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Design of an Optical Terahertz Generator

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Detection of an improvised explosive device (IED) is a significant challenge for security agencies. Last ditch strategy in dealing with terrorists is to maintain an upper edge over crime science in the market. Security officials use dogs, metal detectors, and scanners to sniff out chemical signatures. IED detection devices are available yet 17,000 to 20,000 civilians succumb to death every year. Detection devices and imaging scanners locate buried landmines and concealed weapons at checkpoints but are unable to recognize the suicide bombers in large crowds. Man is an intelligent machine who changes defence strategies with time depending on the feedback of sensing organs. Detection of an adaptive suicide bomber in crowded public places, or car bombs on busy roads in large cities, is still a big challenge requiring innovative research. Hazardous materials (HAZMAT) and metal detectors often fail to recognize high energy materials (HEM) based home-made explosives (HME) wrapped in plastics. Standoff lasers identify HAZMAT by decoding the vapour spectroscopic signatures at 1 m to 1 km distances but, fail to scan the concealed IEDs. The terahertz band (100 GHz to 10 THz, corresponding to the 1 mm to 30.0 mm wavelengths) falls between the high microwave (1 mm to 30 mm) and the low infrared (IR) (0.7 to 30.0 mm) bands. Terahertz photons are reflected off mirrors like light, penetrate tarps like X-rays and are detected by dipole antennas like microwaves. Terahertz waves can readout concealed IED due to their penetrating yet non-ionizing properties. Dogs and robot borne detectors recognize explosives by a physical approach to the site, but spectroscopic and imaging devices from the remote. Lasers facilitate standoff detection of landmines and X-ray scanners, image vehicles, but terahertz are used to scan drivers. Quantum cascade laser (QCL), dipole antennas, time multiplexed laser pulses, impact avalanche ionisation transit time (IMPATT)

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and Gunn diodes based terahertz sources and detectors come in 1 mW to 1 W ranges which require more extensive research for high power designs. Photoconductive switches have low pulse energies, vacuum electronic devices are limited to lower frequencies, and free electron lasers are too expensive. Difference frequency generation (DFG) based terahertz sources due to high conversion efficiency and repetition rate seem to be low-cost options under research worldwide. This work reviews state of the art terahertz technology and introduces the design of an innovative wavelength and time division multiplexed (WTDM) terahertz wave source.

Keywords: Laser, improvised explosive device (IED), dipole antenna, detectors, terahertz, microwaves, infrared (IR), optical, spectroscopy

1 INTRODUCTION

Explosive and hazardous materials (HAZMAT) can enter the human body through food, water, and air. Radioactive matter and poisonous gases can affect the skin. Detection of HAZMAT in public places is a priority for security agencies. Ancient societies relied on animal sniffs but modern civilization uses electronic noses to sniff explosives, electrical tongues to taste poisons, X-ray eyes to scan for concealed weapons, infrasonic ears to listen to whispers and contactless sensors to trace hidden landmines [1].

Wars start and end but the wartime planted landmines continue killing people, especially children, for a long time. An estimated 110 million landmines do exist in Angola, Cambodia, Congo Afghanistan, etc. The MKF Company of Holland is working on robot drones to clear the landmines in war-affected third world countries. Standoff explosives detection devices use polymer electronics, luminescent materials, fluorescent arrays, organic transistors, chemical sensors, metal-semiconductor sensors, neutron, X-ray and T-ray.

State-of-the-art-technologies can recognize concealed explosive, radioactive and biological threats at nanogram, picogram and femtogram levels with millimetre level spatial resolutions [2, 3]. Luminescent sensors have been developed to detect explosive materials down to 1 pg/cm, fluorescent films to 2.3 mg/l, chemiluminescence sensors to 40 ng/l, nanomaterials-based molecularly imprinted polymers (MIP) to 3 mg/l and nanotubes based sensors to 5 ng/l [4]. Chemical sensors are promising for trace detection of explosive vapours due to their high sensitivity. Fluorescent sensors can detect 7 to 8 ppb vapours of TNT in the air but not 5 ppt of RDX or 18 ppt of PETN [5, 6]. Detection of low-pressure RDX and TNT can be facilitated by heating devices [7]. The capillary electrophoresis (CE) analytical technique was slow, but microchip-based CE devices can detect explosives on-site [8]. Light emitting microporous networks such as PSpCz as a luminescent sensor can detect

TNT and DNT vapours in air at the concentration of 5 ppb [9]. Fluorescence quenching process reduces light flow due to energy transport in the excited state which renders it an ideal tool for identification of nitro-explosives used in HME. Detection of poisonous gases in the air and concealed explosives is a concern of health, environmental and security agencies, especially when chemical, radioactive and biological threats all come together. Quantum dots arrays can differentiate 2,4 dinitrotoluene (DNT), 2,4,6 trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX) and pentraerythritoltetranitrate (PETN) down to the parts *per* billion range among a mixture of explosives using electron transition based fluorescence quenching technique [10]. The chemical formulae of common explosive materials are given in Figure 1

Explosive detection challenges include accurate detection, differentiation from non-hazardous materials, inference issues and determination of various quantities. The detection of explosive precursor material is based on matching a particular physical or chemical property of the sample in ever-expanding threat library. Raman band wavenumbers using 248.6 nm excitation laser for TNT (1361 and 1624), PETN (872, 1295, 1511, 1658), RDX (1025, 1280, 1381, 1464), Urea nitrate(1350), HME chlorate (935) are reported in literature [13], [14] and First guard or portable Raman analysers are available in market. Absorption cross-sections of conventional explosive materials are given in Table 1.

Explosives detection techniques include chemiluminescence, mass spectrometry, differential mobility spectrometry, electrochemical sensing, microcantilever vapor sensors, neutrons, X-ray, millimetre, laser and sub-millimetre

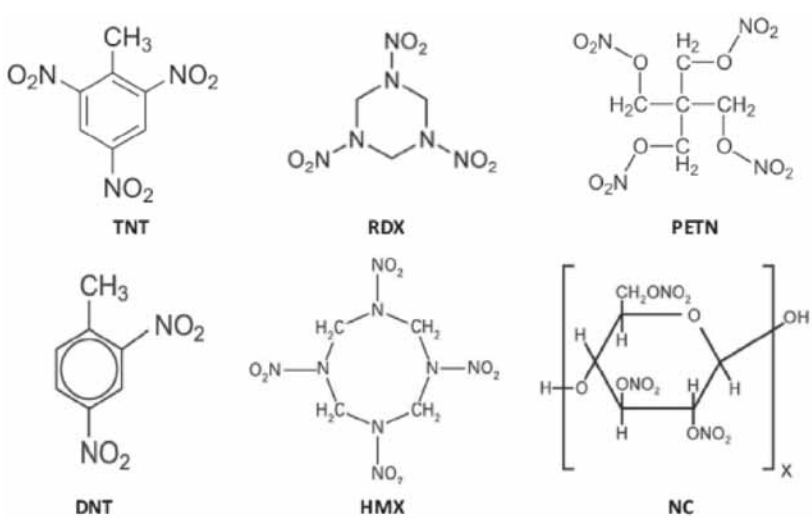

FIGURE 1
Chemical formulas of common explosives [11, 12].

TABLE 1
Mass absorptivity and absorption cross-sections of explosives [14, 15].

