Detection and analysis of RF emission generated by laser-matter interactions

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ABSTRACT

Plasmas produced by laser-matter interactions are a known source of electromagnetic radiation. However, little has been done to systematically study the electromagnetic radiation emitted from laser produced plasmas. It is our intent to provide detailed time and frequency domain measurements of such emitted radiation. An ultra-fast femtosecond high intensity laser and a superheterodyne receiver are employed to study laser-matter interactions for various materials in the frequency range 1-40GHz.

Keywords: Electromagnetic pulses, laser-matter interactions, plasmas, femtosecond pulses

1. INTRODUCTION

Transient electric fields are an established source of electromagnetic pulses. These pulses are generated from currents within material excited by laser-matter interactions or within laser generated plasmas. Not normally intended as part of laser physics experiments these transient electromagnetic signals often introduce excess noise to measurements being conducted and disrupt equipment. For this reason, such radiation is considered undesirable and the normal experimental approach to dealing with the problem is often the introduction of RF shielding or similar countermeasures. Thus far, little has been done to systematically characterize and understand these transient electromagnetic fields. This is a relatively unexplored phenomenon and only a few research groups have conducted studies on basic properties of such pulses.

High intensity femtosecond lasers are capable of creating the conditions necessary for the generation of such pulses. Femtosecond laser experiments have exhibited more and stronger occurrences of electromagnetic pulse events than nanosecond lasers. There are two mechanisms under which transient electric fields and hence electromagnetic pulses are created with the use of femtosecond high power lasers; laser self-filamentation and laser matter interactions.

At sufficiently high laser intensities ($\approx 10^{12}$ W/cm^2) the second-order, intensity-dependent, refractive index increases the overall refractive index of the air through which the beam propagates. When the intensity of the focusing beam reaches a threshold of approximately 10^{14}W/ cm^2 (atmospheric pressure), weak ionization of the air takes place via multi-photon ionization[1]. Electrons are released from air molecules as a consequence of the intense oscillating electric fields within the laser pulse. These electrons provide a negative contribution to the total refractive index thus producing a counteracting weakly defocusing effect. Transient electric fields are created from the interaction of the laser pulse traveling through the filament and the plasma channel. It has been suggested[2] that the plasma within the filament is not locally neutral. It may possess dipole and quadruple moments that give rise to transient fields. It has also been postulated that the ponderomotive forces generated at the focus of the driving ultrafast high intensity laser are sufficiently strong to temporarily separate the electrons and ions within the plasma, giving rise to a transient dipole moment that results in radiation[3]. These theories have been experimentally verified by Proulx[2].

Electromagnetic pulses are also generated when a laser pulse of sufficient intensity strikes the surface of a solid. Upon impact, electrons and ions are violently ejected from the target. Hot plasma of approximate diameter ≈ 200μm is formed at the surface thus creating a shockwave that propagates through the cold media. Transient electric fields are generated either from electrons pushed into the target itself or from the motion of charged particles ejected from the target during the original laser-target interaction. Mead[4] observed transient electric fields generated from induced charges or currents within material that lie within the path of particles ejected from the original laser-target interaction. Streaming collisionless electrons induce an ambipolar electric field. This transient electric field radiates in the radio and microwave frequencies. Resonant transfer of energy to electrons results in electron energies of 10-100keV (X-rays). Witte[5]

Enabling Technologies and Design of Nonlethal Weapons, edited by Glenn T. Shwaery, John G. Blitch, Carlton Land,
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investigated the plasma and electrons generated from the interaction of high intensity laser pulses with an aluminum target. A Ti: Sapphire laser was used to focus pulses of power P = 10^{17} W/cm^2 on the surface of the aluminum. The laser matter interaction resulted in the formation of a keV plasma in front of the aluminum and a layer of fast electrons that penetrated into the target. The resulting plasma had a duration of several picoseconds.

