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Development of a Multi-Point Microwave Interferometer

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Introduction and Motivation

A multi-point microwave interferometer (MPMI) is being developed to non-invasively monitor the internal transit of a shock, detonation, or reaction front in energetic media. Current microwave interferometers provide a single-point, continuum measurement [1]. Such continuum measurements are insufficient to understand the complex wave and material interactions affecting the thermal, mechanical, and chemical response of heterogeneous energetic materials. A multi-point microwave interferometer method can be developed by coupling laser and microwave interferometry techniques with terahertz spectroscopic methods.

MPMI Concept

While theoretically, a spatially-resolved interferometer, such as ORVIS [2], can operate at any wavelength, practically this is not true. The longer wavelength of microwaves leads to impractical interferometer dimensions. There are also challenges associated with collimating a microwave beam and recording it at time scales fast enough for shock physics experimentation. A microwave interferometer concept has been developed to overcome these challenges through an electro-optic (EO) crystal.

An EO crystal is essentially a variable waveplate. The degree of phase lag, δ, between the ordinary and extraordinary light rays is a function of the crystal properties (thickness, L, index of refraction, n, and EO coefficient, rij) and the strength of an applied electric field, E [3].

$$\delta = \frac{\pi L n^3 r_{ij} E}{\lambda}$$

In combination with polarizing optics, an EO crystal can then be used to transfer Doppler shifted microwave information to a laser beam without loss of fidelity.

The use of EO crystals has been previous implemented to image RF leakage in circuits [4]. The evanescent field of the microwaves is used to modulate the laser beam's polarization, which is converted into an intensity modulation with polarization optics.

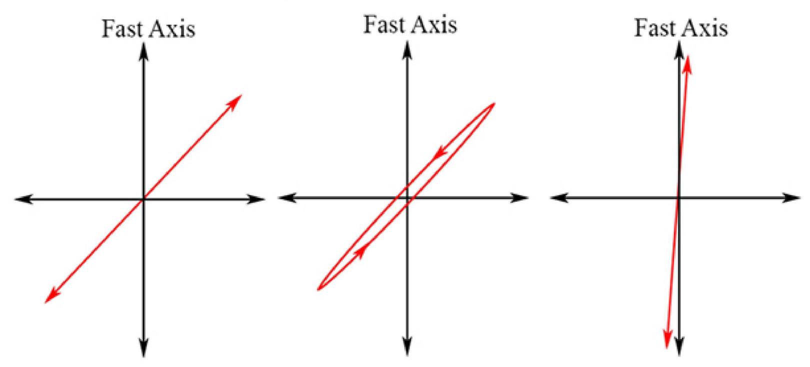

Figure 1. Polarization Changes through the EO Crystal

Initially linearly polarized light is sent into the crystal at an angle to the fast axis. Polarizing optics are used to rotate the beam into S polarized light. When the microwave field is applied the EO crystal generates a phase lag between the S and P polarization components generating an elliptical polarization state. The following polarization optics then returns the beam to a linearly polarized state, but with a slight P polarization component. The magnitude of this P polarization component is directly proportional to the strength of the electric field.

If the speed of the laser beam and microwave beam are traveling at the same speed, this variation in the magnitude of the P polarization component will be at the microwave frequency. The difference in speed of a RF beam and a laser beam through a crystal is termed the group velocity mismatch (GVM) and is a common parameter used in terahertz spectroscopy [5].

Several charts can be found that give the index of refraction for an EO crystal as a function of optical wavelength and terahertz frequency.

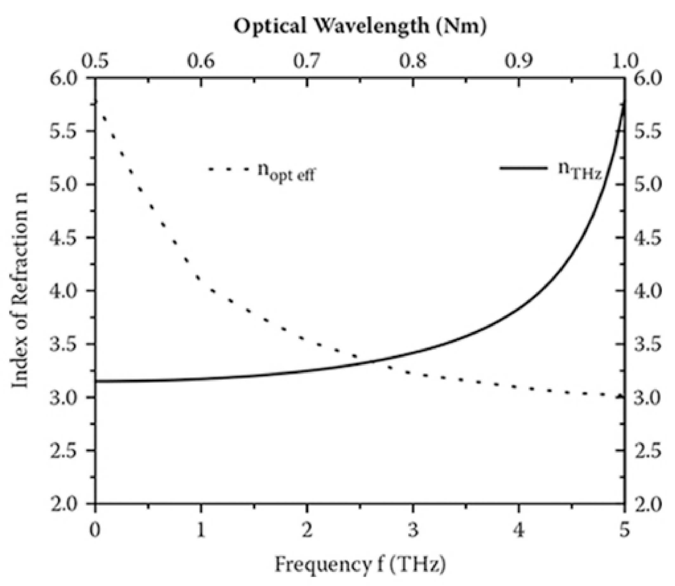

Figure 2. Variation in index of refraction for ZnTe as a function of both optical and terahertz frequencies [5]

Using these fundamental principal, a multipoint microwave interferometer can be developed that is analogous to a typical Photonic Doppler Velocimetry (PDV) system [6].

