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Performance analysis of Raman LIDAR (Light Detection and Ranging) for detecting remote trace explosives

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Abstract- The aim of this paper is to analyze the performance of Raman Light Detection and Ranging (LIDAR) technique to detect trace explosives such as Research Department Explosive (RDX) and Trinitrotoluene (TNT). In various situations, when explosives are prepared, transported or handled, a quantifiable amount of explosive material ends up on surfaces. The main focus lies on the rapid detection of explosives in such surfaces. This standoff technique is implemented under the principle of Raman spectroscopy. Raman spectroscopy is a spectroscopic technique which involves inelastic scattering from a monochromatic light usually a laser source. The advantages and disadvantages of different lasers used in the process have been discussed. The limitations of Raman Spectroscopy have been studied and methods to overcome them have been experimented.

Index Terms- Raman LIDAR, Raman shift, Raman spectroscopy, RDX, TNT

I. Introduction

One of the detection methods that are anticipated to meet the requirements for explosives standoff detection is Raman spectroscopy. Raman spectroscopy serves as an analytical tool that gives detailed molecule-specific information about the molecule studied. This detection technique can be effective in applications such as screening passengers and luggage at airports, military and other sensitive locations. The basic advantages of Raman spectroscopy are its non destructive character and high sensitivity.[1] The main difficulty behind Raman spectroscopy is the low intensity of scattered radiation. The intensity of Rayleigh scattering is ~10^{-3}, which is much higher than Raman scattering ~10^{-6}. Raman scattering occurs for one in approximately 10^{7}incident photons on a sample. This method is the most promising method for solving the problem of standoff detection and identification of particle traces of both known and new types of explosives that is present on the surfaces of objects. Recently Raman spectrometers are designed in a way such that scattered light is collected by a telescope and fed to a spectrograph through an optical fiber. As a result, not only the spectrometer size was reduced but also the design became sufficiently reliable to be used under field conditions.

II. SOFTWARE USED

The software used here is Optisystem 13.OptiSystem is a comprehensive software design suite that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks.

III. WORKING PRINCIPLE

Raman spectroscopy is a spectroscopic technique based on inelastic scattering of monochromatic light, usually from a laser source. Photons of the laser light are absorbed by the sample and then reemitted. Frequency of the re-emitted photons is shifted up or down in comparison with original monochromatic frequency, which is called the Raman Effect. This shift provides information about vibrational, rotational and other low frequency transitions in molecules. The Raman interaction leads to three possible outcomes. First, the material absorbs energy and the emitted photon has a lower energy than the absorbed photon. This outcome is labeled Stokes Raman scattering, (Red shift).Second, the material loses energy and the emitted photon has a higher energy than the absorbed photon. This outcome is labeled anti-Stokes Raman scattering, (Blue Shift). Third, the material absorbs a photon, the excited molecule returns back to same vibration state and emits light with same frequency. This outcome is labeled Rayleigh scattering. [2]

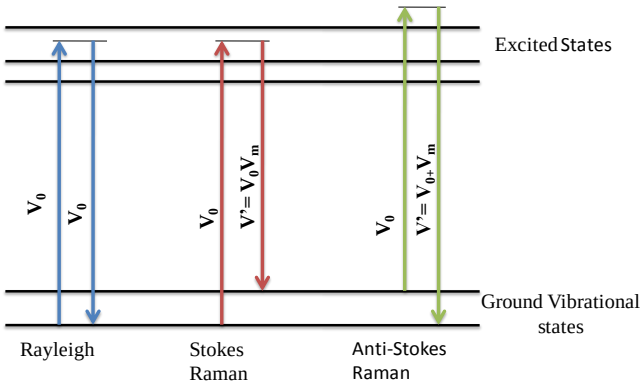

Figure 1: Three possible outcomes of Raman interaction.

