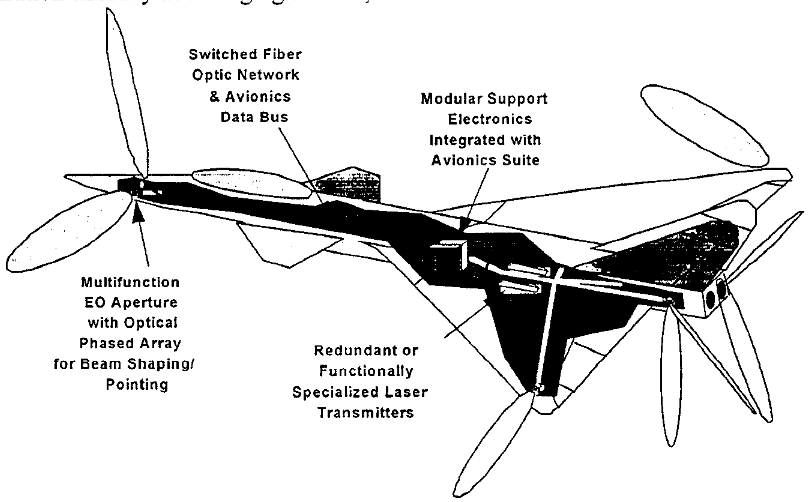

Figure 2. Aircraft-Based View of a MISSIONs System

6.) Missile approach warning as support for the infrared countermeasures function; 7.) Countermeasures against 8 -10.5 μm thermal imaging sensors that may be adjunct trackers for threat systems; 8.) Navigation update by locating fixed objects on the ground using pilot situational awareness sensors (This day / night imaging capability may be used for a landing aid in adverse weather or black out conditions and for functions such as air to air refueling); 9.) Covert inter-aircraft communications using solar blind / atmospheric absorbed UV laser communications; High bandwidth laser communications to satellites or other aircraft at high altitude; 10.) Laser Doppler wind measurement for targeting, bomb drop, airdrop, and safety / economy of flight purposes. Figure 2 shows a conceptual diagram of a MISSIONs system which incorporates the complete set of candidate functions. MISSIONs system cost and the mission of a particular aircraft will be factors in deciding which of the above functions should be available in a given aircraft implementation. Each aircraft type may need a somewhat different implementation of MISSIONs. It is anticipated that a MISSIONs demonstration will encompass most of the above functions.

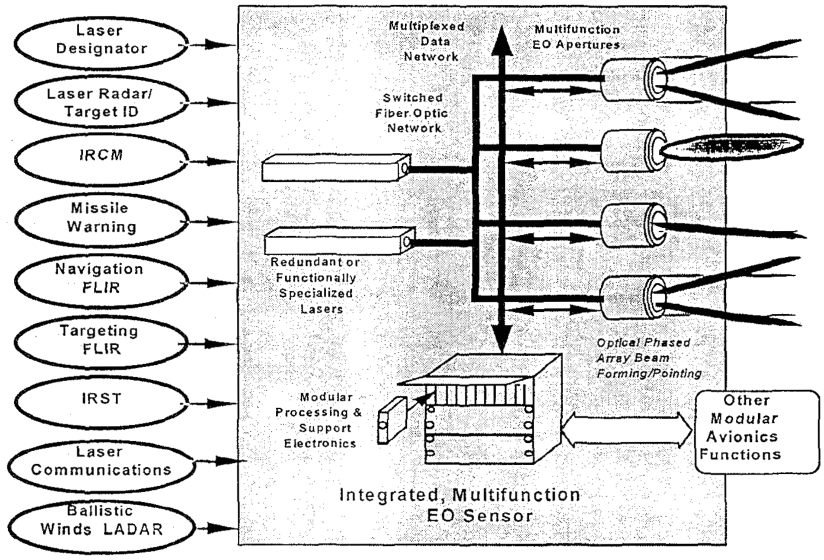

Figure 3. Conceptual Diagram of a MISSIONs System

Consider a seven aperture MISSIONs system. The number of holes in the aircraft can be substantially fewer if no FOV restrictions are present, since multiple telescopes could be mounted in the same aircraft hole. Conversely if obscurations are present we may need more than seven apertures and more than seven holes in the airplane. Nominal coverage could be 60 x 60 degree coverage for each of 6 situational awareness / countermeasure / designator / laser communications apertures (referred to here as situational awareness apertures), and a smaller FOV forward coverage for one large target acquisition / ID aperture. Once a target is acquired in the front aperture it will be necessary to establish active track, and to be capable of handing over that track from the acquisition aperture to the situational awareness apertures. The target designator will be kept on the weapon delivery spot in an over the shoulder delivery by handing off tracking and designation from the acquisition aperture to one or more situational awareness apertures. It is possible that multiple situational awareness apertures will be used for laser designation as the aircraft turns. The baseline approach considered is for each of the six situational awareness apertures to have a 2.5 cm diameter, while the forward target acquisition aperture would have a 10 to 15 cm diameter.