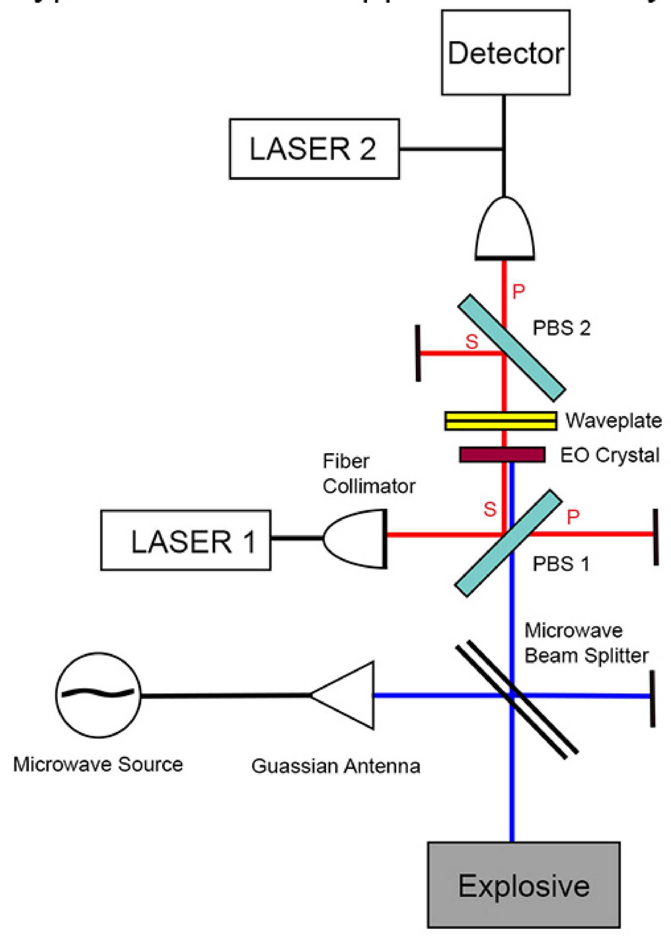

Figure 3. SRMI concept utilizing an EO crystal

Two tunable 1550 nm lasers can set to beat at a frequency slightly below the microwave source (f_{LO}). The first laser is sent through the EO crystal such that its polarization state is modulated at the microwave frequecy (f_{RF}). An amplitude modulated beam is then generated with the polarization optics. This amplitude modulated beam is combined with the second laser and sent to a detector. While many frequencies are present in the signal, only the difference between the beat frequency and the microwave frequency are within the detector's range (f_{RF}-f_{LO}). Any Doppler shift in the microwave frequency will result in a change to the detected frequency. With imaging optics one can then field multiple measurements on experiments similar to multi-point PDV.

Example With Synthetic Data

The MPMI concept can be modeled mathematically. Assume a series of step shocks are generated in a sample.

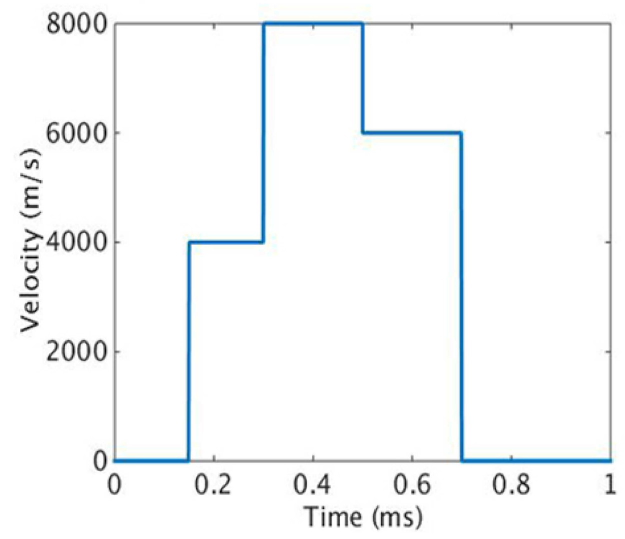

Figure 4. Assumed Velocity profile for a series of shocks

The resulting record generated by the detector can then be modeled. In this example 5% Gaussian noise is assumed to be present in the signal.