IV. EXPLOSIVE

Explosives are mainly divided into two classes: nitro/nitrate based or non nitro/nitrate based. The nitro based explosives include Research Department Explosive (RDX), Trinitrotoluene (TNT) and PETN. They contain not only nitrogen but also hydrogen, carbon, and oxygen. The general property of these materials is that the content of nitrogen and oxygen in their molecules exceeds significantly that of carbon and hydrogen. The relative nitrogen content is several times

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higher than in conventional materials (silk, polyurethane, Nylon, etc.).The molecules of nitrogen-containing explosives include either nitro (NO_2) or nitrate (NO_3) groups. The vibration frequencies of these groups depend on the type of the atom a group is added to in the explosive material. The non nitro/ nitrate based explosives are derived from materials such as peroxides (TATP), per-chlorates and azides. Explosives have extremely low vapor pressure, ranging from parts per million to less than parts per quadrillion. Low vapor pressure places severe limitation on a technique that relies on the ambient vapor above the material for detection. We are detecting nitro based explosives which have at least one NO_2 group. When nitro-based explosives detonate, one of the ultimate end products is N_2 gas, which is very stable due to its N-N triple bond. The formation of this low-energy product from the higher-energy starting material is accompanied by the release of a sizable amount of energy. [3]

V. BLOCK DIAGRAM

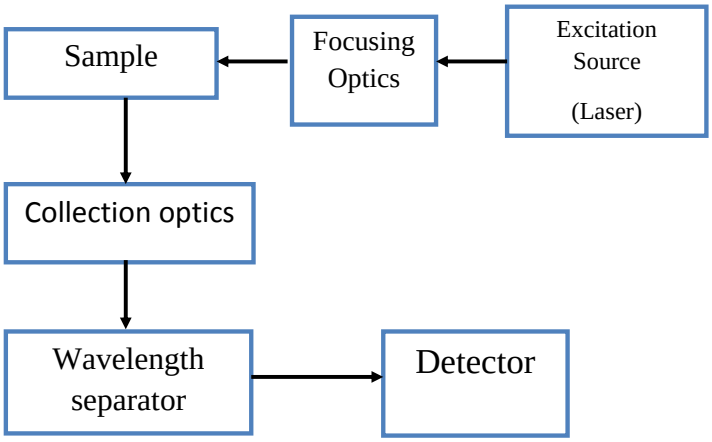

Figure 2: Block diagram of Raman LIDAR

A laser of suitable wavelength acts as the excitation source, hitting the sample placed at a distance of few meters. The focusing optics is used to maximize the output of the laser on the sample. The shifted wavelength is converged through the collection optics. Wavelength separator is used for filtering out the desired wavelength. A charge coupling detector (CCD) or any other form of single or multiple channel detectors is used to detect the shifted Raman wavelength. On comparing the shifted wavelength and Raman shift table, constituents of the sample can be detected

VI.RAMAN LIDAR DESIGN

One monochromatic laser hits an explosive with a particular wavelength, the photon hits the molecules of the explosive .The molecules then increase or decrease the wavelength of the photons upon interaction. This change in wavelength is called the Raman shift which gives us information about the chemical composition of an explosive. The excitation source used here is Nd-Yag laser (532nm). Nd-Yag laser (532nm) falls within the visible spectral region where optical components are easily available and affordable making it uncomplicated to design the instrumentation. It can used under harsh weather conditions. When a single Nd-Yag laser is used a sharp Raman peak is not obtained. However when two laser beams are used a sharper peak is obtained. This is known as CARS (coherent Anti-Stokes Raman Spectroscopy).Two laser beams with frequencies v_1 and v_2 ($v_1 > v_2$) interact coherently, and because of the wave mixing, produce strong scattered light of frequency $2v_1 - v_2$. If the frequency difference between two lasers $v_1 - v_2$ is equal to the frequency of a Raman-active mode then a strong light of frequency $v_1 + v_m$ is emitted, where v_m is the vibrational frequency of the sample. With Coherent Anti-Stokes Raman Spectroscopy (CARS) we can obtain only one strong Raman peak of interest. Coherent Anti-Stokes Raman Spectroscopy derives its name from the fact that it uses two Coherent laser beams and the resulting signal has Anti-Stokes frequency. [1]

