



**HIGH POWER MICROWAVE OPERATIONAL EXPOSURE DETECTION
USING THERMOACOUSTIC WAVE GENERATION IN LOSSY DIELECTRIC
POLYMERS**

DISSERTATION

James J. Frey, Major, USA

AFIT-ENP-DS-22-S-043

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

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Major, USA

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Abstract

A feasibility analysis for the use of microwave-induced thermoacoustic (TA) wave generation in lossy dielectric media to detect pulsed high power microwave directed energy weapons in force health protection applications was conducted based on a series of empirical and computational investigations. A potential target volume material, carbon-loaded polytetrafluoroethylene, was identified for further study based on anticipated complex dielectric properties, with laboratory measurements of select electromagnetic (EM), thermal, and elastic material properties of relevance to the TA effect conducted to determine parameter values. A planar geometry TA-based signal chain model using thin film piezoelectric sensors was developed for both finite element method based numerical simulation and in-beam response testing, with TA signal output evaluated in the time and frequency domain using both approaches. Based on empirically-derived complex permittivity values, a single-term Cole-Cole dielectric relaxation model approximation was developed over the 2-110 GHz microwave frequency region to permit a more general evaluation of EM coupling efficiency of the material. Modeling and simulation of the idealized signal chain allowed the analysis of TA waveform dependency on microwave beam parameters not otherwise accessible during in-beam response testing. High frequency TA signal data was suitably fit to a pulse width sensitivity impulse response function model for the target geometry and found to be in good agreement for personnel exposure applications.

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HIGH POWER MICROWAVE OPERATIONAL EXPOSURE DETECTION USING THERMOACOUSTIC WAVE GENERATION IN LOSSY DIELECTRIC POLYMERS

I. Introduction

1.1 General Issue

Continued advancement in the directed energy weapon (DEW) design space, both within the DOD and the commercial sector, has resulted in increased interest in protection of Air Force personnel from DEW effects across all potential wavelengths. The use of high power microwave (HPM) DEWs in the 1-3 GHz range is an area of particularly active development, as HPM radiation offers reduced atmospheric attenuation when compared to high energy laser (HEL) DEWs and can be employed for non-lethal, reversible counter-materiel effects of interest in select force protection applications where incidental but still potentially harmful personnel exposure is possible. DEW detection is a critical first step in implementing personnel exposure protection systems, providing timely warning of ongoing irradiation so that additional electromagnetic frequency (EMF) shielding provided by structures or vehicles can be leveraged to prevent acute adverse health effects. Commercial EMF field meters or personal monitors could be used to provide such notice but may not be available in the appropriate frequency or power response ranges, and are currently not widely available in U.S. military operational units. For hazard warning applications, select thermal interaction techniques such as microwave absorption thermography and

thermoacoustic (TA) imaging, both currently in use in the research and development community as noninvasive analysis techniques, apply the underlying physics of interest in this research and may be suitably adapted to provide notice of EMF exposure at operationally relevant HPM frequencies and incident power densities (Zhang et al. 2017). While imaging thermography can provide an accurate mechanism to gauge microwave absorption in target materials, under field conditions it is significantly impacted by ambient environmental conditions and may require significant energy deposition before a reliable measurement can be made. As field-deployable HPM DEW systems will likely operate in the pulsed mode to maximize incident EMF power on target, thermoacoustic (TA) wave generation in a lossy dielectric material offers a potentially novel interaction mechanism to determine energy and power deposition across a wide frequency range without the need to measure ambient field intensity values.

1.2 Problem Statement

While the use of microwave-induced TA wave propagation in EMF bioeffects and clinical diagnostic applications has been studied by several researchers for decades, only limited study of this mechanism as a free-field EMF characterization tool has been conducted (Lin and Wang 2007). Previous published work by the 711th Human Performance Wing (HPW) and its predecessor organizations established a framework for use of microwave absorption in carbon-filled polytetrafluorethylene (PTFE) in RF dosimetry

applications, but focused on a very specific operating frequency (Allen and Ross 2007). Significant gaps exist in the literature on the complex permittivity of this and similar materials across the frequency range of military operational interest. The thermoacoustic response of PTFE as the microwave beam duty factor becomes increasingly small, and how to optimize the collection of this vibrational signal, remains undetermined.

1.3 Research Objectives

The objective of this research was to determine the feasibility of a thermoacoustic-based HPM personnel exposure detection system. This process consisted of evaluating thermoacoustic response of select carbon materials to pulsed HPM exposure characteristic of DEWs, determining favorable characteristic dimension and material properties to optimize the sensitivity of a TA HPM detection system, and assessing the ability to collect relevant force health protection data that can be extracted from a TA HPM detection system to minimize adverse health effects.

1.4 Research Hypothesis

1. TA waves generated in carbon-filled PTFE when subject to pulsed microwave fields can be detected using commercial piezoelectric sensors.
2. Microwave-induced TA signals can be analyzed under laboratory conditions to extract incident exposure data.

1.5 Research Plan

The electromagnetic properties of bulk PTFE samples were characterized using focused beam S-parameter analysis to gain insight into frequency-dependent complex permittivity as a function of carbon fill in order to support the selection of microwave exposure beam parameters. Concurrent finite element method (FEM) computational modeling of specific absorption processes complemented the material characterization. Then the relevant physical properties of the samples were assessed using a variety of mechanical and thermal property evaluation systems to determine what effect, if any, the volume fraction of the carbon fill in the bulk sample matrix has on these parameters. Following preliminary frequency response testing, select commercially-procured piezoelectric sensors were electrically coupled to signal conditioning equipment and the resonant acoustic frequency of the combined piezo-detector chain obtained. Samples were exposed to select pulsed microwave radiation in the ranges of 2-110 GHz using sources at the AFRL Materials and Manufacturing Directorate Composites Branch (AFRL/RXCC, Wright Patterson Air Force Base, OH) and 711th Human Performance Wing (HPW) Radio Frequency Radiation Branch (AFRL/RHDR, Fort Sam Houston, TX), and the resulting TA signal was measured by the piezoelectric sensor as a function of microwave beam parameters. The TA signals were analyzed in both the time and frequency domain to determine empirical relationships between signal amplitude and frequency components and the incident microwave exposure properties.

1.6 Sponsorship

The research contained in this document is sponsored and funded by the 711th HPW Airman Biosciences Division, Air Force Research Laboratory (AFRL/RHB) and provides a record of the work accomplished in support of their DEW force health protection (FHP) mission area.

II. Theoretical Background

This chapter details the theoretical background of the relevant physical processes that comprise the proposed TA-based HPM detection chain, highlighting key references from the literature informing target selection decisions based on electromagnetic (EM), mechanical and thermal properties influencing TA behavior. It begins with a summary of the principles of EM wave propagation, both in free space and in lossy dielectric material, providing context for a discussion of key biological effects observed in human tissue when exposed to EMF radiation in the microwave regime. Next, a brief review of the microwave hearing effect is presented, as it provides context for analytical approaches to a phenomenon of which pulsed HPM TA generation is the root cause. Lastly, design considerations for HPM TA-based applications are examined, with a focus on the extraction of measurable quantities of interest from the resultant TA acoustic signals.

2.1 Microwave Propagation and Material Interface Interactions

The propagation of EMF radiation in the microwave regime in a source-less medium is governed by Maxwell's Equations, which in differential form are given as

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.1)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \quad (2.2)$$

$$\nabla \cdot \mathbf{E} = 0 \quad (2.3)$$

$$\nabla \cdot \mathbf{H} = 0, \quad (2.4)$$

where $\mathbf{E}$ (V m⁻¹) and $\mathbf{H}$ (A m⁻¹) are the electric and magnetic field densities, respectively, while $\mathbf{D}$ (C m⁻²) and $\mathbf{B}$ (T) refer to the electric displacement and magnetic flux density fields (Elsherbeni and Demir 2016). Combining the constitutive equations for the case of source-less media

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (2.5)$$

$$\mathbf{B} = \mu \mathbf{H}, \quad (2.6)$$

with eqns (2.1) and (2.2), taking the curl of both, and substituting in eqns (2.3) and (2.4) results in characteristic wave equations for both the electric and magnetic fields, where ε (F m⁻¹) refers to the material's permittivity and μ (H m⁻¹) to its permeability (Benford et al. 2016).

$$\nabla^2 \mathbf{E} - \varepsilon \mu \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \quad (2.7)$$

$$\nabla^2 \mathbf{H} - \varepsilon \mu \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \quad (2.8)$$

From eqn (2.2), the direction of oscillation of the $\mathbf{H}$ field will be orthogonal to that of the $\mathbf{E}$ field for a given propagation direction, but in the far field, the distance equivalence of many wavelengths from any material interface boundaries, their magnitudes are related via the expression

$$\mathbf{H} = \frac{1}{\sqrt{\frac{\mu}{\varepsilon}}} \mathbf{E} = \frac{1}{\eta} \mathbf{E}, \quad (2.9)$$

where η (Ω) is the characteristic impedance of the material (NCRP 1981). The value of $\eta \approx 377 \Omega$ for free space.

Focusing on the electric field, one solution to eqn (2.7) applicable to $\mathbf{E}$ in a spatially homogenous lossless medium in the far field is

$$\mathbf{E} = E e^{i(\omega t - k_x x)} \hat{z} = E e^{i\left(2\pi f t - \frac{2\pi}{\lambda} x\right)} \hat{z}, \quad (2.10)$$

where $\mathbf{E}$ is polarized in the z direction and propagating in the x direction, with an amplitude E (V m^{-1}), angular frequency ω (radian s^{-1}), frequency f (Hz), wavenumber k_x (m^{-1}) and wavelength λ (m) (Benford et al. 2016). This solution represents a continuous wave solution in the frequency domain, but through an appropriate linear combination of such solutions at varying values of ω_i any arbitrary modulation in the time domain can be constructed. The magnitude and direction of the total power carried in the traveling wave is represented by the complex Poynting vector

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}, \quad (2.11)$$

which is of less practical application in radiation protection than the modulus of its conjugate

$$S = |\mathbf{E} \times \mathbf{H}^*| = \frac{E^2}{\eta} = \eta H^2, \quad (2.12)$$

where S (W m^{-2}) is the instantaneous power density in the direction of propagation (International Commission on Non-Ionizing Radiation Protection 2020).

At the interface between two materials of differing electromagnetic properties, boundary conditions apply which restrict possible discontinuities in the electric field components such that

$$E_{\parallel 1} = E_{\parallel 2} \quad (2.13)$$

and

$$\varepsilon_1 E_{\perp 1} = \varepsilon_2 E_{\perp 2}, \quad (2.14)$$

where the parallel and perpendicular notation refers to the field component relative to the interface between materials 1 and 2 (Polk and Postow 1986).

Applying these conditions for the case of eqn (2.10) incident normal to the boundary between two lossless media, the magnitude of the electric field components parallel to and at some infinitesimal distance on either side of the interface are zero and the ratio of the transmitted to reflected electromagnetic wave τ_E is

$$\tau_E = \frac{E_{tr}}{E_i} = \frac{2\eta_2}{\eta_2 + \eta_1}, \quad (2.15)$$

such that the transmission coefficient $\tau_E = 1$ for perfectly matched impedances (NCRP 1981). Similarly, the reflection coefficient is

$$\Gamma_E = \frac{E_r}{E_i} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}, \quad (2.16)$$

and can range in value such that $\Gamma_E \in [-1,1]$, indicating that for an EM wave propagating in vacuum or air and incident on some material, much of the wave amplitude will be reflected as in general either $\eta_1 > \eta_2$ or $\eta_1 \gg \eta_2$. Conservation of energy requires that incident, transmitted, and reflected power densities, S_i , S_{tr} , and S_r , respectively, follow the relationship

$$1 = \frac{S_{tr}}{S_i} + \frac{S_r}{S_i}, \quad (2.17)$$

although absorption losses, as will be discussed in the following section, will reduce the measured power density ratio below unity.

Although a detailed discussion of antenna performance is beyond the scope of this research, a brief introduction to this topic provides context for experimental design considerations presented in Chapter 3. As is the case for any isotropically emitted radiation, geometric attenuation reduces power density incident on a target at range according to the inverse square law

$$S_{inc} = \frac{P_{rad}}{4\pi R^2}, \quad (2.18)$$

where P_{rad} (W) is the radiated power and R (m) is the distance between emitter and receiver. Eqn (2.18) applies in the far field region, a term used previously in this text but defined here for the case of physical antenna systems as the distance from an emitter such that the time averaged Poynting vector $\mathbf{S}_{avg}$ is real-valued and a plane wave approximation for the emitted field is valid. This distance is conventionally defined as

$$L_{ff} = \frac{2D_{ant}^2}{\lambda}, \quad (2.19)$$

where D_{ant} (m) is the characteristic dimension of the antenna (Benford et al. 2016). The gain G of a given antenna represents the extent to which power is preferentially radiated in a given direction and is related to the effective aperture size of the antenna A_{eff} via

$$G = \frac{4\pi A_{eff}}{\lambda^2}, \quad (2.20)$$

and is often given in dB where G (dB) = $10 \cdot \log_{10}(G)$ (NCRP 1981).

2.2 Absorption in Lossy Dielectrics

The discussion in section 2.1 of lossless EM wave propagation presumes real valued and frequency-independent permittivity, while for most dielectric materials of interest in radiation protection this parameter is both complex and dispersive. Focusing on this consideration, the relative complex permittivity is defined as

$$\varepsilon^* = \varepsilon_0 \varepsilon' - i \varepsilon_0 \varepsilon'', \quad (2.21)$$

and although a similar decomposition would strictly apply to relative permeability μ_r , for the non-magnetic dielectric materials addressed in this document, μ_r is always close to unity with a negligible loss term. The imaginary relative permittivity for a low-loss material is related to the dielectric conductivity σ_{cond} ($\Omega^{-1} \cdot m^{-1}$) of the material by

$$\sigma_{cond, ll} = \omega \varepsilon_0 \varepsilon'', \quad (2.22)$$

indicating a likely decrease with increasing frequency as long as conductivity is either constant or slowly varying (Polk and Postow 1986). The loss tangent, defined as

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'}, \quad (2.23)$$

provides a useful quantitative metric of the extent to which EMF radiation is absorbed in a material as heat relative to the idealized case of propagation in free space, with a threshold of $\tan \delta \geq 0.15$ providing a rule-of-thumb dividing line between low-loss and lossy dielectrics (Chao and Chang 2018). Of particular significance to both microwave bioeffects and this research is the effective permittivity of one material given a small volume fraction inclusion of a second. One such model of this phenomenon is the Maxwell Garnett Mixing Formula, given as

$$\varepsilon_{MG} = \frac{1+2f_v \frac{\varepsilon_i - \varepsilon_h}{\varepsilon_i + 2\varepsilon_h}}{1-f_v \frac{\varepsilon_i - \varepsilon_h}{\varepsilon_i + 2\varepsilon_h}}, \quad (2.24)$$

for inclusion material i , host matrix material h , and volume fraction f_v , although more complex and mixture-specific models exist (Markel 2016).

Applying a complex permittivity to the microwave free field by substituting eqn (2.21) into eqn (2.7) results in a modification of the plane wave solution, with complex propagation constant

$$\gamma = i\omega \left[\mu\varepsilon_0 \left(\varepsilon' - i \frac{\sigma_{cond, ll}}{\omega\varepsilon_0} \right) \right]^{\frac{1}{2}}, \quad (2.25)$$

replacing the real valued wave number k . The plane wave solution of eqn (2.10) gains an exponential decay coefficient such that

$$\mathbf{E} = E \left(e^{-\frac{x}{\delta_{skin}}} \right) e^{i(\omega t - \omega \sqrt{\mu \epsilon_0 \epsilon'} x)} \hat{z}, \quad (2.26)$$

where E refers to the electric field magnitude just inside the material interface boundary (NCRP 1981). The skin depth, δ_{skin} (m), is described in more detail in section 4.1.2, but the net effect of this exponential depth-decay profile is that near the interface, the mass density of EMF power absorbed in the material or the Specific Absorption Rate (SAR , $W \text{ kg}^{-1}$) becomes a large fraction of total dissipated power for high-loss materials or for large values of frequency f . Biological tissue and the carbon-filled polymers of interest to this study are dispersive, so in general both the real and imaginary components of the complex permittivity decrease with increasing frequency.

2.3 HPM Bioeffects and Force Health Protection

Although other causative mechanisms for adverse health effects, such as contact currents or direct electrostimulation, exist for EMF exposure at frequencies below ~100s MHz, in the 1 - 300 GHz regime of interest in this study the induced temperature rise resulting from dissipated EMF power is the primary bioeffect of concern. The time-dependent temperature T (K) change in tissue as a response to incident microwave radiation is modeled by the Pennes' bioheat transfer equation (BHTE), a modified form of the heat diffusion partial differential equation, and defined as

$$k_{th} \nabla^2 T - \rho^2 c_p m_b T + \rho SAR = c_p \rho \frac{\partial T}{\partial t}, \quad (2.27)$$

where k_{th} [W (m·K)⁻¹] is the thermal conductivity, c_p [J (kg K)⁻¹] is the specific heat capacity and m_b [m³ (kg·s)⁻¹] is the blood perfusion rate (Foster and Glaser 2007). The BHTE can be rewritten in terms of the peak electric field magnitude and dielectric conductivity σ_{cond} such that

$$k_{th} \nabla^2 T - \rho^2 c_p m_b T + \frac{\sigma}{2} E^2 \left(e^{-\frac{2x}{\delta_{skin}}} \right) = c_p \rho \frac{\partial T}{\partial t}, \quad (2.28)$$

showing more clearly the heat source term dependence on frequency-related parameters of E just inside the tissue interface. Since microwave energy deposition occurs on a timescale of the speed of light in the material, at early times or for pulsed microwaves of sufficiently short pulse length heat is absorbed in tissue much more quickly than can be diffused or removed through the blood perfusion term. In the limit of small values of t , the change in temperature with time reduces to

$$\frac{\partial T}{\partial t} \approx \frac{SAR}{C_p}, \quad (2.29)$$

while at long timescales and ignoring broader thermoregulatory mechanisms the biological system asymptotically reaches a steady state equilibrium temperature distribution (Foster and Glaser 2007)

$$T_{ss} \approx \frac{SAR}{\rho m_b C_p}. \quad (2.30)$$

The nominal mean body core temperature is 37 °C, with some variation across the population, resulting in broadly applicable occupational health consensus guidance available to keep variations in this mean temperature within 1 °C of its mean value (International Commission on Non-Ionizing Radiation Protection 2020). In addition to conductive, convective, and radiative heat transfer mechanisms characteristic of all heat sources, the human body also leverages vasomotor control of the circulatory system and evaporative cooling through sweating as mechanisms to shed excess heat to the environment in order to autonomically maintain this temperature range in response to thermal stressors (Polk and Postow 1986). The extent to which tissue heat deposition from an incident EM field can exceed the capacity of these thermoregulatory channels depends on the resultant *SAR* distribution, itself a function of both free-field power density as measured just before the tissue interface and the frequency of the EMF radiation. Because of the associated permittivity values for the layered components of an idealized slab of human tissue, only frequencies below ≈ 6 GHz have power penetration depths sufficiently large to result in appreciable deposition below the various cutaneous layers. In the case of highly localized *SAR* distributions, whether caused by exposure to non-uniform EMF fields or due to enhancement of the induced field by resonant physiological structures, local temperature increases can well exceed that observed in the body core. A consensus guidance threshold, well supported by the literature, identifies a threshold of 41 °C above which local thermal injury may manifest (International Commission on Non-Ionizing Radiation Protection 2020).

The shallow penetration heating of skin as the result of mm-wavelength radiation represents the logical extension of the above discussion, and for the case of $f = 94$ GHz, has been comparatively well-studied, as this serves as the operating frequency of the non-lethal counter-personnel Active Denial weapon system whose development started under the U.S. Air Force and has continued by the U.S. Army. At frequencies > 30 GHz, the computed transmission coefficient for dry skin exceeds 0.5 and power penetration depth is sub-mm, indicating only superficial dermal heating well-coupled to the incident EM field (Foster et al. 2016). Human subjects research studying bioeffects at 94 GHz have generally focused on narrow beam, short duration exposures, documenting over an order of magnitude difference in power density perception threshold as compared to 2.45 GHz for the same estimated skin temperature increase (Foster and Glaser 2007). Solutions to a 1-D BHTE model of a single layer tissue slab indicate that the maximum temperature rise occurs either at or very near the interfacial surface, with the maximum change in temperature at higher frequencies differing $\sim 1\%$ even for relatively large values in the magnitude of the heat transfer coefficient used in the convective boundary condition (Gajda et al. 2019). The cornea presents a particularly sensitive receptor at these wavelengths due to the potential for constructive interference in the periorbital structures, with nonhuman primate data indicating a threshold for thermal lesion formation at peak temperatures $T_{peak} > 21$ °C; recent numerical simulations indicate a minimum short duration energy density of 21 kJ m^{-2} correlated with this threshold (Foster et al. 2021).

The above discussions of field-dependent tissue thermal effects drive the formulation of current EMF exposure guidance, promulgated primarily by the Institute of Electrical and Electronics Engineers (IEEE) in the U.S. through its C.95.1 consensus standard. For context, the 2005 version of this standard is incorporated by reference in Department of Defense Instruction (DoDI) 6055.11 (Protecting Personnel from EM Fields) and forms the basis for the Services' RF exposure limits (US Department of Defense 2018). Starting from the 1 °C core body temperature rise mentioned previously, an associated $SAR_{1^\circ C} = 4 \text{ W kg}^{-1}$ averaged over a 30 minute period is identified as a basic acute effects threshold, with reference limits (DRLs) established at fractional limits of this value at an occupational and general public level to ensure it is not exceeded (Institute of Electrical and Electronics Engineers 2019). As in-situ *SAR* measurements are generally not practical for radiation protection purposes, exposure reference levels (ERLs) provide approximate solutions to the free-field incident plane wave EMF power density required to generate the reference *SAR* distribution in tissue or RF phantom, examples of which are shown in Table 2.1.

Table 2.1. Exposure reference levels for local (partial body) microwave exposure in general public (unrestricted) and occupational (restricted) settings, for frequency f of 0.4 to 300 GHz and averaging time of 6 min. Above 2 GHz, whole body ERLs are $\frac{1}{4}$ of the local-exposure value. Adapted from (Institute of Electrical and Electronics Engineers 2019).

f (GHz)	Unrestricted Environment ERL (W m^{-2})	Restricted Environment ERL (W m^{-2})
0.4-2	$29.14 \cdot f^{0.463}$	$145.23 \cdot f^{0.463}$
2-6	40	200
6-300	$55 \cdot f^{-0.177}$	$274.8 \cdot f^{-0.177}$

At $SAR_{1^\circ C}$, the power density $S_{1^\circ C} = 500 \text{ W m}^{-2}$ and corresponds to an rms field magnitude of $E_{rms} \approx 434 \text{ V m}^{-1}$ (Institute of Electrical and Electronics Engineers 2019). Of note, the most recent guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), another consensus guidance body active in this domain, mirror the analysis and reference levels issued in C95.1 based on the same body of literature, but afford some additional implementation flexibility for the case of shorter averaging times (International Commission on Non-Ionizing Radiation Protection 2020). Absent some compelling frequency- or application-specific effects threshold, this 500 W m^{-2} (50 mW cm^{-2}) value provides a useful, operationally-relevant, but still conservative benchmark for exposures of immediate concern against which to measure a DEW-oriented detection system.