Electromagnetic pulses are an experimental nuisance turned useful. There is now vast interest in possible applications of such pulses. There is very little known for the reaction of biological cells to high frequency electric fields generated by laser interactions. For instance, a shark is known to be able to detect extremely small in magnitude electric fields over large distances. This experimental field has also become a topic of much activity in the medical sciences. The effect of electric fields on nociceptor cells is currently being investigated; fields of 10kV/m are known to stimulate nociceptors. Moreover, interactions of electromagnetic pulses with organic and inorganic materials may be studied thus bringing forth an array of newly acquired data and applications. Gated electronic circuits may be turned off just by a simple local RF emission generated by a high power laser.

Previous research efforts and methods were sufficient in determining the existence of laser-plasma generated electromagnetic pulses. Data collected provided basic information on the temporal and spectral limits of such pulses. Tzortzakis[6] utilized a heterodyne microwave receiver to measure the electromagnetic field associated with a laser plasma filament. The technique provided finite measurements (reported in arbitrary units) of electromagnetic spectra in the 93-95GHz and 117-119GHz bands.

The current approach utilizes a superheterodyne receiver system to examine electromagnetic pulses emitted from both, femtosecond laser-matter interactions and laser self-filamentation. Properties such as radiated intensity, pulse duration and spectral composition will be determined over a large spectral and temporal range. The system is calibrated and software has been developed to fully reconstruct the electromagnetic pulse in both the time and frequency domain. This is the first time RF emission generated from laser plasmas will be fully characterized.

2. EXPERIMENTAL

2.1 Experimental apparatus

A femtosecond high intensity chirped-pulse amplification laser is used for all experiments. The laser utilizes a mode locked Ti: Sapphire laser oscillator to generate the initial pulse and Cr: LiSAF amplifiers necessary to increase the pulse energy to 1 Joule. The resulting output pulse is centered at 850nm and the repetition rate is 1Hz. This laser system is also capable of burst mode operation where several pulses can be fired at approximately 10ns apart.

Laser-matter experiments are performed in a large 80 cm diameter hemispherical vacuum chamber. Thick walls provide the chamber with adequate RF shielding for noise isolation. Two turbo pumps are utilized to bring the chamber to a pressure of approximately 10^{-6} Torr. This is done to allow plasma and hot electrons to form. The targets are mounted 21.5 cm above the chamber floor on a non-conductive and non-magnetic delrin arm which in turn is connected to a 3-axis translational stage. The translational stage is remotely controlled via a MM4006 Newport 8-axis motion controller. A series of optical mirrors routes the laser beam into the chamber to a 5cm focal lens which in turn focuses the beam to an approximately 50μm spot size.

2.2 RF detection system

In order to conduct the laser-matter RF emission experiments, an innovative system for measurement has been developed. The instrumentation in question needed to simultaneously meet several strict requirements. Because the laser can only fire at a rate of 1 Hz, detection instrumentation cannot be dependent upon reconstructing a measurement by sampling and averaging a continuous series of similar signals, a technique often employed in many modern digital sampling oscilloscopes. Instead, it is necessary that a complete set of data be measured from a single laser triggered electromagnetic pulse. Because of the short duration of the electromagnetic pulse, the system must have extremely high time resolution, preferably in the range of tens of picoseconds. Due to the relatively unknown nature of the electromagnetic field to be measured, a large dynamic range is desired. This makes it possible to simultaneously measure a wide range of varying electric field intensities. Finally, it is required that the instrumentation be readily able to measure any frequency within a 1-40 GHz range. To meet these demands a unique array of RF/microwave antenna, circuitry and techniques are employed.

