Detection of THz Signal Produced by Plasma Filament Using Photoacoustic Technique

F. Yehya[1] , A. K. Chaudhary[2], Konda. S[2], A. Al-taweel & H. Al-sanea [1]

. [1]*Department of Physics, Faculty of Education &Sciences, Rada'a, Albaydha University, Albaydha Yemen* [2]*Advanced Centre of Research in High Energy Materials, University of Hyderabad, Hyderabad500 046, India*

[1]*fahembajash@gmail.com* & [2]*anilphys@yahoo.com*

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Abstract

We have successfully demonstrated, the detection of THz signal in plasma formed in ambient air using Photoacoustic closed window cell filled with methanol vapour. The type-I SHG cut beta-barium borate (BBO) crystal is used to generate Terahertz by focusing a 40 fs, 800 nm laser pulse in the air to create a superposition of the fundamental and the second harmonic optical fields in the plasma filament. In addition, we have studied the effect of and rotation of BBO crystal on the intensity of acoustic signal associated with the signature of THz radiation. We have also characterized the plasma filamentation using external microphone which was placed close to the focusing point. The variation of the PA signal with incident laser power reflected the dependency of generated THz on the incident laser power.

Keywords: *Photoacoustic, THz, BBO crystal, Filamentation, Laser*

الكشف عن إشارة THz الناتجة عن خيوط البلازما باستخدام التقنية الضوء-صوتية

لقد أثبتنا بنجاح ، اكتشاف إشارة THz في البلازما المتكونة في الهواء المحيط باستخدام خلية ضوء–صوتية مغلقة مملوءة ببخار الميثانول. تُستخدم بلورة بورات–بيتا الباريوم (BBO) من النوع SHG–I لتوليد تيراهيرتز من خلال تركيز نبضة ليزر تبلغ 40 fs و 800 نانومتر في الهواء لإنشاء تراكب للحقول الضوئية الأساسية والثانية في خيوط البلازما. بالإضافة إلى ذلك ، قمنا بدراسة تأثير دوران بلورة BBO على شدة الإشارة الصوتية المرتبطة بإشعاع التيراهيرتز. كما قمنا بدراسة خصائص فتيل البلازما باستخدام ميكروفون خارجي تم وضعه بالقرب من نقطة التركيز. اخيرا قمنا بدراسة تباين الموجات الضوء–صوتية مع طاقة الليزر المسلطة والتي تعتمد عليها أشعة التيرا هيرتز المتولدة

الكلمات المفتاحية : ضوء– صوتية, تيراهيرتز, بلورهة BBO, ليزر

Introduction:

The study of Plasma filaments in the air induced by the intense femtosecond laser pulses is of a great interest. It has opened a new channel to study many phenomena associated with long distance propagation of filaments such as THz generation (Hamster-1993), third harmonic generation (Yang-2003, Zhu-2001), white light lidar (Braun-1995), conical emission (Nibbering-1996, Chin-2001&2002, Golubtsov -2003,Kasparian-2003, Fontaine-1999), etc.

The basic mechanism of plasma formation is the balance between the two following dynamics:

1. When intense femtosecond laser pulses propagate in air, then air acts as a Kerr nonlinear medium and focuses the incident laser beam (self-focusing).
2. When femtosecond laser pulse intensity exceeds the air ionization threshold, the air molecules become ionized and generate low-density plasma which defocuses the laser pulses.

The intensity of laser beam in the plasma region is of the order of $6*10^{13}$-$1*10^{14}$ W/cm^2 (Kasparian-2000, Becker-2001) and corresponding electron density is around 10^{16}-10^{18} 1/cm^3 (Yang-2003).

Due to the difficulty in measuring beam intensity directly in the plasma region, other indirect techniques such as interferometry , fluorescence detection , THz detection etc are being widely used. (Brodeur-1997, Talebpour-2012, Dai-2006, Karpowicz-2008)

J. Yu et al have shown that by detecting the sound signal along the filament, the length and electron density of the filaments can be determined precisely . However, the intense fs laser pulses also partially ionized the air molecules through multiphoton ionization (MPI). Moreover, the electrons get accelerated by the incident laser pulses and drift away from their parent's ions with high temperature and kinetic energy (Hosseini -2003, Hao-2005, Yu-2003, Filin-2009, Liu-2002&2010) . As a result, there is transfer of energy between the hot electrons and cold molecules in ambient air through inelastic electron-molecular collision. This process leads to the creation of shock waves which are subsequently decayed to sound wave. Therefore,

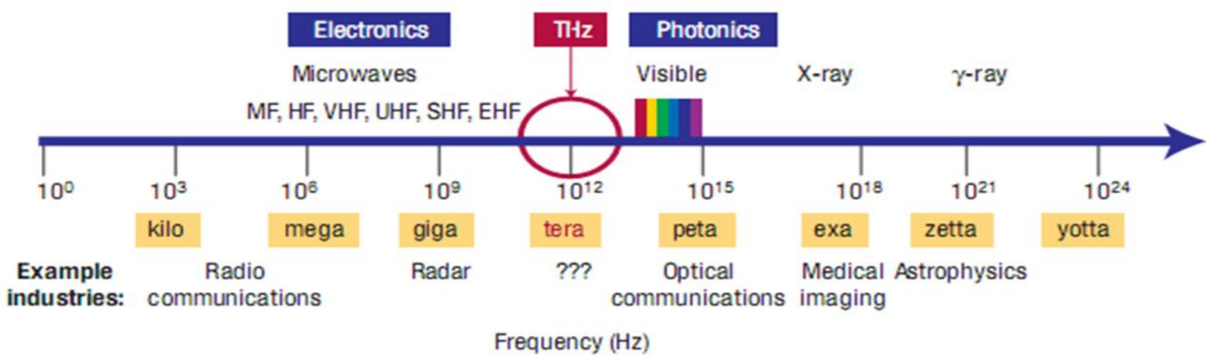


*Fig- 1: The electromagnetic spectrum (*Ferguson-2002*)* the recoding of generated sound waves can be used to characterize the filament.