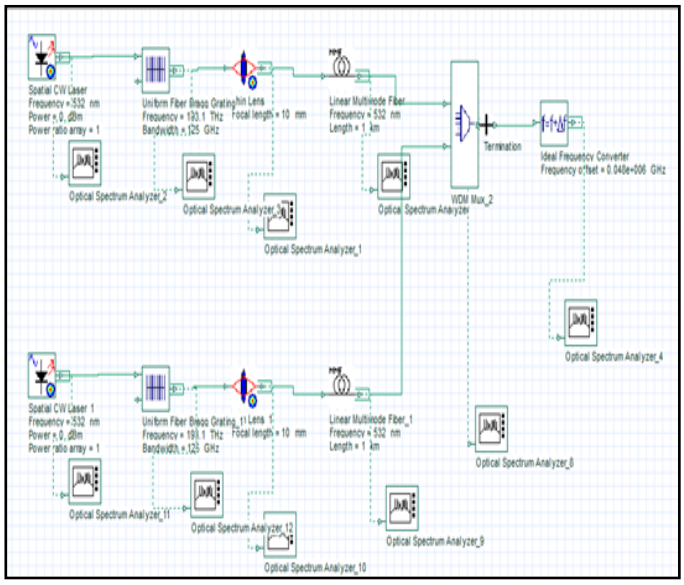

Figure 2: Raman LIDAR circuit diagram

The laser beam passes through a fiber Bragg grating. A fiber Bragg grating is a distributed Bragg reflector that reflects particular wavelengths of light and transmits all others. It can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector. The filtered wavelength is then converged through a thin optical lens. The converged output then passes through a multimode fiber. Multimode fiber optic cable has a large diametric core that allows multiple modes of light to propagate. Because of this, the number of light reflections created as the light passes through the core increases, creating the ability for more data to pass through at a given time. Because of the high dispersion and attenuation rate with this type of fiber, the quality of the signal is reduced over long distances. After this, we pass the

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light wave through an ideal frequency converter which provides wavelength shift. Red shift and Blue shift describe how light changes as objects move closer or farther away from us. When an object moves away from us, the light is shifted to the red end of the spectrum, as its wavelengths get longer. If an object moves closer, the light moves to the blue end of the spectrum, as its wavelengths get shorter.

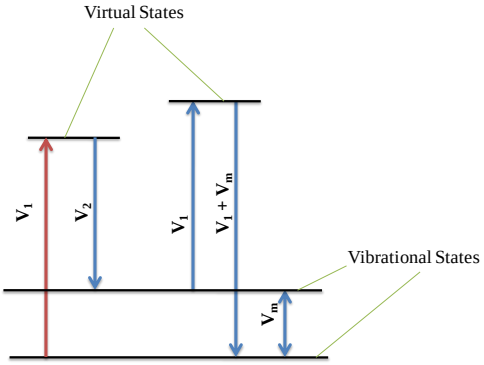

Figure 3: Energy Level diagram of CARS (Coherent Anti-stokes Raman spectroscopy)

VII. FIGURES AND TABLES

The table below shows the numerical values of Red shift and Blue shift of different chemical constituents when they are excited by a laser of 532nm.

Table 1: Examples of Red shift and Blue shift.[5]

Raman Wavelength & Wavenumber Solver Chart												
Excitation Laser				532	nm			18,797	cm^{-1}			
Shift (cm^{-1})			Group	Intensity	Red Shift(nm)			Blue Shift(nm)				
100	-	210	Lattice Vibration	Strong	534.8	-	538.0	529.2	-	526.1		
150	-	430	Xmetal-O	Strong	536.3	-	544.5	527.8	-	520.1		
250	-	400	C-C Aliphatic Chain	Strong	539.2	-	543.6	525.0	-	520.9		
295	-	340	Se-Se	Strong	540.5	-	541.8	523.8	-	522.5		
425	-	550	S-S	Strong	544.3	-	548.0	520.2	-	516.9		
450	-	550	Si-O-Si	Strong	545.0	-	548.0	519.6	-	516.9		
490	-	660	C-I	Strong	546.2	-	551.4	518.5	-	514.0		
505	-	700	C-Br	Strong	546.7	-	552.6	518.1	-	512.9		
550	-	790	C-Cl	Strong	548.0	-	555.3	516.9	-	510.5		

Table 2: Wave number ranges and vibrational mode assignment of spectra of explosives.