2.4 Microwave Hearing Effect

The potential adverse health impacts described in section 2.3 occur primarily in the limit where exposure timeframes are long enough such that tissue conduction and circulatory heat transfer terms materially impact thermal response. These impacts may be described as a frequency domain response for continuous or near continuous wave microwave radiation. For pulse modulated beams of sufficient power density, the microwave hearing effect represents a somewhat unusual manifestation of the EMF absorption phenomenon best described in the time domain and is the inspiration for the detection scheme proposed in this research. First identified by Frey in the 1960s and studied

extensively via computational methods in the intervening decades by Lin et al., microwave hearing refers to the auditory perception of incident EMF radiation by humans and animals, reported by individuals as a clicking or buzzing (Lin and Wang 2007). As there exists an approximate five order of magnitude difference between the human audible frequency regime and that of the incident EM radiation, microwave-induced TA wave generation was ultimately identified as the indirect coupling mechanism responsible for this effect. A qualitative summary of this signal chain is shown in Fig. 2-1.

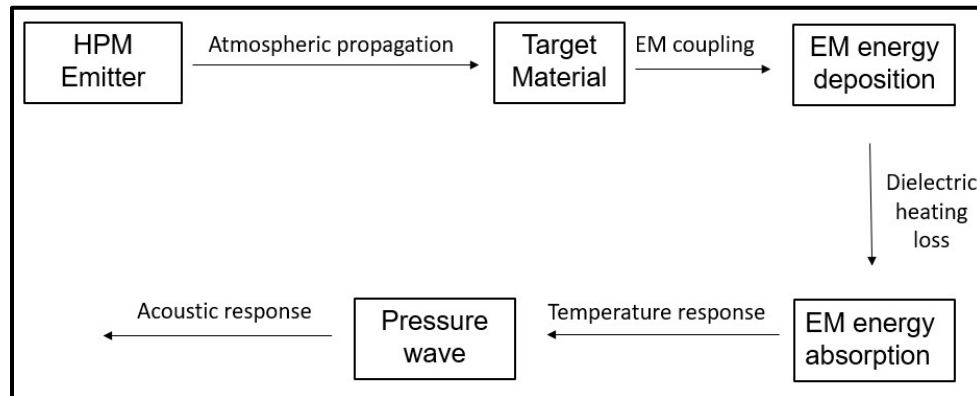


Fig. 2.1. Highly localized energy deposition at microwave frequencies results in a small but abrupt temperature rise, generating a thermoelastic wave in tissue perceived by the individual as an auditory acoustic signal. Adapted from (Lin and Wang 2007).

A limited body of human subject and animal study data provides some bounding values on relevant parameters influencing the perception of pulsed microwaves through TA processes. At its most straightforward as shown in Fig. 2.2, the existence of this phenomena was demonstrated through the direct irradiation of the head by a horn antenna emitting at 2.45 GHZ, with the human

subject indicating via handheld switch when hearing an acoustic signal and various time domain characteristics of the incident beam adjusted to determine perception thresholds (Lin 1980).

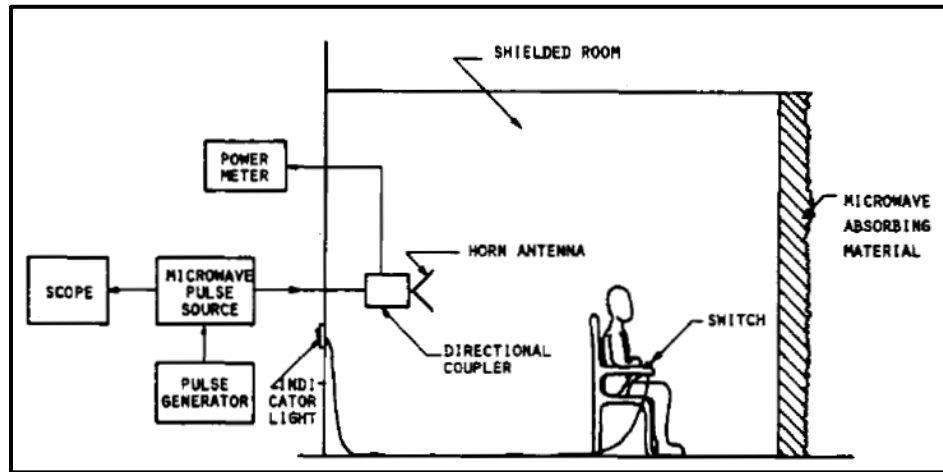


Fig. 2.2. Experimental design summary for establishing perception thresholds of the microwave hearing effect. © 1980 IEEE. Reprinted with permission from (Lin 1980).

Given a low background acoustic environment, a perception threshold peak power density of 400 kW m^{-2} was noted for the shortest ($1 \mu\text{s}$) microwave pulse widths investigated, with this value decreasing to 12.5 kW m^{-2} for $32 \mu\text{s}$ pulses and an implicit peak energy density of around 0.4 J m^{-2} observed across pulse width-power density permutations (Lin 1980). A series of studies involving cats and guinea pigs, with one example presented in Fig. 2-3, recorded direct measurements of the resultant neurological and cochlear signals when subject to similar microwave exposure parameters. The result was a similar trend of minimum effect threshold of incident energy density per pulse across pulse

widths (Lin 1978). Of note, both the human and animal studies described above involved exposures at low pulse repetition frequencies (PRFs), in the range of 10 - 100s Hz.

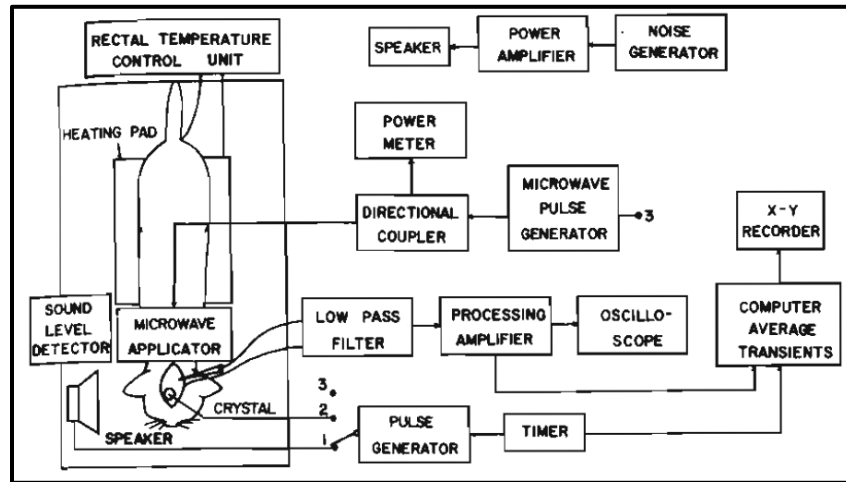


Fig. 2.3. Measurement of feline neuroresponse to the microwave hearing effect, with comparison to direct acoustic excitation generating similar impulse magnitude. Reprinted with permission from (Guy et al. 1975).

While the peak power densities discussed in the context of microwave-induced auditory sensations are large compared to the pertinent *SAR* threshold described in section 2.3, the low average power densities of the short pulse widths and low PRF in these studies preclude the bulk increase in tissue temperature noted as the primary source of adverse health impact of microwave exposure. Even at *SAR* values five times this threshold value, the induced peak pressure generated in the brain would result in sound levels above the human auditory perception threshold but below that associated with discomfort (Lin and Wang 2007). Therefore, the microwave hearing effect is historically considered

something of a harmless irritant, with subjects in animal behavioral studies reacting to pulsed microwaves meeting the above TA criteria broadly similar to behaviors elicited by acoustic stimuli. However, a recent study on causative factors for symptoms observed in personnel working in the U.S. Embassy in Havana, Cuba reportedly exposed to an unknown DEW in Havana in 2016 suggests that at select microwave and pulse repetition frequencies, the resultant pressure waves are of sufficient magnitude to result in clinical findings commonly associated with mild Traumatic Brain Injury (mTBI) (Hubler et al. 2020). The HPM beam parameters of relevance to efficiency of TA coupling are discussed in subsection 4.1.2.

Qualitatively, the mechanics of this EM to acoustic energy conversion places bounds on some of the time domain characteristics of the incident microwave beam over which the above approximations would still hold. From the beam's pulse length and PRF, the duty factor of the emitter is defined as

$$DF = \tau_p \cdot PRF = \frac{\tau_p}{T_p}, \quad (2.31)$$

where T_p (s) is the pulse period. Increasing the duty factor through longer pulse lengths results in a breakdown in the linear relationship between temperature change and SAR as elastic energy leaves the energy deposition region via a propagating TA pulse and heat is transported away from its initial deposition site through conductive and convective losses. Alternately, an increased duty factor caused by increasing the PRF results in energy being added to the system faster than can be carried away through acoustic means. For comparison purposes,

the formative human and animal subjects research described previously involved exposure duty factors < 0.01 , and often much lower.

The actual solution to the time-dependent pressure distribution in tissue following pulsed microwave exposure is much more complex than described above owing to the stratification of tissue types with varying physical properties and the boundary conditions required to mimic the human anatomy. Retaining the far-field, plane wave assumption for the incident radiation field, a spherical model of the head, either with or without stepwise defined tissue material properties, has been used with some success to predict some of the frequency domain acoustic behavior later observed experimentally. Solving an acoustic wave equation for the case of an isotropic, homogenous and stress-free sphere of brain tissue-equivalent material indicates contributions at an infinite series of characteristic resonant frequencies proportional to the speed of the sound in the medium and inversely proportional to the radius (Lin 1978). These fundamental frequencies generally scale inversely with the characteristic dimension of the target and provide some prominent component of the acoustic frequency domain signal regardless of imparted microwave-induced thermoacoustic excitation. The addition of a rigid shell of bone as an analogue representing the human skull adds a level of complexity to the analysis, as it both constrains acoustic displacement at the skull-brain interface and provides an additional interface at which electromagnetic coupling effects will occur. Of note, the pulse width of the incident radiation will generate some resonant effects, as the characteristic dimension of the tissue model imply some time period at which a launched

acoustic wave reflects from the far side of the spatial domain and returns to the EM-tissue interface (Guo et al. 1984).

2.5 Microwave-Induced TA Wave Applications

The underlying physics described in section 2.4 has been leveraged most robustly in the realm of novel clinical diagnostic imaging modality development, although these decades-long efforts do not appear as of yet to have resulted in commercially available systems. These designs combine a high peak power pulsed microwave source with a clinical ultrasound transducer array operating in receive mode, using static and tomographic image reconstruction techniques of widespread use in diagnostic ultrasound. An example of such a system is depicted in Fig. 2.4.

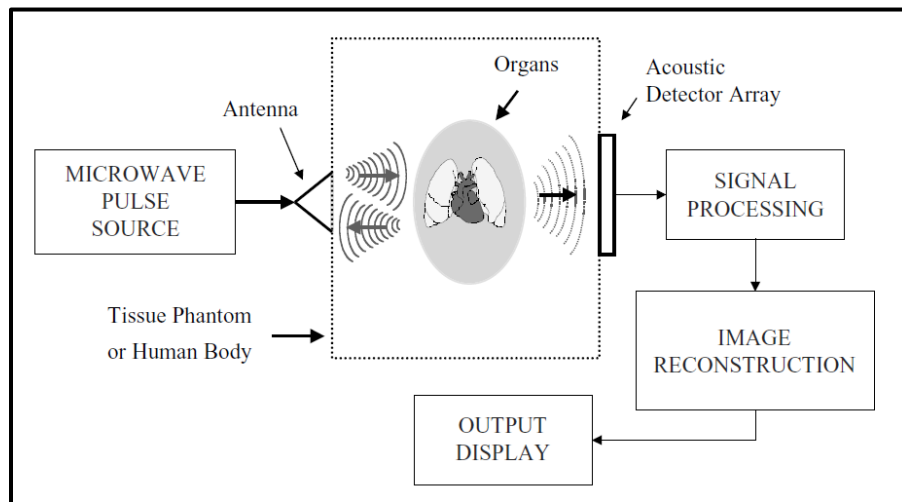


Fig. 2.4. Overview of a microwave TA imaging system, with simultaneous collection of acoustic and EM backscatter signals. Reprinted with permission from (Lin 2005).

The primary benefit from such a system as compared to traditional ultrasound is evident in the skin effect described above, whereby through suitable selection of microwave frequency the power penetration depth can be tuned to selectively heat tissues of interest. This can result in an image with a spatial resolution much better than could be achieved through direct microwave imaging. The high peak power emitter required to achieve reasonable signal-to-noise ratio (SNR) presents some engineering challenges to realizing such a system in a clinical environment, especially in regards to electromagnetic interference (EMI) considerations in both the acoustic detector chain and nearby electronic systems. For therapeutic or diagnostic modalities where high intensity EMF fields are already in use, such as magnetic resonance imaging (MRI), the acoustic detector portion of the above signal chain can be coupled to the exposed tissue to compute a spatial distribution of the induced *SAR*. A recent feasibility study demonstrated the utility of this methodology through numerical simulation and experimental phantom data. An estimated net SNR of 22 dB was obtained based on conservative values for component signal loss and an idealized thermal noise of

$$\langle p^2 \rangle df = \frac{4\pi k_b T f^2}{v_l^2} Z df = \frac{4\pi k_b T f^2}{v_l^2} \rho v_l df, \quad (2.32)$$

where k_b (J K^{-1}) is the Boltzmann constant and $Z = \rho v_l [\text{kg (m}^2\cdot\text{s)}^{-1}] = (\text{Rayl})$ is the acoustic impedance of the material (Winkler et al. 2017).

Of greater relevance to potential applications of the TA effect to non-ionizing radiation protection applications, non-medical studies have greater

flexibility in selection of microwave frequency and target dielectric properties to better optimize the magnitude of the resulting TA signal. In particular, various forms of bulk carbon have been noted as being particularly effective TA wave generators due to their relative high loss tangent across a wide microwave frequency range while maintaining a reasonable transmission coefficient. Of note, these EM absorption properties extend beyond the microwave regime, as photoacoustic-based detection schemes using carbon allotropes or nano-composites have been demonstrated at the THz and optical regions of the EM spectrum (Chen et al. 2014). A common design consideration noted across both medical and material science implementations is that of acoustic coupling between the TA target material and acoustic sensor, as wave mechanic phenomena similar to that observed in electromagnetics results in a transmission coefficient of

$$\tau_A = \frac{2Z_2}{Z_1 + Z_2} \quad (2.33)$$

at the interface, resulting in greater than -60 dB pulse magnitude attenuation at the air gap boundary, assuming tissue equivalent sample properties (Singhvi et al. 2019).

With appropriate acoustic coupling and suitable sample geometries, even water has been employed as an effective TA sample target, used with some success to map the spatial distribution of a 6 GHz near-field radiation pattern of an open waveguide (Ding et al. 2015). Given the relative dimensions of receiving antennas to that of a wave guide sized for the target microwave frequency, the

level of spatial resolution achieved in this analysis would be difficult to accomplish using conventional field probe methods and would require a much more complex deconvolution of the measured signal. As discussed above, reducing the characteristic dimension of the TA target has the effect of monotonically increasing the fundamental resonant acoustic frequency. As this particular study used a 1 mm drop of water as the point absorber, and assuming an isotropic and constrained spherical model, an ultrasound transducer with a 2.5 MHz central frequency was selected as the acoustic sensor given an expected fundamental frequency on the order of 1 MHz. As was implemented in other research efforts noted in this review, mineral oil was used as the acoustic coupler as it offers an intermediate impedance between that of the dielectric target and other segments in the acoustic transmission pathway (Ding et al. 2015). Recalling eqns (2.15), (2.22) and (2.26), the effective microwave absorption coefficient of a TA target material can be enhanced through the judicious selection of aggregate complex dielectric properties. An RF dosimetric technique, pioneered by the Air Force for characterization of steady-state 94 GHz beam power density, does exactly this through the use of carbon loading in a polymer that would otherwise be transparent to microwave radiation (Allen and Ross 2007). A combination TA-based EM field power characterization with tailored lossy dielectric properties forms the core of the present research effort, which is summarized in Chapter 3.

III. Methodology

This chapter describes the experimental methods employed to construct, assess, and computationally-model a TA-based pulsed microwave detection system, starting with a general description of the signal chain and outlining the relevant analytic tasks necessary to characterize the performance of each of the system's primary components. Subsequent sections introduce the laboratory equipment, processes, and ancillary material used in each of these component evaluation efforts, generally acting as an introduction to more detailed discussions presented in Chapters 4 and 5. The final section details the techniques employed during experimental in-beam testing and numerical simulation of the integrated detection system, with modeling of individual component behavior occurring as refined material or response properties were obtained.

3.1 Approach

The premise of this proposed research is to evaluate the acoustic signal generated during pulsed HPM irradiation of lossy dielectric polymers, with a focus on carbon as the microwave absorber fill and polytetrafluorethylene (PTFE) as the bulk test sample matrix. Incident short duration microwave pulses, with pulse lengths on the order of 100 ns to 100 μ s, interact with the target inclusion fill material and are substantially absorbed, converting the electromagnetic energy into heat. The resulting small temperature change, on the order of 10-100 μ K, generates a longitudinal acoustic pressure wave in the target material

launched away from the EM energy interface. This pressure wave propagates throughout the sample target as dictated by material geometry and thermomechanical properties. Signal data is captured at the far side of the target material relative to the approximate EM incident plane wave via a polyvinylidene fluoride (PVDF) -based piezoelectric sensor connected to a logging digital oscilloscope for evaluation in the frequency domain (FD) through a Discrete Fourier Transform (DFT). A detailed description of this experimental set-up is presented in section 5.2.

To support analysis of the results and to facilitate concurrent finite element modeling of the experiment using commercial simulation software, characterization of relevant electromagnetic, mechanical and thermal properties of the system components were conducted as summarized below.

1. S-Parameter Analysis

- a. Task: Measure 2-port scattering matrix coefficients of each sample carbon fill volume fraction at discrete microwave frequency intervals from 2 to 110 GHz, as well as free-field power density at select frequencies and system power output.
- b. Purpose: Compute values of the power reflection coefficient, power penetration depth and internal peak *SAR* as a function of frequency under a 1-D, thick sample approximation.
- c. Output: Both real and imaginary components of complex permittivity as a function of frequency at each carbon volume fraction, extracted numerically from S-parameter values.

2. Thermal Response Characterization

- a. Task: Perform thermomechanical analysis (TMA) and scanning differential calorimetry (DCS) of each sample carbon fill volume fraction.
- b. Purpose: Obtain empirical values for the coefficient of thermal expansion β_{th} and specific heat capacity C_p and compare to vendor specifications for virgin PTFE.

- c. Output: Temperature-dependent values for thermal properties of interest to TA wave generation.
- 3. Piezoelectric Response Characterization
 - a. Task: Perform benchtop and numerical simulation signal-driven frequency response testing of PVDF piezoelectric film sensor and signal conditioning component.
 - b. Purpose: Obtain response bandwidth and assess the impact of impulse response characteristics on measured piezoelectric signal.
 - c. Output: Confirm whether the bandwidth of the sensor chain matches or exceeds the PVDF thin film vendor specification, and that amplifier oscillation is absent for pulse widths in the range of interest.
- 4. Modal Analysis
 - a. Task: Perform vibrational eigenfrequency analysis of plate samples using acoustically- and mechanically-driven laser vibrometry.
 - b. Purpose: Compute values for Young's modulus E_{YM} , Poisson's ratio ν_{pr} and the longitudinal speed of sound v_l and compare to literature values for virgin PTFE.
 - c. Output: Elastomechanical parameter values extracted from empirical resonant frequencies as a function of carbon volume fraction, with good agreement for predicted resonant frequencies when these values are used in finite element analysis.
- 5. TA Detector System Response
 - a. Tasks: Conduct multiphysics 2-D finite element analysis of idealized detector configuration using COMSOL, with a focused beam system as a source and empirical material property data where possible. Irradiate lossy dielectric polymer targets using focused beam pulsed microwave radiation and collect acoustic signal data across select values of microwave frequency, power density, pulse widths and PRFs.
 - b. Purpose: Assess TA response behavior in the time and frequency domain that could form the basis of a specific absorption rate-based personnel exposure system and compare to simulation results.
 - c. Output: TA response waveforms at each carbon fill volume fraction, with beam parameter sensitivity analysis accomplished via parameter sweeps across select values.

3.2 S-Parameter Analysis

3.2.1 Focused Beam System

In collaboration with the AFRL/RXCC electromagnetics group, a substantial portion of the experimental data for this project was collected using two focused beam microwave systems operated in Building 654, Area B, Wright-Patterson AFB, OH. These systems are used primarily for measurement of microwave absorption and reflection in novel material samples, and provide the benefit of free field data collection at low system output power. As the scale of microwave system components generally scale with EM radiation wavelength, the physically larger of the two systems is used to evaluate material properties in the lower region of the frequency range of interest (~2 to 18 GHz). This mechanically sealed focused beam system employs Rexolite lens approximately 61 cm in diameter air-coupled to internal feed antennas to achieve enhanced but spatially inhomogeneous peak power densities at the system focal plane. A table-top focused beam system employing shaped metallic reflectors to achieve a similar effect was used at frequencies from 18 to 110 GHz.

Both systems assume a paraxial Gaussian beam approximation and so are designed around a diffraction-limited minimum focal spot size. Returning to eqn (2.7), the EM wave equation for the case of a vertically polarized beam propagating in the x direction can be satisfied assuming a solution of the form

$$\mathbf{E}(x, y) = A(x, y)e^{-ik_x x \hat{z}}, \quad (3.1)$$

where $A(x,y)$ varies much more slowly than the oscillatory component (Vaveliuk et al. 2007). Factoring out the propagation term, eqn (2.7) reduces to the paraxial wave equation

$$\frac{\partial^2 A}{\partial y^2} - 2ik_x \frac{\partial A}{\partial x} = 0, \quad (3.2)$$

with a solution

$$A(x, y) = \sqrt{\frac{w_0}{w(x)}} e^{\frac{-y^2}{w(x)^2}} e^{\frac{ik_x y^2}{2R(x) + i\frac{1}{2}\tan^{-1}\left(\frac{x}{x_R}\right)}}, \quad (3.3)$$

where $w(x)$ (m) is the beam radius, w_0 (m) is the beam radius at the zero plane, x_R (m) is the Rayleigh range, and $R(x)$ is function of the axial position x (Mizuyama 2016). As shown in Fig. 3.1, the beam waist also defines the distance from the beam center at which the Gaussian beam has reduced to e^{-2} of its peak intensity, so uniquely defines the axially symmetric spatial power distribution at the zero plane.