Next I will summarize laser requirements for the active system functions. Table 1, below gives some approximate laser parameters for the required functions. Laser Energy per pulse and power requirements certainly are approximates. In some cases I have limited energy / power based upon practical / cost considerations

I assumed that for the longer wavelength IRCM cases a degenerate optical parametric oscillator, OPO, is used to get from 1.064 to 2.13 μm. Actually doing it that way we probably can get about 30% conversion efficiency from 1.06 μm to 4 μm, but I only assumed 25 %. Even using the degenerate OPO, getting to 5 μm with 25% conversion efficiency is somewhat aggressive. Quasi cw diode bars of 100 watts currently run about $1K, although in volume people may be able to beat that price. Cw diodes are more expensive, and run about $3K for 20 watts. 100 watts of cw diodes is however just $15K, much more affordable than the 5000 watts of quasi cw diodes. There is an issue of whether all of the above applications will use the same diodes, or the cw pumped applications will be separated from the quasi cw pumped applications. At this time we should assume quasi cw diode arrays have a 5% - 20% duty cycle limitation.

Another interesting table is a wavelength table for an OPO pumped by a 1.064 μm pump. This is shown in table 2. For this table I have assumed we can convert 80% of the pump energy into one or the other new wavelengths (signal, or idler), and that the only other loss is the quantum defect. This is an aggressive assumption for pulsed conversion. CW conversion can exceed 80%. Pulsed conversion might be more likely to be at 75%.

Table 1 Laser Parameters

Function	**Wavelength**	**Rep Rate**	**Pulse Width**	**Ave Power**	**Energy / pulse**	**Ave power at 1.064 µm**	**energy per pulse 1.064 µm**	**Pump Energy per pulse**	**Pump duty cycle (200 µsec pulse)**	**Pump Peak power**	**Diode cost**
IRCM (jamming)	2.5 -5.0 µm	20, 000 Hz	15 nsec-200 usec	10 watts (@ 4µm)	.5 mj	40 watts	2.5 mj	10 mj	CW	200 watts	$30K
IRCM vs FLIRs	8 - 10.5 µm										
Designator	1.06 µm, 1.54 alt	100 Hz (10 per target)	15 nsec	40 watts	400 mj	40 watts	400 mj	1.6 joule	2%	8000 watts	$80K
ID (snapshot)	1.5 -2.5 µm. 3.5-4 µm alt	250 Hz	3 nsec	100 watts	400 mj	194 watts	775 mj	3.1 joule	5%	15500 watts	$160K
ID (Scanning)	1.5 -2.5 µm. 3.5-4 µm alt	20,000 Hz	3 nsec	26 watts	1.275 mj	40 watts	2.5 mj	10 mj	CW	200 watts	$30K
Laser Comm	.266 µm	300 hz	10 – 15 nsec	.6 watts	2 mj	1.5 watts	5 mj	20 mj	6%	100	$1K
Laser Comm	1.5 µm	125 Khz	15 nsc	25 watts	.2 mj	40 watts	.5 mj	2 mj	CW	250	39K

Table 2:OPO Wavelengths

Pump	**Signal % Power**	**Signal**	**Idler**
1.064 µm	55.3	1.54 µm	3.44 µm
"	54.2	1.57 µm	3.3 µm
"	40*2	2.12 µm	2.12 µm
"	24.3	3.5 µm	1.53 µm
"	22.7	3.75 µm	1.485 µm
"	21.3	4.0 µm	1.45 µm

For laser radar target ID wavelengths around 1.5 µm are of interest, as well as the degenerate line at 2.12, and wavelengths around 3.5 - 4 µm. The 3.5 - 4 µm region is of interest because of smoke penetration capability. A resonator structure needs to be designed to allow switching the idler and the signal, so we can chose either one as the signal of interest.