HAZMATs	Formula	Frequency (THz)	α (cm^2/mg)	σ × 10^{-24} (cm^2)
PETN	$C_6H_8N_4O_{12}$	2.0655±0.0083	0.1052 ± 0.0014	55.2 ± 0.7
RDX		0.8206±0.0041	0.0891 ± 0.0016	32.9 ± 0.6
RDX	$C_3H_6N_6O_6$	1.545 ± 0.011	0.0209 ± 0.0001	7.72 ± 0.05
RDX		1.935 ± 0.0054	0.0738 ± 0.0015	27.2 ± 0.55
HMX		0.950 ± 0.052	0.0157 ± 0.0068	7.7 ± 3.3
HMX	$C_4H_8N_8O_8$	1.352 ± 0.031	0.0253 ± 0.0078	12.5 ± 3.9
HMX		2.060 ± 0.0056	0.116 ± 0.01	57.2 ± 4.9
TNT		0.086 ± 0.097	0.0042 ± 0.0014	1.57 ± 0.55
TNT	$C_7H_5N_3O_6$	1.176 ± 0.047	0.0083 ± 0.0019	3.13 ± 0.70
TNT		2.311 ± 0.018	0.061 ± 0.001	23.2 ± 0.2

terahertz imaging techniques [16]. The chemiluminescence consists of detecting light by chemical reaction with hazmat. Chemiluminescence systems consist of thermal energy analyser (TEA), pyrolyser, luminal and electroluminescence [17]. Mass spectrometry is based separation and analysis of substances according to their masses of atoms and molecules. It may be based on time separation of geometric separation. Different types of analysers include quadrupole mass analyser, ion trap mass analyser, time of flight mass analyser and tandem mass spectrometer [18]. Differential mobility spectrometers need no ion shutters, grid aperture or multiple high voltage components like ion mobility spectrometers (IMS) [19]. Electrochemical sensing of explosives may be carried out using disposable strips, real-time monitors and lab-on-chip devices [20]. A cantilever may be used to detect explosives using its adsorption/desorption based bending. It consists of cantilevers, piezoelectric readout devices, vapour generators and pattern recognition [21]. Neutron techniques include neutron in and gammas out, elastic scattering and transmission methods. It uses bismuth germinate (BGO) and NaI detectors [22]. Nuclear quadrupole resonance (NQR) spectrum depends on chemical shifts, J-coupling and dipole-dipole interactions. NQR detection techniques include Faraday detection, superconducting detector coil, superconducting quantum interference device (SQUID) magnetometer, atomic magnetometer, and force detection [23]. Explosives can be detected by X-ray diffraction imaging (XDI). Explosive detection is carried out by XDI using effective atomic number determination or high energy trip region analysis (HETRA), molecular interference function, radial distribution function, density descriptor and tomography imaging techniques [24]. XDI has high resolution but cannot be applied to suicide bombers in the crowd for which millimetre (2 to 9 mm resolution) and sub-millimetre (0.03 to 1.00 mm resolution) techniques are

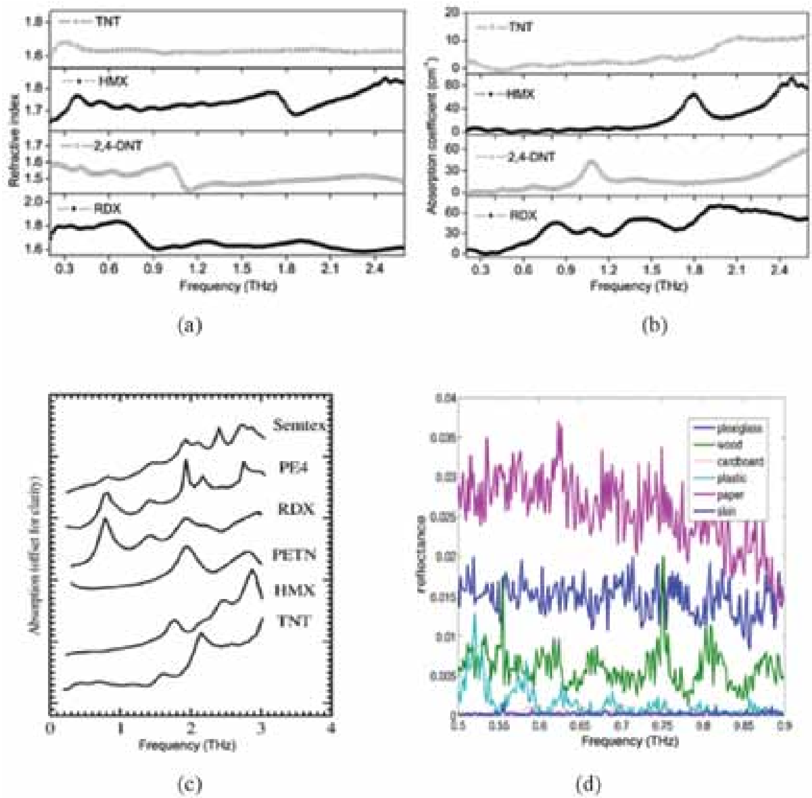

FIGURE 2
Plots showing the physical and chemical characteristics of explosive materials: (a) refractive indices [28]; (b) absorption coefficients [28]; (c) transmission spectra [29]; and (d) reflectance spectra [30].

under extensive research [25, 26]. Laser-based explosive detections methods include vibrational spectroscopic, laser-induced breakdown spectroscopic (LIBS) methods. Laser absorption methods use tuneable diode laser (TDLAS), optical parametric oscillators (OPO), free electron laser (FEL) and CO_2 lasers. Cavity ring-down spectroscopy (CRDS) and Raman laser spectroscopy are used to analyse explosive gas samples. Difference frequency for CRDS may be generated by two off-tuned lasers or fundamental and harmonic of the infrared (IR) laser. Quantum cavity lasers are under extensive research for standoff explosive detection in a LIDAR configuration [27]. Refractive indices, absorption coefficients, transmittance and reflectance of conventional explosive materials are shown in Figure 2.

Where electronic noses and chemical sensors fail, the X-ray and T-ray imaging systems take over. X-rays are used to image baggage at security check posts and T-rays may be deployed to detect suicide bombers among crowds due to their non-ionizing properties. A semiconductor-based pump-probe system may be used to generate and detect Terahertz waves to obtain material fingerprints [31]. Pump and probe lasers are excited by synchronized radio-frequency beams and tune to slightly different frequencies to excite dipole antenna to produce terahertz waves. The design procedure for a GaAs photoconductive dipole antenna with 500 mm spaced electrodes under ±70 V bias was described by Li [32]. A Si lens may be added to source chip to collimate the terahertz beam using parabolic mirrors [33]. A GaAs trap enhanced field (TEF) terahertz source may be configured to be pumped by laser to emit in the same direction at opposite angle. Terahertz output may be generated using GaAs, InP, GaSb, CdTe, and CdSe and from Si. Photoconductive antennas have high power in microwave and IR regions, but hardly 10 mw powers in the 0.1 to 10.0 THz (3 mm to 30 mm) regions. Photomixing materials such as InGaAs may be pumped with the laser to produce continuous wave (CW) terahertz waves. Research has been extended to the terahertz region from high microwave and low IR regions. Microwave sources such as impact avalanche ionisation transit time (IMPATT) and Gunn diodes have been extended to the low terahertz region but rapidly drop off in power in 0.1 to 1.0 THz region. Similarly, III-V laser diodes were optimized but quickly drop off in power in the 100 to 1 THz areas [34].