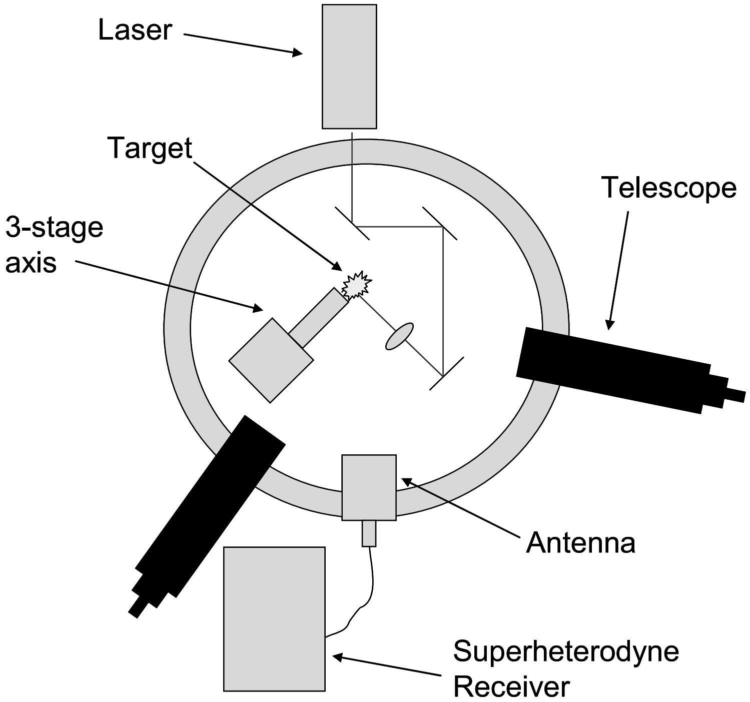

Fig. 1. Displayed is the experimental setup for all laser-matter interaction RF emission experiments. The telescopes are installed for future focal mapping of the target for the optimization of laser intensity.

Two ridged waveguide horn antennas are used to detect radio frequency emission. The first antenna, Sunol Sciences DRH-118, is used in the 1-18GHz frequency range whereas the second antenna, Q-Par Angus QSH-180K, is used in the 18-40GHz range. The antenna used for each particular frequency range is placed facing the target material. Plastic wrap is applied on the antenna to protect it from ablated target debris. These antennas are polarization sensitive; data will be analyzed for both configurations.

The antenna is connected through a vacuum feedthrough into a pre-amplifier. The pre-amplifier is used to assist the detection of extremely weak RF emission. The pre-amplifier is connected via a low attenuation coaxial cable into the superheterodyne receiver. The receiver is connected to a Tektronix CSA7404 DC 1-4 GHz bandwidth oscilloscope with a 2mV vertical resolution and a 1ps horizontal resolution. The receiver is responsible for the 1-40 GHz bandwidth of detectable RF emission. While extending the frequency resolution of the system the receiver is also responsible for retaining time and magnitude resolution of the signal.

The inverse superhetereodyne receiver used for these experiments is a purely microwave analog electronic system limited only by its analog bandwidth. Depending on the measurement spectral range, the system has a gain of 3.70 – 7.26 dB, a noise figure of 9.99-10.75 dB, sensitivity of 0.04-0.82 V/m and a dynamic range of 30 dB. The purpose of the inverse superheterodyne receiver is to demodulate frequencies from 1-40 GHz to DC while filtering all but 4GHz of the received signal to match the CSA7404's bandwidth limitation and to eliminate overlap of the measured signal's spectral components in the Fourier domain. Essentially, the input signal is demodulated into windows of 4GHz and then displayed on the 1-4GHz oscilloscope. The first mixer of the receiver, M2-0250, is responsible for mixing the input signal, S_i, with the external oscillator signal, S_e. Depending on the frequency range of the input, the mixer either subtracts the external oscillator signal from the input or adds the two signals. The second mixer, DM0520LW1, is responsible for subtracting 16 GHz (local oscillator – Series 600) from the total signal input of the first mixer. Therefore, the signal measured at the oscilloscope, S_m, is governed by the following relation[7]

$$S_m = S_i \pm S_e - 16 \tag{1}$$

where + S_e corresponds to the 1-18GHz range and - S_e corresponds to the 18-40GHz range. A DC 4GHz filter is employed after the second mixer in order to eliminate signals that fall out of the demodulated signal range.

