

Dielectric characterization and microwave interferometry in HMX-based explosives

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Abstract. Microwave interferometry is a useful technique for understanding the development and propagation of detonation waves. The velocity of the front can be determined directly with the dielectric constant of the explosive and the instantaneous phase difference of the reflected microwave signal from the detonation front. However, the dielectric constant of HMX-based explosives has been measured only over a small range of wavelengths. Here we employ an open-ended coaxial probe to determine the complex dielectric constant for LX-10 and other HMX-based explosives over the 5-20 GHz range. The propagation of a detonation wave in a lightly-confined cylindrical charge geometry is described where the microwave-reflective properties of the detonation front are characterized with a waveguide. For comparison, piezoelectric pins were used to measure the detonation velocity and indirectly estimate the dielectric constant of LX-10 at 26.5 GHz. Future work in this area will also be discussed.

1. Introduction

Microwave interferometry (MI) can directly measure the velocity of detonation, compaction and deflagration fronts in explosives and porous materials. First demonstrated in the 1950's on detonation waves in explosives [1, 2], the technique has subsequently been refined and expanded to enable velocity measurement in a wide range of materials [3-6]. The spatial resolution of front motion is limited to a fraction of the wavelength of the interrogating signal in the medium, which may be as small as a few mm. While optical techniques such as Photonic Doppler Velocimetry (PDV) and Velocity Interferometer System for Any Reflector (VISAR) offer significantly better spatial resolution from optically-reflective surfaces, MI has the important advantage that it can interrogate moving fronts inside of most explosives and many other insulating materials.

As previously described [3, 4], the front velocity U_s measured by MI can be calculated from the Doppler period T of the return signal and the microwave wavelength, λ_g , inside the interrogated medium:

$$U_s = \frac{\lambda_g}{2T}. \quad (1)$$

The interrogated medium is typically enclosed in a cylindrical waveguide. The reflection of the microwave energy results from a dielectric discontinuity in the medium, which may be a detonation front, for example, or a shock-induced density change. Deflagration fronts or other non-shock related transformations may also be observable as long as the phenomenon under study creates a moving boundary separating regions with different dielectric constants.



The wavelength of the microwaves inside the medium, λ_g , can be estimated by:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_r - (\lambda_0/\lambda_c)^2}}, \quad (2)$$

where λ_0 is the vacuum wavelength of the microwave signal and λ_c is the cutoff wavelength of the signal in the waveguide. ϵ_r is the relative dielectric constant of the medium at the interrogation frequency.

From equations (1) and (2) it may be observed that the calculated front velocity U_s is a function of the relative dielectric constant ϵ_r . However, previous measurements of the dielectric constant of HMX-based explosives have been made at low frequencies, or at discrete higher frequencies such as 8.3 GHz [7]. This dearth of data motivates the investigation of the coaxial probe technique as a method for measuring the dielectric constant of HMX-based explosives over a larger frequency range.

The coaxial probe method for dielectric constant estimation relies on the theory of circular diffraction antennas. This approach employs Maxwell's equations and the variational method for calculating lumped circuit elements [8]. Scattering parameters are determined for a coaxial line terminated by a semi-infinite medium with uniform dielectric constant.

Experimentally, the coaxial probe dielectric measurement is relatively straightforward. Compared to transmission line and resonant cavity dielectric measurement techniques, this approach has the advantage that sample geometry does not need to be rigidly fixed to accommodate the geometry of the sampling apparatus. A specialized coaxial probe termination is connected to a network analyzer; the probe is then brought into contact with the material under test which may be a solid with a planar surface, or a granular solid or a liquid. The system is typically calibrated with a liquid standard such as water or methanol. We employ software from SPEAG (Switzerland) to calculate the frequency-dependent dielectric constant of the material under test based on measured scattering parameters, together with the calibration standard results. We use the SPEAG DAK 1.2 probe which has a nominal frequency measurement range 5-50 GHz [9]. In practice the upper frequency was limited by the network analyzer, an Agilent E8362B, to 20 GHz.

2. Coaxial probe results

Figure 1 shows the coaxial probe termination in contact with a 2.54 cm (1") diameter, 2.54 cm tall explosive pellet. We confirm the validity of the assumption that this sample is effectively semi-infinite for the purpose of the dielectric constant measurements over 5-20 GHz by placing a conductive (metal) base below a 2.54 cm diameter, 2.54 cm tall Teflon pellet. The extracted dielectric constant values were the same with and without the conductive base. Similarly, we used a 5.08 cm diameter Teflon pellet and found that the extracted dielectric constant was comparable in the range 5-20 GHz to the dielectric constant extracted from a 2.54 cm diameter pellet. To measure the dielectric constant of explosive pellets, we use a mechanically-compliant foam base to ensure stable contact between probe and sample without applying excessive force. Measurements were made in air at approximately 23 C, 40% relative humidity.