A typical terahertz source consists of sliced blackbody source, like mercury lamps, akin to a band of supercontinuum light source but these suffer from directivity and coherence length problems. A pointed sharp edge dipole antenna gives off more power than standard dipole antenna [35]. Spiral cavity super-luminescent emitters at 5 mm provide 57 mW at 250 K having 107 mm coherence length [36]. Dipole antennas may be used as source and detector and conversion efficiency may be enhanced to 26% by using bow tie periodic spiral design [37]. Dipoles and monopoles require no earth and the circuit is completed through capacitance which may be increased using a dumbbell and top hat designs. Subsequent research shows that a quantum cascade laser (QCL)-pumped graphene on bimetal support also emits terahertz at higher frequencies than GaAs [38]. Recent advances in the terahertz devices and the systems for spectroscopic analysis of biomolecules are reported in the literature [39]. Mid-IR QCL can deliver 5.1 W CW power at room temperature at 3 to 12 mm wavelengths [40]. On-chip terahertz generation and detection have been demonstrated using coupled cavity single semiconductor heterostructure [41]. Terahertz materials suitable for the 1.2 to 1000, 50 to 1000 and 100 to 1000 mm ranges are Si, quartz, and sapphire, respectively. Polymer materials such as TPX, Picarin, and high-density polyethylene (HDPE) are good for 1 to 2000 mm range optics [42]. TOPTICA Photonics AG of Germany has launched distributed feedback (DFB) lasers and GaAs crystals based terahertz wave sources and detectors. Photoconductive switches are used in pulsed mode and photomixers in CW mode terahertz sources [43]. Pulsed terahertz Source requires femtosecond lasers. Dynamic ranges are 100 dB at 0.5 THz. 50 dB at 3.5 THz and 20 dB at 6.0 THz. InGaAs antennas have >5 THz bandwidth >50 mw average power. The transmitter and receiver power are higher at high microwave and low IR range but very low in the terahertz range.

Application of terahertz waves for standoff detection of explosive materials is using terahertz time-domain spectroscopy (THz-TDS) considered useful for imaging RDX, DNT, TNT and PETN molecules. A 0.82 THz wave is helpful for RDX and DNT due to its frequency between two strong water absorption lines at 0.78 and 0.98 THz frequencies [44]. Two photons based radio frequency (RF) excited pump and probe lasers to excite photoconductive antenna using sweeping frequency delay technique [31] may alternatively be realized using the three-photon method in air plasma by abruptly autofocusing of pump, second harmonic and probe (three photons) beams [45, 46]. Terahertz waves are naturally generated during the lightning strikes so artificially triggered lightning or near threshold high voltage conditions may emit terahertz waves, like corona discharge, before spark gap discharge. QCL driven explosive sensors have high power T-rays yet terahertz laser sources and detectors need improvements [47]. Terahertz waves have great potential in imaging through rucksacks and tarps for identification of concealed weapons, chemical explosives and biological agents. THz-Raman spectroscopy can identify materials at a distance from their molecular energy transitions (phonons) in 200 to 5000 cm^{-1} (1.5 to 6 THz) range. Spectroscopic analysis of molecular structure reveals fingerprints of materials which help recognize explosives. THz-Raman low frequency regime (10 to 200 cm^{-1}) provides molecule structural information and high-frequency fingerprints (200 to 2000 cm^{-1}) supply chemical information. This technique has successfully been demonstrated to recognize bipolar disorder drug carbamazepine and ammonium nitrate used in home-made explosives. It is also helpful in forensic analysis and chemical explosive and biological detections [48]. Ultraviolet (UV), visible and IR differential reflectometry can recognize suicide bombers with explosive jackets wrapped around their waists [49]. Use of UV, visible and IR THz have a distinct advantage of being outside water vapour absorption range. Terahertz spectroscopic methods and instruments have been developed for imaging of concealed hazmat [50]. Now the terahertz time-domain spectroscopy (THz-TDS) is being applied commercially for gems to bombs detection worldwide [51].

2 TERAHERTZ SCIENCE AND TECHNOLOGY

The science of terahertz (0.1 to 10 THz) consists of a discreet millimetre and sub-millimetre bands sitting between high microwave and low IR light regions. Millimetre waves (10 to 1 mm) range from 3 to 30 GHz frequencies, and sub-millimetre waves (1 mm 30 mm) range from 30 to 10 THz. Radio waves (1 km to 100 mm) with a few neV to meV/photon energy, terahertz (1 mm to 30 mm) with few meV/photon energy, IR-UV light (1.0 to 0.1 mm) with 1 to 10 eV/photon energy, soft X-rays (10 to 1 nm) with 100 to 1000 eV/photon energy, Hard X-rays or G-rays (10 to 1 ps) with 10 to 1000 keV/photon energies have a specific significance in communication, diagnostics, lighting and imaging applications. T-rays (non-ionizing), far infrared (FIR) and X-rays (ionizing) are used for imaging [52, 53].

T-rays safety limit is 1 W/cm^2 which has no bio-effects at low powers except common thermal effects which render it attractive for human body search [54]. A terahertz system consists of sources, components, and detectors. Natural source of terahertz may be a band of blackbody radiations from anything at temperature >10 K. Milky Way dust emits terahertz waves, but these are absorbed into the atmosphere. Extra-terrestrial thermal sources of terahertz include sun and cosmic background radiation. Terahertz are also emitted during lightning and electric discharges. A lab-based terahertz thermal source may be mercury lamp or carborundum (SiC). The emissivity of a global at 1650 K varies from 2 to 50 μm range [55]. Sub-millimetre waves can hardly travel 10 m distance in the humid air. Terahertz waves can be generated by gyrotrons, backward wave oscillators (BWO), organic gas FIR laser, Schottky diode or varactor multipliers, a QCL, a free electron laser (FEL), synchrotrons, DFB lasers pumped photomixing crystals, laser time division multiplexing (TDM), photoconductive, surface field, photo-Dember and optical rectification, IMPATT, Gunn and resonant tunnelling diodes (700 GHz). DFB lasers based THz generator may consist of 883 and 785 nm lasers causing difference frequency of 1.8 to 2.0 THz using GaAs (TeraScan 780; TOPTICA Photonics AG) or 1533 and 1538 nm lasers causing difference frequency of 1.2 to 2.7 THz using InGaAs emitters (TeraScan 1550; TOPTICA Photonics AG). CW terahertz spectrum of plastic explosive RDX shows minimum transmittance at 800 GHz. Terahertz sources and detectors have been reviewed in the literature [56]. A review of terahertz diffraction tomography, time of flight (TOF), three-dimensional (3-D) holography time domain techniques and their applications to security systems, food, pharmaceutical, paper and polymer industries is discussed in the literature [57]. Terahertz optics is taking off due to its unique capability to detect hidden and subsurface explosive materials. MIR spectra of some explosive materials are shown in Figure 3.