Vibrational Mode Assignment	Explosive (Type)	Wavenumber (cm^{-1})	Shifted Wavelength (nm)
NO_2 deformation and ring stretch	Nitramine(RDX), TNT	650-850	510-513
N-N Stretch	Nitramine(RDX)	1200-1230	499-504
NO_2 symmetric stretch	Nitramine(RDX)	1260-1320	499-501
NO_2 asymmetric stretch	Nitramine(RDX), TNT	1450-1600	490-491

The table above has a list of different components present in RDX and TNT. It also shows their shifted wavelength and the amount of shift in their wave number.

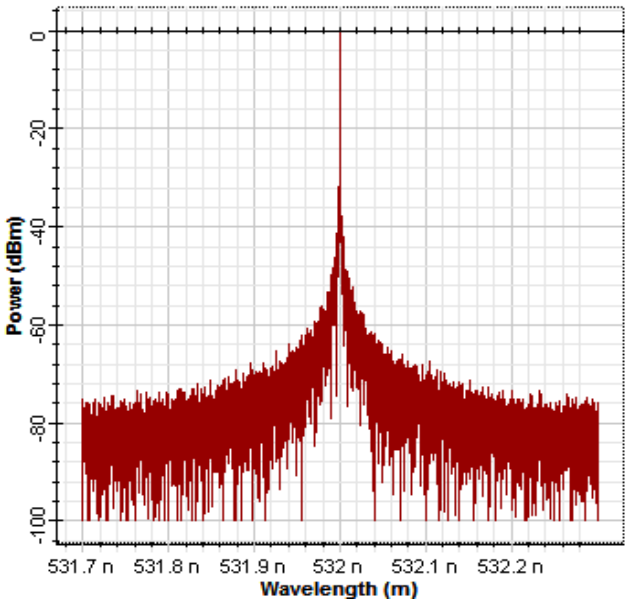

Figure 4: Input from the Nd-Yag laser source (532nm).

This is the graph obtained using an optical spectrum analyzer.

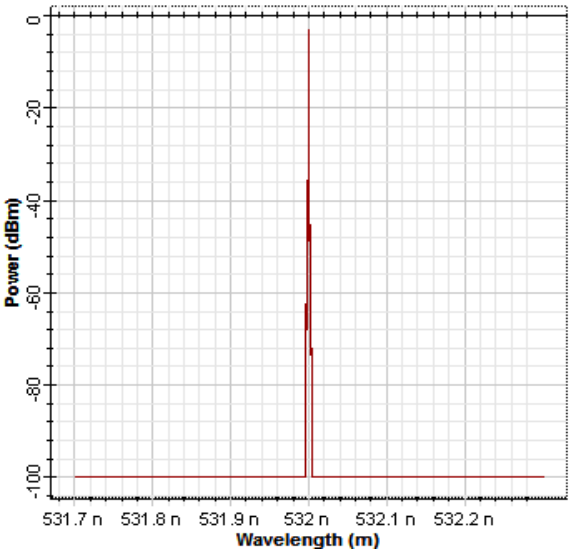

Figure 5: Output from single laser source

When a single laser source of 532nm is used, peak is obtained at 532nm wavelength which is slightly distorted and not sharp.