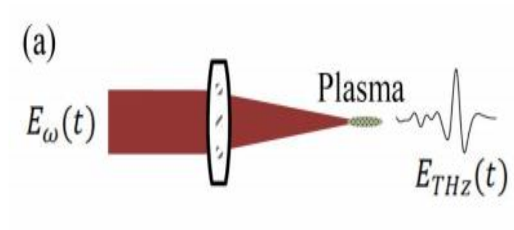
The electromagnetic spectrum shows that the Terahertz (THz) radiation has a frequency range of 0.1 to 10 THz which is located between infrared light and microwave radiation as shown in Fig- 1 (Ferguson-2002). Terahertz (THz) emission from laser-induced plasma was observed for the first time by Hamster et al. in 1993. Loffler et al have increased the intensity of THz radiation by applying a DC bias to the plasma region. In the meantime, Cook et al. have experimentally demonstrated that when laser pulses composed of a superposition of both fundamental and second-harmonic spectral components are focused into air, the strength of the generated THz-pulses are found to be 3 times stronger than the previously reported work . Many researchers have extensively explored the generation of THz by the two colors Femto seconds laser based techniques (Löffler -2002, Cook-2000, Bartel-2005, Xie-2006, Houard-2008, Zhang-2009). Dai et al and Chan et al have separately reported that the intensity of generated THz emission from two colors (i.e. W and 2W) plasma filaments can be increased by increasing the number density of the two-colored air plasma . The enhancement is referred to the coherent superposition of the THz waves which produced by each individual air plasma. Karpowicz and Zhang (Kaipowicz-2009) have explained the physical mechanism of terahertz radiation in air filament using a quantum mechanical model in two steps:

1) THz photons are emitted due to the acceleration of the electron wave packet which gives a net dipole moment through the asymmetry introduced by the two-color fields.
2) Due to collisions of these wave packets with neighboring atoms they emit bremsstrahlung in the THz range.

The beta barium borate (BBO) crystal is widely used for optical frequency doubling and other nonlinear optical processes. Due to its large birefringence, remarkable nonlinear coefficients, and high damage threshold is also considered as a potential candidate for the generation of strong terahertz radiation by means of optical rectification process .

Practically, there are three arrangements for the THz generation from laser-induced plasma in air or gases as shown in fig-2(a-c) (Kim -2008, Dai-2007, Chen-2008, Kaipowicz-2009, Eimerl-1987)

1) A single optical beam excitation (i.e. W or



2W) as shown in fig- 2(a)

Fig- 2(a): Single optical beam

In this case, a single optical beam W or 2W is used to create gas plasma and generate THz waves through the ponderomotive force (Hamster -1993).

2) Two beam mixing (i.e. W and 2W) as shown in fig-5.2(b):

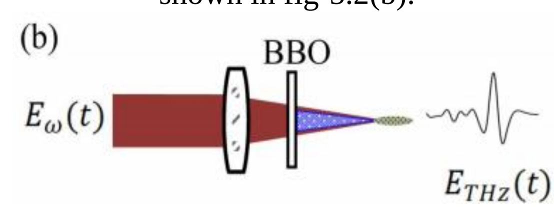


Fig- 2(b): Two beam mixing

In this case: a fundamental beam (ω) is focused through a very thin beta barium borate (BBO) crystal to generate second harmonic beam (2ω), which is thereafter mixed with the residual fundamental beam in the gas plasma to generate stronger THz signal(Cook-2000)

3) Coherent control method is used to control the individual polarization and phase of each beam using an interferometric phase compensator as shown in fig-2(c) (Xie -2006).

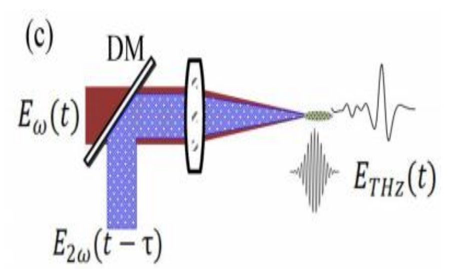


Fig- 2(c): coherent control method

This chapter deals with three parts: **Part (a)**, deals with characterization of the filamentation channel using acoustic technique. **Part (b),** discusses the role of α and β rotation angles of BBO crystal with the generation of THz and photoacoustic signal. **Part (c),** deals with the generation of THz radiation in the PA cell filled with methanol molecules. In addition, the time delay technique between two 800nm pulses which is focused through Type-I beta-barium borate (BBO) crystal to create plasma filament and used to record the THz signal at zero delay position/time.

The dependency of the PA signal with incident laser power and gas pressure has been studied also.