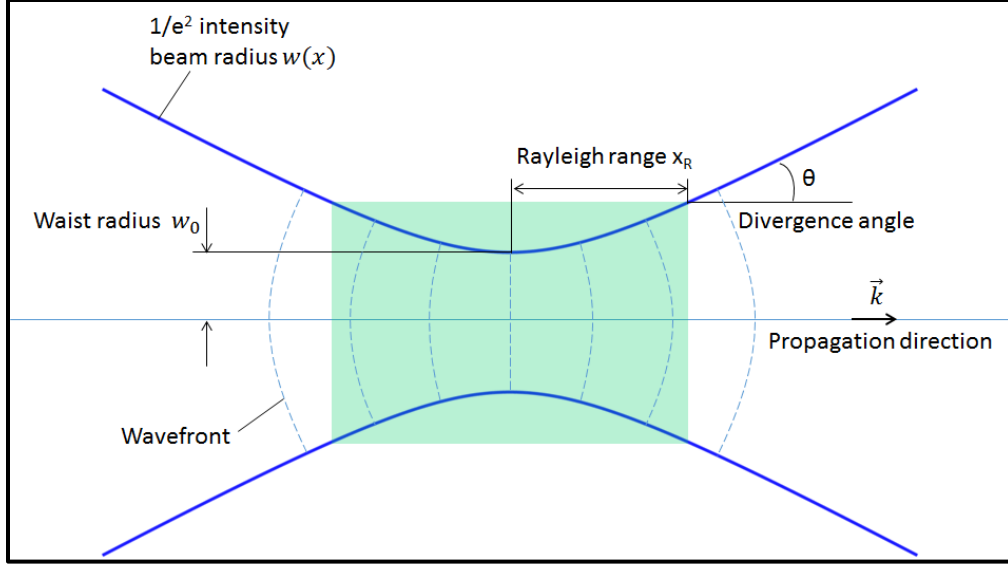


Fig. 3.1. Characteristics of a paraxial Gaussian beam. Reprinted with permission from (Mizuyama 2016).

Adapting the FBS for use as an excitation source for preliminary TA response testing, 50 Ω line terminators were used on the port associated with the same polarization direction on each end of the system, with one of the two remaining ports used to inject the pulsed EMF signal and the other at the far end connected via an adapter to an oscilloscope channel for qualitative monitoring of the attenuated signal transmitted through the sample. An E8257N signal generator (Agilent Technologies, Santa Clara, CA) operating at 10 dBm (10 mW) output power, routed through a 30 dB Agilent 83020A microwave amplifier, was used to generate pulsed EMF input into the FBS and collect TA response data at select combinations of frequency and pulse width, with the external trigger from the signal generator used to time data acquisition.

3.2.2 Power Density Characterization

To provide a power density benchmark against which to normalize in-beam TA detector output, the free-space microwave power density was obtained at the target zero plane along the beam axis using approaches which varied for each of the three microwave TA excitation sources used in this study. For the sealed FBS, in-beam power density measurements were obtained directly using a Narda NBM-520 RF survey meter with EF-5092 electric (E) field probe (Narda Safety Test Solutions GmbH, Pfullingen, Baden-Wurtemberg, Germany). For the S-band and millimeter wave (mm Wave) HPM sources discussed in section 5.2, incident power density was calculated from empirically-supported numeric models and monitored during TA target exposures through the use of diode detectors directionally-coupled to the source-specific waveguide. Unlike the sealed FBS, the average power output of these two sources is generally much lower than the rated peak power density at distance would suggest, due to limitations on the fraction of beam-on time (duty factor) inherent in their design.

3.2.3 2-Port Scattering Measurement

Thin, nominally 6.5 mm (1/4 in) thick sample plates of carbon-filled PTFE, procured from industrial plastic suppliers, were sized for mounting in the focused beam systems and 2-port scattering parameters obtained across the operating frequency range. Defining the input signal from each emitter as 'a' and received signal 'b', this set-up is depicted in Figure 3.2. For both the sealed and table-top focused beam systems, input and output signal generation and monitoring was

simultaneously implemented by a single system-specific Keysight network analyzer

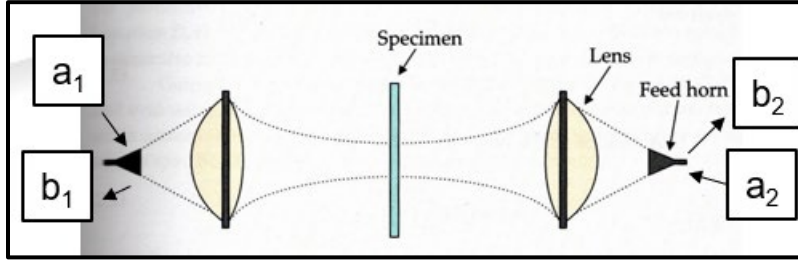


Fig. 3.2. Collection geometry for the 2-port scattering measurement of a thin plate sample. The nominal lateral sample dimension for the sealed focused beam system was 305 (mm) x 305 (mm), while the table top system supported both this size and 152 (mm) x 152 (mm), depending on frequency. Adapted diagram reprinted with permission from (Schultz 2012).

The coefficients R_{ij} of the cascading network scattering matrix R are defined as the ratio of the signal power in dBm received at port i to that transmitted at port j , resulting in the linear system of equations

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} \quad (3.7)$$

and S scattering matrix conversion defined as

$$S = \frac{1}{R_{22}} \begin{bmatrix} R_{12} & R_{11}R_{22} - R_{12}R_{21} \\ 1 & -R_{21} \end{bmatrix}, \quad (3.8)$$

which represents a more commonly encountered formulation of the 2-port network (Schultz 2012). The S-parameters are obtained from the voltage ratios following calibration to account for horn and cable losses, which as implemented for this study requires both an associated clear (without sample in place) and short (reflective aluminum plate in lieu of sample) measurement. For a given

sample thickness x_t [m], the calibrated scattering coefficients are then (Schultz 2012)

$$S_{ij} = \frac{S_{ij,raw}}{R_{ij,short}} \text{ for } i = j \quad (3.9)$$

and

$$S_{ij} = e^{-ik_0 x_t} \frac{S_{ij,raw}}{R_{ij,clear}} \text{ for } i \neq j. \quad (3.10)$$

The frequency-dependent scattering parameters are related to the sample impedance η and field reflection coefficient Γ_E via the equations

$$S_{ij} = \begin{cases} \frac{(1 - \eta^2)\Gamma_E}{1 - \eta^2\Gamma_E^2}, & i = j \\ \frac{(1 - \Gamma_E^2)\eta}{1 - \eta^2\Gamma_E^2}, & i \neq j \end{cases}, \quad (3.11)$$

where S is symmetric for thin samples (Kondawar and Modak 2020). Of note, both focused beam systems support the simultaneous measurement of both vertical and horizontal microwave signal polarizations at each physical aperture, and therefore can collect 4-port S-parameters if needed to characterize anisotropic sample material or to confirm polarization-independent complex permittivity as anticipated for the polymers of interest in this study. The numerical extraction of complex permittivity values from measured S parameters is described in subsection 4.3.1.

3.3 Thermal Response Characterization

3.3.1 Thermomechanical Analysis

At the material thermal property laboratory managed by the AFRL Materials Integrity Branch (AFRL/RXAS), cylindrical samples with diameters ≈ 6 mm and lengths 3-6 mm were prepared via impact press for each mass fraction carbon-fill PTFE formulation. Using a Q400 thermomechanical analyzer (TMA; TA Instruments, New Castle, DE) equipped with an expansion probe tip, each sample was cycled using a constant pre-load force and a linear ramp of ≤ 5 °C/min through a 0-200 °C temperature range to ensure bracketing phase transition regions noted for virgin PTFE (Blumm et al. 2010). As the TMA furnace heats the sample, a thermocouple placed in close proximity monitors the temperature and controls the heat flow accordingly. The expansion of the sample is measured as a function of temperature via a linear variable differential transducer, which translates displacement of the probe tip to a signal recorded by the system control software (Riga and Neag 1991). The coefficient of linear thermal expansion α_{th} (°C⁻¹) is taken as the slope of the temperature vs. expansion plot normalized to length, with the coefficient of volume thermal expansion β_{th} given by (Takenaka 2012)

$$\beta_{th} = 3\alpha_{th} . \quad (3.12)$$

After weighing each sample, the material density was determined assuming right cylindrical symmetry and was found to be a roughly constant value of $\rho = 2180$ kg m⁻³ across all three carbon-fill percentages. Cylindrical samples with both diameters and heights of 5 mm were prepared via impact press for each volume fraction carbon-fill PTFE formulation.

3.3.2 Differential Scanning Calorimetry

Also in the AFRL/RXAS thermal analysis lab, modulated differential scanning calorimetry (MDSC) was performed using a TA Instruments DSC2500 calorimeter to determine heat capacity C_p as a function of carbon-fill mass fraction. A 20-30 mg sample was extracted from the material coupon via impact press and placed in one of two aluminum sample pans, ensuring the empty mass of the pans were within 0.01 mg of each other. Both pans were then placed in the DSC2500 autosampler and a scanning protocol of 1 °C/min linear ramp rate, overlaid with sinusoidal modulation from negative 40 °C through the same temperature range for that of the TMA, set in the instrument management software (Dugan 2018). During the heating cycle, the differential heat flow required to raise the temperature of the sample pan through the prescribed thermal scanning cycle was recorded, with the presence of the reference experiencing an identical thermal cycle allowing elimination of the contribution of the pan from the measurement. For the most general case of a sample subjected to the thermal cycle described above and for which latent heat exchange processes occur within the temperature range of interest, the heat flow rate can be modeled as

$$\Phi(T, t) = C_p \beta_0 + \Phi^{ext}(T, t) + C_p T_{A,th} \omega_{th} \cos(\omega_{th} t) + \frac{\partial \Phi^{ext}(T, t)}{\partial T} T_{A,th} \sin(\omega_{th} t), \quad (3.13)$$

where β_0 is the underlying heating rate with no sample present, $\Phi^{ext}(T,t)$ is the latent heat exchange, $T_{A,th}$ is the amplitude of the sinusoidal heating signal and ω_{th} is its angular frequency. Inverting eqn (3.16) for the heat capacity given known values of the other parameters was accomplished via the instrument management software (Höhne et al. 2003). TMA and DSC outputs at ambient laboratory temperature are incorporated into subsection 4.3.2, but a more general depiction of the thermal analysis of the three types of PTFE is depicted in Figs. 3.3a and 3.3b, with anticipated solid state phase transitions at 19 °C and 27 °C clearly visible (Blumm et al. 2010).

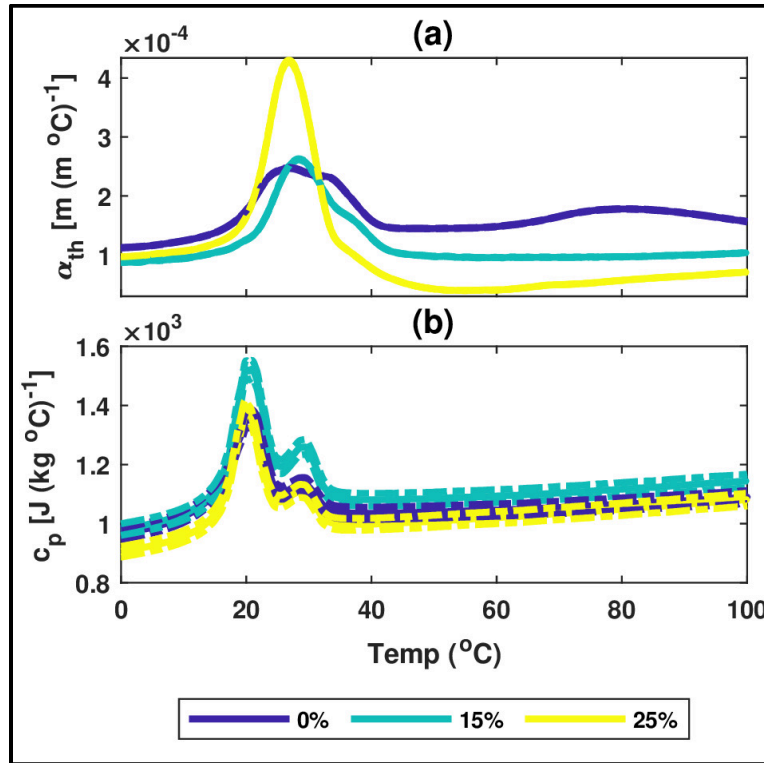


Fig. 3.3. Temperature-dependent coefficient of linear thermal expansion **(a)** and specific heat **(b)** for PTFE with three levels of mass carbon-fill percentage. The temperature range plotted is reduced from that of collected data for clarity of the transition peaks. Dotted lines reflect uncertainty values.

A temperature parameter sweep was not incorporated into the thermoacoustic response testing within this study, but the net effect in terms of anticipated TA signal is a potential factor of up to 2-4 difference in peak pressure in this region versus at the nearby baseline temperatures.

3.4 Piezoelectric Response Characterization

The issue of effective acoustic coupling noted in previous microwave TA studies, represented by the transmission coefficient τ_A given by eqn (2.33), suggests that acoustic impedance of piezo sensors used in contact applications must be as closely matched to the vibrating target material as possible. However, the inherent capacitance and thus complex impedance of the sensor due to its construction results in a piezoelectric signal magnitude which varies depending on the frequency of the acoustic excitation. A Piezo Film Lab Amplifier (Measurement Specialties, TE Connectivity, Hampton, VA) was used in-line as a signal conditioning stage in order to amplify and filter the piezo sensor signal prior to capture by the logging oscilloscopes used in this study. The amplifier incorporates a number of discrete stages, which in sequence integrate the time dependent charge generated in the film, bandpass filter the signal spectrum, and then apply a presumably linear voltage gain to the result. A graphical depiction of the equivalent circuit model of this process, generated using MATLAB Simulink Simscape graphical modeling program (MathWorks, Inc., Natick, MA) for numerical simulation purposes, is shown in Fig. 3.4.

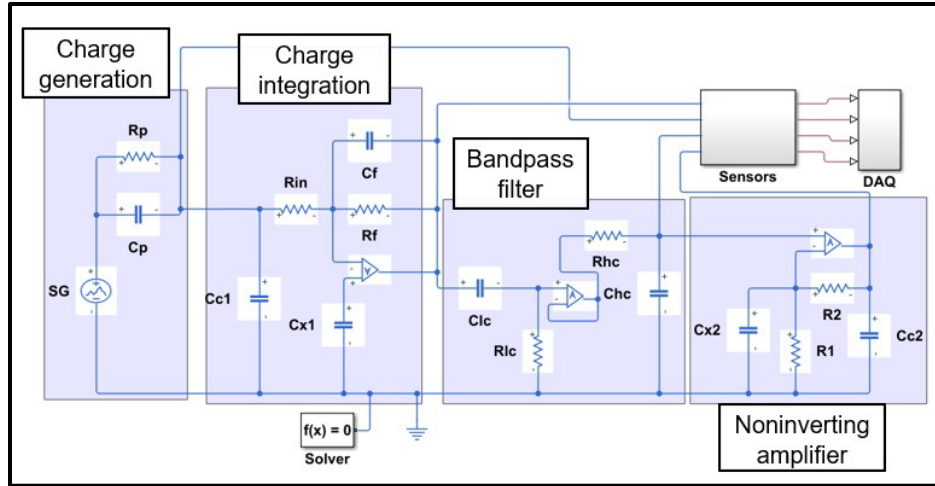


Fig. 3.4. Idealized circuit model for a multi-stage piezo film amplifier conditioning chain. While the charge generation block represents the piezo film sensor itself, the remaining three framed stages correspond to controllable inputs of the system. The sensor, DAQ, and solver blocks are artefacts of the numeric simulation process. Adapted from (Karki 2000), (Mancini 2002).

The film is represented as a variable voltage source in series with a piezo resistance R_p and capacitance C_p , representing basic properties of the sensor in isolation. An arbitrary voltage signal input results in a time-dependent charge generation across C_p , which is then collected at the feedback capacitor C_f at the inverting node of the operational amplifier (op amp) in the charge integration stage. The feedback resistor R_f provides a path for current discharge to minimize saturation of the feedback capacitor, while the remaining components in the circuit model of this stage represent input and stray capacitance and resistance. The low and high frequency cutoffs in the second order bandpass stage are determined by the respective values of the RC combinations, in this model selected to reflect the bandpass filter inputs in the physical lab amplifier as was the case for the resistor values in the noninverting amplifier stage which

determine the voltage gain (Mancini 2002). Benchtop frequency response testing of the aggregate piezo chain was accomplished using a 4075B Arbitrary Waveform Generator (BK Precision, Yorba Linda, CA) as the input voltage source for Measurement Specialties SDT-1 shielded PVDF sensor, with a BNC splitter used to provide both a conditioned and direct waveform into two channels of a MSO5204 digital oscilloscope (Rigol USA, Portland, OR). Using input settings representative of the those used during TA response as described in Chapter 5, the ratio of conditioned to reference signal amplitude for single frequency inputs across approximately four decades indicate a flat response from ~1 kHz to ~100 kHz, as shown in Fig. 3.5, and confirming that these bandpass filter stage settings are the limiting factor for frequency response. Numerical circuit simulation results using nominal component values and a simulated TA input signal (see subsection 4.4.2) suggest the low-pass portion of this filtering smooths the amplified signal while still capturing the primary spectral features of interest.

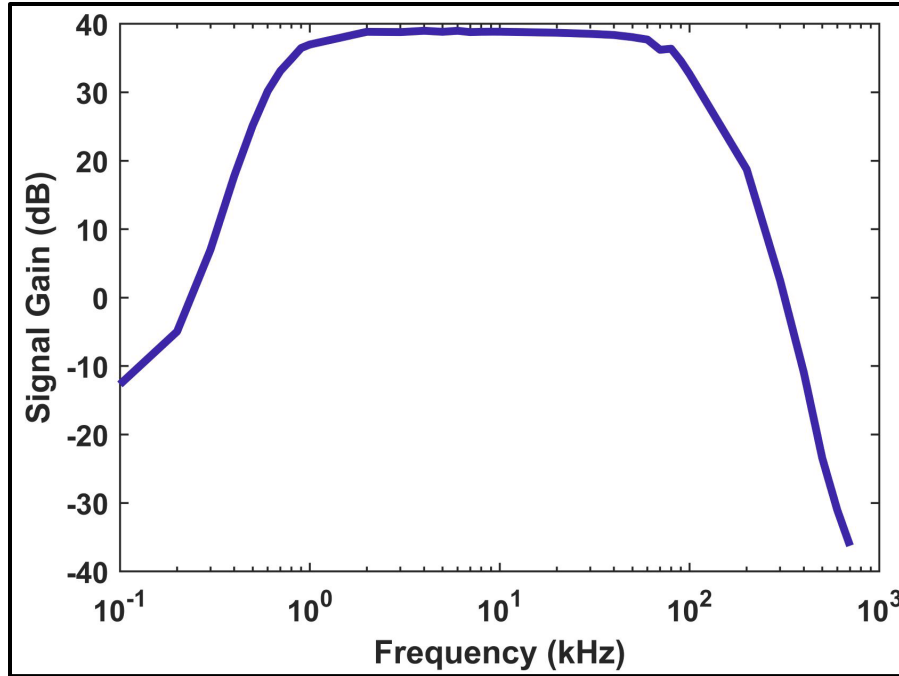


Fig. 3.5. Frequency-dependent gain of conditioned piezo film sensor. Signals with frequency components above this frequency range are significantly attenuated, with an almost 40 dB(V) reduction in peak gain in the decade above 100 kHz.

3.5 Modal Analysis

Replicating a methodology used with some success by recent AFIT research into the vibration characteristics of small solids, suspending a carbon-filled PTFE sample plate from a thin nylon string adhered to one edge provided an approximation of the full-free boundary conditions required for the numeric relationships between resonant frequency and elastic properties outlined in subsection 4.2.3 (Macchia 2019). A Polytec PSV-400 scanning laser vibrometer (Polytec, Inc., Irvine, CA), part of the Department of Aeronautics and Astronautics (AFIT/ENY) vibrational analysis capabilities and shown in Figure 3.8, was used to obtain the vibrational modes and associated frequencies.

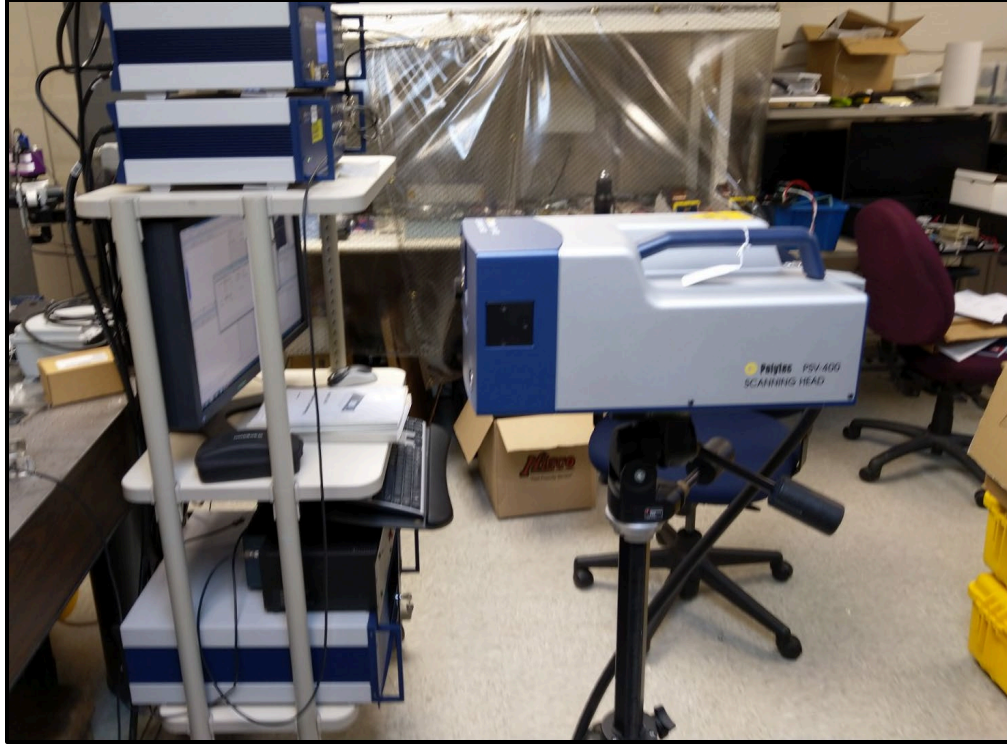


Fig. 3.6. Polytec PSV-400 Scanning Laser Vibrometer, configured for surface scanning normal to small object face.

Modal excitation was obtained acoustically via air horn, selected as needed to ensure sufficient displacement in the plate thickness direction without inducing pendulum motion that would exceed the measurement capability of the vibrometer. The excitation source was air gap-coupled to select points on the rear of the plates, as close as possible to the surface while still preventing the vibrating sample striking the source device during pseudo-unconstrained oscillation. Displacement scans were conducted across the acoustic frequency range of up to four times the value of the highest first mode shape of samples under test, with the same excitation range used for all samples. The spatial density of the vibrometer scan points were set to ensure at least nine points were

obtained per axis dimension, which was high enough to ensure accurate convergence on both the eigenfrequency and eigenmodes of interest while keeping total sample scan times manageable. By taking of a ratio of the third and second resonant vibrational frequencies of a square plate whose mode shapes are shown in Figure 3.7, a close approximation of the material's Poisson ratio is obtained via the formula

$$\nu_{pr} \cong 1.389 \frac{\frac{f_{(2,0)+(0,2)}^2}{f_{(2,0)-(0,2)}^2} - 1}{\frac{f_{(2,0)+(0,2)}^2}{f_{(2,0)-(0,2)}^2} + 1}, \quad (3.17)$$

or through higher fidelity tabular data (Alfano and Pagnotta 2006). A more detailed discussion of elastic material property measurements is presented in subsection 4.2.3.