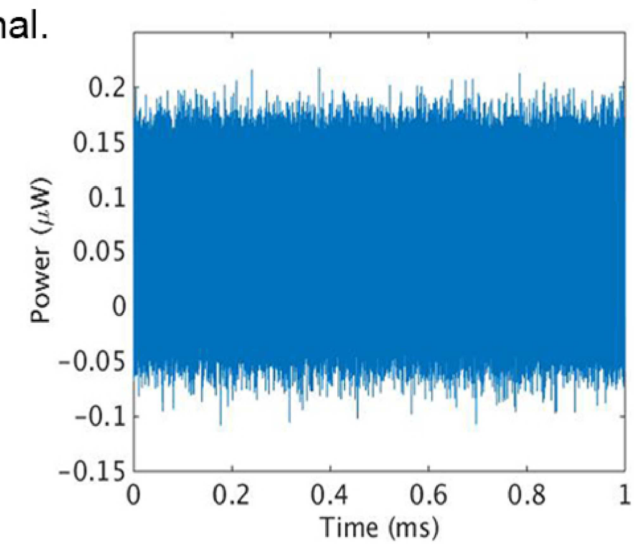

Figure 5. Signal Generated by the MPMI concept

The signal can then be processed with standard FFT methods to give the following frequency spectrogram.

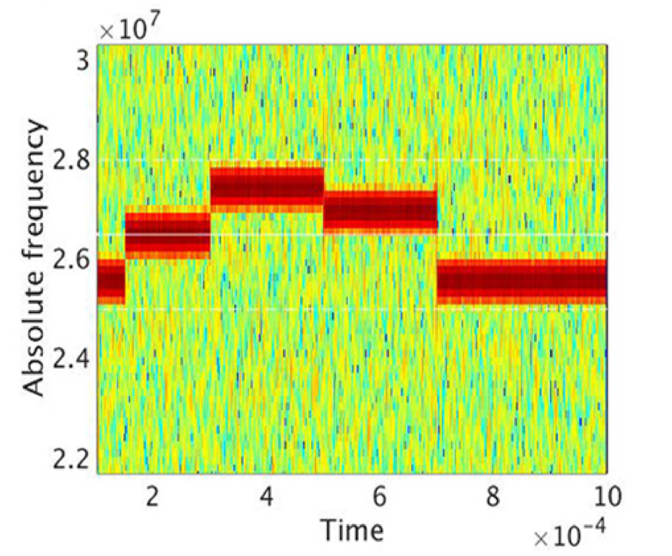

Figure 6. FFT Spectrogram of the MPMI signal

From this a history plot can be generated to reproduce the input velocity.

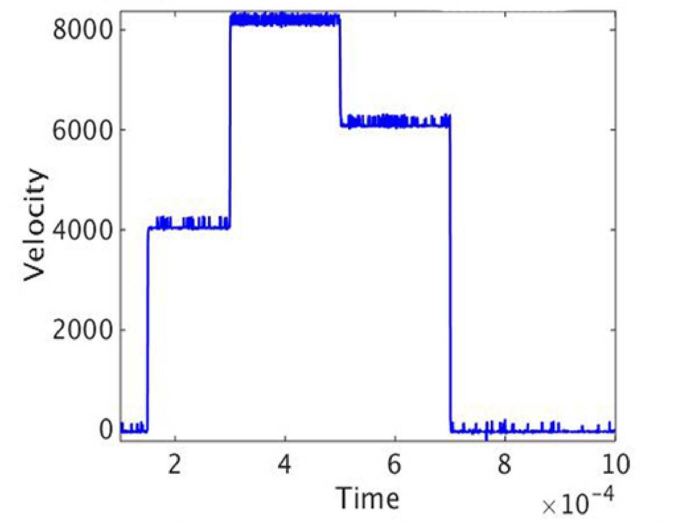

Figure 7. Velocity Recorded from the MPMI

Summary

A multi-point microwave interferometer concept has been presented for the non-invasive, internal measurement of a shock or detonation wave in energetic materials. The design utilizes an EO crystal for transferring the Doppler shifted microwave information to a laser. The overall design concept is analogous to PDV and the expected data can be processed with established FFT methods. Challenges to the design are tied to possible low light return levels and temporal resolution limitations due to the longer wavelength.

References

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