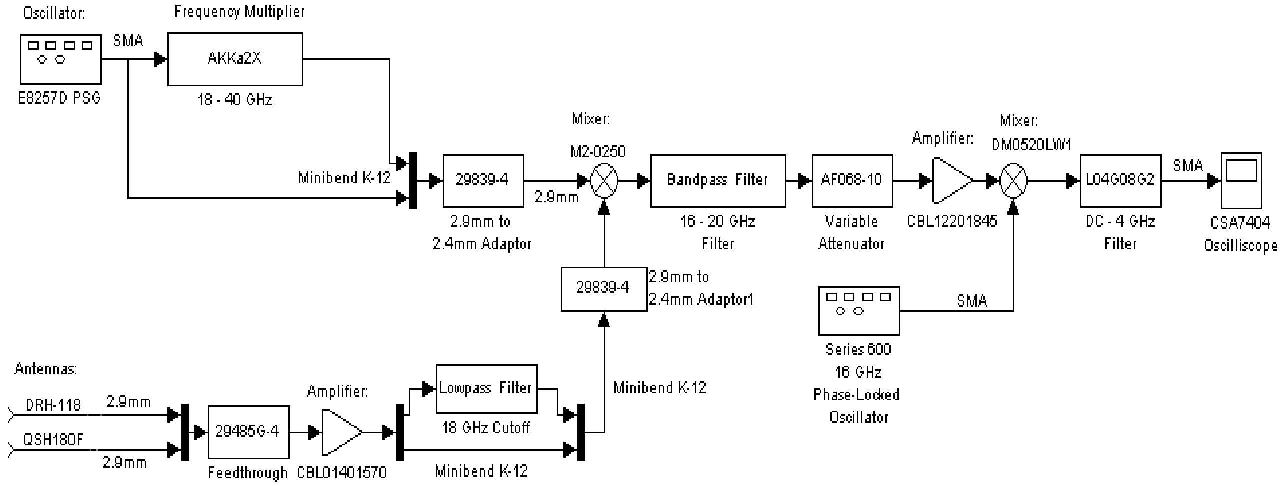

Fig. 2. Displayed is a detailed schematic of the inverse superheterodyne receiver system[7].

3. CALIBRATION AND PRELIMINARY TESTS

3.1 Calibration

The RF emission detection system consists of an array of different electronic components. It is very important to be able to characterize the system for the entire frequency range of interest. Calibration sheets were acquired by the manufacturers for the antenna and preamplifier gain with respect to the measured frequency. However, antenna effective aperture and superheterodyne system response needed to be included in the total system response function.

Antenna theory states that the power measured by the antenna, P_m, is given by the following relation

$$P_m = A_{em} P_r \tag{2}$$

where P_r is the power radiated by the laser-matter interaction event and A_{em} is given by the following relation

$$A_{em} = G(\nu)\frac{\lambda^2}{4\pi} \tag{3}$$

Based on equation (3), high frequencies are equivalent to smaller wavelengths which are in part equivalent to a smaller effective aperture. Thus, for the high frequency measurements, high system attenuation is expected due to small effective aperture of the antenna.

Two RF signal generators were used to account for the inverse superheterodyne system attenuation. The first generator, Anritsu 68047C 1-20GHz, is used as the external oscillator of the receiver. The second generator, Anritsu 68369B 1-40GHz, was employed as a simulated input signal. The system was calibrated for frequencies 1-40GHz and figure 3 displays the compilation of the antenna gain, antenna effective aperture calculations, pre-amplifier gain, cable attenuation and superheterodyne receiver response function. The system is therefore fully characterized and the attenuation graph is used to analyze all the impending raw data.

To calibrate the electric field magnitude measurement capability of the system an LG Vx6000 cell phone was used as a constant output electric field device. The electric field emitted by a cell phone may be calculated using the SAR equation (Specific Absorption Rate). This equation is of standard use for cell phone manufacturers in order to determine the amount of power emitted by the cell phone and therefore absorbed by human skin. The electric field output of the cell phone is related to the SAR according to the following relation

