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Instant identification of explosive material: Laser induced photoacoustic spectroscopy versus fourier transform infrared

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ABSTRACT

Terrorism by means of explosive materials has become a serious threat. Instant identification of common explosive material is an urgent demand. Even though FTIR spectroscopy can offer signature based on chemical structure; this technology requires sample handling and processing. On the other hand, laser induced photoacoustic spectroscopy (LIPAS) can offer outstanding characteristic signatures. Common commercial explosive materials were subjected to LIPAS analysis via stimulating the tested material with pulsed Q-switched Nd:YAG laser. Generated photoacoustic signature was captured and processed via high response piezoelectric transducer and novel digital signal processing algorithm designed for time and frequency domain analysis respectively. Each explosive material demonstrated characteristic absorption coefficient as well as frequency response. The main finding of this study is that phase-resolved domain analysis offered an outstanding signature. This phase-shift signature is candidate for data-base operation mode. LIPAS offered superior identification signatures compared with FTIR spectroscopy with the advantages of standoff detection capabilities.

1. Introduction

More than thousand of terrorist attacks, involving application of explosives, took place from 2000 to 2016 [1]. Placing an improvised explosive device (IED) in public areas where large-scale events are running is a common scenario. High explosive materials are the favored weapon for terrorism [1–4]. All explosive reactions are extremely fast oxidation-reduction reactions [5,6]. Molecule *or* ionic compound containing an internal oxidizer-reducer pair is the most high-energy material that can be developed [1,7,8]. Some commercial fertilizers and industrial materials (i.e. ammonium nitrate, urea nitrate, and ammonium perchlorate) can have the oxidizing and reducing elements on the same molecule. These materials can demonstrate explosive properties; they are able to undergo highly exothermic reactions with high heat output and gaseous products [4,9,10]. The most common industrial explosive-materials include:

1.1. Ammonium nitrate (NH_4NO_3)

Ammonium nitrate is the most common industrial material that this has been widely employed in many terrorist activities [4]. Ammonium nitrate, with oxygen content of 34.98%, have the oxidizing and reducing element on the same molecule [5]. It decomposes producing large amount of gaseous products 980 l/Kg with high heat output of 2479 kJ/kg. Ammonium nitrate to have 60% explosion strength relative to TNT [11].

1.2. Urea nitrate ($CH_5N_3O_4$)

Urea nitrate is one of the most common industrial materials that have been employed in the manufacture of improvised explosive devices [4]. Urea nitrate, with oxygen content 34.14%, decomposes producing gaseous products of 910 l/Kg with explosion heat of 3211 kJ/kg [5]. It has explosion strength is 90% relative to TNT [11].

1.3. Ammonium perchlorate NH_4ClO_4

Ammonium perchlorate is one of the most powerful oxidizer that has been widely employed in improvised explosive devices [4]. Ammonium perchlorate, with oxygen content 34.04%, decomposes

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producing 1972 kJ/kg and 799 l/Kg gaseous products [5]. It has an explosion strength 65% relative to TNT [11].

These commercial materials have can explode with violent explosive nature. A fast and reliable identification technology of such hazardous materials is an urgent need [4,12].

Reliable technology that can offer instant discrimination between energetic and non-energetic material is a real demand for homeland security [13,14]. Several established techniques can be employed for explosive detection. These techniques include infrared spectroscopy, ion mobility spectroscopy, mass spectrometry. These techniques still have some drawbacks such as time efficiency as well as library based operations [4]. Furthermore all these techniques required direct contact of the operator with the explosive material. The capability for trace level detection of commercial explosive materials on contaminated surface is a crucial issue for counterterrorism activities [15–19]. Trace level detection can identify ultra-small quantity via characteristic specific chemical signature from a library of target compounds; this means low probability of false alarm [3]. Trace detection technique should be capable to detect and identify micro amounts of explosive materials associated with the threats [20–26].

There are many emerging laser-based technologies which can offer instant detection capabilities of explosive materials at the trace level [27]. These emergent technologies include laser induced breakdown spectroscopy [28,29], Raman spectroscopy [27,29,30], laser induced fluorescence spectroscopy, and IR spectroscopy [31,32]. However laser induced photoacoustic spectroscopy (LIPAS) is an attractive technology in terms of high sensitivity and ruggedness [31,33–37]. We address the potential of LIPAS as an effective and reliable approach for explosive material identification based on library operation mode. LIPAS can offer many advantages including [10,27]:

- Elimination of sample handling.
- Remote operation.
- Distinguished signals for the tested material.
- High sensitivity.