Experimental Details:

The amplified Femtosecond Ti: sapphire laser system is used with output energy up to 2.5 mJ in 40 fs FWHM. The central wavelength is 800nm and the repetition rate is 1 kHz. The laser pulses were focused using a 20 cm lens in the air through BBO crystal. The Type –I, SHG cut BBO crystal generates second harmonic at 400 nm wavelength. The Teflon sheet has been used as a filter to allow only THz radiation to pass into PA cell. The window of the PA cell is also made of Teflon sheet. One Teflon sheet is placed directly after the focus geometry of the beam while the second Teflon sheet is fixed as a PA cell window. Moreover, the silicon lens is also placed between the two Teflon sheets to enhance the filtering process of THz. The Photoacoustic cell is filled with methanol vapor. The THz based photoacoustic signal (PA signal) is detected by two pre-polarized microphones of 50mV/Pa (BSWA, China). The first microphone is placed in the center of the cell while the second microphone is placed on a X-Y stage near the focused geometry (region of filament) of the laser beam. The output signal of the microphones has been fed to the preamplifier which is coupled to the 200 MHz Oscilloscope (Tektronix, U.S.A.). The

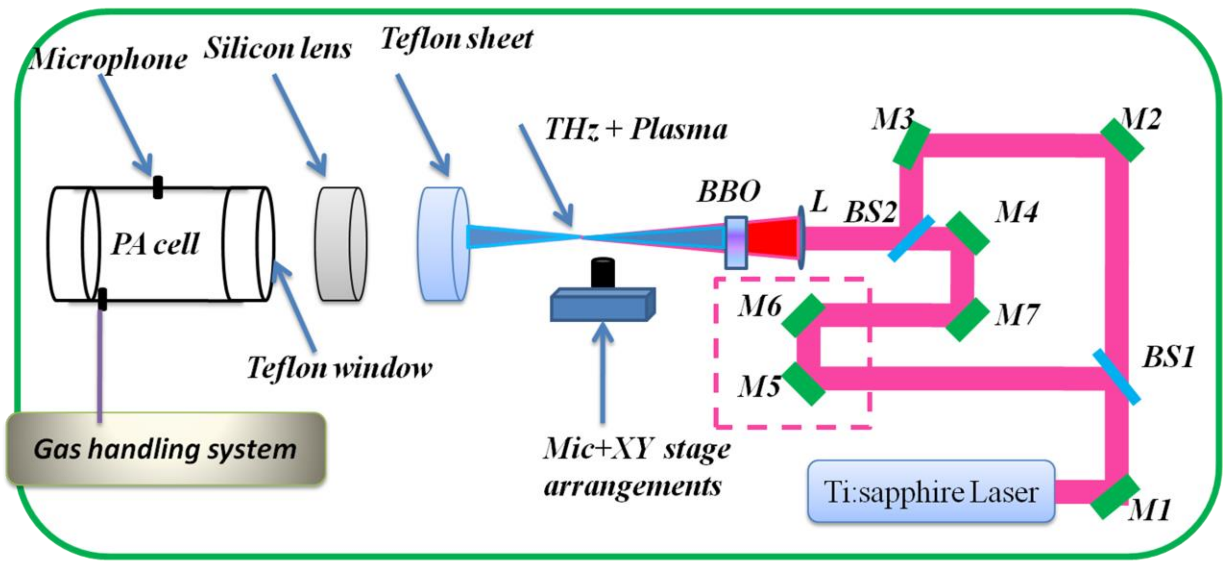


Fig- 3: Experimental setup

USB/GPIB interfacing is used for data acquisition through Boxcar integrator (Stanford Instruments Inc., USA). Schematic layout of photoacoustic experiment is shown in fig- 3.

Characterization of plasma filament by acoustic waves:

The technique based on measurement of acoustic waves is one of the convenient techniques to study and characterize the plasma filament in air and gases (Hosseini -2003, Hao-2005, Yu-2003, Filin-2009). We have developed an improvised acoustic technique to record the time and frequency domain acoustic signal which gives the signature of the generated radiation THz associated with plasma filaments. The length of the filament as well as the limit of THz characteristic acoustic signals is measured with the help of precise X-Y mechanical stage.

Recording of Acoustic waves associated with Plasma filament:

We have used 800 nm wavelength, 40 fs laser pulses at 1 KHz repetition rate obtained from a femtosecond amplifier for the generation of THz signal. The FS pulses are focused with a lens and passed through the Type-I, SHG cut BBO crystal to record the acoustic signal associated with the generated THz radiation in the ambient air. Fig-5.4 shows the typical acoustic signal produced by plasma filament in the ambient air. The duration of acoustic wave is around 50µs which is based on the average of 500 pulses. The pulses are repeated at regular interval of 1ms which confirms the direct resemblance with the Femto seconds laser pulses at the rate of 1 KHz. The Fourier transformation of acoustic signal is presented in fig- 4(a) (inset). It shows that the acoustic spectra peak at 30 kHz and the cut off is around 50 kHz. Fig- 4(b) shows that the time between two acoustic pulses is exactly 1m which is equal to the time between two fs pulses.

Filamentation profile:

Different techniques have been used to diagnose the plasma filaments profile induced by focusing the intense femtosecond laser pulse in the air. For example, electromagnetic pulse (EMP) , Backward Propagating Fluorescence signal (BF) , cross section imaging, resistivity measuring and acoustic technique (Wen -2009, Hosseini-2003, Iwasaki-2003, Hao-2006). Among all above mentioned techniques, acoustic diagnosis is one of the simplest and most convenient techniques in real time scale.

The non-filtered laboratory environment has very small error contribution to the acoustic signal. Therefore, strong acoustic signal provides characteristic signature of THZ radiation produced by plasma filaments (Hosseini -2003, Hao-2005, Yu-2003, Filin-2009) . Fig-5 shows the acoustics signal as a function of the longitudinal propagation direction of filament. One can see that, the critical changes in the intensity of the acoustic signals by changing the distance of the microphone along the plasma channels. It lies between 25-35 mm range. The higher intensity signals as shown in Fig-5 represent the zone of higher free-electron density inside the plasma filament. In order to reduce the background noise, the signals averaged over 500 laser pulses.

The rapid increase of the acoustic signal is restricted between 25 – 35 mm range which directly provides the length of plasma filament of the order of 10mm.