The terahertz spectrum shows water absorption lines at 1.10, 1.19, 1.40, 1.68 and 1.70 THz. Terahertz detectors are available from 0.1 to 30 THz (T-ray 5000; Luna) allowing spectroscopy in 0.03 to 7 THz range (TAS7400; Advantest Corporation). Terahertz power meters in the range 100 mW to 20 mW are available in the 0.3 to the 10 THz range (TAS5500; Advantest Corporation). Terahertz waves are considered excellent for personnel screening to detect concealed metallic and explosive devices. A typical terahertz fiber

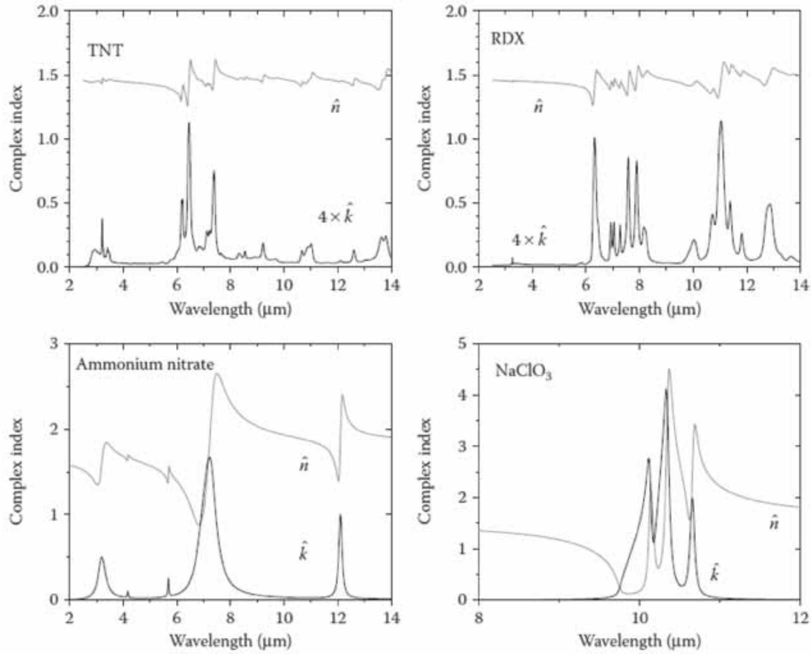

FIGURE 3
MIR spectra of common explosive materials [14].

optic spectrometer may cost to the tune of $119,000 (Rigel-1550; TeTechS Inc.). A 0.05 to 4.00 THz pulse imaging and spectroscopy platform (TPS Spectra 3000; TeraView, Ltd.) may cost even more. Terahertz cameras cost $10,000 to $50,000 due to expensive optics but commentary metal–oxide–semiconductor (CMOS) technology is likely to drive down costs soon. TeraScan 780, TeraScan 1550 and TeraFlash (TOPTICA Photonics AG) cost €42,000, €55,000 and €87,000, respectively plus €4,730 installation and training charges. This is to give a feel of terahertz system costs. The future of terahertz sources will extract the signatures of potential suicide bomber [58]. The terahertz gap remained long hidden due to high water absorptions in the air. THz-TDS is widely used to characterize spectral properties of drugs and explosive materials. THz-TDS measures molecular signatures and dynamics of explosive materials to obtain information of amplitude and phase. THz-TDS is based on an electric field in contrast to Raman and Fourier transform infrared (FTIR). Coherent terahertz waves can fetch fingerprint of explosive materials and hydrocarbons due to their penetration capabilities [59]. A 1 mJ, 800 nm, 40 fs pulse, the 1 to 10 kHz laser can produce terahertz waves by the interference of fundamental (800 nm) and second harmonic (400 nm) waves. These terahertz are focused on gas biased by HV to extract 400 nm light signals. Femtosecond laser-matter interactions, especially metamaterials, hold the key to elixirs on infinity and beyond [60].

Standoff detection of explosives is an open challenge to the scientific community to help security agencies identify IEDs. Researchers have reported some countermeasures against landmines [16] and suicide bombers [61]. Security agencies use handheld metal (GP3003B1), walk-through door (DP-111C), portable X-ray (DP2300) and explosive (GT200) detectors. Traditional metal detectors fail to identify explosives wrapped in plastic materials in baggage passing through X-ray machines in airports [62]. We have many reliable methods for forensic analysis in a laboratory environment, but none is ready for standoff detection of suicide bombers and landmines [63]. Spectroscopic methods to identify explosives include ion mobility spectroscopy (IMS) [64], optical fiber coupled reflection/absorption infrared spectroscopy (RAIRS) [65], laser-induced FTIR [66], laser-induced multiphoton ionization (LIMPI) [67], resonance enhanced multiphoton ionization (REMPI) [68], cavity ring-down spectroscopy (CRDS) [69], laser-induced breakdown spectroscopy (LIBS) [70], differential optical absorption spectroscopy (DOAS), atmospheric pressure chemical ionization (APCI), Photoacoustic spectroscopy (PAS) [71], multiphoton electron extraction spectroscopy (MEES), terahertz spectroscopy [28, 30], fluorescent bacterial/chemical materials, biological (nose/tongue) and electrochemical sensors [4,71]. IMS is a successful technology but suffers from matrix effects, whereas CRDS, LIBS, and LIDAR technologies are good but have poor sensitivity in field applications. The LIMI and REMPI techniques require vacuum which is hard to achieve in the field environment, LIBS require moderate HEM vapours, MEES seems to be a good candidate with field deployment prospects and T-rays are under extensive research worldwide [72]. A QCL, a resonant tunnelling diode (RTD) and multiplexer based terahertz sources are ideal candidates to bridge the so-called terahertz technology gap (Tech-Gap), as shown in Figure 4.

Explosive is a substance, when subjected to heat, impact, friction or detonation, releases a massive amount of energy in short interval of time. Conversion of explosives into gases suddenly increases temperature and pressure to trigger a shockwave. A bomb disposal squad head constable died on 17^{th} August 2016 while disabling an IED on the bank of Put Kanal in Suhbatpur, Baluchistan, Pakistan. Bomb disposal squad must wear the proper uniform as terrorists continue changing wire colours and circuits which may cheat even experienced security staff. An IED may consist of initiating primary (Lead azide, HMTD, TATP), secondary (RDX, HMX, TNT, etc.) and tertiary (ANAL, ANFO). Military grade explosives include PETN, RDX, HMX, commercial grade explosive include TNT, ANAL, ANFO, and suicide bomber grade explosives include TATP, HMTD, etc. [12]. IED detection devices come in onsite and standoff technologies. Onsite devices include fluorescent sensors or induction based metal detec-

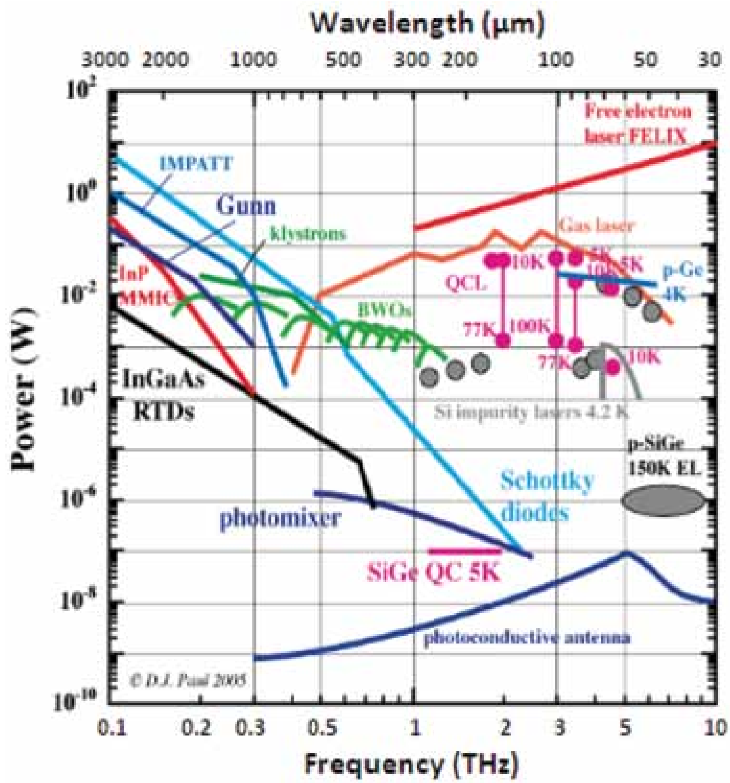

FIGURE 4
Graph showing terahertz power performance of different sources around the Tech-Gap [34].

tors, and standoff devices include laser and terahertz Wave analysers [29]; [73]. Advance standoff detection of explosives from long distances makes the world safer [74]. Identifying explosives from 1 to 10 km distances using random Raman laser seems promising for especially fertilizer-based bombs which yet requires extensive research [75].