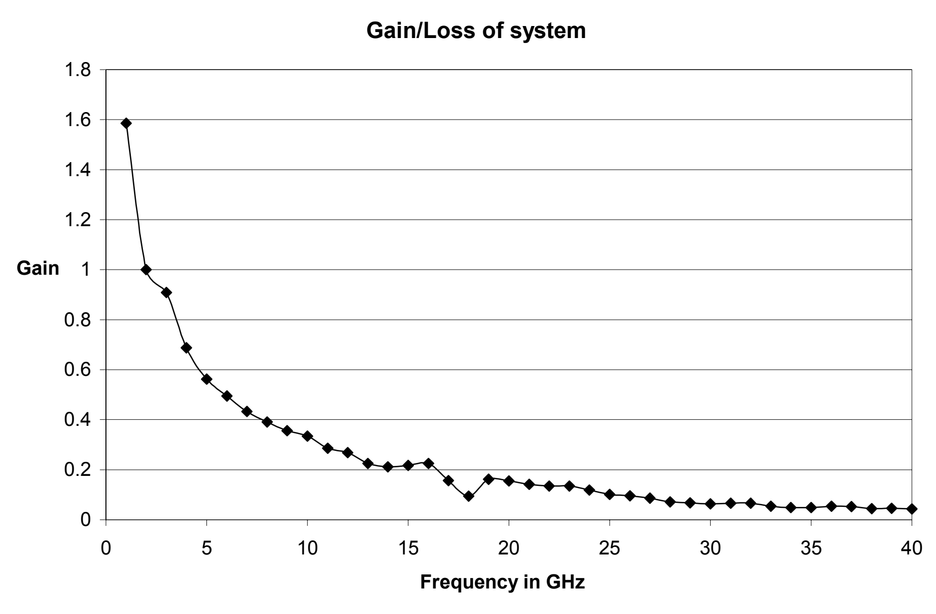

Fig. 3. Displayed is the attenuation of the RF detection system for the frequency range 1-40 GHz. The gain is unitless.

$$E = \left(\frac{\rho}{\sigma} SAR\right)^{1/2} \tag{4}$$

where σ = conductivity of tissue-simulant material, ρ = mass density of the tissue-simulant material and SAR = specific absorption rate. The manufacturer's specifications sheet provides values $\sigma = 1.50\ 1/\Omega m^2$, $\rho = 1 g/cm^3$ and SAR = 1.2 mW/g. Inserting these values into equation 4 results in an electric field magnitude E = 28V/m. The cell phone emitted at a frequency ~ 2GHz and its sinusoidal RF emission wave is displayed in figure 4. The amplitude of this wave (~656mV) corresponds to the electric field emission of this cell phone. Thus, an electric field of 28V/m at 2 GHz corresponds to 656mV of measured signal amplitude on the oscilloscope. This analogy is used to determine the electric field magnitude for further experiments.

3.2 Fast discharge

A rapid high voltage discharge source was designed and built to test the low frequency capabilities of the receiver system. The discharge source is powered by a 10 kV power supply placed in series with a large resistor (1MΩ), which fed a 3300pF doorknob capacitor. The capacitor was then placed in parallel with a spark gap and with a leakage resistor to ensure the safe discharge of the capacitor when the device is not in use. The spark gap is formed by a pair of 8-32 screws whose tips have been ground to form sharp electrode tips. The distance was adjusted to form sparks of different lengths and voltage.

Data was acquired using the inverse superhetereodyne receiver for fast electric discharges of various voltages. All modulation frequencies were tested for the 18GHz bandwidth antenna and the data was analyzed based on previous system calibrations. The duration of the observed electromagnetic pulses was approximately 1ns. Tests were conducted to determine the system's effectiveness in recognizing different discharge voltages. The distance between the electrode tips was varied thus creating discharges with varying voltages. Figure 5 displays data for three discharges, where the discharge voltage was increased by increasing the distance between the two electrodes. There is an observed correlation between the voltage discharge and the electric field strength measured by the system.