Fig- 6: shows the limit of acoustic signal propagating away from a plasma filament. It is recorded when the microphone is moved in transverse direction. The curve indicates that, the signal is losing its strength in a significant manner after crossing the distance of 2.5cm from the plasma filament.

The Role of BBO crystal on the THz generation:

The optical rectification is an important optical technique to generate THz signal in nonlinear optical media. That has been demonstrated in various nonlinear materials such as BBO, ZnTe, $LiNbO_3$, etc (Zhang -2011, Xie -2006, Wu -1996, Kress -2004,Wen -2009). The beta barium borate (BBO) crystal is a uniaxial negative nonlinear material and widely used in up and down frequency conversion including THz generation. In this part we have studied the role of α and β rotation angles of BBO crystal in the generation of THz and Photoacoustic signal.

The role of α and β rotation angles of BBO crystal

The THz polarization is extremely sensitive to the relative phase of the optical beams. Wen et al reported that the THz polarization smoothly rotates through 2π radians as the relative phase between the two pulses is adjusted (Wen -2009). The relative phase depends on many factors such as, the distance between BBO crystal and filamentation and α and β rotation angles of BBO crystal. Fig- 7 shows the

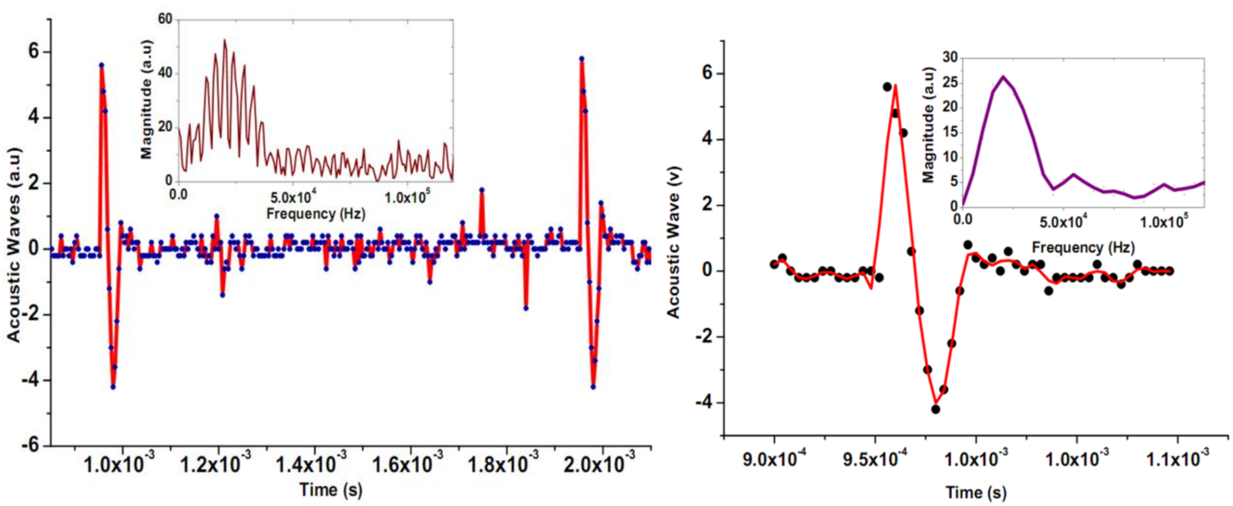
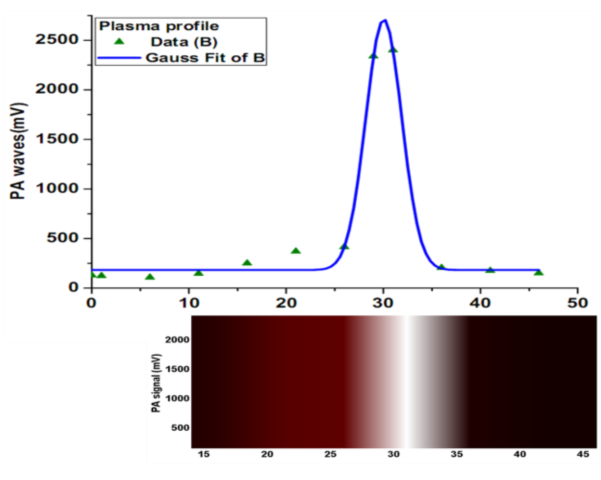


Fig- 4: (a) single acoustic signal with FFT (inset) (b) acoustic signal in time=1ms with FFT (inset)



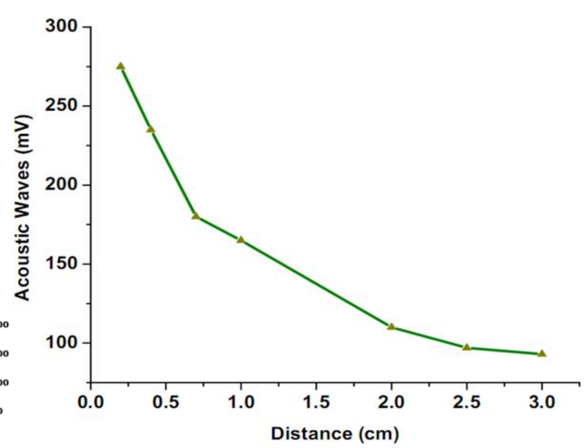


Fig-5. : Gaussian fit of plasma filament

Fig- .6: limit of acoustic signal propagation away from a plasma filament acoustic waves intensity as a function of α rotation angle of BBO crystal. It shows that the intensity of the electric field of transmitted laser beam including generated SHG directly depend on azimuthal angle α. Therefore, to maximize the THz/PA generation from plasma filament, the BBO crystal should be fixed on the selected α in a degree which corresponds to the maximum intensity. We also studied the effect of the tilt angle β of BBO crystal as shown in fig- 8. The curve shows that, the modulation of acoustic wave amplitude can be minimized by slight horizontal rotation of the BBO crystal. In addition, the figure indicates that, the rotation of tilt angle β of BBO crystal has another two angles at 3,-3 degrees which have a maximum signal intensity.