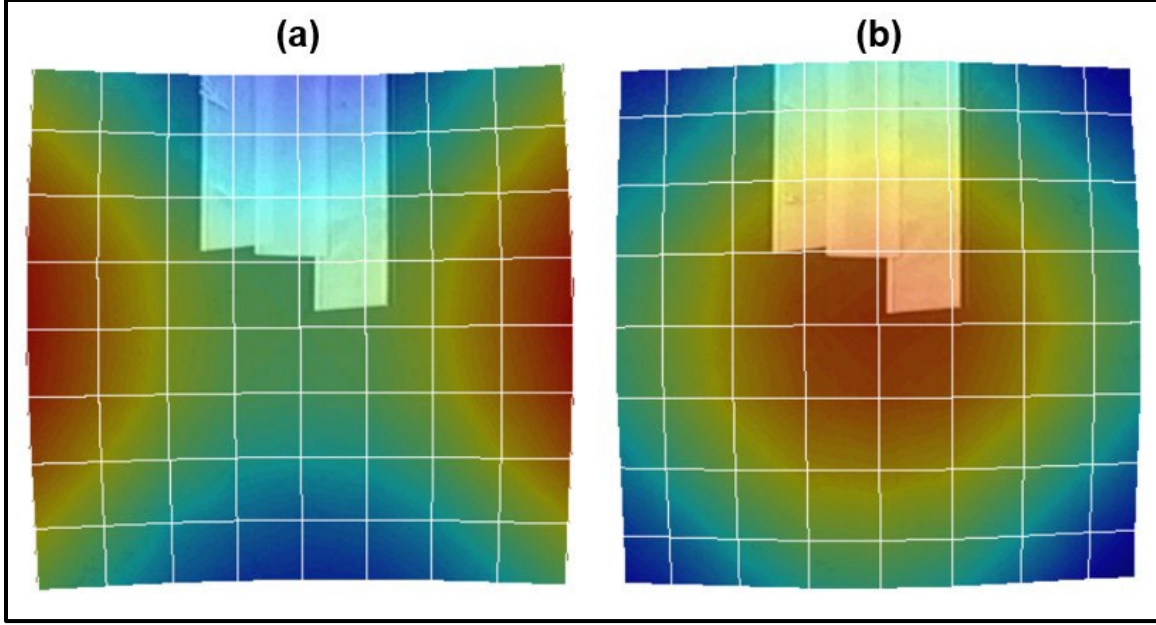


Figure 3.7. Second and third non-rigid body movement mode shapes for a free isotropic thin square plate as reconstructed from laser vibrometry data. Sample is 152 mm x 152 mm x 7.1 mm 25% CF-PTFE. The X-mode represented by $f_{(2,0)-(0,2)}$ is denoted by **(a)** here, while the O-mode $f_{(2,0)-(0,2)}$ is **(b)**.

3.6 TA Detector System Response

3.6.1 Modeling and Simulation

The numeric TA modeling component of this study forms the central topic of Chapter 4, so is only summarized briefly here. Implemented concurrently throughout the material property and signal chain component characterization process detailed in the preceding sections in this chapter, the goals of the modeling and simulation effort were to inform appropriate component selection from the available options on hand to optimize impedance matching in the EM, acoustic and electrical domains, as well as predict the anticipated behavior of the TA signal for a given set of incident microwave beam parameters. The

interactions of interest in the study occur in widely varying time scales, so some care was required in linking the various components of the computational model as implemented in commercial computational multiphysics package COMSOL version 5.6 (COMSOL, Inc., Stockholm, Sweden) to ensure simulation run times were tractable. The conceptual framework for physics modules used to construct the TA signal chain in COMSOL is summarized as follows:

1. RF Module

- a. Task: In the frequency domain, solve Maxwell's equations everywhere in the computational domain given a Gaussian beam background field and scattered field formulation.
- b. Initial/Boundary Condition(s): Perfectly Electrical Conducting (PEC) shell buffered by attenuating Perfectly Matched Layer (PML).
- c. Output: Time-invariant, single frequency electric field distribution everywhere within the spatial domain, from which the time-independent SAR distribution is computed.

2. Heat Transfer Module

- a. Task: Solve the time-dependent heat diffusion equation within the sample target given SAR distribution computed by the RF Module as the heat source and modulated to match the beam time domain characteristics of interest.
- b. Initial/Boundary Condition(s): Target at ambient temperature at time zero, with convective boundary at the target-air interface with constant heat transfer coefficient representing dry, still air.
- c. Output: Time-dependent heat and temperature distribution everywhere in the within the target.

3. Acoustics Module

- a. Task: Solve the time-dependent acoustic wave equation everywhere in the target sample and surrounding air with the thermal expansion induced by EM heat distribution acting as a volumetric, time-dependent pressure source.
- b. Initial/Boundary Condition(s): No internal pressure source at time zero and PML shell surrounding spatial domain.
- c. Output: Time-dependent acoustic pressure distribution everywhere in the target sample and surrounding air medium.

4. Solid Mechanics Module

- a. Task: Solve the linear elastic equations of motion everywhere within the piezoelectric sensor material and target sample, with the latter domain restricted to an alternate TA propagation solution technique.
- b. Initial/Boundary Condition(s): No initial material displacement or velocity in piezo sensor (and target, as appropriate), and pressure distribution within target sample acting as a time-dependent pressure boundary load at the coupling interface.
- c. Output: Time-dependent vector displacement and stress fields everywhere within the piezoelectric material.

5. Electrostatics Module

- a. Tasks: Solve the stress-charge piezoelectric equation everywhere within the piezo sensor material, with the acoustically-driven stress field acting as the source term.
- b. Initial/Boundary Condition(s): Initial charge distribution zero everywhere.
- c. Output: Electric potential difference computed across select locations on surface boundaries of the piezo sensor as a function of time.

While the finite element method (FEM) mesh density used to compute numeric solutions for segments of the computational model described above is highly tailorable, the Nyquist sampling criteria limits the coarseness of the mesh to at least two nodes per wavelength of the highest frequency of interest and preferably at least ten or more (Davidson 2010). To address this issue, a 2-D system model was implemented to keep the number of degrees of freedom (DOFs) in the integrated system at a level manageable by the available laptop computer used to process data in this study. An example of the EM solution output for this process, using the sealed focused beam system as a template for the source and CF-PTFE target plate, is shown in Fig. 3.8.

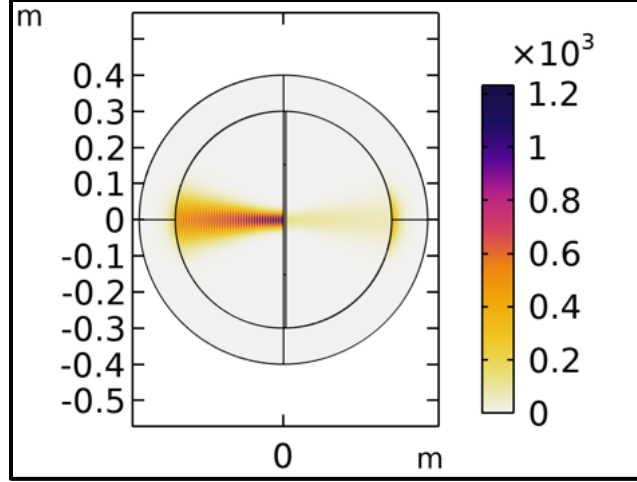


Figure 3.8. Computed absolute value of the electric field (V m^{-1}) for the case of a 6.5 mm thick 25% carbon-filled PTFE plate irradiated by a linearly polarized (Z-direction) 20 GHz Gaussian beam. Total input power is 20 W and the beam waist at this frequency is ≈ 2 cm.

3.6.2 Experimental Technique

Following the collection of material property and system characterization as described in the preceding subsections, preliminary in-beam detector configuration testing was accomplished using the sealed FBS acting as the microwave source per the method outlined in subsection 3.2.1. A frequency-matched PVDF piezo sensor was elastomechanically coupled to the PTFE target plate face opposite microwave incidence and the piezo signal routed through the piezo film amplifier with appropriate control setting so as to maximize the magnitude of the PVDF voltage output relative to the ambient acoustic background. Over the 2-18 GHz operating band shared by the components of the amplified FBS source, a nominal ~ 40 dBm (10 W) microwave output power resulted in a measured frequency-dependent axially power density of ≈ 1 -30 mW

cm^{-2} (10-300 W m^{-2}) at the zero plane. Waveform data for the FBS source permutation was captured using an Agilent Technologies InfiniiVision DSO-X 3034A digital oscilloscope using the same target-detector configuration used during HPM TA response testing. The specific components comprising this signal chain, as well the data collection and analysis methodology used for the 2.8 GHz S-band and 94 GHz mm Wave sources, forms the central focus of Chapter 5 so is described in detail in subsection 5.2. While FBS testing proved formative in converging on a target assembly design later used with the S-band and mm Wave sources, the relatively low peak power density available for TA wave generation and potential for resonant reflections following non-power port termination resulted in inconsistent waveform output. A qualitative review of data collected using targets with varying levels of carbon fill indicated that the PVDF film sensor exhibits some direct sensitivity to the EM signal, especially at lower microwave frequencies, an issue discussed more fully in subsection 5.4.2.

IV. Modeling a Lossy Dielectric Polymer-Based Thermoacoustic High Power Microwave Directed Energy Exposure Detection System

This chapter is derived from a paper published in the June 2022 edition of the *Health Physics Journal*, edited for consistency with the dissertation format and uniformity in definitions of terms. The collaborating authors are Frey, J., McClory, J., and Cobb, R., and the article is titled, “Modeling Lossy Dielectric Polymer-Based Thermoacoustic High Power Microwave Directed Energy Exposure Detection System.”

Abstract

Presented are design considerations for a potential detection and measurement technique that could provide operational awareness of high power microwave (HPM) directed energy weapon exposure for force health protection applications, leveraging thermoacoustic (TA) wave generation as the field interaction mechanism. The HPM electromagnetic frequency (EMF) regime, used in applications in both the counter-materiel and non-lethal counter-personnel design space, presents real-time personnel exposure warning challenges due to the potentially wide variation in time and frequency domain characteristics of the incident beam. As with other EM-thermal interactions, the thermoacoustic wave effect provides the potential to determine EM energy and power deposition without the need to measure ambient field intensity values or overload sensitive EMF survey equipment. Following measurement of relevant EM, thermal, and elastic material property values, a carbon-filled

polytetrafluoroethylene lossy dielectric medium subject to pulsed HPM was computationally modeled using the commercial finite element method multi-physics simulation software package COMSOL. The simulation was used to explore the impacts of various material properties on TA signal output as a function of simulated incident field power density, EM frequency, and pulse length, thereby informing the selection of system components for the further development of a full TA-based HPM detection chain.

4.1 Introduction

4.1.1 General Issue

The high power microwave (HPM) electromagnetic frequency (EMF) regime is of particular interest in Department of Defense and commercial sector directed energy weapon (DEW) system development, as it provides a reasonable balance of beam propagation and power density thresholds that make achieving effects on certain categories of electronic systems more likely (Tatum 2020). Even when employed for counter-materiel effects, incidental but still potentially harmful personnel exposure is possible, making real-time detection of ongoing DEW exposure a critical first step in preventing acute health effects through the timely use of EMF shielding such as structures and vehicles. The microwave hearing effect, the auditory perception of pulsed HPM as clicking or buzzing, provides a template for a potential detection technique (Lin and Wang 2007). As field-deployable HPM DEW systems will likely operate in pulsed mode to maximize incident EMF power on target, thermoacoustic (TA) wave generation in

a lossy dielectric material offers a useful mechanism to determine EMF energy personnel exposure across a wide frequency range even at high peak powers.

4.1.2 Thermoacoustic Wave Generation

The key EMF dosimetric quantity of interest for radiation protection purposes is the specific absorption rate (SAR), defined as the dissipated power from the electric field within a material per unit mass and is given by

$$SAR = \frac{\sigma_{cond}}{\rho} E_{rms}^2, \quad (4.1)$$

where σ_{cond} ($\Omega^{-1} \text{ m}^{-1}$) is the conductivity, ρ (kg m^{-3}) is the material volumetric density, and E_{rms} (V m^{-1}) the electric field magnitude's root-mean-square value (Institute of Electrical and Electronics Engineers 2019). The real and imaginary components of the complex permittivity,

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} = \epsilon' - i\epsilon'', \quad (4.2)$$

will decrease with increasing frequency f for the lossy dielectric polymers used in this analysis. For a low-loss material, the imaginary relative permittivity is related to the conductivity $\sigma_{cond,ll}$ ($\Omega^{-1} \text{ m}^{-1}$) by

$$\epsilon'' = \frac{\sigma_{cond,ll}}{2\pi f \epsilon_0}, \quad (4.3)$$

indicating a likely decrease with increasing frequency as long as conductivity is either constant or slowly varying (Polk and Postow 1986). More generally,

spatial power deposition is characterized by the skin depth δ_{skin} (m) as a function of frequency f (Hz) and an expanded σ_{cond} as in

$$\delta_{skin} = \frac{1}{\sqrt{2}\pi f \sqrt{\mu_0 \epsilon_0} \left[\sqrt{(\epsilon')^2 + (\epsilon'')^2} - \epsilon' \right]^{\frac{1}{2}}} = \frac{1}{\sqrt{\pi f \mu_0 \sigma_{cond}}}, \quad (4.4)$$

where μ_0 (H m⁻¹) and ϵ_0 (F m⁻¹) are the permeability and permittivity of free space, respectively. The δ_{skin} value represents the distance over which the electric field magnitude decreases by e⁻¹ and is twice the value of the power penetration depth δ_{pd} (m) (Yoshikawa et al. 2015).

The frequency of the incident EMF radiation drives both the reflection of the beam through its impact on intrinsic impedance as well as the skin depth over which transmitted power is absorbed as heat, and the *SAR* distribution for a plane wave normal to a semi-infinite slab of single layer material is given by

$$SAR(f) = \frac{\sigma_{cond}}{2\rho} E^2 \left(e^{-\frac{2x}{\delta_{skin}}} \right) = \frac{\sigma_{cond}}{2\rho} E^2 \left(e^{-2x\sqrt{\pi f \mu_0 \sigma_{cond}}} \right), \quad (4.5)$$

where ρ (kg m⁻³) is the mass density and E (V m⁻¹) is instantaneous electric field magnitude. For short pulses at timescales where heat transfer mechanisms are negligible, the rate of temperature change as a function of material depth x (m) and frequency is then

$$\frac{\partial T}{\partial t} \approx \frac{SAR(f)}{c_p} = \frac{\sigma_{cond}}{2\rho c_p} E^2 \left(e^{-2x\sqrt{\pi f \mu_0 \sigma_{cond}}} \right), \quad (4.6)$$

where c_p [J (kg K)⁻¹] is the specific heat. The rate of temperature change shown in eqn (4.6) is constant in time for square pulses. Since the total change in

temperature scales linearly with both SAR and pulse width, the same magnitude of instantaneous pressure is generated in tissue for a given specific absorption SA ($J\ kg^{-1}$), where SA is defined as

$$SA = \int_0^t SAR\ dt' \approx SAR \cdot \tau_p, \quad (4.7)$$

and τ_p (s) is the time-domain width of the pulse. This pressure wave is generated due to thermal expansion of the material in response to the change in temperature and can be modeled as

$$p_0 = \beta_{th} \rho v_l^2 \frac{\partial T}{\partial t} \tau_p = \beta_{th} \rho v_l^2 \frac{SAR}{C_p} \tau_p, \quad (4.8)$$

where p_0 (Pa) is the pressure, β_{th} (K^{-1}) is the coefficient of volumetric thermal expansion, and v_l (m/s) is the longitudinal speed of sound in the medium (Singhvi et al. 2019). The unit-less Grüneisen parameter Γ combines the thermal and elastic properties of the material into a single factor, so

$$p_0 = \Gamma SAR \rho \tau_p. \quad (4.9)$$

Of note, eqns (4.8) and (4.9) are only valid under the limit of stress confinement where $\tau_p < \delta_{pd}/v_l$ (Manohar and Razansky 2016).

Once generated, the wave is launched into the tissue governed by the acoustic wave partial differential equation

$$\left[\nabla^2 - \frac{1}{v_l^2} \frac{\partial^2}{\partial t^2} \right] p = -\frac{\rho \beta_{th}}{c_p} \frac{\partial SAR}{\partial t}, \quad (4.10)$$

with the microwave-induced pressure change acting as the source term and subject to the continuity boundary conditions at the air interface boundary determine by the relative value of the material's acoustic impedance (Lin 1978). The pulse repetition frequency (PRF, Hz) of the incident radiation will also influence both the magnitude and frequency domain characteristics of the induced pressure waves.

The underlying physics described here have been leveraged most robustly in the realm of novel clinical diagnostic imaging modality development, although these decades-long efforts do not appear as of yet to have resulted in commercially available systems. These medical TA application designs combine a well-characterized high peak power pulsed microwave source with a clinical ultrasound transducer array operating in receive mode, using static and tomographic image reconstruction techniques of widespread use in diagnostic ultrasound (Lin 2005). Comparatively, non-medical application studies have greater flexibility in the selection of microwave frequency and target dielectric properties to better optimize the magnitude of the resulting TA signal, with various forms of bulk carbon noted as particularly effective TA wave generators due to its relative high loss tangent across a wide microwave frequency range while maintaining a reasonable transmission coefficient. A few-layer sample of graphene immersed in mineral oil provided sufficient EM depth at 1.4 GHz to support TA mapping of a sample surface, although high peak system output power was required and no quantitative values of acoustic pressure were reported (Wang et al. 2016). With appropriate acoustic coupling and suitable

sample geometries, even water has been employed as an effective TA sample target. A point water absorber was used with some success to map the spatial distribution of a 6 GHz near-field radiation pattern of an open waveguide (Ding et al. 2015). These non-clinical evaluations of HPM-induced TA effect applications likewise assume a priori knowledge of the incident EMF radiation, which may not be immediately available in the case of DEW exposure assessments.

4.1.3 Current Work

The research discussed in this chapter seeks to develop a simple computational model of a broadband TA-based detection chain to assess the feasibility of this technique in pulsed HPM force health protection applications in terms of key parameters and processes. This assessment included a limited subset of relevant beam parameters for a scoping study focused on the 2-18 GHz frequency range, a nominal 1 μ s pulse width, and a 50 mW cm⁻² reference incident power density as a sensitivity threshold. Carbon-filled polytetrafluorethylene was chosen as the lossy dielectric coupling medium based on previous implementations as a microwave absorber in millimeter wave RF dosimetry applications (Allen and Ross 2007). This reference use of CF-PTFE indicates an ability to operate across a wide swath of potential HPM DEW operating carrier frequencies and incident power densities not well addressed by commercially available EMF detectors. As significant gaps exist in the literature on the EM, elastic, and thermal properties of CF-PTFE as a function of the levels of carbon fill (% weight), laboratory measurements were conducted to determine

reasonable values for necessary model parameters. The simulated TA signal was analyzed in both time and frequency domains to determine empirical relationships between signal amplitude and frequency components and incident microwave frequency.

4.2 Materials and Methods

4.2.1 Modeling Approach

Modeling and simulation was used to evaluate the acoustic signal generated during pulsed HPM irradiation of lossy dielectric polymers with amorphous carbon as the microwave absorber fill and polytetrafluorethylene (PTFE) as the bulk matrix (Professional Plastics, Fullerton, CA and Queen City Polymers, West Chester, OH). The carbon fill for a given sample was assumed to be homogeneously dispersed within the material and the percentage fill by mass was provided by the vendor. Simulated signal data was captured at the far side of the target material relative to the EM incident wave via a polyvinylidene fluoride (PVDF) piezoelectric sensor. In lieu of tailored numeric codes for the EM, thermal, and acoustic processes governing the TA effect, the finite element method (FEM) based commercial computational multiphysics package COMSOL ver. 5.6 (COMSOL, Inc., Stockholm, Sweden) was used to generate an integrated, end-to-end model of the detector chain. Integrated capabilities within COMSOL, including a Gaussian beam background field of relevancy to the anticipated microwave source used for future experiments as well as robust

perfectly matched layer (PML) boundary conditions to ensure effective mesh termination, were of particular use in efficiently modeling the governing physics.

The conceptual framework, COMSOL's physics modules, and types of input parameters used to construct the FEM-simulated TA signal chain are summarized in Fig. 4.1.

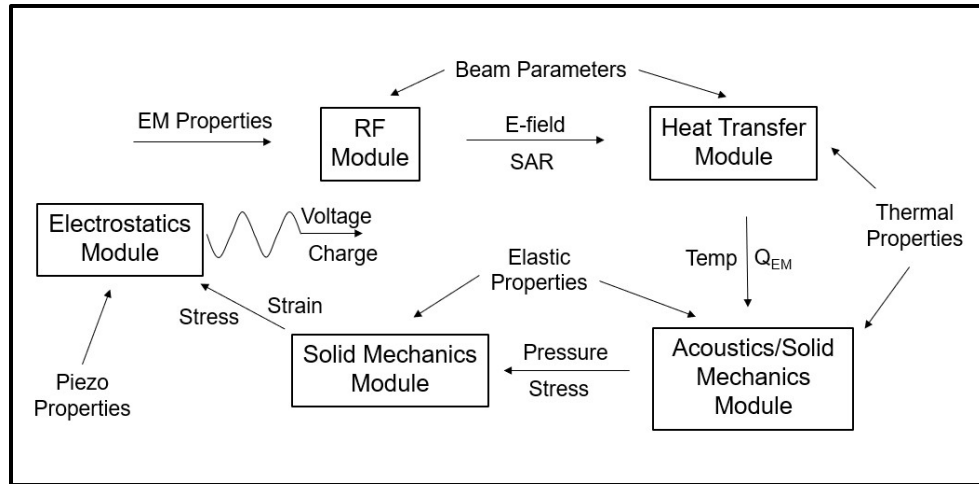


Figure 4.1. Graphical depiction of TA-based pulsed microwave detection chain simulated in COMSOL. Wave propagation microwave absorber material is implemented via an acoustic or continuum mechanics approach, depending on model configuration.

For a given set of beam parameters and EM properties, the RF Module determines the time-harmonic (FD) electric field, SAR and other derived EM quantities everywhere in the domain. The Heat Transfer Module bridges the EM solution data and wave propagation in the Acoustics and Solid Mechanics Modules, running in the TD and providing the mechanism to modulate the pulsed power deposition. Coupling between the Acoustics and Solid Mechanics Modules transforms computed pressure or stress into mechanical deformation in

the PVDF sensor, resulting in charge generation and thus a voltage signal through the use of ground and floating potential boundary conditions on the two sides of the film. All time dependent portions of the model employed COMSOL's physics-controlled adaptive time stepping functionality, with time step values varying from ~1 ns to ~100 ns depending on the phase of the simulation and which module was used for TA wave propagation. As Nyquist limit 3-D FEM meshing requirements scale poorly beyond even modest microwave frequencies, the 2-D system model shown in Fig. 4.2 was implemented to keep the number of degrees of freedom and resultant computation time tractable (Davidson 2010).