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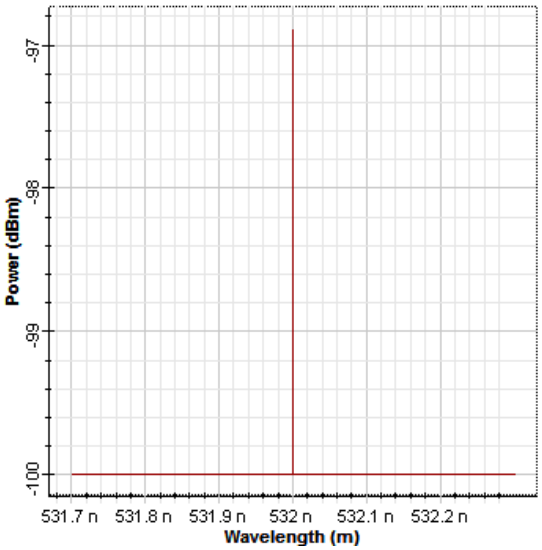

Figure 6: Output from double beam laser.

In order to overcome the distortion of the previous figure, two lasers of 532nm are used to obtain a sharp peak at 532nm. This is the practical implementation of Coherent Anti-Stokes Raman Spectroscopy (CARS). [1]

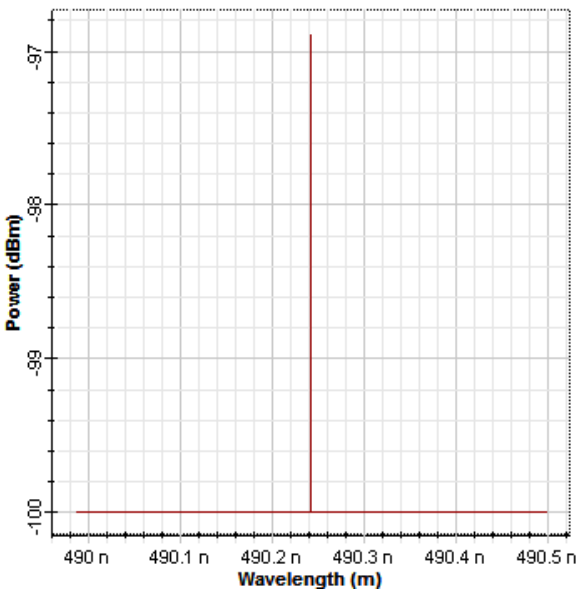

Figure 7: NO_2 Asymmetric Stretch (RDX, TNT)

The initial wavelength of 532nm has been shifted to ~490nm.The shifted wavelength gives the corresponding wave number which is used to determine the component in the explosive. Here NO_2 Asymmetric Stretch in RDX, TNT. [5]

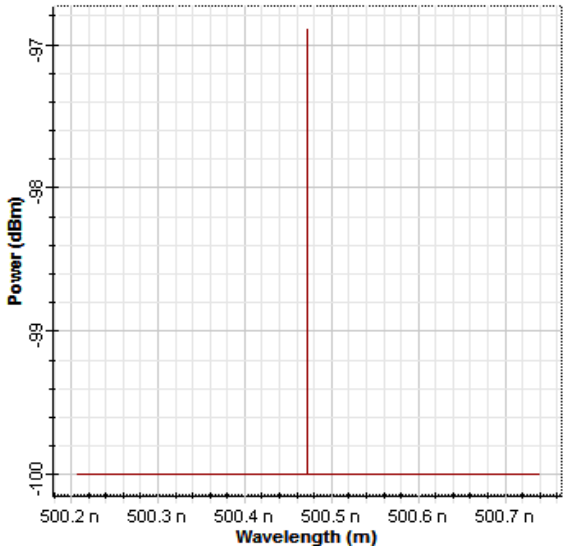

Figure 8: NO_2 Symmetric Stretch (RDX)

Here the shifted wavelength is ~500nm which corresponds to a shifted wave number of 1300cm^{-1}.Hence, it can be concluded that NO_2 Symmetric Stretch is present in RDX. [5]