THz Detection Using PA technique: Methanol (CH_3OH) is the common laboratory reagent and similar to the water molecules. It is a polar molecular with hydrogen bonds which refer to the charge displacement in the hydroxyl group (-OH).

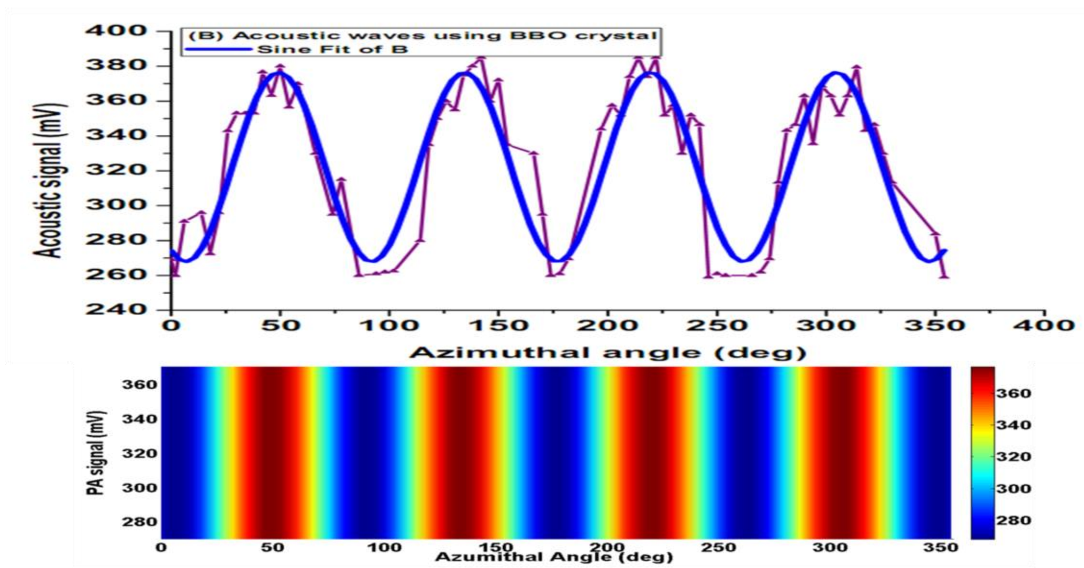


Fig- 7: The effect of BBO rotational angles α on acoustic signal intensity (red line) and sin fit (blue line), surf graph (down)

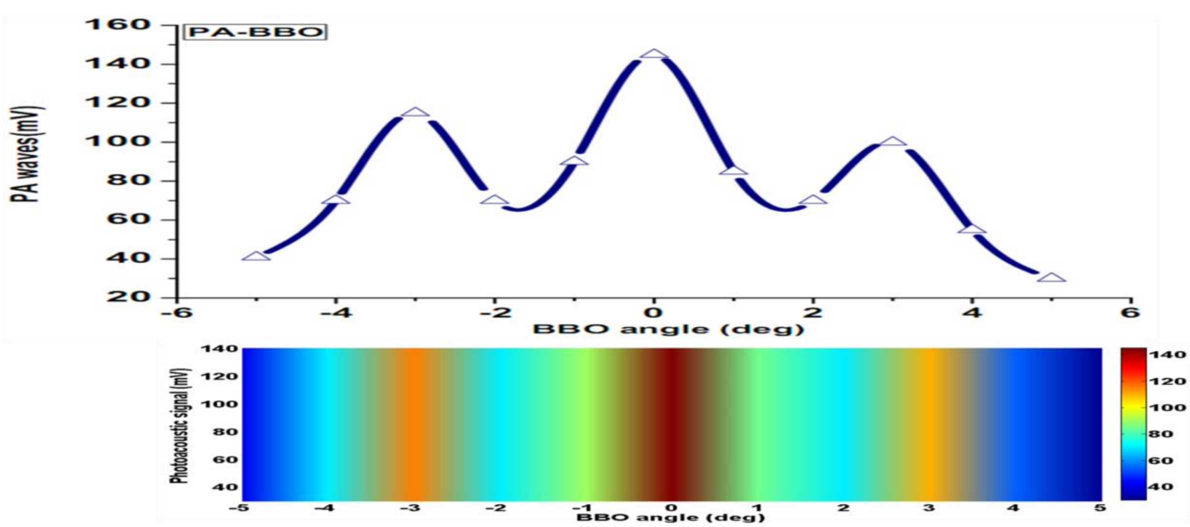


Fig- 8: The effect of BBO rotational angles β on acoustic signal intensity, surf graph (down)