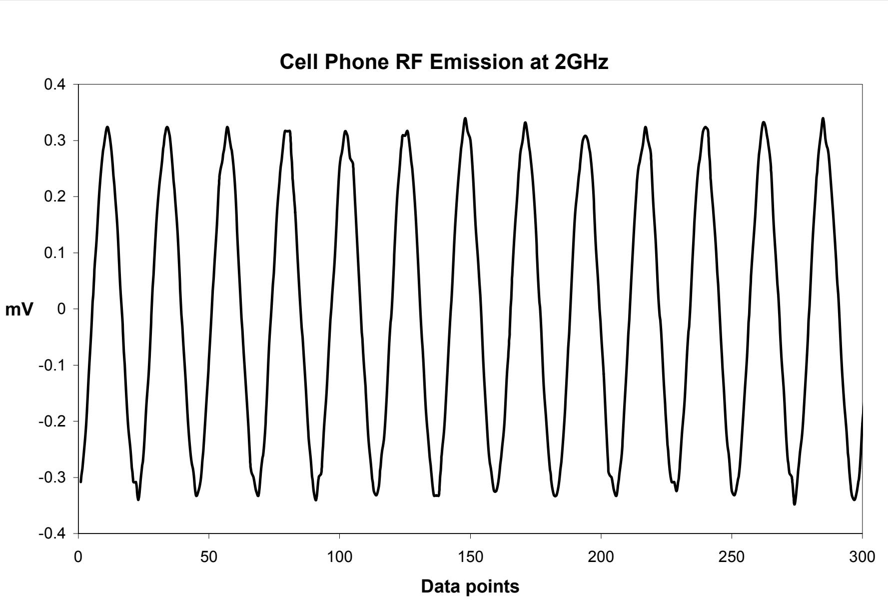

Fig. 4. Displayed is the RF signal emitted by the cell phone at 2 GHz. The 656mV amplitude of the signal corresponds to a 28V/m electric field.

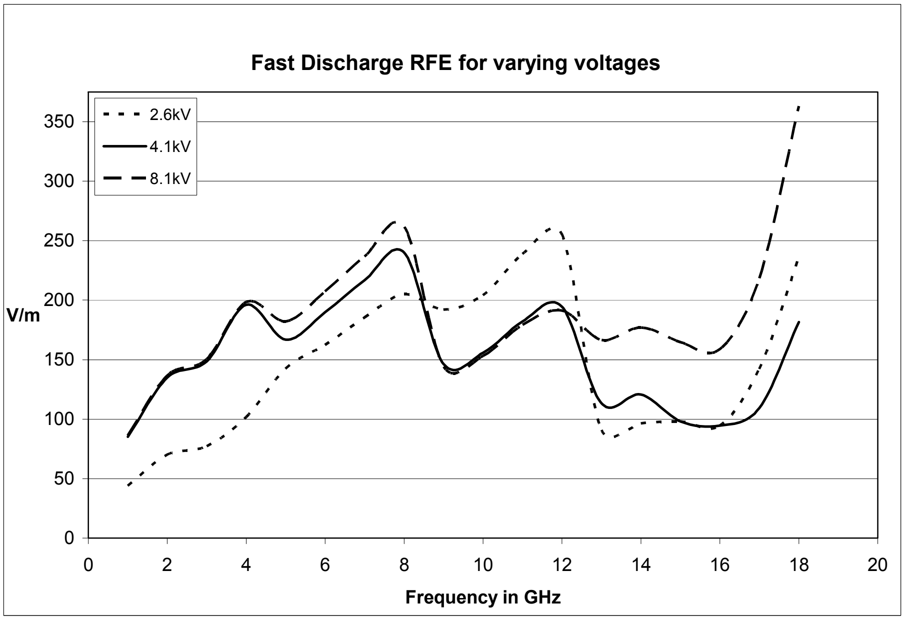

Fig. 5. Displayed are electric fields emitted by the fast discharge source versus frequency. The legend provides the discharge voltages for which data was acquired.