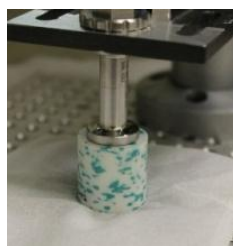


Figure 1. Coaxial probe measurement of an LX-10 explosive pellet.

The DAK 1.2 probe system calibration is similar to a one port, port extension vector network analyzer (VNA) calibration. It is performed with three standards: open, short and load. After the calibration the reference plane of the S11 scattering parameter measurement is the flat flange of the probe. Deionized water is used as the load since its complex dielectric constant is well known as a function of frequency and temperature [10]. The S11 values of the load are calculated by the SPEAG software; calibration coefficients are then calculated for each frequency point and stored. Finally, these coefficients are applied to subsequent measurements so that the corrected S11 values are used to calculate the complex dielectric properties of the unknown material under test.

Because of the large dielectric mismatch between water and the explosives in the frequency range 5-20 GHz, results obtained for explosives were further normalized to the ratio of the known to measured ϵ_r value for Teflon, $2.1/1.5 = 1.4$. Measured ϵ_r values for Teflon and explosives were somewhat constant in the frequency range 5-20 GHz, generally decreasing 10-20% over the measurement range. Calculated ϵ_r at 10 GHz are shown in table 1 for three HMX-based explosives, LX-04, LX-14, and LX-10. Pressed ultra-fine TATB (no binder) is also shown as a reference. Calculated ϵ_r for explosives at 100% theoretical maximum density (TMD) were determined using the Maxwell-Garnett mixing formula,

$$\epsilon_{eff} = \epsilon_r + 3f\epsilon_r \frac{\epsilon_i - \epsilon_r}{\epsilon_i - 2\epsilon_r + f(\epsilon_i - \epsilon_r)} \quad (3)$$

where ϵ_{eff} is the effective (measured) dielectric constant, ϵ_i is the inclusion's dielectric constant (here, air, $\epsilon_i = 1$), and f is the volume fraction of the inclusion [11].

Table 1. Calculated relative dielectric constant ϵ_r at 10 GHz.

Explosive	Binder, fraction (wt%)	Density (%TMD)	ϵ_r at 10 GHz for 100% TMD, Teflon normalized
LX-04 (HMX)	Viton A, 15	95.6	3.8
LX-14 (HMX)	Estane-5702, 4.5	95.9	4.1
LX-10 (HMX)	Viton A, 5	98.2	3.9
UF TATB	N/A	92.9	4.6

The extracted ϵ_r values for the HMX-based explosives are close to 4.1, previously estimated for HMX at 100% TMD and 8.3 GHz [7]. The extracted ϵ_r values for UF-TATB is close to 4.5, previously estimated for TATB at 100% TMD and 10 GHz [12]. For the HMX-based explosives the dielectric constant of the binder itself should be taken into account in the future when uncertainties associated with the coaxial probe dielectric measurement technique for explosives can be reduced.

3. Dynamic measurement results

Given the dependence of the MI-measured velocity on the dielectric constant of the material under test (equations (1) and (2)), the effective dielectric constant may be calculated from the front velocity if this velocity can be independently measured. Figure 2 shows the experimental geometry used for this type of characterization [13].

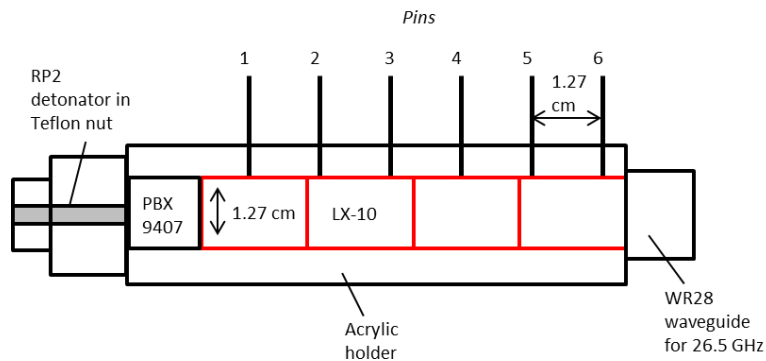


Figure 2. Geometry for dynamic estimation of LX-10 permittivity at 26.5 GHz.

In the experiment shown in figure 2, an acrylic tube is filled with four 1.27 cm diameter pellets of LX-10 pressed to 1.862 g/cc, or 98% theoretical maximum density (TMD). Each pellet is 1.91 cm long. The explosive is interrogated by a 26.5 GHz signal, corresponding to a free-space wavelength of 1.13 cm. The explosive is instrumented with 6 piezoelectric pins to provide an independent estimate of the detonation velocity. The detonation velocity measured by the pins is 0.887 ± 0.0014 cm/ μ s.