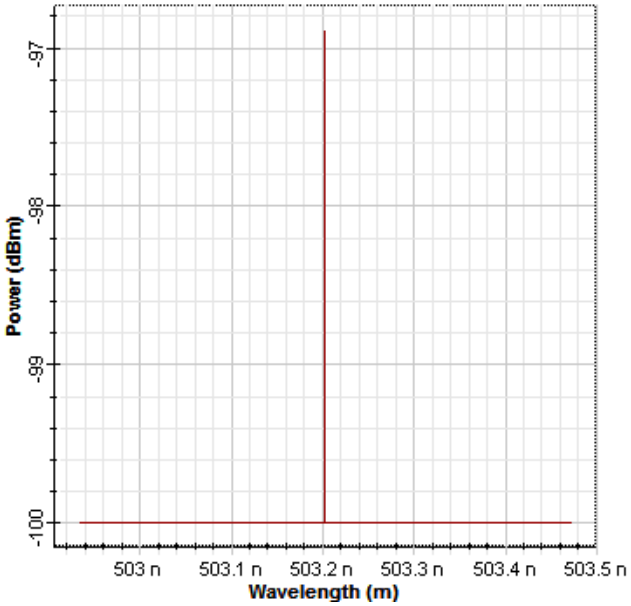

Figure 9: N-N Stretch (RDX)

Similarly like the above two shifts a blue shift of ~ 1200cm-^{1} helps to detect N-N Stretch in RDX. [5]

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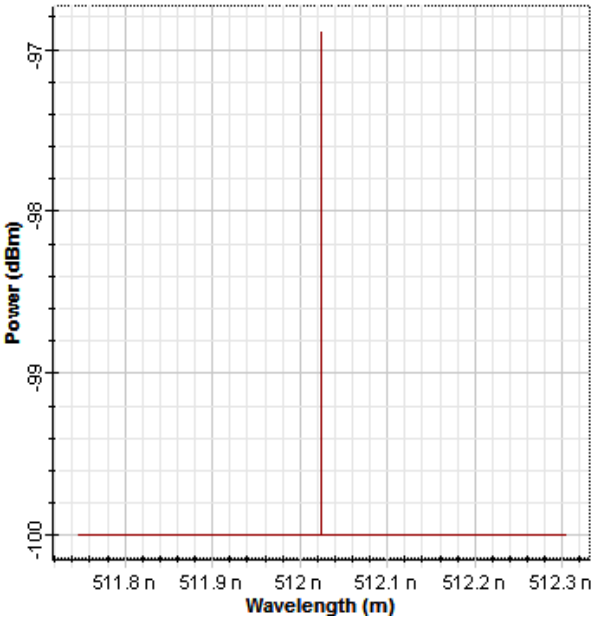

Figure10:NO_2 Deformation and Ring Stretch (RDX, TNT)

The presence of NO_2 Deformation and Ring Stretch in RDX, TNT gives a shifted wavelength of ~512nm which corresponds to shifted wave number 725cm^{-1}.Hence a sharp peak is obtained at 512nm. [5]

VIII.CONCLUSION

Standoff detection of explosives is one particular area where the laser appears to be uniquely capable, where the laser properties of long-distance radiation propagation are providing capabilities not possible with other techniques. Although the use of lasers for standoff detection of explosives is a very promising technique, it is still an emerging area of application which requires time to mature. One major area of improvement is using an excitation source which has wavelength in the UV range. Since a Raman signal is inversely proportional to the fourth power of the incident laser radiation wavelength, the latter must be in the UV range to yield the strongest Raman intensity. This increase is even more significant in the case of resonant effect of radiation on molecules in the deep UV region. To add to it, 532 nm is not the optimal Raman probing wavelength because fluorescence often occurs in this spectral region. The Raman signal intensity scales with $1/\lambda^4$, leading to the conclusion that UV wavelengths would be the better choice.[4] However, 532 nm falls within the visible spectral region where optical components are easily available and affordable, making it flexible enough to design the experimental setup or instrumentation.

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BIOGRAPHIES

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