4. RF EMISSION EXPERIMENTS

In initial test experiments the high power femtosecond laser was used to fire onto two types of targets, copper and dielectric. Measurements were completed in the target chamber under vacuum conditions (~10^{-3}Torr). A pulse duration of approximately 100ps was measured for both laser-material interactions. The RF emission of laser-copper interaction was measured for the frequency range 1-40 GHz. Figure 7 displays a comparison between the RF emission magnitude of copper and dielectric material in the frequency range 1-18 GHz. There are distinct features that differentiate the two emissions; it is clear that laser-matter generated RF emission depends on the composition of the target material.

The Poynting vector magnitude equation was used to calculate the conversion efficiency of the laser-copper RF emission. Irradiance is related to electric field according to the following equation

$$I = \frac{c\varepsilon_0}{2} E^2 \tag{5}$$

Inserting known values and E_{max}= 440V/m yields I = 257 W/m^2. The conversion efficiency is given by the ratio of the RF emission output power per area over the input power per area of the laser beam. Assuming a laser intensity of approximately 10^{15} W/cm^2 yields a conversion efficiency ~10^{-9}.

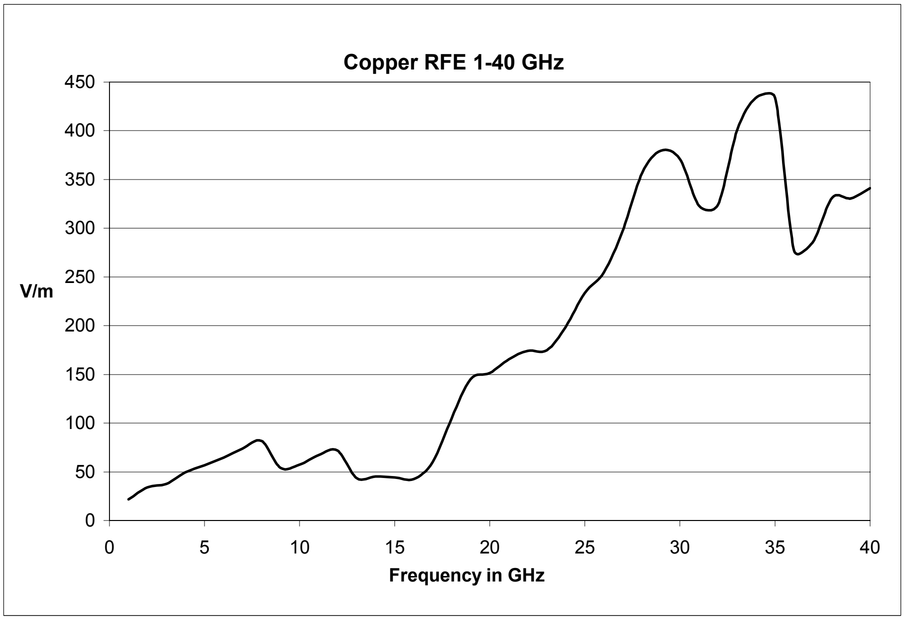

Fig. 6. Displayed is the RF emission of laser-copper interaction. Electric fields in excess of 400V/m were observed for higher frequencies.