Lasers have been used for detection of landmines and IEDs since long ago [76], yet no reliable solution exists in the market against civilian IED threats [77]. Terahertz explosive sensors have long been supposed to be last-ditch option to deal with terrorist and their IEDs [26]. The truth about terahertz is that its frequency spectrum spans from 100 GHz to 10 THz corresponding to 1 mm to 30 μm wavelengths. Terahertz wave sources usually have low power at higher frequencies and relatively higher at lower frequencies [78]. Voltage controlled oscillators with subsequent frequency multiplication can produce milliwatt power in 0.5 to the 5 THz range. Several researchers [79] have claimed a generation of the tuneable microwave to terahertz sources, yet sources beyond 5 to 6 THz are hardly

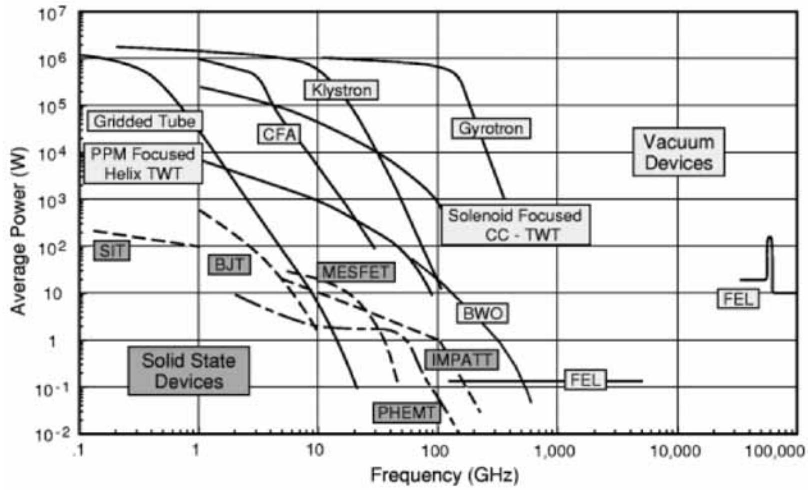

FIGURE 5
Graph showing terahertz sources by the start of the 21[st] century [84, 85].

available [80]. Simulation studies show the possibility of direct current (DC) to 100 THz waves, yet technology gap exists from 1 to 3 THz bands [81]. High power T-ray source is the working horse behind the standoff IED detectors. When two lasers with flux densities of 10 GW/m^2 are focused on tungsten tip, it creates 0.1 to 10 THz waves of 4 to 6 V/nm static field at 200°C. Use of super tips may increase power to 10 mW at 10 THz. A solar cell, piezoelectric, VO_x, Bi or Nb microbolometers, Si MOSFET, Si FET and HgCdTe HEB detector can measure from 0.6 to 30 THz range yet Schottky or SIS mixers based sources are limited to 1 to 4 mW powers maximally [82]. Terahertz waves have attenuation in the atmosphere in 0.1 to 1000 dB/km range [83]. Terahertz may be produced detected using gyrotrons, magnetrons, klystrons, cavity coupled traveling wave tubes (CC-TWT), gridded tubes and vacuum electronics devices, as shown in Figure 5.

GaN-based Gunn, InP and Sb-based high-electron-mobility transistor (HEMT) and IMPATT diodes are excellent sources of terahertz waves. SiGe vertical-cavity surface-emitting laser (VCSEL) and photo mixing, and multiplexed laser pulses are optical options [86]. All terahertz can be detected by RTD, electro-acoustic detectors (HEMTs) and photon-assisted tunnelling in QWs [87]. Carbon nanotubes and nanowires and GaN and GaSe are seen as potential candidates for future terahertz sources [88], [89]. Terahertz wave faces high attenuation at 1 to 10 THz and low above or below it. Terahertz can easily distinguish between explosive materials, metals, plastics and a range of packing materials in homemade HAZMATs, as shown in Figure. 6.

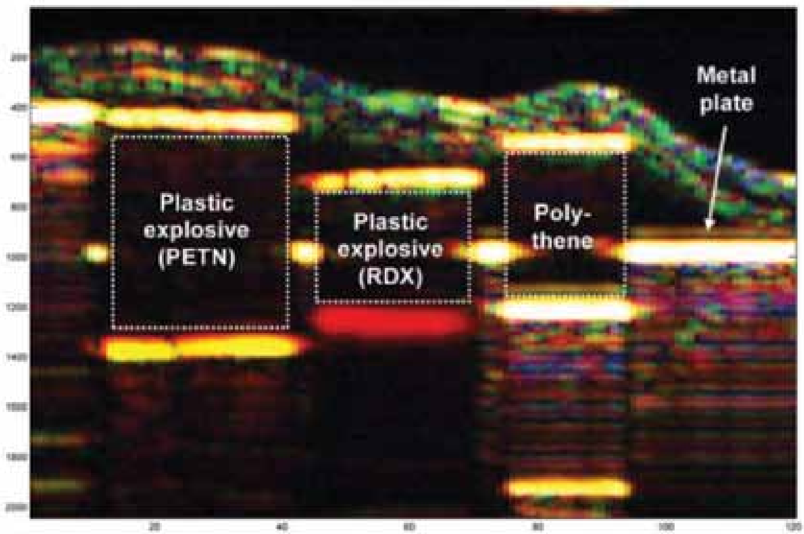

FIGURE 6
Broadband and multispectral terahertz cross-sectional images of a number of objects hidden beneath two layers of cloth [90].

3 OPTICAL TERAHERTZ GENERATOR

Terahertz window is located between microwave and IR bands. Naturally, T-rays are produced as part of blackbody radiations which may be filtered to obtain incoherent terahertz. Free electron, FIR, and quantum cascade lasers can produce coherent terahertz waves. Sub-femtosecond pulsed lasers have bandwidths in the range of terahertz. Gyrotrons, synchrotrons, frequency mixing techniques and optical rectification methods may be used to obtain terahertz frequencies.

The most straightforward method may consist of repetition rate multiplication of common lasers at any frequency. It is easy to multiply multiple wavelengths laser with 50 to 100 nm tuning facilities to convert a few gigahertz repetition rate pulsed source to several gigahertz to terahertz sources [91]. Femtosecond laser pulse pumping creates terahertz waves by surface electric field under photo Dember effect. A surface plasmonpolariton is a coupled state between EMF and electron plasma oscillations at the surface between a metal and dielectric. Integration of DFB principle in surface plasmon amplification by stimulated emission of radiation (SPASER) leads to terahertz plasmonic laser [92].