For countermeasures it seems reasonable that a degenerate OPO be used to pump a second OPO. Either that or a source around 2 µm could be used to pump the OPO. A degenerate OPO has loss , but avoids a factor of 2 of the quantum loss since two photons are generated for one photon in. This will increase the over-all efficiency. In addition, if one is interested in getting out to 5.5 µms, then more reasonable nonlinear crystal options are available. Table 3 gives estimated efficiency, and potential energy per pulse, assuming a 250 mj per pulse pump at 1.064 µm, and 80% conversion efficiency in both OPOs. As stated earlier, that conversion efficiency is aggressive for pulsed lasers.

Table 3 Energy at mid IR. Wavelengths

Idler λ	**Signal λ**	**Efficiency**	**Energy per pulse**
4.8	3.8	35.7%	89
4.5	4.0	34%	85
4	4.5	30%	75
3.8	4.8	28.3%	71
3.7	5.0	27%	68
3.5	5.5	24.6%	61.5

For my assumptions this is a factor of 1.6 times more energy per pulse than if we just pumped directly with 1.064, rather than having the degenerate OPO stage. If the OPOs are less than 80% conversion efficiency, then this gain will be less. For going to the longer wavelengths it may not be possible easily in a single stage. We need a material that is transparent at 1.064 µm out to 5.5 µm. Using the degenerate OPO allows us to break this large region into two stages. There is an issue whether we have to go al the way to 5.5 µm. Laser tuneability out to 5 µm is probably sufficient against Mid IR seekers.

4. MULITIDISCRIMINANT SPACE BASED LASER RADAR

This concept has some similarity to the aircraft case. In this case for many applications it adviseable that a multispectral / hyperspectral passive sensor be used to acquire the target. A multidiscriminant laser radar can then be used to identify the target, even very difficult targets. "Soft" targets such as wind sensing and chemical or biological clouds are also included. Figure 4 shows the concept.

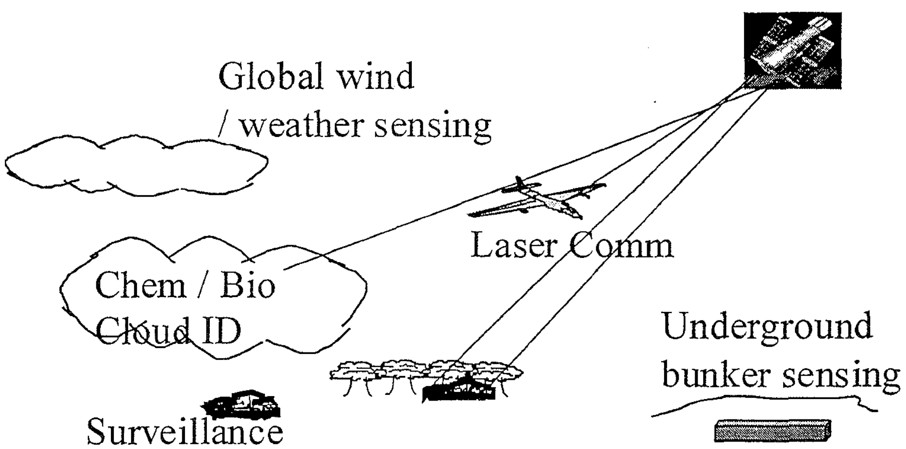

Figure 4: MultifunctiON IndenTification Optical Remote (**MONITOR**) Sensor

Laser radar has the richest phenomenology of any sensor. It has all the modes of a passive electro-optical sensor plus many additional " dimensions". It has finer angular resolution than microwave radar, as well as being able to hit certain molecular lines that identify materials. Below you can see in figure 5 pictorials that represent the images that can be obtained for 1D, 2D, and 3D laser radar imaging. We have conducted work in of these spatial imaging modes. 1D imaging is simly high range resolution imaging. 2D is a range gated TV. 3D uses all the spatial dimensions, providing range / angle / angle imaging.