Furthermore LIPAS technology can offer characteristic signature that can be employed for instant identification of explosive materials [38]. This can be accomplished via determination of thermal, optical, and acoustical properties of the tested material [12,39]. Additionally LIPAS can offer standoff detection capabilities; therefore it can eliminate material handling and processing [12,32,40,41]. Fig. 1 is a schematic for the basic concept of LIPAS spectroscopy, where high-power laser is tuned to stimulate the tested material [36,42].

We continue our previous research by comparing the capability of LIPAS to FTIR spectroscopy for explosive identification. LIPAS was successfully employed for instant detection of common commercial explosive materials comprising ammonium nitrate, urea nitrate, and ammonium perchlorate [38]. Trace explosive material was stimulated with laser beam of 1064 nm. The generated photoacoustic signals were captured using high response piezoelectric transducer and processed using novel time domain analysis algorithm. This algorithm offered the measurement of characteristic optical properties (absorption coefficient) of each tested material [44]. Furthermore photoacoustic signal processing using frequency domain analysis offered the measurement of characteristic frequency signature for each tested material. LIPAs offered many advantages compared with FTIR spectroscopy as it offered many characteristic signatures; that can confirm each other. No two compounds could have identical optical, acoustical, thermal properties, as well as frequency spectrum. Frequency spectrum demonstrated stable base line with sharp characteristic peaks compared with FTIR spectroscopy.

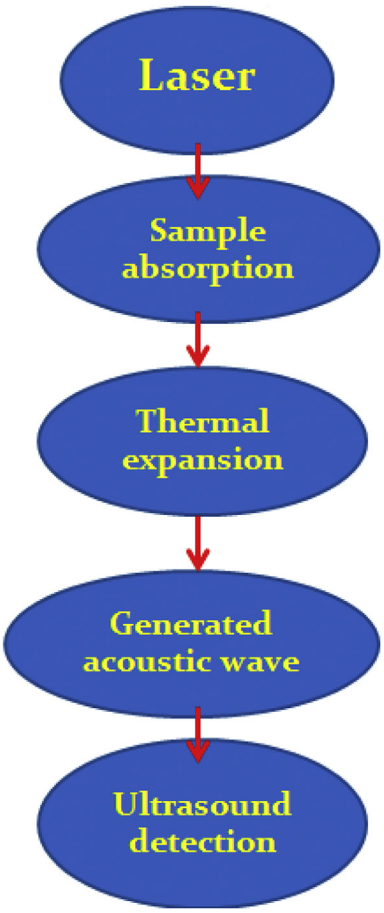

Fig. 1. Mechanism of laser induced photoacoustic spectroscopy [43].

One of the main findings of photoacoustic spectroscopy is that each explosive material demonstrated its own unique phase-shift response via employed customized algorithm for phase-shift domain analysis. The generated phase-shift response can be employed as an outstanding finger-print correlated to chemical structure of the tested material. Consequently an electronic library could be developed for instantaneous identification of explosive material.

2. Experimental

The capability of developed LIPAS spectroscopy technique associated with signal processing algorithms for time and

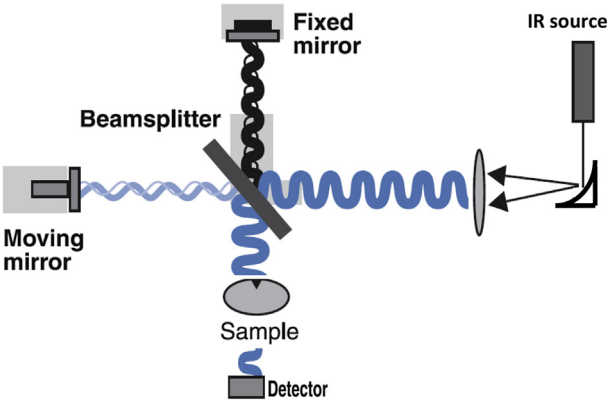

Fig. 2. Schematic for FTIR spectrometer employed.