Pulse energy, lower frequencies, and costs are limitations of PC switches, vacuum electronic devices and FEL systems which may be overcome using energy efficient DFG [93] and cost-effective optical clock generators. Nonlinear crystals can produce photon pair (3w/2) such that $w_p=w_1+w_2$ [94]. Two QCL operating at slightly different repetition rates may allow multiheterodyne spectroscopy and CW operation [95]. Laser-induced air plasma gives of enhanced terahertz emission by autofocussing the probe beam [45]. Terahertz wave generation phenomenon becomes efficient at higher repetition rates, which eventually becomes terahertz wave at terahertz repetition rates [96]. Such an economical method may consist of wavelength and time division multiplexed optical free space processor to convert multiple wavelengths mode-locked pulses to multicolour pulses comb patterns, similar to standard parallel to serial converter. It is much easier to do in optical form compared to microelectronic phases.

Multifrequency tuneable lasers are available in solid, liquid and gas forms [97]. Multicolour UV to IR tuneable lasers increase our understanding of chemical dynamics, biological transformations, charge carrier mobility and explosives signatures [98]. Several researchers have reported four wavelengths for dye, 405, 447, 532 and 637 nm; eight wavelengths for dye and semiconductor fiber coupled lasers with the range of 405 to 640 nm [99, 100]. The working horse behind the time and wavelength division multiplexed technique is multiple pulses pumped DFB laser producing simultaneous subpicosecond rainbow combs of pulses which are spectrally packed in one another at 1 to 3 nm bands hard to generate directly without using expensive optical parametric oscillators or supercontinuum generation techniques with a combination of few angstrom filters (another barrier in optics). Proposed multiple pulses pumped DFB laser can produce discrete lines from inter subband of organic materials such as Rh6G and semiconductor materials such as InAs. The wavelength to time transformation of multiple lines pulsed system may be carried out using varying length optical fiber l-t transforms [101]. DFB lasers are typically recommended for pulse repetition rate multiplier circuits [102]; [103], even without using the wavelength division multiplexed (WDM)/TDM techniques [104]. Schematic block diagram explaining essential stages of WDM/TDM free space multiplier are shown in Figure 7.

A multiple colours DFB laser pulse, even ultrashort pulse, may be characterized by space, time and frequency (colour). Space, time and frequency pulses may be the frequency to time converted in first stage and time to space converted in the second phase. Laser pulse frequency to time and time to space conversion is illustrated in Figure 8.

Wavelength and time division multiplexing (WTDM) is based on WDM and TDM techniques. A WTDM terahertz wave train requires a multiple lines DFB laser. The University of Essex has already reported a model of producing multiple lasing lines [106]. DFB lasers are customarily recommended for pulse repetition rate multiplier circuits even without using the WDM/TDM techniques. The pulse repetition rate (PRR) is equal to the product of input PRR and 2^N, where N is the number of multiplier stages. It is possible to use multiple wavelengths generating lasers, possessing additional 50 to 100 nm

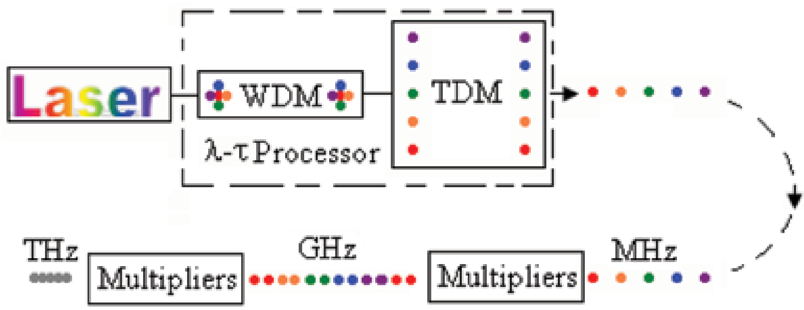

FIGURE 7
Schematic diagram of the wavelength and time multiplexed free-space pulse pinnate multiplier.

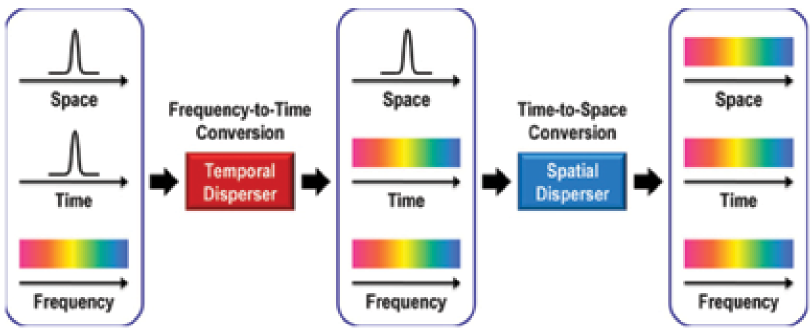

FIGURE 8
Schematic diagram of the pulse train frequency, time and space converter [105].

tuning facilities, to extend tens gigahertz range to hundreds gigahertz rather than terahertz. Such an economical method may consist of wavelength and time division multiplexed optical free space processor to convert multiple wavelengths mode-locked pulses to multicolour pulses comb pattern, similar to standard parallel to serial converter. It is much easier to do in optical form compared to microelectronic phases. Multiple pulse pairs pumped distributed feedback dye laser emits various colour pulses [107], [108].

An advantage of the optical terahertz train is the possibility of imaging reflected signatures using ordinary optical cameras due to high $40,000 prohibitive costs of sub-millimetre range terahertz cameras. The vision of WTDM terahertz wave train consists of time multiplexing of l_1 to l_9 laser lines within one pulse of a Q-switched and mode-locked DFB laser between two successive pulses of 10 to 20 pulses burst. DFB laser 200 ps pulses are 5 ns apart within which nine lines appear at 425 ps intervals, as shown in Figure 9 [108]. A mode-locked Ti-sapphire laser producing 130 fs pulses at repeti-