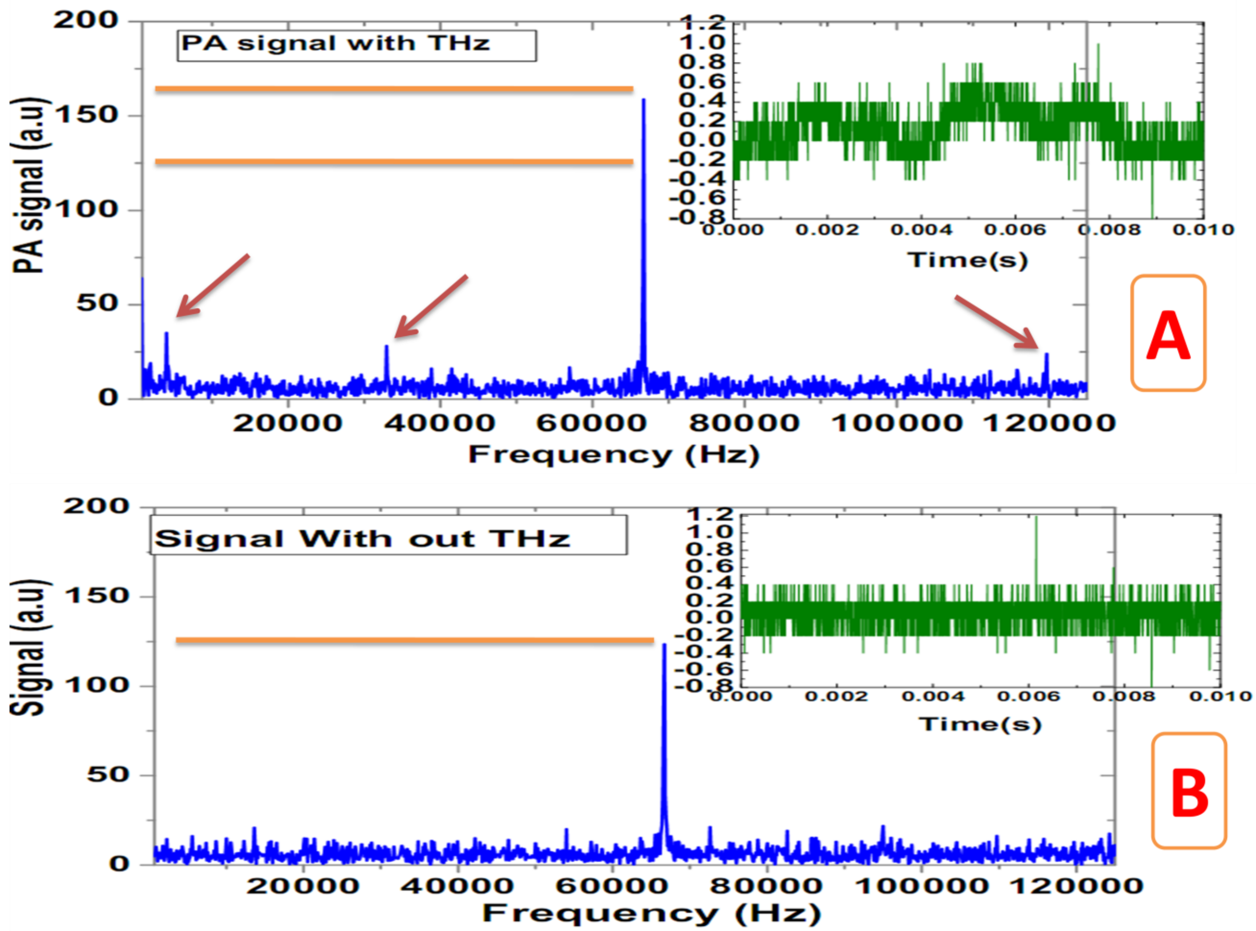


Fig- 9(A): PA signal due to absorption of THz radiation by Methanol, Three arrows indicated the acoustic modes at 4, 33, 120 kHz and enhancement of 35 units for the frequency 67 kHz. (B)The background signal/Noise without THz

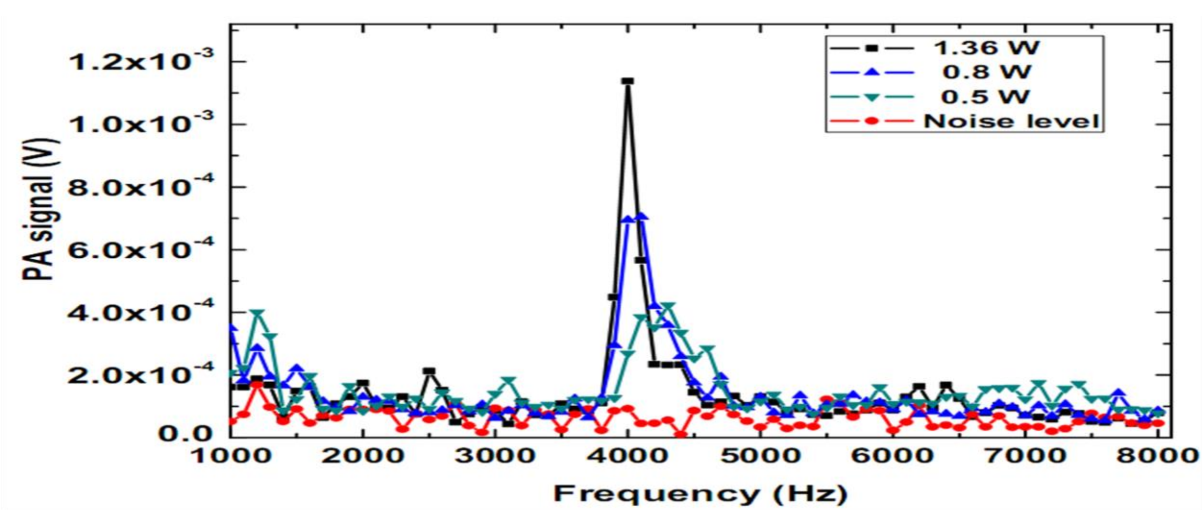


Fig-10: PA signal at 4 KHz frequency with incident laser power

In this part, a PA cell filled with Methanol is used to detect THz radiation generated by ultrashort laser pulses obtained from Femto second laser amplifier at 1 kHz and focused in the ambient air after passing from type-I BBO crystal.