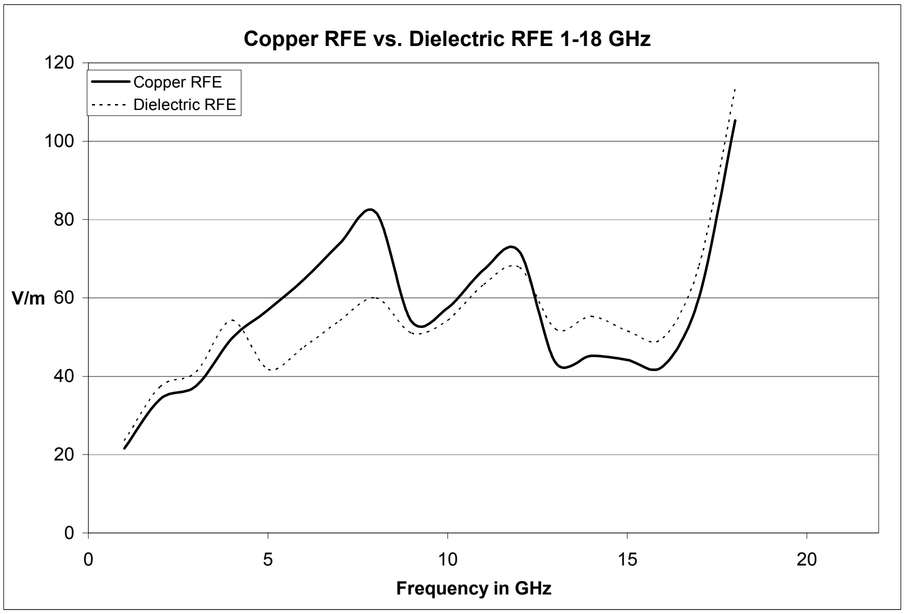

Fig. 7. Displayed is the RF emission of laser-copper versus laser-dielectric interaction. Distinct features between the two emissions are observed.

5. CONCLUSION

We have demonstrated the ability to measure RF emission generated by laser-matter interactions for 1-40GHz. Radio frequency emissions for copper suggest electric fields in excess of 400V/m at 35GHz; nociceptor stimulation requires an electric field of magnitude approximately equal to 10kV/m. Higher frequencies will be investigated by incorporating hybrid RF/Optical receivers This new technology will enable the detection of RF emission above 40GHz and into the THz spectral regions. Moreover, we have measured pulses of 100ps in duration; the electromagnetic pulses in question comprise an event belonging to the femtosecond temporal range. Thus, stronger electric fields are bound to be detected in higher frequency ranges. Strong electric fields generated by laser matter interactions or by laser self-channeling may pave the way for new scientific and medical applications.

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REFERENCES

1. Chung-Chieh Cheng, E. M. Wright, J. V. Moloney, “Generation of Electromagnetic Pulses from Plasma Channels Induced by Femtosecond Light Strings”, Physical Review Letters **87**, 3001, 2001
2. A. Proulx, A. Talebpour, S. Petit, S.L. Chin, “Fast pulsed electric field created from the self-generated filament of a Femtosecond Ti: Sapphire laser pulse in air”, Centre d’Optique, Photonique et Laser (COPL) and Departemente de Physique, Universite Laval, Quebec, Qc, Canada, G1K 7P4. November 5th, 1999.
3. H. Hamster, A. Sullivan, S. Gordon, and R. W. Falcone, “Sub-picosecond, electromagnetic pulses from intense laser-plasma interaction”, Physical Review Letters **71**, pp. 2725-2728, 1993.
4. Mead, M. J. Atomic Weapons Establishment, Aldermaston, Reading, RG7 4PR, United Kingdom. D. Neely, J. Gauoin, and R. Heathcote. CLRC Rutherford Appleton Laboratory, Chiliton, Didcot, OX11 0QX, United Kingdom. P. Patel. Lawrence Livermore National Laboratory, Livermore, California 94550. “Electromagnetic pulse generation within petawatt laser target chamber” October 14, 2004.
5. K. Witte, U. Andiel, K. Eidmann, E. Fill, C. Gahn, J. Meyer-ter-Vehn, G. Pretzler, A. Pukhov, R. Rix, T. Schlegel, and G. Tsakiris. Max-Planck Institut fur Quantenoptik, Hans-Kopfermann-Strabe. I. Golovski, R. Mancini. Department of Physics, University of Nevada, Reno NV 89557-0058, USA. D. Habs. Sektion Physik, LMU Munchen, AM Coulombwall 1, D-85748 Garching. “Hot Superdense Plasmas and Fast-Electron Jets from Intense Femtosecond Laser Pulses”
6. S. Tzortzakis, G. Mechain, G. Patalano, Y. B. Andre, B. Prade, M. Franco, and A. Mysyrowicz, “Coherent subterahertz radiation from Femtosecond infrared filaments in air” , Optics Letters **27**, pp. 1944-1946, 2002.
7. N. Barbieri, “Measurement and characterization of microwave transient electromagnetic fields generated from laser/matter interaction”, Thesis work, College of Optics and Photonics – CREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando, Florida 32826, 2005.