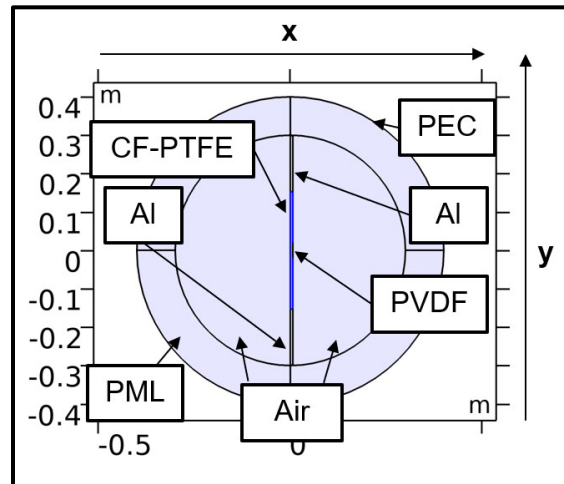


Figure 4.2. 2-D COMSOL computational model geometry used for numeric simulations of TA wave propagation in carbon-filled PTFE. The target material plate is mounted in an aluminum sample frame, surrounded by an air volume with a perfectly matched layer (PML) and a perfect electric conductor (PEC) boundary at the edge of the spatial domain. The PVDF film sensor is center mounted on the rear of the plate. The finite element mesh in the plate and film employs high-aspect ratio boundary layer elements to increase solution spatial fidelity in the x-direction and two levels of adaptive mesh refinement to reduce truncation error in the computed electric field values.

Instead of the default triangular mesh elements used in the air domain, bisected-quadrilateral boundary layer elements were used for the PTFE and PVDF to ensure adequate mesh density in the direction of wave propagation at the expense of lateral fidelity.

4.2.2 Electromagnetic Properties

4.2.2.1 Focused Beam System

A focused beam microwave system designed and fabricated by the Georgia Tech Research Institute (GTRI, Fairborn, OH) was used for the measurement of free-field microwave transmission and reflection properties of the samples and acted as the basis for the pulsed microwave source in simulation. This mechanically sealed system was used to evaluate material properties in the 2-18 GHz frequency range and employs approximately 61 cm diameter Rexolite (C-Lec Plastics, Inc., Philadelphia, PA) lenses air-coupled to two dual polarized quad-ridged horn antennas (L3Harris, Melbourne, FL) to achieve enhanced but spatially non-homogeneous peak power densities at the focal plane.

Microwave focused beam systems assume a paraxial Gaussian beam approximation and so are designed around a diffraction-limited minimum focal spot size. The beam radius $w(x)$ (m), defined as

$$w(x) = w_0 \sqrt{1 + \left(\frac{x}{x_R}\right)^2}, \quad (4.11)$$

is at its minimum value w_0 at the zero plane and the Rayleigh range x_R [m], defined as

$$x_R = \frac{k_0}{2} w_0^2, \quad (4.12)$$

indicates the distance from the zero plane as a function of wave number k_0 (m^{-1}) at which the square of the beam waist has increased by a factor of 2 (Mizuyama 2016). The beam waist also defines the distance from the beam center at which the Gaussian beam is reduced to e^{-2} its peak intensity. Therefore, the beam waist uniquely defines the axially symmetric spatial power distribution at the zero plane, and through the Rayleigh range, bounds a cylindrical volume over which a plane wave approximation in phase is valid. The frequency scaled parameter (FSP)

$$FSP = k_0 w_0 = \frac{2\pi}{\lambda_0} w_0 = \frac{2\pi f_0}{c_0} w_0, \quad (4.13)$$

where λ_0 (m) and c_0 are the free-space wavelength and propagation velocity of the EMF radiation, respectively, is a common metric specifying a given combined lens/microwave horn beam's spatial behavior and is assumed to be an approximately constant value of $FSP = 8$ based on design references and limited in-beam RF survey measurements (Schultz 2012).

4.2.2.2 2-Port Scattering Measurements

Thin, nominally 305 mm x 305 mm x 6.5 mm (12 in x 12 in x 1/4 in) sample plates of virgin (0%), 15%, and 25% carbon-filled PTFE were used to

obtain 2-port scattering parameters across the operating frequency range at a frequency resolution of <100 MHz intervals. Defining the input signal from each emitter as ‘a’ and received signal ‘b’, signal generation and monitoring was simultaneously implemented by an Agilent Technologies N5242A PNA-X network analyzer (Agilent Technologies, Santa Clara, CA).

The coefficients S_{ij} of the sample scattering matrix S are defined as the ratio of the signal power in dBm received at port i to that transmitted at port j , resulting in the linear system of equations (Schultz 2012)

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}. \quad (4.14)$$

The S-parameters are obtained from the power ratios following calibration to account for horn and cable losses and phase errors, requiring both an associated clear (without sample in place) and short (reflective aluminum plate in lieu of sample) measurement for each sample. The frequency-dependent scattering parameters are related to the electric field propagation $T_E = e^{-\gamma \Delta x}$ and reflection Γ_E coefficients via the system of equations

$$S = \frac{1}{1 - \Gamma_E^2 T_E^2} \begin{bmatrix} \Gamma_E(1 - T_E^2) & T_E(1 - \Gamma_E^2) \\ T_E(1 - \Gamma_E^2) & \Gamma_E(1 - T_E^2) \end{bmatrix}, \quad (4.15)$$

noting that S is approximately symmetric for samples that are thin relative to microwave wavelength (Schultz 2012).

4.2.3 Elastic Properties

4.2.3.1 Laser Vibrometry

PTFE sample plates 152 mm x 152 mm x 6.5 mm (6 in x 6 in x 1/4 in) were suspended from kite string to provide an approximation of the free-free boundary conditions required for modal frequency analysis (Macchia 2019).



Figure 4.3. Experimental set-up for collecting vibrational eigenfrequencies of thin plate samples. The acoustic excitation source is oriented towards the lower-center side of a PTFE plate, while a Polytec PSV-400 Scanning Laser Vibrometer is aligned for velocity measurements approximately 1 m from the other face.

Depicted in Fig. 4.3, a Polytec (Polytec, Inc., Irvine, CA) PSV-400 scanning laser doppler vibrometer was used to obtain pointwise out-of-plane velocity measurements of the plate surface while subject to a periodic 60-1000 Hz

acoustic excitation chirp from a conically-shrouded speaker. The source was oriented obliquely at the lower edge of the rear plate surface at one of two different alignment points, and as close to the plate as possible without the vibrating sample striking the source device during oscillation. As the vibrometer remained fixed across sample measurements, the spatial density of the vibrometer scan points varied in nominal density from 81 (9 x 9) to 121 (11 x 11) per plate due to line-induced variations in the positioning of the sample in the vibrometer's field of view. Eigenfrequencies and corresponding eigenmodes were extracted from the averaged frequency domain scan data through the associated Polytec control and analysis software.

4.2.3.2 Modal Analysis

The focused beam microwave system described above was configured for the use of thin square material samples of sufficient lateral dimensions to ensure the beam waist at a given operating frequency falls within the sample boundaries. For a plate with dimensions a (m) and b (m) $\gg$ thickness x_t (m), the thickness-direction displacement u (m) as a function of space and time is governed by

$$\frac{\partial^4 u}{\partial y^4} + 2 \frac{\partial^4 u}{\partial y^2 \partial z^2} + \frac{\partial^4 u}{\partial z^4} + \frac{12\rho(1 - \nu_{pr}^2)}{E_{ym} g x_t^2} \frac{\partial^2 u}{\partial t^2} = 0, \quad (4.16)$$

where E_{ym} is the Young's modulus (Pa), ν_{pr} is the Poisson's ratio and g (m s⁻²) is the acceleration due to gravity (Warburton 1954). The particular solution to this equation is influenced heavily by the mechanical boundary conditions of the

system and relative lengths of the plate sides, but in general square plates result in an infinite series of periodic functions in spatial coordinates y and z each with characteristic modal frequencies of the form

$$f_{m,n} = \frac{\pi \lambda_{plate} x_t}{2a^2} \left[\frac{E_{ym}}{12\rho(1 - \nu_{pr}^2)} \right]^{\frac{1}{2}}. \quad (4.17)$$

The non-dimensional scaling factor λ_{plate} is dependent on the mechanical boundary conditions at the four plate edges, the ratio of the length of the plate sides, and the mode numbers m and n in each lateral dimension (Warburton 1954). By taking the ratio of the measured second through fourth resonant vibrational frequencies of a square plate over its first, an approximation of the material's Poisson ratio is obtained via high-fidelity tabular data (Alfano and Pagnotta 2006). With a known value for Poisson's ratio, the Young's modulus is then calculated by inverting eqn (4.17) and using the empirically determined resonant frequency for a vibrational mode and interpolated tabular value of λ_{plate} such that

$$E_{ym} = \frac{48}{\pi^2} \left(\frac{f_1}{\lambda_{plate}} \right)^2 \frac{ma^2(1 - \nu_{pr}^2)}{x_t^3}, \quad (4.18)$$

where $m = \rho a^2 x_t$ (kg) is the mass of the plate.

4.3 Results

4.3.1 Complex Permittivity Extraction

The microwave system control package Materials Measurement Suite (Keysight Technologies, Colorado Springs, CO) was used on the network

analyzer to compute EM properties from measured S parameters, although algorithms used to accomplish back-calculation of real and imaginary permittivity are considered proprietary and so are often not well documented. However, the fundamental goal of all such methods is to solve the Jacobian matrix equation of the form $\mathbf{J}\Delta\mathbf{X}=\mathbf{Y}$

$$\begin{bmatrix} \frac{\partial f_S}{\partial \varepsilon} & \frac{\partial f_S}{\partial \mu} \\ \frac{\partial g_S}{\partial \varepsilon} & \frac{\partial g_S}{\partial \mu} \end{bmatrix} \cdot \begin{bmatrix} \Delta\varepsilon \\ \Delta\mu \end{bmatrix} = \begin{bmatrix} f_S \\ g_S \end{bmatrix} \quad (4.19)$$

where the functions f_S and g_S of the unit-less EM reflection and propagation coefficients Γ_E and T_E are defined as

$$f_S = (1 - \Gamma_E^2 T_E^2) S_{11} - \Gamma_E (1 - T_E^2) \quad (4.20)$$

and

$$g_S = (1 - \Gamma_E^2 T_E^2) S_{21} - T_E (1 - \Gamma_E^2), \quad (4.21)$$

assuming a symmetric S matrix and noting that $\mu \approx \mu_0$ at all frequencies for the dielectric polymers in this study, so derivatives with respect to permeability vanish (Schultz 2012). Complex permittivity values obtained through 2-port S -parameter analysis using a transmission-based (S_{21} and S_{12}) algorithm, collected at 0 dBm (1 mW) output power and a frequency step size of $\Delta f = 15$ MHz, are presented in Fig. 4.4.

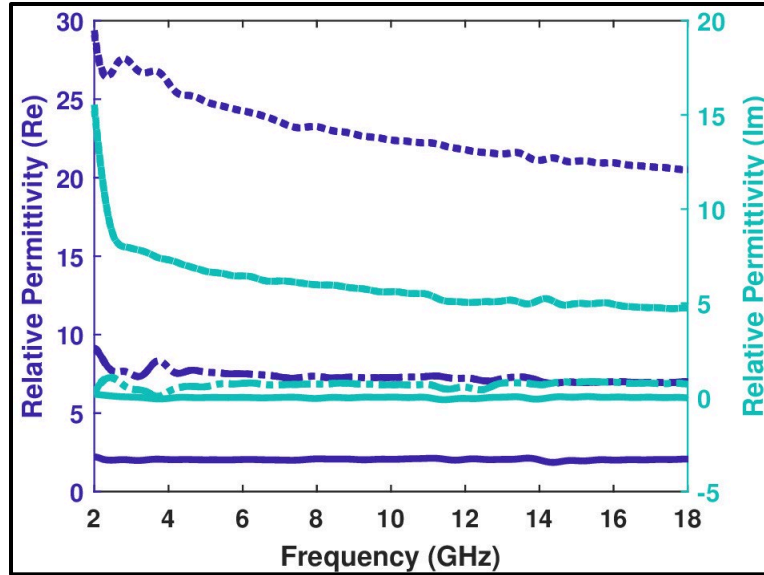


Fig. 4.4. Real (Re) and imaginary (Im) components of the complex permittivity three varieties of PTFE, obtained via focused beam S-parameter analysis from 2 to 26 GHz. Plot legend entries are —0% CF-PTFE, --15% CF-PTFE, and ··25% CF-PTFE, with line colors corresponding to either the Re or Im y-axis. A peak relative error of ≈ 0.01 occurs for both 15% and 25% CF-PTFE in the imaginary permittivity component at the lower frequency bound, with the uncertainty dropping to under 1×10^{-3} for both components of 25% CF-PTFE above ≈ 5 GHz. A real relative permittivity of $2.04 \pm .05$ for virgin PTFE across the frequency range compares favorably to published reference values (Geyer 1990).

For the 15% and 25% CF-PTFE, an initially relaxed but asymptotic convergence is noted for both components. As TA wave amplitude increases with increasing microwave power deposition in the material, the complement of the linear sum of the port 1 reflection (S_{11}) and transmission (S_{21}) S-parameters shown in Fig. 4.5 provides a measure of the fraction of beam power absorbed in the sample plates.

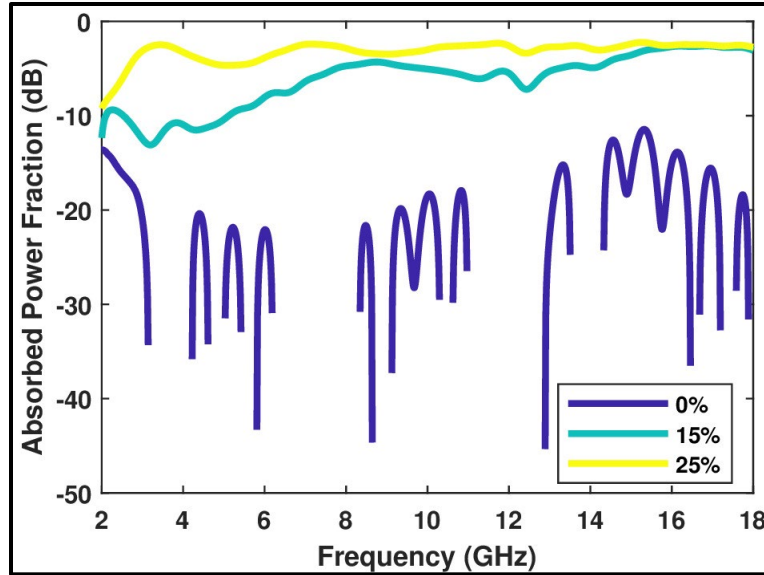


Fig. 4.5. Fraction of incident beam power absorbed in sample plates of three varieties of CF-PTFE. Gaps in plots indicate residual error remaining in S-parameters following calibration, as the linear sum of S_{11} and S_{21} exceeds unity.

The calibration does not fully address the potential sources of error in the permittivity measurements, which include phase error contributions from geometric uncertainty associated with the on-axis positioning and thickness of the sample plates, in addition to inherent uncertainties associated with the design of the focused beam system (Schultz 2012). Relative uncertainty of measured permittivity values for each sample type were calculated from ten successive cycles of S-parameter and EM property extractions, with a full unmounting and remounting of the sample between each iteration.

4.3.2 Elastic Property Extraction

Values of E_{ym} and ν_{pr} are sufficient to define the elastic properties of a given isotropic PTFE sample of interest to this study. Formulated as Lamé's constants, the shear modulus μ_{sm} (Pa), also known as G , is defined as

$$\mu_{sm} = G = \frac{E_{ym}}{2(1 + \nu_{pr})} . \quad (4.22)$$

λ (Pa) is given as

$$\lambda = \frac{E_{ym}\nu_{pr}}{(1 + \nu_{pr})(1 - 2\nu_{pr})} \quad (4.23)$$

and taken together allow the computation of the bulk compression modulus K (Pa) (Ophir et al. 2002)

$$K = \frac{3\lambda + 2\mu_{sm}}{3} = \frac{E_{ym}}{3(1 - 2\nu_{pr})} . \quad (4.24)$$

Of greatest utility across these parameters in approximating the relative magnitude of a microwave-TA pressure wave, the longitudinal speed of sound within a PTFE sample can be computed from these Lamé's constants through the relationship

$$v_l = \left[\frac{(\lambda + 2\mu_{sm})}{\rho} \right]^{\frac{1}{2}} = \left[\left(\frac{E_{ym}}{\rho} \right) \frac{(1 - \nu_{pr})}{(1 - 2\nu_{pr})(1 + \nu_{pr})} \right]^{\frac{1}{2}} , \quad (4.25)$$

with the threshold value of

$$\frac{\mu_{sm}}{\lambda} \ll 1 \Rightarrow \nu_{pr} \rightarrow \frac{1}{2} \quad (4.26)$$

for the implicit condition of no shear stress required for much of the TA wave generation analysis provided in the Introduction (Lin 1978). An example of a laser vibrometry power spectrum distribution used as an input to determine E_{ym} and ν_{pr} is depicted in Fig. 4.6 while computed values for these parameters and speed of sound for the three PTFE variants are summarized in Table 4.1.

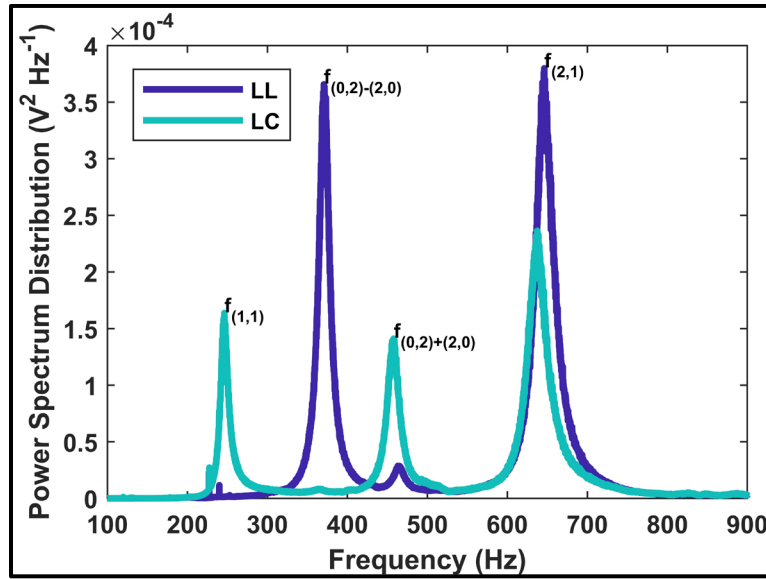


Fig. 4.6. Vibrational power spectrum distribution of a 25% CF-PTFE plate acoustically-excited at the lower-left (LL) and lower-center (LC) of the face under approximate full-free boundary conditions. Subscripts m and n on peak labels indicate mode numbers in the y and z direction, respectively.

Table 4.1. Summary of PTFE sample elastic material properties and Grüneisen parameter for three levels of mass carbon-fill percentage. The computed value of v_l for virgin PTFE is around 7% larger than that obtained via an immersion-based technique using ultrasound frequency region excitation (Hartmann and Jarzynski 1972).

% Carbon-fill	v_{pr}	E_{ym} (GPa)	v_l (m s ⁻¹)	Γ
0	0.459 ± 0.004	1.04 ± 0.01	1470 ± 70	$0.89 \pm .09$
15	0.360 ± 0.002	2.48 ± 0.01	1381 ± 9	$0.49 \pm .01$
25	0.330 ± 0.002	3.61 ± 0.02	1566 ± 7	$1.00 \pm .02$

The reported Grüneisen parameter values incorporate measured values of β_{th} and c_p at 294 K (≈ 21 °C) obtained via modulated differential scanning calorimetry and thermomechanical analysis, respectively, and a roughly constant value of $\rho = 2180$ kg m⁻³ across all three carbon-fill percentages. While the general trend of increased speed of sound with higher carbon-fill results in increased TA wave magnitude, the corresponding decrease in v_{pr} indicates that the no shear condition of eqn (4.26) can only reasonably be applied to virgin PTFE. As a verification method for the computed elastic properties, a coarse FEM thin plate eigenfrequency analysis was conducted using MATLAB's built-in Partial Differential Equation Toolbox (MathWorks, Inc., Natick, MA) and empirically-derived physical parameters, with good agreement between the measured and predicted frequencies for the first four eigenmodes, as shown in Fig. 4.7.

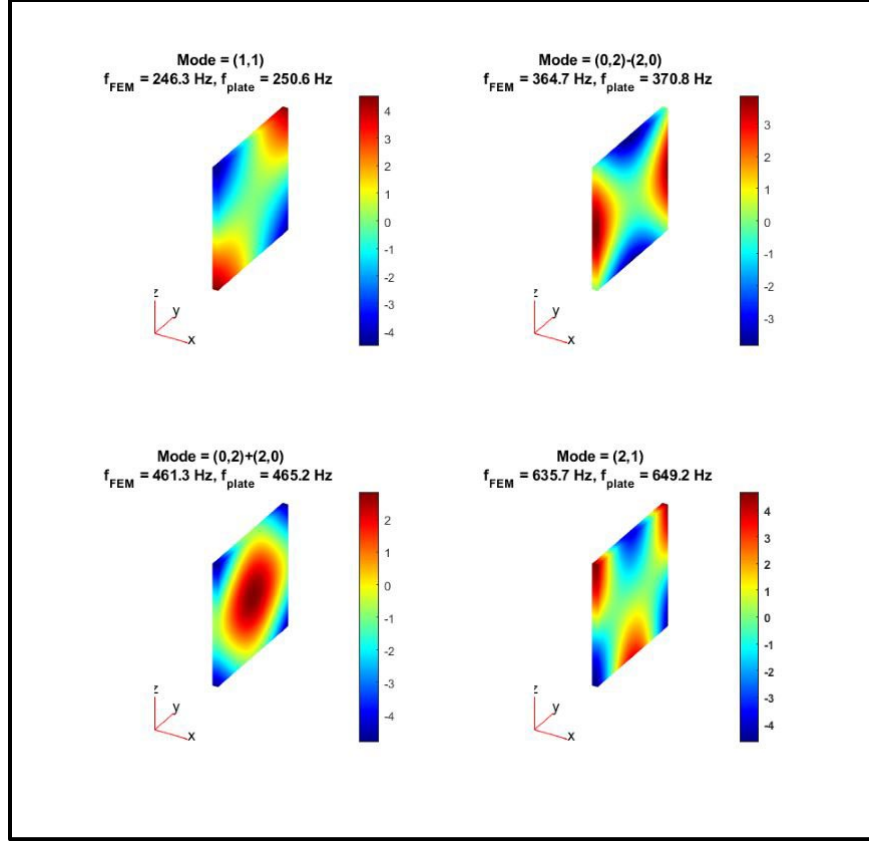


Figure 4.7. Comparison of eigenfrequencies computed by finite element analysis versus measured values for the first four mode shapes of a free-free isotropic thin plate. Elastic properties are those for 25% CF-PTFE extracted from scanning laser vibrometry data. Mode indices (m,n) on peak labels indicate the numbers of nodal lines in the y and z direction, respectively.