Recording of PA-THz Signal of Methanol :

Fig- 9(A) shows the PA signal/spectrum due to absorption of THz radiation by Methanol molecules filled in PA cell. The figure shows the presence of three new acoustic modes excited at 4, 33, 120, kHz frequency. In addition, an enhancement of 35 units for the frequency located 67 kHz. Fig- 9(B) shows the background signal/Noise without THz. These PA spectra represent the strong rotational lines of Methanol which is excited by the incident THz radiation. The intensity of THz radiation is controlled by changing the incident laser power using a small aperture. Fig- 10 shows that the PA signal intensity at 4 kHz frequency is slowly increasing with respect to the incident laser power. However, when the laser power crossed 0.8 W, the PA signals are rapidly increased as shown in Fig-11(B). This can be attributed to the enhancement of the THz intensity after this value of laser power which excite more molecules of methanol and subsequently enhance the intensity of the PA signal at the typical frequency 4 kHz.

We also studied the effect of pressure on the PA signal as presented in Fig- 11(A). It clearly shows

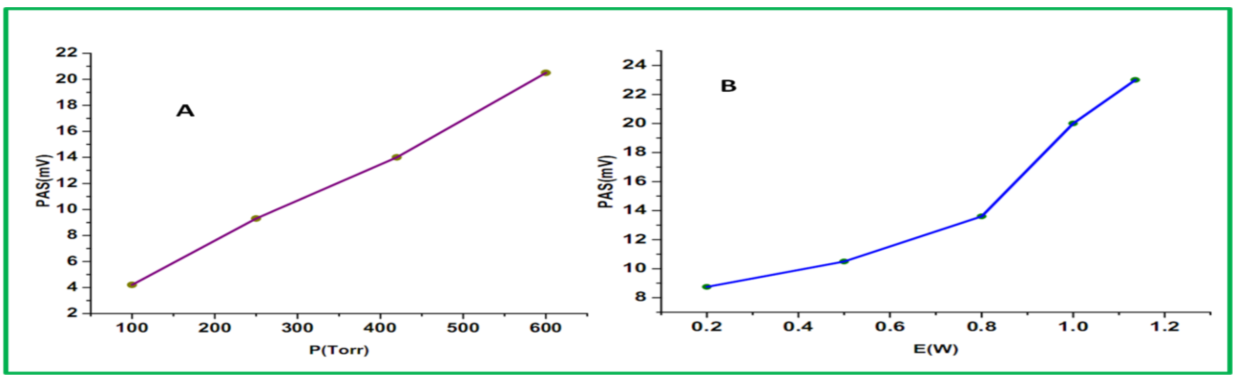


Fig- 11(A): PA signal with pressure (B) with laser power measured after focusing

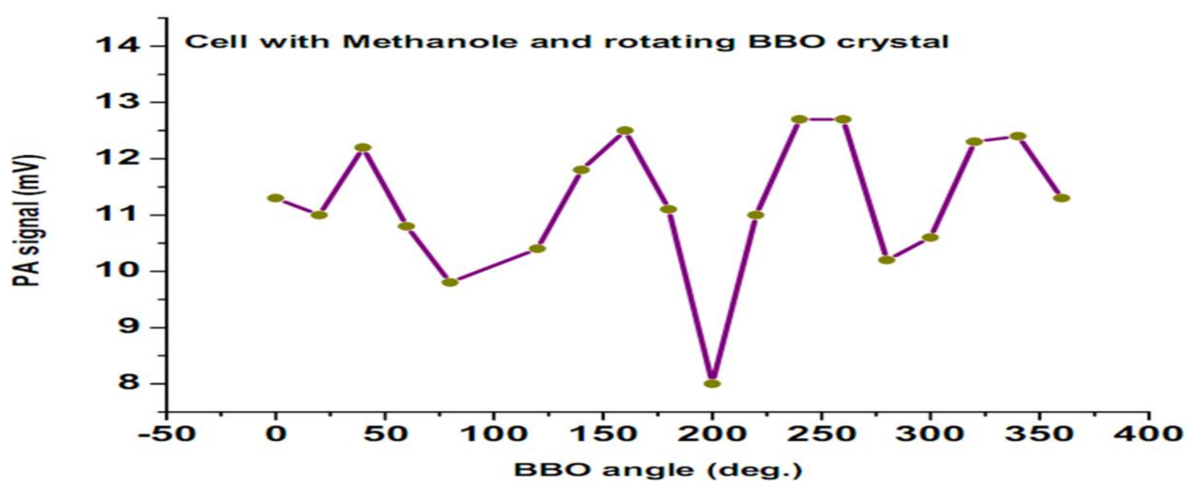


Fig- 12: The effect of BBO rotational angles α on acoustic signal/THz intensity in PA cell that the PA signal is responding linearly with Methanol Pressure. Even the signal to noise ratio (SNR) is very less due to the weak THz radiation entering into the PA cell in presence of high level acoustic noise inside the laser lab, but it’s still good enough to record the PA signal generated inside the closed window cell as a signature of terahertz field for the first time.

PA signal with respect to α rotational angle of BBO crystal:

Fig- 12 shows the PA signal generated inside the PA cell duo to the absorption of THz radiation by methanol molecules as a function of α rotation angle of BBO crystal. It shows that the PA signal which depends directly on THz field is varying with rotational angles α in a similar way as shown in Fig- 7. The maximum intensity of PA signal at different angles of α rotation indicates the suitable position of BBO crystal to generate high amplitude THz.