MI data from the side of the charge remote from the detonator is shown in figure 3. The data was analyzed by multiplying the return signal by a simultaneously-obtained reference signal, then low-pass filtering the product with a 5 MHz pass band and 10 MHz stop band. An oscillating pattern between ~ 7 and 17 μ s contains the information relevant to detonation velocity.

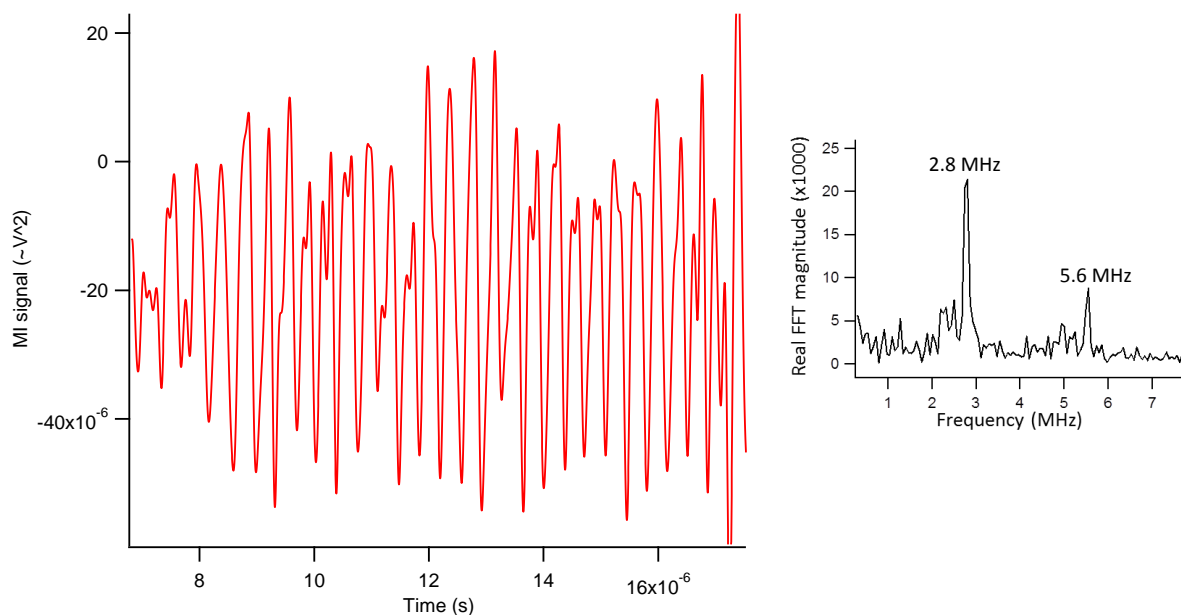


Figure 3. (a) MI signal extracted from 26.5 GHz interrogation of the LX-10 experiment shown in figure 2. 28 Doppler cycles are observed over 10 μ s. (b) FFT of data in (a) showing primary peak at 2.8 MHz with harmonic at 5.6 MHz.

With a known detonation velocity from the shorting pins, the effective dielectric of LX-10 at 26.5 GHz can be calculated from equations (1) and (2). From data shown in figure 3(a), $T = 10 \mu$ s/28 cycles = 0.357 μ s/cycle. This period corresponds to a Fourier transform frequency of 2.80 GHz, which matches the 2.8 GHz peak found in the actual FFT of the data (figure 3(b)). The pin-measured velocity

of 0.887 cm/ μ s then implies $\epsilon_r = 3.5$ at 26.5 GHz. This value is somewhat lower than the 3.9 value obtained by the coaxial probe technique for LX-10 at 10 GHz, and lower also than the 4.1 value at 8.3 GHz previously determined for 100% TMD HMX with a waveguide scheme [7].

4. Summary and future work

MI is an effective method for characterizing detonation velocity and the velocity of other propagating fronts in explosives. The independent estimation of front velocity by MI, however, requires the characterization of the dielectric constant of the explosive or propagating medium. Preliminary measurements on the HMX-based explosives LX-04, LX-10 and LX-14, as well as TATB, indicate that the coaxial probe technique may be useful for routine dielectric characterization of these materials at frequencies up to 20 GHz. Alternately, the dielectric constant may be estimated by making an independent measure of the front velocity, as was demonstrated in this work for a 1.27 cm diameter cylinder of LX-10 at 26.5 GHz. The permittivity of all HMX-based explosives measured in this work by coaxial probe, or calculated from the front velocity, are in the range 3.5-4.4, comparable to the value of 4.1 which has been previously measured for neat HMX at 8.3 GHz. In the future we will use the coaxial probe method to measure the dielectric constant of explosives over an extended range of densities and samples for frequencies up to 50 GHz. We will use MI to examine a variety of deflagration, shock-related, and detonation phenomena in explosives and reactive materials.

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