4.3.3 Computational Modeling

The utility of the Gaussian background scattered field formulation in simulating microwave absorption processes is demonstrated by focusing on the stationary component of the model, implemented with the COMSOL 2-D geometry outlined in Fig. 4.2 for a nominal combination of beam parameters (20 W input power and 20 GHz microwave frequency) and using empirical complex

permittivity values for 25% CF-PTFE. The resulting distribution of the out-of-plane electric field component displays the anticipated convergence of the beam at the focal plane, near total attenuation within the thickness of the sample plate and then complete absorption within the perfectly matched layer. EM variables derived from the electric field similarly behave as anticipated. Using a parametric sweep across the frequency range of the focused beam system, the combined effect of EM coupling and beam focusing results in an oscillatory increase in the field quantity peaks with increasing frequency as shown in Fig. 4.8.

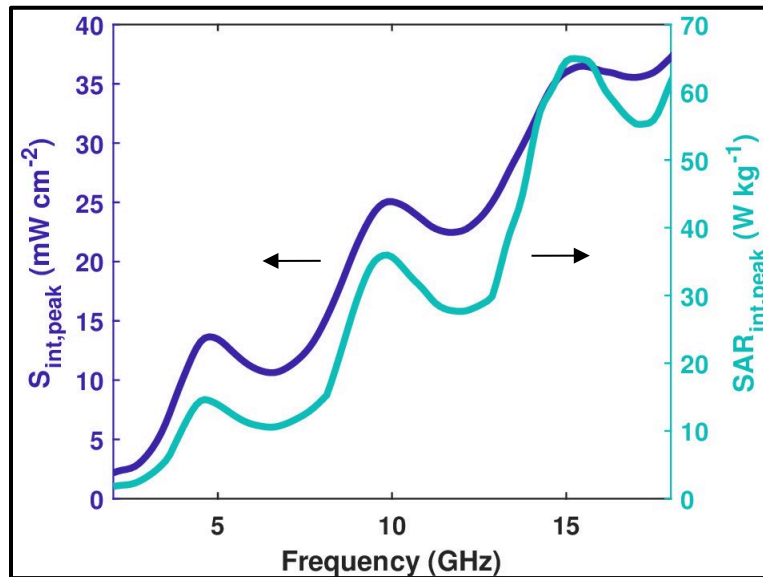


Fig. 4.8. On-axis focused beam simulated peak power density (left axis) and SAR (right axis) for a 6.5 mm thick 25% carbon-filled PTFE plate, with a total input power of 20 W. Local maximums in peak SAR at intermediate frequencies correspond to multi-reflection resonances occurring when the plate thickness equals an integer half wavelength of the microwave beam frequency.

4.4 Discussion

4.4.1 Predicted Peak Pressure

The time harmonic field quantities can provide some additional insight into the magnitude of the pressure wave ultimately initiated within the material due to the spatial distribution of transmitted power. As peak power density at any given y-slice of the Gaussian beam will be located along the x-axis, numerically evaluating the internal power density S_{int} along a cut line through the plate thickness until the condition

$$S_{int}(x) > \left(\frac{1}{e}\right) S_{int} \quad (4.27)$$

is met yields an estimate of δ_{pd} . Comparing this value to that calculated using eqn (4.4), as depicted in Fig. 4.9a, shows some divergence between the two methods which decreases with increasing frequency until convergence at around 10 GHz. From the same figure, the 1 μ s nominal pulse length used for this study meets the stress confinement criteria for all evaluated beam frequencies. This likely occurs due to the form of the electric field solution within the plate, which contains both the anticipated exponentially decaying component as well as a spatially harmonic term which is much more pronounced when δ_{pd} is comparable to the thickness of the plate. Assuming a 1 μ s pulse length, the penetration depth can be used to compute an alternate estimate for the peak magnitude of the thermoacoustic wave via the expression

$$\sigma_{max} = \frac{\Gamma S_{int} \tau_p}{\delta_{pd}} . \quad (4.28)$$

Eqn (4.28) represents an idealized peak magnitude for a semi-infinite 1-D half-space of isotropic material subject to an exponential depth energy deposition profile in the limiting case of instantaneous energy deposition ($\tau_p \ll \delta_{pd}/v_l$) (Choi et al. 2003). In a continuum (solid) mechanics treatment, eqn (4.28) yields a maximum value of the x-component of the Cauchy stress tensor σ_{max} (Pa) in a succinct elastic wave analogue to the peak pressure metric used in the acoustic approximation. A comparison of predicted peak pressure computed from the δ_{pd} and SAR is shown in Fig. 4.9b. At a constant incident energy density, increasing the pulse length results in a non-linear decrease in the peak stress magnitude, with a reduction to around 0.4 of the eqn (4.28) value when pulse length equals the stress confinement time (Bushnell and McCloskey 1968).

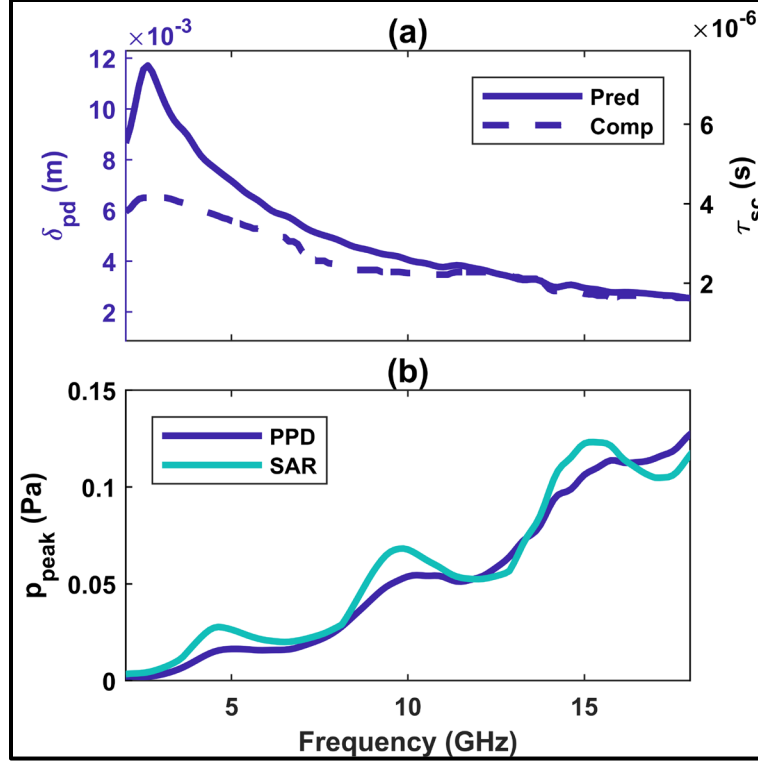


Fig. 4.9. Power penetration depth δ_{pd} **(a)** and predicted peak pressure **(b)** as a function of microwave frequency for a 6.5 mm thick 25% carbon-filled PTFE plate with a total input power of 20 W. Below around 5.8 GHz, penetration depth exceeds the thickness of the plate and the local maximum around 3 GHz corresponds to a region in Fig. 4.4 where the real component of the complex permittivity is increasing relative to the imaginary component. Stress confinement time τ_{sc} scale on the right y axis is computed as the ratio δ_{pd} and the longitudinal speed of sound and at 18 GHz is $\approx 1.6 \mu s$. In **(b)**, peak pressure is computed using either eqn (28) and the predicted power penetration depth or directly from the peak SAR using eqn (9), with a total input power of 20 W and assuming stress confinement.

4.4.2 Transient Solution

Retaining the above beam parameters and assuming a smoothed square pulse with $\tau_p = 1 \mu s$, simulation runs directly implementing the Acoustics Module within the CF-PTFE for vibrational wave propagation yielded non-physical results, with peak pressure values at the front and rear plate faces two and five

orders of magnitude greater than the anticipated values, respectively. From the material property values in Table 4.1, the ratio of the two Lamé's constants in eqns (4.22) and (4.23) implied by v_{pr} is < 0.5 and so fails to meet the fluid-like no shear threshold of eqn (4.26) by a wide margin. Attempts to identify specific causative mechanisms for this behavior through permutations of boundary conditions and inter-module physics couplings were unsuccessful, although some sensitivity to the very steep *SAR* time derivative caused by the square pulse excitation was noted during an iso-fluence pulse rise time sweep. Also, a consistently high pressure gradient across the air-PTFE boundary suggests that an implicit constraint on displacement at the interface may be a contributing factor.

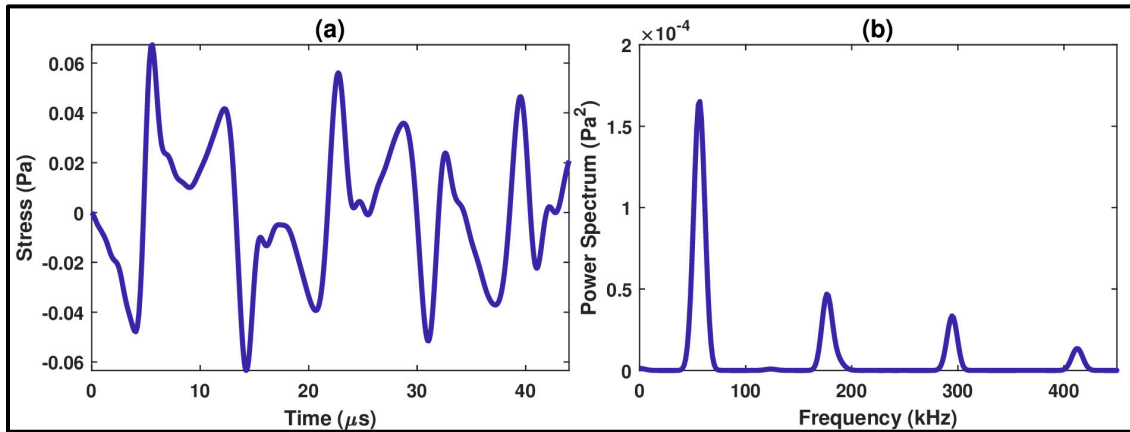


Fig. 4.10. Modeled transient normal component thermoelastic wave as seen at the plate center on the side opposite the incident radiation following a single 1 μ s pulse, 18 GHz microwave frequency and 20 W total input power. Time duration plotted in (a) represents 10 full transits of the plate thickness at the calculated longitudinal speed of sound. Total duration of time-domain signal used for the power spectrum (b) was approximately 200 μ s, with an average sampling frequency of around 4.7 MHz.

Implementing thermoelastic wave propagation through the Solid Mechanics Module with the Acoustics Module limited to simulating pressure waves in the air due to plate displacement yielded much better results. From Fig. 4.10a, peak elastic stress is around half of the value predicted using eqns (4.9) and (4.28). The finite rate of energy deposition drives this decrement in peak stress intensity, as the wave front generated at the start of the incident EM radiation continues to advance through the power penetration region throughout the pulse duration, resulting in less energy deposited into the peak of the elastic wave (Bushnell and McCloskey 1968). A coarse pulse length sweep centered around 1 μ s at the upper range of the evaluated microwave frequency band indicates a factor of two decrease in peak elastic stress with increasing pulse length through to the stress confinement time, with a transition to a much slower $\approx O(\tau_p)^{-1}$ decrease at around 1.7 of this threshold time value. For a beam PRF on the order of kHz, successive EM pulses should be sufficiently separated in time so that the assumption of non-overlapping induced transient thermoacoustic signals is valid. In the frequency domain, as shown in Fig. 4.10b, the first prominent peak outside of the acoustic region occurs at around 55 kHz and so it is not obviously correlated with the time required for the pressure wave to transit the plate and reflect from the PTFE-air boundary. A more detailed eigenfrequency analysis would be necessary to determine what aspects of the problem geometry are contributing to these resonances.

4.4.3 Piezoelectric Response

Effective acoustic coupling requires that the acoustic impedance of piezo sensors used in contact applications be as closely matched to the vibrating target material as possible. PVDF piezoelectric film, comprised of an electric field poled polymer volume sandwiched between printed conductive electrodes, has an acoustic impedance of $\approx 2.7 \times 10^6$ Rayl [$\text{kg/m}^2\cdot\text{s}$] compared to 30 MRayl for lead zirconate titanate (PZT) ceramic piezo sensors (Measurement Specialties Inc. 1999). This tighter impedance match to CF-PTFE's ≈ 3.3 MRayl more than doubles the vibro-acoustic power transmission efficiency, but the electrical properties of thin film sensors present some design considerations when integrated into the detector chain. Since charge is generated in what is effectively a parallel plate capacitor, the input impedance R_i of an acquisition system connected to the sensor will dominate at lower frequencies, resulting in significant attenuation of signal content below a cut-off frequency inversely proportional to both R_{in} and the piezo capacitance C_p , absent suitable conditioning electronics (Measurement Specialties Inc. 1999). For a 30 mm x 16 mm x 5.6 μm PVDF sensor, representative of a shielded design suitable for in-beam applications, a nominal capacitance of $C_p = 2.8$ nF results in a 3 dB roll-off well below those frequencies, as noted in Fig. 4.10b, assuming a high impedance (>1 M Ω) signal acquisition (Measurement Specialties Inc. 2002). Using these characteristics along with built-in material properties from COMSOL's material library, the results of a combined frequency parametric-transient solution sweep

shown in Fig. 4.11 indicate that the peak voltage response of the detector chain relative to peak specific absorption converges to an order of magnitude value of $0.01 \text{ V (J kg}^{-1}\text{)}^{-1}$ at the higher end of the bandwidth.

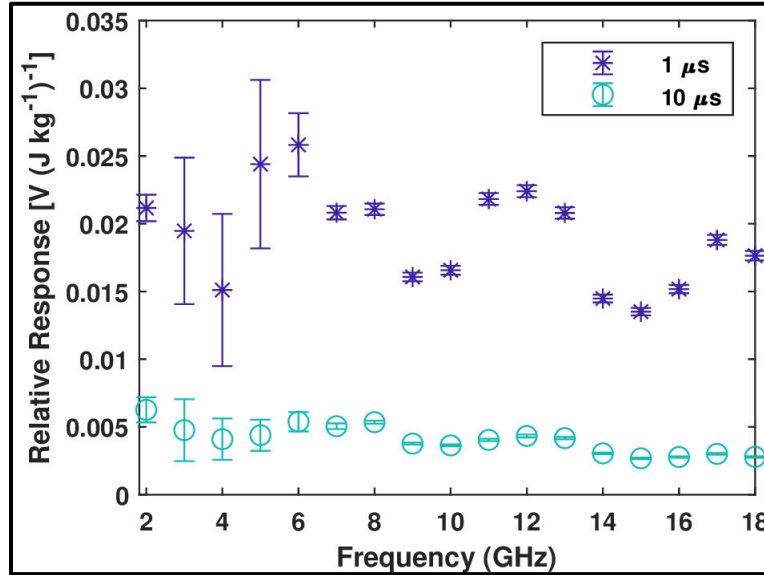


Fig. 4.11. Modeled relative response of TA signal chain as a function of incident microwave frequency for pulse lengths near and above the stress confinement time, computed as the ratio of peak PVDF film piezo voltage to maximum induced specific absorption in the 25% CF-PTFE sample plate.

For a $1 \mu\text{s}$ long square pulse meeting the stress confinement criteria, this equates to an intrinsic sensitivity of $0.01 \mu\text{V (W kg}^{-1}\text{)}^{-1}$ relative to peak SAR and around $0.02 \mu\text{V (mW cm}^{-2}\text{)}^{-1}$ in terms of peak incident power density, applying a 2:1 ratio of $SAR \text{ (W kg}^{-1}\text{)}$ to $S_{int} \text{ (mW cm}^{-2}\text{)}$ suggested by Fig. 4.8. To obtain at least a 10 mV output from an incident wave with a power density of 50 mW cm^{-2} , a basic thermal effects threshold associated with continuous wave exposure at prescribed continuous wave averaging times, a gain of at least 10^4 would be needed for the raw piezoelectric signal through a suitable selection of signal

conditioning components (Institute of Electrical and Electronics Engineers 2019). At $5 \times 10^{-5} \text{ mJ cm}^{-2}$ per $1 \text{ } \mu\text{s}$ pulse, prolonged personnel exposure at this power density and a PRF in the acoustic frequency range would result in a time-averaged *SAR* an order of magnitude or more lower than the thermal effects threshold.

The time-domain waveform depicted in Fig. 4.10 is an idealized case that ignores elastic damping in the material, which will result in an exponential attenuation of the magnitude of the stress wave with total distance traveled in the plate across multiple reflections. The inverse of the ring-down time as measured at the piezo sensor that results from total system damping will determine the maximum PRF that could be detected by the signal chain. The MHz-wide acoustic frequency bandwidth of PVDF piezo film sensors provides a starting point to fully capture the frequency domain response of the TA signal for further characterization (Measurement Specialties Inc. 1999).

4.5 Conclusions

The HPM-induced TA signal chain computational model described herein, informed by measured CF-PTFE material properties, provides a useful tool to explore the impacts of various material properties on TA signal output as a function of simulated beam property parameters such as frequency, pulse length, and incident power density, while also showing the promise of meeting a useful beam energy density sensitivity threshold under stress confinement conditions with appropriate data acquisition electronics. From a component selection

perspective, approximately one power penetration depth across the frequency range of interest provides a starting point for minimum plate thickness to ensure sufficient EM coupling, and frequency domain analysis of the transient TA signal indicates that piezoelectric sensors with bandwidths in the low ultrasound acoustic frequency range are needed to capture the TA output. Increasing plate thickness to three or more power penetration depths would provide clearer visualization of the anticipated bipolar exponential time domain TA waveform but would likely decrease the dominant resonant frequency excited in the plate (Foster et al. 2021). In addition to future work required to incorporate the post-piezo sensor acquisition chain into the simulation and assessing the available pulse length-peak power density trade space inherent in the specific absorption-based response, implementing a time-harmonic frequency sweep using a layered model for human tissue as the absorber would be the next step in linking the TA signal in CF-PTFE to possible thresholds for adverse health effects in personnel. The convergent behavior of specific absorption sensitivity at higher frequencies indicate that the proposed detector chain offers a pulse-sensitive exposure monitoring capability across at least a 16 GHz bandwidth, with additional complex permittivity data needed to confirm if this convergence holds at higher frequencies up through the millimeter wave range.

V. Characterization of a Thermoacoustic-based Pulsed High Power Microwave Detector Chain

This chapter is derived from a paper submitted to the *Health Physics Journal* in May 2022 and accepted for publication in August 2022, modified for consistency with the dissertation format. The collaborating authors are Frey, J., Barnes, R., and McClory, J., and the article is titled, “Characterization of a Thermoacoustic-based Pulsed High Power Microwave Detector Chain.”

Abstract

Detection of microwave-induced TA wave generation was evaluated as a potential technique for detection of high power microwave (HPM) directed energy exposure. Even when HPM is employed for counter-materiel effects, incidental but still potentially harmful personnel exposure is possible. Real-time detection of ongoing exposure with potentially unknown time and frequency domain characteristics is a critical first step in preventing acute health effects by alerting and then enabling the timely use of electromagnetic (EM) energy shielding such as structures and vehicles. Leveraging the TA effect as a field interaction mechanism, a lossy dielectric polymer subjected to pulsed HPM was tested using a planar sample geometry, with thin film piezoelectric sensors used to capture the resulting TA output. The piezoelectric signal was analyzed in both the time and frequency domain to determine empirical relationships between incident microwave beam properties and signal components. This analysis was coupled with an empirically-based single term Cole-Cole model approximation fit for the

complex permittivity. The results were used to identify appropriate signal conditioning and processing techniques needed to convert the TA response into a useful form for personnel exposure applications. These results also served as a comparison point for multi-physics finite element method computational modeling of the electromagnetic response of a simplified three-layer tissue model.

5.1 Introduction

5.1.1 General Issue

Continued advancement in directed energy weapons (DEWs), in both military and the commercial applications, has resulted in increased interest in protection of personnel from DEW effects across all potential wavelengths. The use of HPM electromagnetic DEWs is an area of particularly active development, as HPM radiation in select frequency bands offers reduced atmospheric attenuation when compared to high energy laser DEWs and can be employed for non-lethal personnel and reversible counter-materiel effects of interest in select force protection applications (crowd control, counter-unmanned aircraft systems, etc.) (Tatum 2017). DEW detection is a necessary precondition for managing potential operational personnel exposure, providing the needed alert mechanism to minimize the risk of acute adverse health effects through the use of field expedient EM radiation shielding provided by structures or vehicles.

Thermoacoustic-based pulsed microwave detection offers a potential approach to determining EM energy personnel exposure across frequency and peak power

density ranges for which commercial EM field meters or personal monitors may not be suited or are currently unavailable.

5.1.2 Thermoacoustic Pressure Amplitude

Thermoacoustic wave generation results from the thermal expansion of material subject to microwave radiation, where a small temperature increase results in a peak pressure change than can be modeled as a restated eqns (4.8) and (4.9)

$$p_0 = \beta_{th} \rho v_l^2 \frac{SAR}{C_p} \tau_p = \Gamma SAR \rho \tau_p, \quad (5.1)$$

where p_0 (Pa) is the pressure, β_{th} (K^{-1}) is the coefficient of volumetric thermal expansion, ρ ($kg\ m^{-3}$) is the mass density, v_l (m/s) is the longitudinal speed of sound in the medium, c_p [$J\ (kg\ K)^{-1}$] is the specific heat, and SAR ($W\ kg^{-1}$) is the EM-induced specific absorption rate in the material (Singhvi et al. 2019). The unit-less Grüneisen parameter Γ combines the thermal and elastic properties of the material into a single factor and the peak pressure expressed in eqn (5.1) assumes that a rectangular HPM pulse width duration τ_p (s) meets the thermal confinement condition such that EM heating during a given pulse occurs on timescales much shorter than is required for thermal diffusion (Gournay 1966).