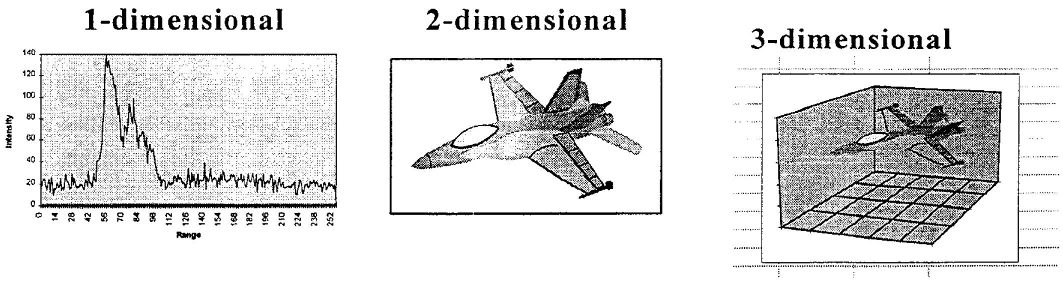

Figure 5: Spatial Imaging Dimensions

Beyond spatial there are still many dimensions available for laser radar disrimination. Wavelength is one of those dimensions. Figure 6 shows the relative reflectance of various materials as a function of wavelength. As can be seen various materials have different reflectivity spectrums. We have all experienced this in the visible region. Most things we see have color. This is just color carried into the infrared regions so it can be seen at night as well as during the day. This fourth dimension can be a very useful adjunct to the 3 spatial dimensions.

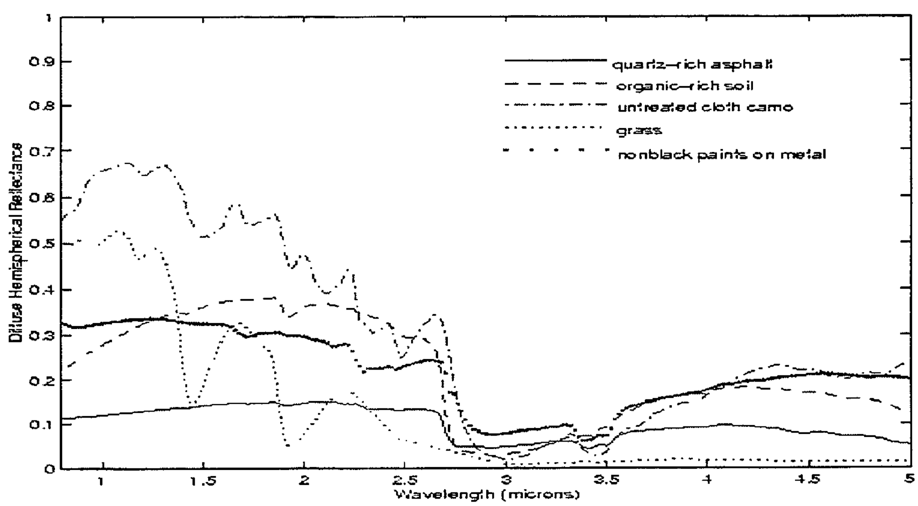

Figure 6 : Material Reflectivity Spectra

Another dimension that can be used is velocity. In this case I want to use the measurement of target vibrations as an identifier of a target. Figure 7 shows two measured vibration spectra.[7]

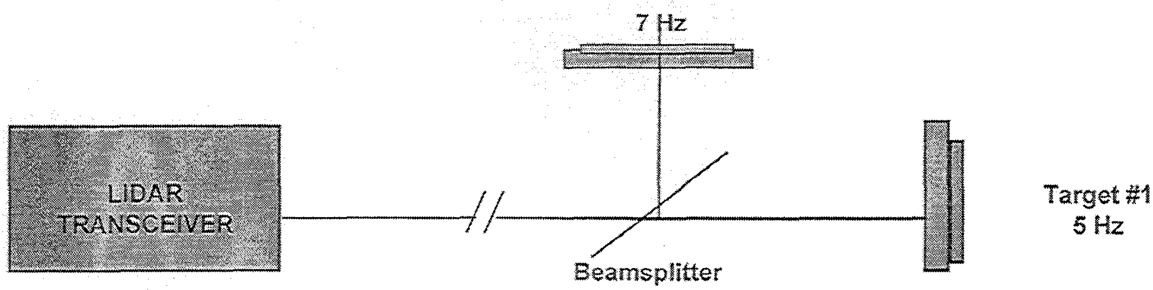

Figure 7 : CTI Doublet Pulse Vibration Detection

5. CONCLUSIONS

Laser radar technology is developing to provide many critical functions in affordable sensors. Laser radar has the richest phenomenology of any sensor, and is therefore the most robust sensor at detecting and identifying targets with high probabilities and low false alarm rates. For certain difficult targets laser radar may be the only viable choice. For example material identification, whether in a gas cloud or a solid, laser radar technology is by far the most promising sensor technology because it is possible to hit the material with photons that are at the correct energy states to cause a reaction in the material (absorption, flourencse, etc). While laser radar is not yet widely deployed it is an emerging sensor technology.

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