Time delay study of plasma filamentation and THz:

Conventionally, the THz signal is detected either by Photoconductive Antennas or Balance detector techniques which is based on pump probe delay arrangement in pico seconds time domain. The actual position/ time of THz signal is known as zero delay position .Where is sharp THz time domain characteristic pulse can easily be identified among the noise.

Similarly, we have adopted the similar approach to detect the THz signal using our Photoacoustic technique. We have selected two 800 nm pulses received from the beam splitter and treated one as a

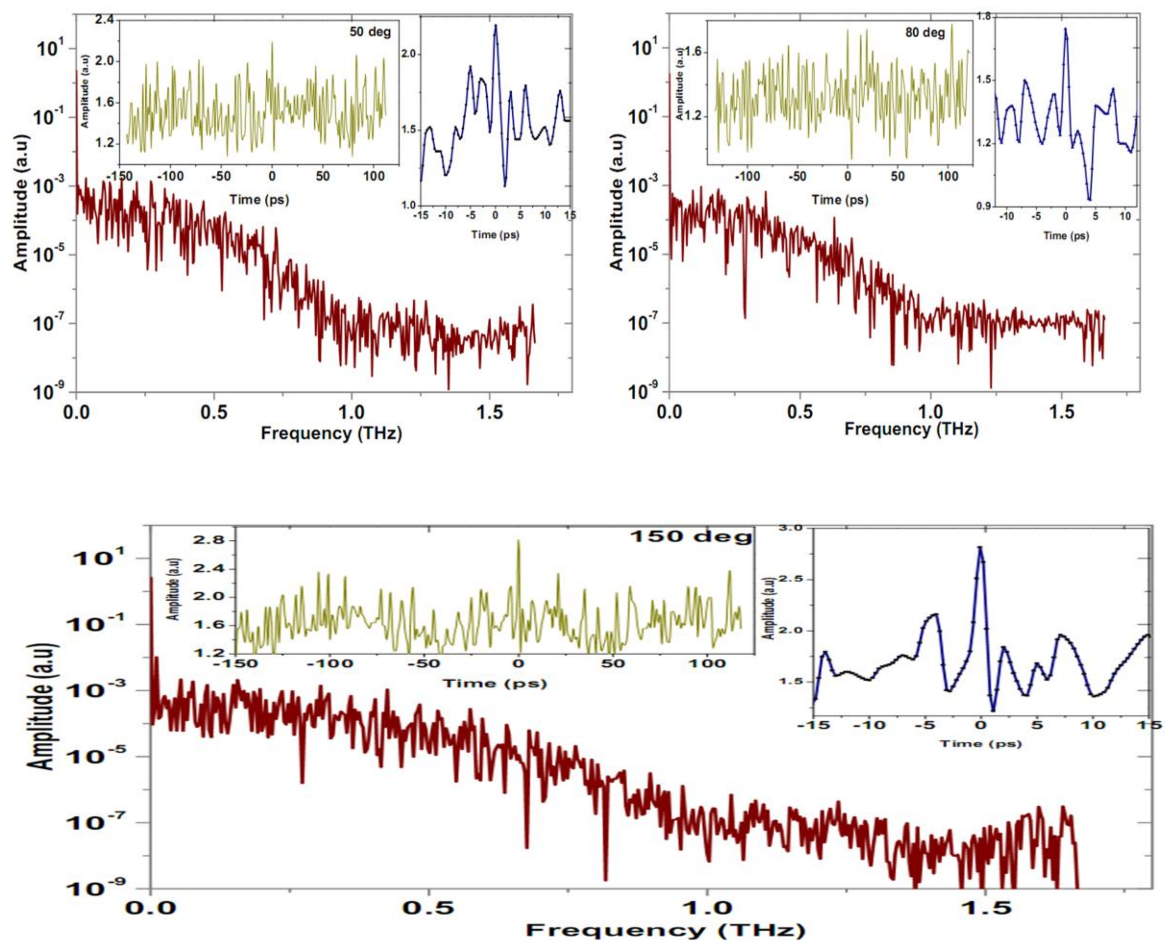


Fig- 13(a-c): Acoustic wave at different time delay between two 800nm wavelengths pump and other one as a probe and focused them by the same lens and allowed them to pass through a Type-I , SHG cut thin BBO crystal. The THz signal is generated by filaments produced by 800 nm and 400 nm (SHG) in the ambient air which is weak in nature and needs optical technique to detect. However it becomes very strong at the time of zero delay which can easily be detected by our acoustic system / arrangement.

The recording of acoustic wave at different time delay between two 800nm wavelengths passing through BBO crystal to create a plasma filament is presented in Fig-13(a-c)

The figures show two important things:

1) Inset (I) shows the periodic variation of acoustic wave's intensity in this range of PS time delay whereas inset (II) shows the intensity distribution of the acoustic signal in 4 pico second range at zero delay.
2) Fig- 13 shows the FFT of time signal as shown in inset (II) in THz frequency range.

Conclusion

We have successfully demonstrated, for the first time, the detection of THz signal in plasma formed in ambient air using Photoacoustic closed window cell filled with methanol vapour. The type-I SHG cut beta-barium borate (BBO) crystal is used to generate Terahertz by focusing a 40 fs, 800 nm laser pulse in the air to create a superposition of the fundamental and the second harmonic optical fields in the plasma filament. In addition, we have studied the effect of α and β rotation of BBO crystal on the intensity of acoustic signal associated with the signature of THz radiation. We have also characterized the plasma filamentation using external microphone which was placed close to the focusing point. The variation of the PA signal with incident laser power reflected the dependency of generated THz on the incident laser power.

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