For the case of an EM beam normally incident on a semi-infinite half space of target material, the spatial SAR distribution follows an exponential decay model with increasing distance from the interface. For a non-magnetic absorber, it is characterized by the power penetration depth δ_{pd} (m) as a function of

frequency f (Hz) and the real and imaginary components of the complex relative permittivity $\epsilon_r^* = \epsilon' - i\epsilon''$ so that

$$\delta_{pd} = \frac{1}{2\sqrt{2}\pi f \sqrt{\mu_0 \epsilon_0} \left[\sqrt{(\epsilon')^2 + (\epsilon'')^2} - \epsilon' \right]^{\frac{1}{2}}}, \quad (5.2)$$

where μ_0 (H m⁻¹) and ϵ_0 (F m⁻¹) are the permeability and permittivity of free space, respectively (Yoshikawa et al. 2015). Eqn (5.2) represents the distance over which the internal EM power density S_{int} (W m⁻²) decreases by e⁻¹ and is half the value of the skin depth δ_{skin} (m). Some fraction of the free field power density incident on the material surface S_{inc} (W m⁻²) will be reflected at the air interface instead of absorbed, which in terms of complex permittivity is

$$\Gamma_P = |\Gamma_E|^2 = \left| \frac{\sqrt{\frac{1}{\epsilon_r^*}} - 1}{\sqrt{\frac{1}{\epsilon_r^*}} + 1} \right|^2 = \frac{-\sqrt{2 \left(\sqrt{(\epsilon')^2 + (\epsilon'')^2} + \epsilon' \right)} + \sqrt{(\epsilon')^2 + (\epsilon'')^2} + 1}{\sqrt{2 \left(\sqrt{(\epsilon')^2 + (\epsilon'')^2} + \epsilon' \right)} + \sqrt{(\epsilon')^2 + (\epsilon'')^2} + 1}, \quad (5.3)$$

where the real-valued power reflection coefficient Γ_P is the square of the modulus of the complex-valued electric field reflection coefficient Γ_E (Schultz 2012). For planar materials of finite thickness of up to several power penetration depths, some portion of S_{inc} will reach the far side and be transmitted through the target. Treating the interaction from a shielding perspective, the total EM power balance incorporating both reflection and transmission losses relative to S_{inc} is then

$$1 - \Gamma_P = A_P + T_P, \quad (5.4)$$

with A_P and T_P representing the power absorption and transmission coefficients, respectively, and neglecting a multireflection component that only becomes

significant at material thicknesses less than δ_{pd} (Kondawar and Modak 2020). For fluids, or for solids under a uniaxial strain condition as described here, combining eqns (5.1), (5.2), and the left-hand side of (5.4) results in eqn (5.5) as a bounding value for the peak TA pressure or elastic stress. This relationship is in terms of a generally dispersive complex relative permittivity and the fraction of the free field power density not reflected at the interface which, as implied by eqn (3), is also dispersive (Oraevsky et al. 1997).

$$p_0 = \Gamma(1 - \Gamma_p) \frac{S_{inc}}{\delta_{pd}} \tau_p \quad (5.5)$$

The exponential SAR-depth profile results in a bi-phasic pressure waveform launched into the material, with a leading edge representing the initial forward traveling compressive pulse and a trailing tensile edge resulting from the reflection of the backwards traveling pulse at the free acoustic boundary. At some distance well beyond the power penetration depth δ_{pd} , the spatial profile of the TA pulse at time t (s) centered about position x' (m) takes the form of

$$p = \frac{p_0}{2} f_{eff}(r_{sc}) \begin{cases} -e^{\frac{x'}{\delta_{pd}}}, & x' < 0 \\ e^{-\frac{x'}{\delta_{pd}}}, & x' > 0 \end{cases} \quad (5.6)$$

where $x' = t v_l$ and the unit-less f_{eff} is an efficiency function of r_{sc} , the ratio of the pulse width to the stress confinement limit τ_{sc} (s) (Gusev and Karabutov 1993).

The power penetration depth defines τ_{sc} , as pressure generated in some infinitesimally narrow region near the incident air-material interface takes time to traverse δ_{pd} , therefore

$$\tau_{sc} = \frac{\delta_{pd}}{v_l}. \quad (5.7)$$

The asymptotic behavior of f_{eff} is to converge to unity for small values of r_{sc} ($r_{sc} \ll 1$) and to scale with $(r_{sc})^{-1}$ for large values ($r_{sc} \gg 1$), representing pulse widths well within and well beyond the stress confinement limit, respectively, and with peak pressure magnitudes well below the nominal upper bound of $p_0/2$ for the latter case.

These physical relationships and models were applied to the field of clinical diagnostic imaging, primarily via photoacoustic (PA) modalities which combine laser excitation of surface tissue with ultrasound image reconstruction techniques (Xia et al. 2014). Non-medical TA and PA application studies have greater flexibility in the selection of frequency (or wavelength) and the targeting of dielectric properties to optimize TA signal generation, either through tailoring beam properties when evaluating novel target materials or using well-characterized materials to analyze some unknown beam parameter. Nanoscale metallic films deposited on quartz substrates have been used successfully to capture EM pulses in the 1-100s of GHz frequency region, although a liquid medium thermally coupled to the radiofrequency (RF) absorber was needed to generate the TA pulses and transmit it to the piezoelectric acoustic sensor (Andreev et al. 2014). Non-clinical TA applications such as this assume prior knowledge of at least some of the incident EM radiation parameters, which may not be available the case in DEW exposure assessments.

5.1.3 Current Work

The current research seeks to characterize the piezoelectric response of a TA-based detection chain to assess the feasibility of this technique in pulsed HPM force health protection applications, with a key focus on the 2-110 GHz microwave frequency range and peak *SAR* as the personnel exposure endpoint. A limited subset of potential beam parameter combinations of incident power density and pulse length were applied within this bandwidth, with frequency-pulse length permutations both well within and well beyond the stress confinement condition. Carbon-filled PTFE in a planar geometry was used as the lossy dielectric target volume based on its relatively high power absorption coefficient within the frequency range of interest and its use as a microwave absorber in millimeter wave RF dosimetry applications (Allen and Ross 2007). As significant gaps exist in the literature on the broadband properties of this material as a function of the levels of carbon fill (% weight), laboratory measurements and model-based extrapolation were conducted to determine reasonable permittivity values for use in the analysis of TA response. The measured piezo signal was analyzed in both the time and frequency domain to determine empirical relationships between signal amplitude, acoustic frequency components, and incident microwave beam properties.

5.2.1 Experimental Approach

The diagram illustrates the experimental setup for measuring the dielectric properties of a PVDF film. The setup is divided into two main functional areas, indicated by dashed boxes.

Left Section (Signal Generation and Emission):

- An **HPM Source** provides input to an **Amplifier**.
- The **Amplifier** is connected to an **RF Emitter**.
- A **Signal Generator** is also connected to the **RF Emitter** and has a direct line to the **Oscilloscope** in the right section.

Central Interaction Region:

- A **Microwave Pulse** is directed towards a **CF-PTFE** probe.
- The **CF-PTFE** probe is positioned adjacent to the **PVDF Film Sensor**.
- An **Attenuated EMF Signal** is generated by the PVDF film sensor upon interaction with the microwave pulse.

Right Section (Signal Processing and Measurement):

- The **Attenuated EMF Signal** is captured by the **Signal Conditioning** unit.
- The **Signal Conditioning** unit is connected to the **Oscilloscope**.
- The **Oscilloscope** is connected to the **Data Acquisition** unit.
- The **Data Acquisition** unit is connected to a **TD** (Time Delay) unit and an **FD** (Frequency Divider) unit.
- There is a bidirectional connection between the **TD** and **FD** units.

For a given microwave frequency, a linearly polarized pulsed RF signal is generated, amplified, then emitted so as to be normally incident on a sample target plate of amorphous CF-PTFE as the bulk polymer matrix (Queen City Polymers, West Chester, OH) The carbon fill for a given sample, cut to lateral size from the procured 610 mm x 610 mm x 6.5 mm (2 ft x 2 ft x ¼ in) plates, was assumed to be homogenously dispersed within the material and the percent fill by mass taken as provided by the vendor. A thin film PVDF piezoelectric film sensor, comprised of an electric field poled polymer volume sandwiched between

printed conductive electrodes, was mechanically coupled to the target plate so that the electromagnetic (EM)-induced TA pulse generates mechanical deformation in the sensor, thereby producing a time varying piezoelectric charge in response to the vibrational excitation. This resulting signal was conditioned to both amplify and filter its frequency content, then captured by the oscilloscope using an appropriate external voltage signal as a trigger to center the time window about the rising edge of the compressive TA pulse. The Fast Fourier Transform was used to evaluate the resonant frequency domain (FD) components of the time domain (TD) acoustic signal, both in real time via oscilloscope math functions and later as one of several steps during data analysis.

5.2.2 Complex Permittivity Measurements

A tabletop focused beam system (TT-FBS) (Thomas Keating Ltd, West Sussex, England, UK), leveraging curved reflectors and using thin nominally 6.5 mm thick (1/4 in) sample plates, was used to obtain free-space 2-port scattering parameters across the 18-110 GHz frequency range, supplementing existing 2-18 GHz data (Frey et al. 2022). As the various bands covered by the TT-FBS required different combinations of microwave horns, reflectors and sample mounts, scattering parameters below 67 GHz were obtained using nominally 305 mm x 305 mm (12 in x 12 in) samples, while sample dimensions for data above 67 GHz were 152 mm x 152 mm (6 in x 6 in). Signal generation and monitoring was implemented using an Agilent Technologies 5227A network analyzer

(Agilent Technologies, Santa Clara, CA) with millimeter wave (mm Wave) frequency extenders as needed.

For input signal ‘a’ and received signal ‘b’ from each emitter, the coefficients S_{ij} of the sample scattering matrix S are defined as the ratio of the signal received at port i to that transmitted at port j , resulting in the linear system of equations already defined but restated here as (Schultz 2012)

$$\mathbf{b} = \mathbf{S}\mathbf{a} . \quad (5.8)$$

The frequency-dependent S-parameters, usually expressed in dB, were obtained from the voltage ratios following calibration to account for horn and cable losses and phase errors and are related to the electric field interaction coefficients. A value of the complex permittivity is therefore obtainable through suitable iterative inversion algorithms, noting that S is approximately symmetric for thin samples and that the square of the linear S_{11} and S_{22} parameter magnitudes are both equal to the power reflection coefficient as shown in eqn (5.9) (Kondawar and Modak 2020).

$$|S_{11}|^2 = \left(10^{\frac{|S_{11}|_{dB}}{20}}\right)^2 = 10^{\frac{|S_{11}|_{dB}}{10}} \approx |S_{22}|^2 \approx \Gamma_p. \quad (5.9)$$

Similarly, the complement of the linear sum of the squares of S_{11} and the transmission S_{21} parameter provides a measure of the fraction of beam power absorbed in the sample plate, as implied by eqn (5.4).

5.2.3 High Power Microwave Sources

Due to the much higher pulsed power output and commensurate increase in technical complexity, a description of the RF generation component chain for the single frequency S-band and mm Wave high intensity HPM sources used for TA excitation is beyond the scope of this work (Hurt et al. 2004). However, once generated, EM pulses for both systems were emitted through open ended waveguides (OEWs) of appropriate dimensions for their operating frequency, with targets centered on and perpendicular to the beam axis and at sufficient distance to be in the far field of the OEW. The radiation-absorbent material lining the source anechoic chambers was of sufficient thickness so that any reflected EM radiation from the chamber walls impinging on the target were treated as negligible. Both sources supported variable peak power output by means of a mechanically adjustable input voltage. For the S-band system, a separate, low amplitude trigger voltage for RF generation initiation was used for oscilloscope timing, while for the mm Wave system, the voltage signal from a diode detector connected to the waveguide via directional coupler served that purpose. As the maximum peak power output of the mm Wave source was approximately three orders of magnitude lower than that of the S-band system, a greater dynamic range of power density values was scanned by obtaining TA data at three source-sample separation distances, versus the single position used for the S-band. A summary of the key operating characteristics of the two high-intensity sources is shown in Table 5.1.

Table 5.1. Summary of relevant beam parameters of microwave sources used for TA excitation. The nominal power output P_{nom} values indicate peak power, proportional to the average power via the inverse of the duty factor (Hurt et al. 2004).

Source	f_{nom} (GHz)	τ_p (μ s)	P_{nom} (kW)	PRF (Hz)
S-band	2.8	0.5, 1, 2	2000	50
mm Wave	94	≥ 0.5	4	50

5.2.4 Target Plate Assembly

For the 1-D TA wave model described above, an initial compressive wave of constant magnitude across the plate (i.g. in the y-z plane) is launched in the thickness direction (x-axis). In order to convert this x-direction stress into lateral strain within the PVDF film and so generate a charge signal of sufficient amplitude for analysis, SDT-1 (Measurement Specialties, TE Connectivity, Hampton, VA) and PKS--050010-Pin-1 (PolyK, State College, PA) rectangular sensors of approximately 10 μ m width (z-direction) were laminated near the center of a nominally 305 mm x 305 mm x 3.2 mm (12 in x 12 in x 1/8 in) polycarbonate backing plate using 10 μ m thick acrylic tape. The polycarbonate plate was clamped under slight tension over the rear of a nominally 152 mm x 152 mm x 6.5 mm (6 in x 6 in x 1/4 in) CF-PTFE sample using an aluminum mount plate and frame. In this configuration, depicted in Fig. 5.2, the TA pulse in the target plate pushes the polycarbonate backing plate, driving the piezo film in the d_{31} mode corresponding to tensile stress in the y-direction to which it is much more sensitive as compared to z-direction d_{33} mode (Measurement Specialties

Inc. 1999). During TA response evaluation, the target assembly was placed as a unit into the beam path, mounted at the zero plane via an aluminum frame for the S-band and mm Wave sources.

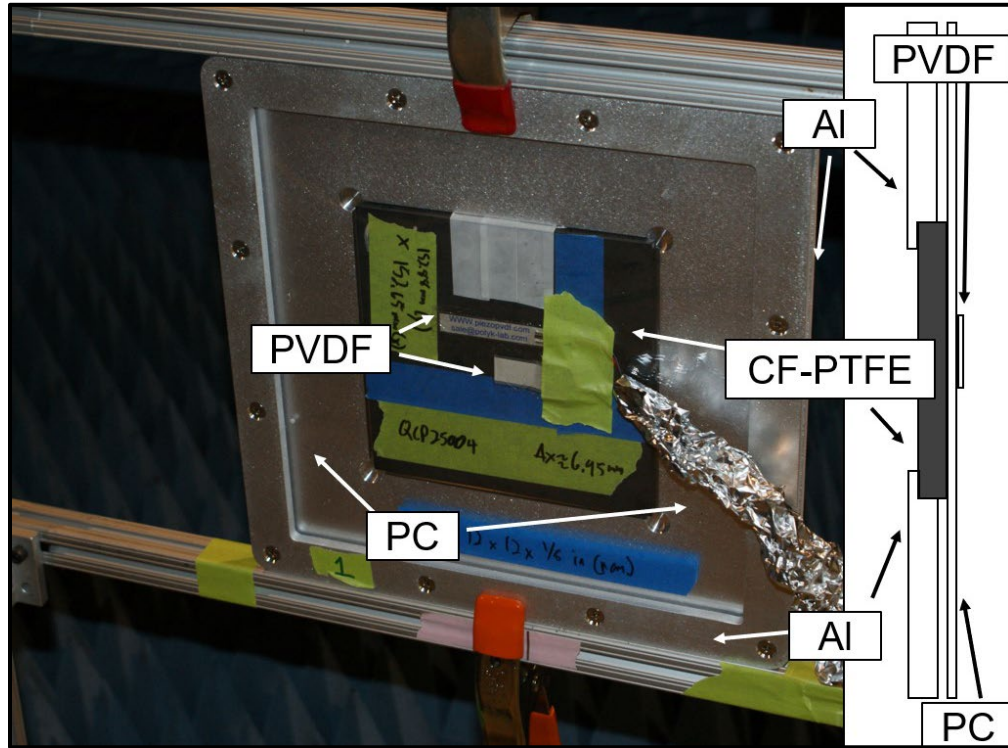


Figure 5.2. Target plate assembly comprised of a carbon-filled (CF-PTFE) absorber plate, polycarbonate (PC) backing plate, aluminum (Al) aperture plate, and PVDF thin-film piezo sensors (PVDF), mounted in test stand. The photo depicts the rear view of the unit (-x-direction), opposite the HPM incidence plane, while the inset line drawing shows a side view cutaway (y-direction).

5.2.5 Data Acquisition

The equivalent circuit model of PVDF film sensor connected to an acquisition system is that of a capacitor C_p in parallel with input resistance R_i , resulting in significant attenuation of signal content below the cut-off acoustic frequency,

$$f_c = \frac{1}{2\pi R_i C_p}. \quad (5.10)$$

To afford greater control over the input signal gain and detector frequency response, a Measurement Specialties Piezo Film Lab Amplifier operated in charge mode was used in-line prior to signal capture by the logging oscilloscope, thereby incorporating single charge amplifier, bandpass filter, and voltage amplifier stage into the chain. The initial gain of the output signal, along with the frequency response from eqn (5.10), is then controlled by the feedback resistance R_f and feedback capacitance C_f of the charge amplifier stage instead of the respective piezo sensor values. The passband window roll-off frequencies were set at their highest respective values, 1 to 100 kHz, in order to reduce the impact of acoustic noise from the ambient environment while capturing as much low ultrasound (> 20 kHz) signal as possible. Using a fixed feedback capacitance, voltage gain was adjusted depending on the microwave source in order to maximize signal amplitude but to avoid saturating the operational amplifiers that comprise the stages. The conditioned piezo signal was recorded on an Agilent Technologies Infinium DSO9254A digital oscilloscope, with 256 waveform acquisition averaging set for both instruments to further reduce background noise. Shielded enclosures for the piezo amplifiers and aluminum foil wrapping for cable leads were used to protect electronic components during EM irradiation and minimize spurious electromagnetic interference (EMI) signals from conditioning components in the recorded waveform data.

5.3 Results

5.3.1 Electromagnetic Property Extraction

The Materials Measurement Suite (Keysight Technologies, Colorado Springs, CO) microwave system control package was used on the network analyzer to iteratively compute EM properties from measured S-parameters. The approach used a transmission-based permittivity recovery algorithm under the assumption that as a non-magnetic sample material $\mu \approx \mu_0$ at all frequencies within the bands analyzed. The mean and relative uncertainty of measured permittivity values for each sample type were calculated from ten successive cycles of measurement and EM property extractions at a system output power of 0 dBm (1 mW) and with full unmounting and remounting of the sample between each iteration. The physical dimensions of the CF-PTFE sample plates, selected to ensure adequate EM thickness at lower microwave frequencies for EM energy absorption, proved to be an impediment during permittivity measurements at higher frequency bands. As implied by eqn (5.2), δ_{pd} decreases approximately in inverse proportion with frequency so that above some sample-specific threshold, in the > 67 GHz range in the case of the 15% and 25% CF-PTFE samples studied here, the transmission S-parameters S_{12} and S_{21} begin to approach the noise floor of the network analyzer. The large order of magnitude difference in reflection vs. transmission parameters resulted in either non-physical results in the case of the algorithm used here or iterative non-convergence when other numeric approaches were attempted.

For many dielectric polymer and biological materials, the Cole-Cole empirical relaxation model provides a method to predict complex permittivity ε^* at an arbitrary frequency via the expression

$$\frac{\varepsilon^*(\omega)}{\varepsilon_0} = \varepsilon_r^* = \varepsilon_\infty + \frac{\varepsilon_{DC} - \varepsilon_\infty}{1 + (i\omega\tau_{rel})^{\beta_{skew}}} , \quad (5.11)$$

where $\omega = 2\pi f$ is the angular frequency, ε_{DC} and ε_∞ are the limiting values of the real relative permittivity at zero (i.e. direct current) and infinite (i.e. THz) frequency, respectively, τ_{rel} is a characteristic relaxation time that is the inverse of the frequency at which imaginary permittivity is at a local maximum, and β_{skew} is a distribution parameter between 0 and 1 indicating the extent to which the permittivity is skewed from a perfect circle when plotted in the complex plane (Ojha et al. 2019). At frequencies well beyond the relaxation region, the magnitude of the imaginary term in the denominator of eqn (5.11) becomes much larger than unity, such that

$$\varepsilon_r^* \approx \varepsilon_\infty + \frac{\varepsilon_{DC} - \varepsilon_\infty}{(i\omega\tau_{rel})^{\beta_{skew}}} = \varepsilon_\infty + \Delta\varepsilon(i\omega\tau_{rel})^{-\beta_{skew}}. \quad (5.12)$$

Taking the real and imaginary components of the complex relative permittivity of eqn (5.12) yields the power law approximations $y = ax^b + c$ and $y = ax^b$ where

$$\varepsilon' = \text{Re}\{\varepsilon^*\} \approx (\Delta\varepsilon)\cos\left(\frac{\beta_{skew}\pi}{2}\right)(2\pi\tau_{rel})^{-\beta_{skew}}(f)^{-\beta_{skew}} + \varepsilon_\infty = a_1f^b + c \quad (5.13)$$

and

$$\varepsilon'' = \text{Im}\{\varepsilon^*\} \approx (\Delta\varepsilon)\sin\left(\frac{\beta_{skew}\pi}{2}\right)(2\pi\tau_{rel})^{-\beta_{skew}}(f)^{-\beta_{skew}} = a_2f^b. \quad (5.14)$$

With the exception of out-of-band perturbations and transition regions between

data captured with different horn configurations, both the real and imaginary permittivity data for the 25% CF-PTFE decreased monotonically throughout the 2-67 GHz useful measurement range. Treating that as an indication that the relaxation time constant corresponded to a frequency well below the range of interest for this study, the value of ε_∞ was obtained from the value of ε' at the ε'' intercept via a linear fit to the data plotted in the complex plane using MATLAB's Curve Fitting Toolbox ((MathWorks, Inc., Natick, MA). A nonlinear regression fit to eqns (5.13) and (5.14) using the same toolset over a reduced frequency range (< 60 GHz) was then used to generate single relaxation Cole-Cole model power law approximations for the material, with the final band (60-67 GHz) used to validate the fit. The resulting equations were then used to extrapolate beyond the microwave frequency where target absorption precluded permittivity data extraction out to the 110 GHz upper bound nominally covered by the table top focused beam system and up to which additional dispersions are absent in the PTFE matrix (Chang et al. 2018). The results of this analysis are depicted in Fig. 5.3, which summarizes the available permittivity results using Cole-Cole model fit, and in Fig. 5.4, which shows the effect this dispersion has on the power penetration depth, stress confinement time, and power reflection coefficient. Coefficients of the two-term power law fit for the real relative permittivity of the form $y(x) = a_1x^b + c$ were $a_1 = 8880$, $b = -0.284$, and $c = 9.93$, while the complex permittivity single term power law ($y(x) = a_2x^b$) coefficient not shared with the real permittivity component was $a_2 = 4080$. The ratio of $1-\Gamma_P$ to δ_{pd} ranges from ≈ 40 to ≈ 1000 over the bandwidth presented here, which from eqn (5) indicates that for a

given incident power density, higher frequency HPM will yield greater TA pulse amplitudes assuming stress confinement can be maintained. Of note, this extrapolation process was not attempted for the 15% CF-PTFE sample, as the shape of the Cartesian and complex plane plots of the permittivity data did not support the high frequency limit assumption described by eqn (5.12).