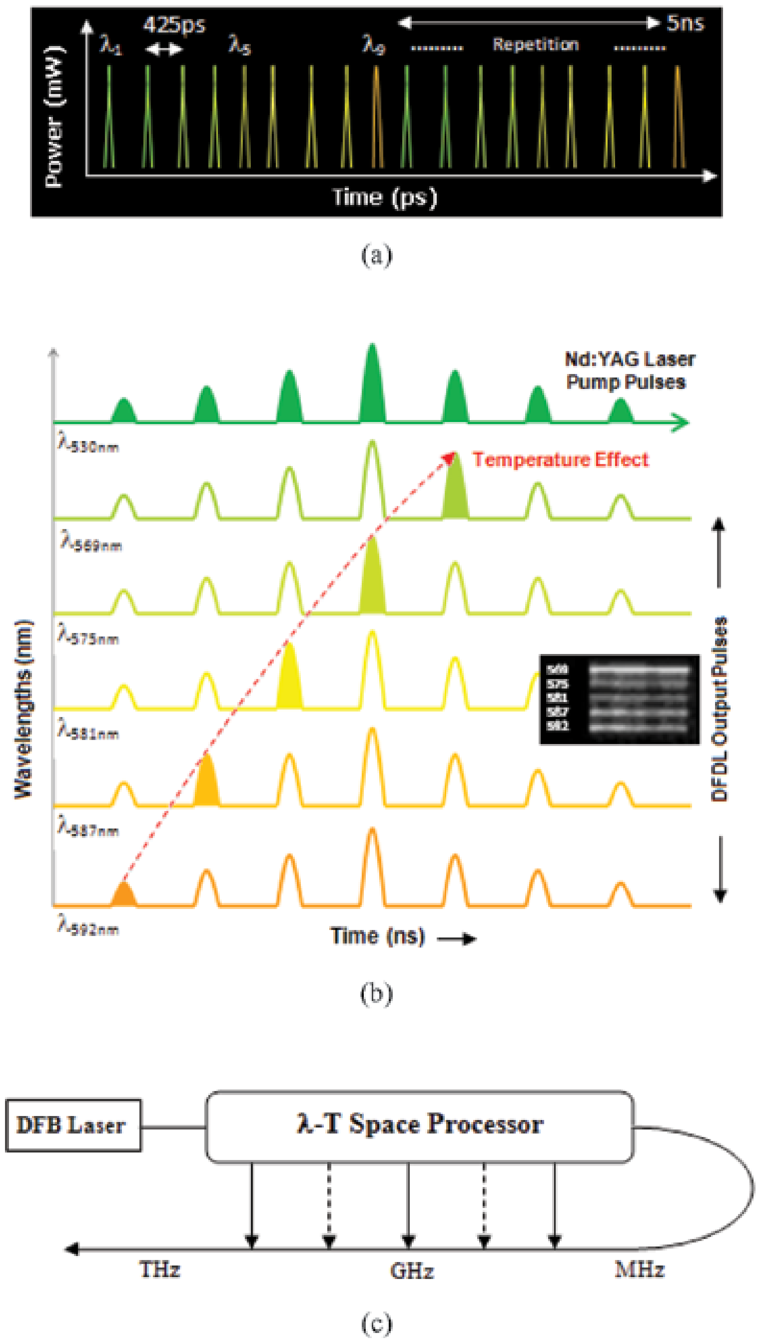

FIGURE 9
Wavelength, time and space processing and peak intensity wavelength shift for (a) WDM and TDM pulses, (b) Nd:YAG and distributed feed-back on dye laser (DFDL) pulses and (c) the experimental configuration for WTDM [109].

tion rate of 76 MHz can produce terahertz waves. Higher repetitions may be multiplied by pulse interleaving technique to increase repletion rates direct into the terahertz regime.

4 TEST AND MEASUREMENT LIMITATIONS

Generation and measurement of attosecond pulses and THz waves is not a simple task. Compressing petawatt pulses, bearing tens of joules of energies, to single cycle size opens a floodgate of attosecond to zeptosecond applications. These pulses being in X-ray regime have teV/cm gradients enabling on-chip accelerators [110]. To measure short duration pulses, it may be stretched using grating and fiber expanders and compressed after measurement and amplification back to original size by a well-designed and calibrated expander/compressor circuit. 800 ps (PWS-TPSR) and 10 ns (PWS-PSR) stretchers are readily available in the market. Commercial stretchers can handle light pulses in 750 to 2200 nm range. Usually, shorter pulses are generated in the XUV region for which other stretchers are available. Fiber pulse compression technology was limited to nJ to μJ in 1985 which increased to μJ to mJ during 1995 to 2015 using noble gas-filled capillary tubes and thin-films. Thin film compressors using plastic sheets can increase peak power up to 1 to 10 TW. Thin films cause spectral and temporal dispersions by self-phase modulation (SPM) and group velocity dispersions which can be compressed thin film and chirped mirror compressors down to attosecond level. Coherent acceleration of ions using a pondermotive force of single cycled pulse leads to 1 GeV pulses. Today 100 PW pulses of the 2.5 fs single cycle are produced in routine which can be focused to spot size limited by laser wavelength. Significant temporal and spectral stretching is well-developed state of the art technology. Several manufacturers offer 1000 to the 25000-time stretcher which decreases frequency range from terahertz to gigahertz for measurement. The stretched pulses may compressed by a pair of 1500 lines/mm gratings. Optical clock stretchers can stretch 20 fs (50 THz) pulses to 520 ps (1.92 GHz) which is 26500-times pulse lengthening. It is ultimately limited by an interpulse period which is several times longer than the pulse duration. Optical repetition rate multiplier can convert megahertz and gigahertz pulse trains of mode-locked lasers into the terahertz regime. Short pulse high lasers have more potential of terahertz optical clocks compared long pulse lasers. Semiconductor lasers can be electrically tuned to obtain desired repetition rate. Electronic components available in the market have 100 ps rise time (10 GHz), but extensive research on 100 to 200 GHz devices is underway [111]. Agilent Technologies of the USA manufacture 33 to 63 GHz (80 to 160 Gs/s) oscilloscopes (DSA X96204Q) and Tektronix, Inc. of the USA have launched the 33 to 70 GHz (100 to 200 Gs/s) oscilloscopes (70000SX). When LeCroy Corporation of the USA and others started the 100 GHz oscilloscope race the Tektronix, Inc. began to research on the 200 GHz oscilloscope.

Several research groups are working on the development of 100 to 200 GHz electronics devices. Explosive telecom growth in the 1990s led to fiber line rates beyond 100 Gbits/s. Today's 10 Tbits/s capacity represents a factor of 25,000 increases since the standard single mode fibres began carrying 400 Mbits/s in the mid-1980s [112]. So far, the communication was limited to 10 GHz microwaves and IR carriers which need to be extended to 100 GHz carriers using terahertz, sub-terahertz and visible light to increase wireless data rate capacities for which novel antenna are under extensive research worldwide [113-115]. These technologies use parallel processing techniques to design nearly real-time oscilloscopes. It is argued by high data rates and terahertz electronics the future electronics depends on lasers, not quartz. This research will produce a terahertz clock oscillator to be used as a source for standoff detection of explosive materials. Optical fiber version of this design would help reduce size due to QCL laser. Initial setup will be tested using Nd:YAG or Ti:sapphire laser later it would be downsized by a QCL. Tunnelling, IMPATT and Gunn, and diodes have a capacity of 700 to 1500 GHz, yet measurement oscilloscopes and spectrum analysers are limited 10 to 25 GHz frequencies. Time and wavelength division multiplexed communication signals may reach terahertz frequencies [116], [117]. NASA's Cosmic Background Explorer (COBE) initiative motivated scientists for research in terahertz region. The terahertz eyes can see 98% of things which are not visible in rest of electromagnetic spectrum. Half total luminosity since big band falls in sub-millimetre and FIR regions. Time multiplexed lasers and frequency multiplied solid state devices can generate low power terahertz radiations from 2.0 to 4.7 THz [118]. Lasers produce maximum 4.25 mm (QCL), 10.6 mm (CO_2) and 15 to 25mm (FEL) wavelengths which are smaller than 30 mm to 1 mm terahertz band [119, 120]. Past and recent developments in FIR and sub-millimetre wave technologies have successfully demonstrated operations of 66, 192 and 496 μm lasers [121]. Lasers with 100 to 1000 μm wavelengths are sources of CW terahertz. Broadly tuneable external cavity Cherenkov terahertz radiation sources produce 1.2 to 5.9 THz waves [122]. Light-matter interaction gives of terahertz waves and situation becomes interesting in case of metamaterials. Millimetre wave characterization is as complex as T-ray generation, especially using CMOS technology [123]. Frequency-resolved optical grating (FROG) and spectral interferometry for direct electric field reconstruction (SPIDER) techniques are used for ultrashort pulses with bandwidths approaching terahertz regimes. Specific laser systems produce 1 to 2 cycle pulses with 5 to 6 fs durations at 200 nm. A XUV light source can produce <1 fs pulses. A transform-limited laser pulse time, t, and bandwidth product, ω, is given by:

$$\Delta t \Delta \omega \geq 0.5 \qquad (1)$$

A 1 ps pulse has a bandwidth of 441 GHz. Regarding full width at half maximum powers the above equation modifies to:

$$\Delta t \Delta v \geq k \tag{2}$$

where k is 0.441 for a Gaussian pulse, 0.140 for exponential and 0.892 for rectangular pulses. A 13.2 ns pulse has the 75 MHz bandwidth. A femtosecond pulse has a bandwidth in the range of terahertz. Nd:YAG Laser pulse needs extra amplification due to 0.5 J/cm^2 saturation limit. Shorter the pulse higher the bandwidth philosophy allows harmonics generation for pulse shortening. For a laser cavity with length L and oscillating mode m, then

$$m\lambda = 2L, \tag{3}$$

$$v = \frac{mC}{2L}, \tag{4}$$

$$\Delta v = \frac{C}{2L}, \tag{5}$$

$$T = \frac{2L}{C}, \tag{6}$$

and

$$\Delta t \Delta \omega = \frac{C \Delta \lambda}{\lambda^2}. \tag{7}$$

To measure an ultrashort pulse it needs temporal and spectral broadening. Temporal broadening is necessary for pulse duration measurement and spectral broadening to amplify temporally broadened flat pulses. Dispersion and grating stretcher [105] and compressor [124] technologies are well advanced now. A 1000-times temporal stretcher brings terahertz waves in the regime of gigahertz to measure it by an oscilloscope. Terahertz can travel through plastic, hollow core and pipe waveguides. Development of metamaterial single mode fibres has allowed controlling temporal and spectral broadening of terahertz pulses [125]. The French COM'TONIQ project is focused on developing 50 Gb/s at 280 GHz over 100 m to 1 km distance. Tektronix, Inc. has demonstrated 0.4 THz (400 GHz) using advance signalling coding. To measure the THz waves, we can use non-invasive imaging properties as well as stretching the terahertz to gigahertz techniques to broaden and measure using the reference bit rate multiplier on 10 GHz oscilloscope. A 10 to 20 GHz scope or spectrum analyser is required for terahertz wave characterization, but the COMSATS Institute of Information Technology, Pakistan, has only a 6 GHz oscilloscope in the department of electrical engineering. Due to extra high repletion rate measurement limitation, we are left with 100 to 1000 calibrated fiber optic pulse length stretcher option to measure the high repetition rates by an ordinary 1 GHz oscilloscope. Mode locking is done either actively or passively by modulating cavity losses using Pockel cell, Kerr cell and saturable absorber techniques [126]. A 1.5 m long resonator yields 100 MHz repetition rate pulses. Conventional DFB lasers have 10 kHz repetition rates which can be increased either by adding repletion rate multiplier units or high speed pulsing circuits [127]. A 100 GHz photonic crystal resonator [128] has been reported and 350 to 500 GHz optical light sources are available in the market [129]. Generation and detection of pulsed and CW terahertz may be accomplished by photoconductive antennas, photomixers, optical beats, nonlinear crystals, Schottky diodes, high electron mobility transistors, resonant tunnelling diodes, vacuum electronic devices (klystrons, clinotrons, magnetrons), quantum cascade lasers, plasmons in graphene and active/passive metamaterials [130]. Terahertz waves detection may be based on electric field rectification, thermal, plasma wave, HEMT and metal-oxide semiconductor (MOS)-based techniques. Terahertz wave coupling, guiding, focusing and handling techniques are well documented in the literature [131].

5 SCIENCE AND ENGINEERING ETHICS

The ethics and mastery of science are both important for society. When a person or company falls, then there is no limit to the depth of descent. The strength of a community depends on the strength of its ethics. Ethics are an integral part of society, business, and research. Human trust is compromised when security appliances do not help detect suicide bomber in a crowd, or life-saving drug is found fake on a heart attack. According to the French News Agency (AFP), the collective death of 323 civilians in Iraq on 3rd July 2016 was because of fake ADE-651 bomb detectors. Radical groups cause hundreds of mortalities and fatalities every day in Pakistan, Afghanistan, Iraq, Libya, Yemen, Syria and Nigeria. Terrorist activities now span half the world from Philippines and Thailand to the Middle East and Europe. Afghanistan, Pakistan, Iraq and Syria are among the most affected countries. Terrorists use concealed suicide jackets, car bombs and buried landmines against civilians, infrastructures and military vehicles. Technology is available to detect buried landmines and image concealed bombs, yet some con companies launched fake/defective detectors to collect windfall profits or reinforce terror networks. Fake companies played a key role to reinforce the diehards by flagging the security agencies, drug and narcotic control authorities [132]. It is almost the end of morality to charge money and deliver fake life-saving drugs or sham bomb detectors to protect schools and hospitals against terror attacks.

Quadro Corporation and Homeland Safety International, Inc. sold sham/defective Quadro Trackers (valued at $8,000) and Sniffex (valued at $6300) metal detectors. ATSC and Global Technical, Ltd. sold fake/defective ADE 651 (valued at £23,000), Mole (valued at $36,000), GT200 (valued at $27,000), Alpha 6 (valued at $22,600) and XK9 (valued at $12,000) bomb detectors to terror-hit countries like Iraq, Pakistan, Afghanistan Mexico and Thailand [133]. Individual performance tests on the ADE 651 in Thailand, Bangladesh and Iraq using real explosives showed that these metal detectors had no sensor in it to detect any HAZMAT [134]. Iraq and Thailand lost $60M to $80M for nothing which is a white collar crime against the international community [135]. The government of Pakistan in 2009 bought multiple ADE 651 metal detectors for their Airport Security Forces (ASF) in Karachi which did not work on time [136]. Genuine, GARRET stick metal detectors and walk through metal detectors cost $29 to $1500 and $3000 to $5000 but fake companies sold sham detectors from $5000 (Congo) to $36000 (Iraq). If bomb detectors were genuine, then it was no more challenging to detect bombs at checkpoints, yet it is hard to detect a mobile suicide bomber in crowded places like railway stations, airports, markets, mosques, shrines, churches, temples and schools.

6 CONCLUSIONS

The war ends yet the roadside landmines remain for a long time, continuing threaten to society, especially small children playing around. Dogs can sniff out hidden landmines, explosives and drugs but suicide bombers use perfumes to conceal its odour. Security agencies can detect suicide bombers by thermal imaging, but due to blackbody radiations, the terahertz differential reflectometry based technique seems more attractive. Spectroscopic signatures and imaging are viewed two options to detect concealed HAZMAT at a distance. Magnetic resonance imaging (MRI) and x-ray imaging are matured technologies which cannot be used in battlefields and bazaars due to their big size and ionizing properties. Laser-induced breakdown spectroscopy (LIBS) can detect vapors of buried landmines, yet it is hard to use to identify suicide bombers in crowds. Luminescence technologies can indicate concealed explosives by a physical approach to the target. Luminescence and laser spectroscopy methods fail when suicide bombers wrap explosives tightly in plastic bags around their waists. Terahertz waves are considered better option to locate suicide bombers in crowds due to their non-ionizing properties. Semiconductor photoconductive and vacuum devices are available in low terahertz bands (100 GHz to 1 THz) whereas lethal explosives require high terahertz bands (1 to 10 THz) sources and detectors. Time and wavelength multiplexed laser pulses can be tailored to any repetition rate and power by multiplying the mode-locked laser combs. Holography allows a three-dimensional (3-D) view of concealed HAZMAT in crowds. Optical pulse trains with repetition rates in the terahertz regime seem to be the way forward to detect HAZMATs.

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