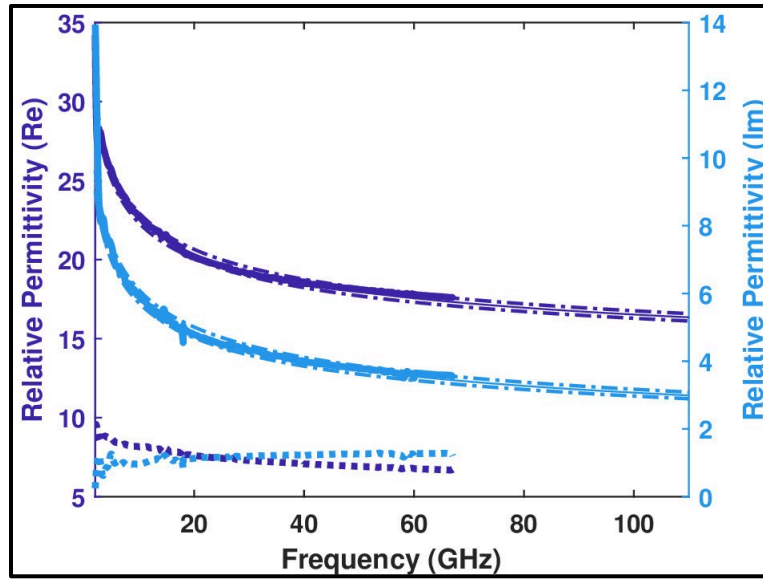


Fig. 5.3. Real (Re) and imaginary (Im) components of the complex relative permittivity for 25% CF-PTFE obtained via focused beam S-parameter analysis from 2 to 67 GHz and associated single pole Cole-Cole permittivity model approximation fit. Plot legend entries are —25% CF-PTFE data, - -25% CF-PTFE mode fit, with line colors corresponding to either the Re or Im y-axis. The relative error of the model fit estimated from validation band data was 0.02 (real) and 0.03 (imaginary). Empirical permittivity values for 15% CF-PTFE (· ·) are included for comparison purposes.

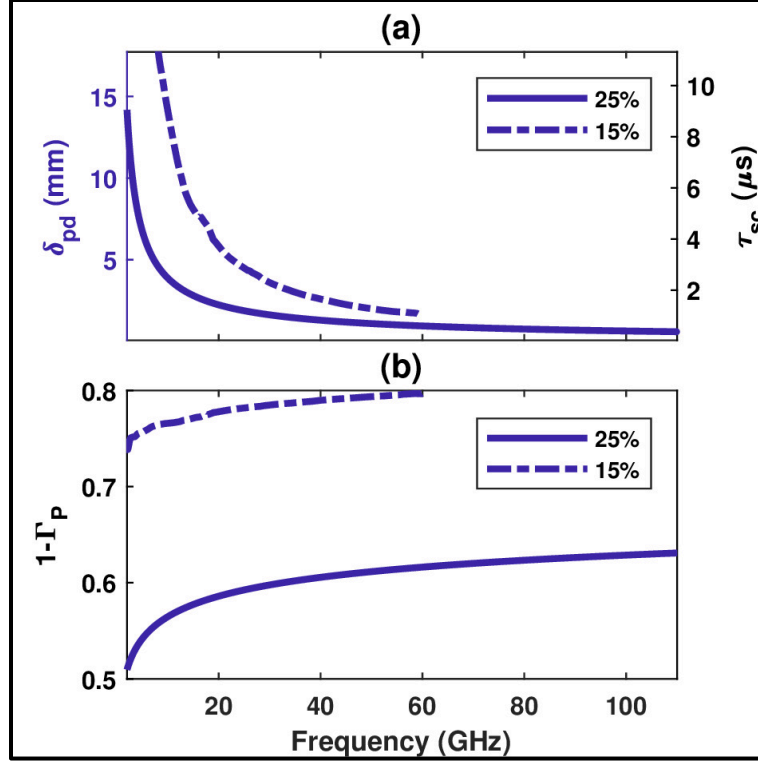


Fig. 5.4. Computed power penetration depth δ_{pd} **(a)** and fraction of incident power density available for TA conversion **(b)** as a function of microwave frequency for 25% CF-PTFE, based on Cole-Cole approximation fits to experimental permittivity data and assuming a plane normally incident on an electromagnetically thick sample. The maximum value of the relative uncertainty is 0.03 for power penetration depth and 0.001 for the complement of the power reflection coefficient, both of which occur at the upper bound of the frequency range. The stress confinement time τ_{sc} scale on the right y axis of **(a)** is computed as the ratio of δ_{pd} and the longitudinal speed of sound of $v_l = 1566 \text{ (m s}^{-1}\text{)}$, with a relative uncertainty also around 0.03.

5.3.2 High Power Microwave Response

The simple 1-D model of TA wave generation described by eqn (5.6) assumes target material of infinite depth such that the only contribution to the pressure signal is from the pulse during its initial transit. For material of finite depth, the piezo voltage signal recorded at the oscilloscope represents serial

convolutions of the response functions of the various stages in the TA detection chain described above, from elastic reflections inside the target through electromechanical coupling to the film sensor to charge collection and amplification during signal conditioning. About a given characteristic acoustic frequency, the detection chain can be modeled as a single degree of freedom system (SDOF), with the aggregate response to a pulsed mechanical excitation being a damped harmonic oscillator. Such behavior was observed during S-band irradiation across four target types, as shown in Figs. 5.5a and 5.5b, with differing sensitivities noted depending on the combination of plate material and pulse width.

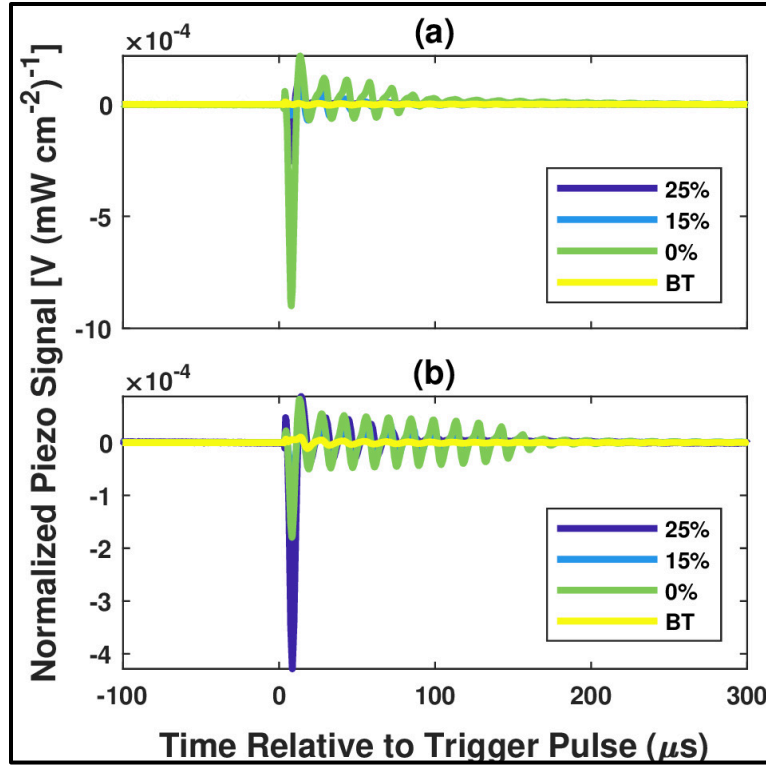


Fig. 5.5. Comparison of time domain relative piezoelectric response of target assembly with absorber plates of three levels of carbon-fill and with no plate installed (bare target, BT), taken at pulse durations of $\tau_p = 0.5 \mu\text{s}$ **(a)** and $2 \mu\text{s}$ **(b)**. The increased duration of the damped acoustic waveform for virgin PTFE due to higher order harmonics in the signal conditioning amplifier is visible in **(b)**.

As virgin PTFE is essentially lossless at frequencies of GHz to THz, the large peak magnitude of the 0% CF-PTFE sample relative to that of 25% at $\tau_p = 0.5 \mu\text{s}$ indicated some direct coupling of the PVDF film to the EM field (Chang et al. 2018). For the 15% and 25% carbon fill plates, increasing the pulse width increased the magnitude of the peak response, although not in direct proportion. Comparing the available pulse widths for the S-band source in Table 5.1 to Figs. 5.4a and 5.4b, the stress confinement condition was met by all CTFE sample types but physical sample thicknesses were all substantially less than the

associated δ_{pd} in the S-band. Under this condition, the multiple reflection component of the electric field distribution is no longer negligible. The resulting standing wave resonances can substantially alter the relative magnitudes of the power reflection and transmission coefficients, providing a reason as to why the virgin PTFE plate produced a larger response compared to the bare target permutation with only the polycarbonate backing plate separating the sensor from the incident beam (Dassan et al. 2020). This is in marked contrast to the 25% CF-PTFE mm Wave excitation case, as the much smaller power penetration depth relative to sample thickness resulted in a power transmission coefficient near the noise floor as previously noted and thus resulted in a piezo signal driven completely by the TA pulse in the sample.

5.4 Discussion

5.4.1 Piezo Signal Distortion

Further review of Fig. 5.5b presents an additional consideration that may preclude accurate estimation of the EM environment from a TA piezoelectric pulse train. In addition to the obvious sawtooth behavior of the damped acoustic waveform, in the time domain this deviation from expected behavior also manifested as a noticeable increase in the bias voltage underlying the observed piezoelectric signal, which at higher power densities became twice as high as compared to low-signal baseline values. Figs. 5.6a and 5.6b show a comparison between 25% and 0% CF-PTFE in the frequency domain.

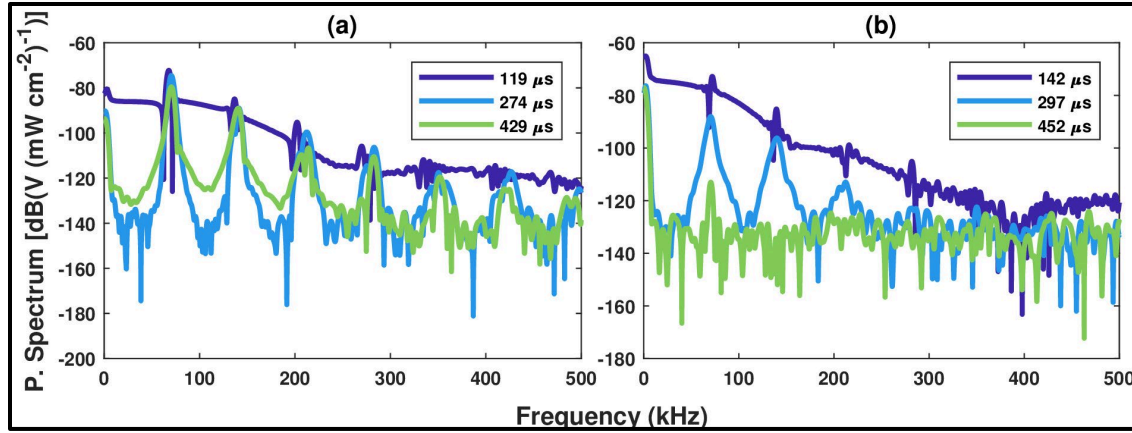


Fig. 5.6. Time weighted Fourier transform (TWFT) representations of $\tau_p = 2 \mu\text{s}$ S-band relative response waveforms from Fig. 5, comparing the acoustic frequency response of 25% CF-PTFE **(a)** and 0% fill PTFE **(b)**. Legend entries indicate the center of the moving time window over which TWFTs were computed.

Energy deposited in the plate over the $2 \mu\text{s}$ pulse duration resulted in excitation of a resonant low ultrasound mode at $\approx 70 \text{ kHz}$ along with many of its higher order harmonics. Although operating at the same resonant frequencies, the modes decay much more rapidly in the virgin PTFE compared to 25% CF-PTFE, suggesting a mechanical excitation in the latter case beyond just the initial electromagnetic interference signal. As the magnitude of damping scales with frequency, these harmonics decay more quickly than the primary mode and the collective behavior was to elongate the pulse beyond the simple exponential time decay region (Casiano 2016). Attenuation of these additional modes occur more rapidly in the case of the 0% PTFE sample in Fig. 5.6b, resulting in a TD waveform that more closely matches the SDOF idealized response to periodic excitation. From a detection perspective, this extended damping time directly impacts the ability to resolve and analyze a given TA pulse for EM exposure

purposes, setting a trade-space of power density and beam pulse repetition frequency outside of which error due to signal processing challenges would substantially increase. To a great extent this can be resolved via the use of an absorber target of greater electromagnetic thickness, reducing the direct excitation electromagnetic interference (EMI) component of the signal and restoring greater proportionality with areal energy density (fluence) instead of areal power density (flux).

5.4.2 Pulse Width Sensitivity

Since TA waveform generation during 94 GHz pulsed microwave irradiation of 25% CF-PTFE presents a very close approximation of the 1-D semi-infinite half-space case assumed above, the variation in waveforms with increasing pulse width as depicted in Fig. 5.7a shown below provides some insight needed to address the issue of pulse magnitude sensitivity to the stress confinement ratio r_{sc} . Returning to eqns (5.5) and (5.6) and focusing on the leading compressive edge of the initial pulse, the 1-D TA waveform generated by an arbitrary microwave pulse shape can be expressed as the convolution of the exponential decay impulse response function of the target and the time domain microwave modulation function $f(t)$ such that

$$p = \frac{\Gamma(1 - \Gamma_P)}{2} \frac{S_{inc}}{\delta_{pd}} \int_{-\infty}^{\infty} f(t) e^{\frac{v_l}{\delta_{pd}}(\tau-t)} dt, \quad \text{where } \tau < t \quad (5.15)$$

and where τ is a reduced time taking into account time of flight. It is negative for the leading edge of the wave and time (t) is the inverse of the product of distance

and the speed of sound (Gusev and Karabutov 1993). Assuming a rectangular pulse as before, $f(t) = 1$ during the pulse and 0 at all other times, reduces the limits of integration in eqn (5.15) to $[0, \tau_p]$. After evaluation, this results in an expression with dependency on the pulse width ratio, r_{sc} , as shown in eqn (5.16).

$$p = \frac{\Gamma(1 - \Gamma_p) S_{inc}}{2 \delta_{pd}} \left[\tau_{sc} \left(1 - e^{-\left(\frac{\tau_p}{\tau_{sc}}\right)} \right) \right] e^{\left(\frac{\tau_p}{\tau_{sc}}\right)} = \frac{p_0}{2} \left[\frac{1}{r_{sc}} (1 - e^{-r_{sc}}) \right] e^{\frac{x}{v_l \tau_{sc}}} \quad (5.16)$$

The quantity in square brackets in eqn (5.16) represents the pulse width conversion efficiency function

$$f_{eff}(r_{sc}) = \frac{1}{r_{sc}} (1 - e^{-r_{sc}}) \quad (5.17)$$

given in eqn (5.6), with asymptotic behavior already described. For an incident power density that scales inversely with pulse width to maintain a constant fluence, the aggregate response for eqn (5.16) when the magnitude of r_{sc} is much smaller than unity is to converge to $p_0/2$, while pulse widths much larger than the stress confinement time result in a peak pressure bounded by the stress confinement time of the material.

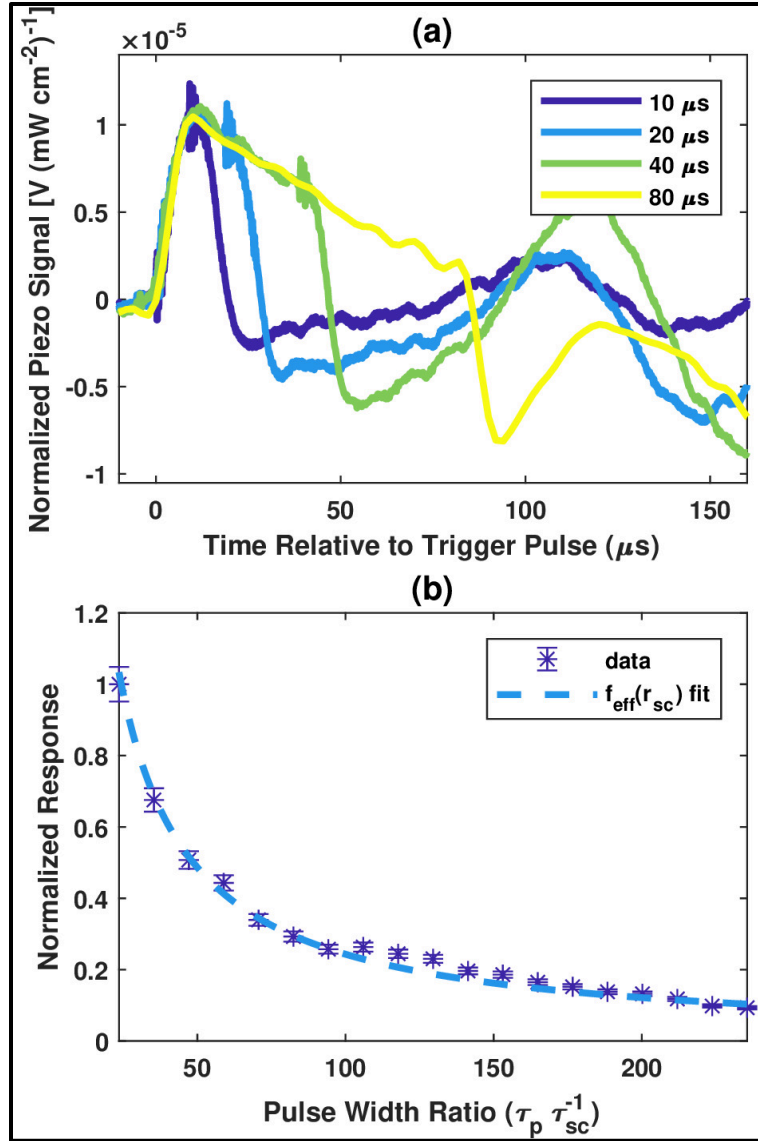


Fig. 5.7. Thermoacoustic response of target assembly under 94 GHz mm Wave irradiation at the nearest of three source separation distances with select pulse durations between 10 and 100 μ s. In (a), the consistent peak amplitude of the leading edge of the TD waveforms show that TA pulse generation is occurring well outside the stress confinement condition. In (b), normalized response as a function of the pulse width ratio r_{sc} is fitted to eqn (5.18), with a factor of 24 estimated as the ratio of the stress confinement signal amplitude to the one measured at of $\tau_p = 10 \mu$ s as provided by the single fit parameter in the numerator.

In Fig. 5.7a, the initial peak voltage response amplitude following the trigger corresponds to the elastic pulse's first incidence at the target plate where it is coupled into the polycarbonate backing plate. At a fixed power density as used here, this peak magnitude was essentially constant across the decade of pulse width durations tested. Normalizing these peak amplitudes to the fluence at which they occurred and plotting them as a function of the pulse width ratio, as depicted in Fig. 5.7b, shows good agreement with the 1-D model response model summarized by eqn (5.17). As the data was scaled to the maximum value in range, the single parameter in the fitted curve

$$y(x) = \frac{a}{x} (1 - e^{-x}) \quad (5.18)$$

allows extrapolation back to the stress confinement region ($r_{sc} < 1$) as a multiple of the response sensitivity at the shortest measured $\tau_p = 10 \mu\text{s}$, for a peak sensitivity of around $3.1 \text{ V (J m}^{-2}\text{)}^{-1}$ ($3.1 \cdot 10^4 \text{ mV (mJ cm}^{-2}\text{)}^{-1}$). Using this response relationship in support of EM exposure detection would then require values for the stress confinement time, derived from δ_{pd} , and the pulse width, which for the case where HPM source parameters are unknown can be estimated via signal processing of the TD TA waveforms. Lower acoustic frequency modes, not visible in the time window shown in Fig. 5.7a, contributed substantially to the piezo signal at longer pulse durations, indicating a need for more aggressive high-pass filtering for accurate waveform capture when an external trigger and data averaging techniques are not used.

5.4.3 Tissue Response Comparison

Comparing the 25% CF-PTFE material properties described here to the EM response of a simple 1-D three-layer tissue model comprised of skin, subcutaneous adipose tissue (SAT, fat), and muscle provides a mechanism to tie a potential TA-based detector chain signal back to human biological response. Relevant tissue properties needed for numerical simulation, entered as model inputs in COMSOL, are available from the Foundation for Research on Information Technologies in Society (IT'IS) Tissue Property Database (IT'IS Foundation, Zurich, Switzerland) (Hasgall et al. 2022). The permittivity properties from this database are computed via a multi-relaxation four pole Cole-Cole model with fit parameters unique to each tissue, covering a range of RF frequencies which extend well below the lower threshold addressed in this study. This allowed the last two relaxation and final static permittivity terms to be omitted without adversely impacting the analysis (Gabriel 1996). Using layer thickness values from the literature of 1.5 mm, 1.5 mm, and 67 mm for skin, SAT, and muscle, respectively, the idealized case of a plane wave incident from air on a semi-infinite half-space can be implemented in a 2-D COMSOL RF module analysis through use of periodic boundary conditions at the domain edges parallel to the beam and perfectly matched layers along the two edges perpendicular to the beam (Gajda et al. 2019). The results of a coarse frequency sweep across the band of interest, presented in Fig. 5.8, show the aggregate change in $1 - \Gamma_P$ and δ_{pd} with increasing microwave frequency, indicating that to a rough approximation *SAR* sensitivity per unit S_{inc} in both materials can be treated

as linear. From eqns (5.5), (5.6), and (5.7), the sensitivity in terms of induced *SAR* for the mm Wave response testing case can be computed from the relationship

$$SAR = \frac{SA}{\tau_p} = \frac{(1 - \Gamma_p)}{\delta_{pd}\rho} S_{inc}, \quad (5.19)$$

where the specific absorption *SA* (J kg⁻¹) is the time integral of the *SAR*, yielding a peak value around 71 μV (W kg⁻¹)⁻¹. Relative residual error for the linear frequency response model was < 10% for *f* ≥ 18 GHz, increasing to a factor of 2 at the lower frequency bound.

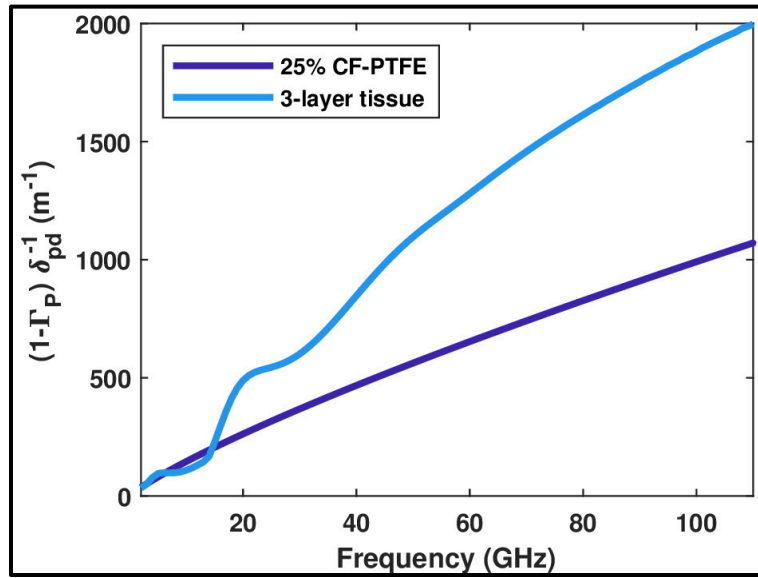


Fig. 5.8. Comparison of the ratio of the fraction of incident power density to power penetration distance for 25% CF-PTFE and a pseudo 1-D three-layer tissue model as a function of microwave frequency, computed from Cole-Cole model fit to empirical permittivity data or through time harmonic finite element analysis simulation data, respectively. Treating both responses as linear over the frequency domain results in an approximate slope ratio of two.

Accounting for differences in mass densities, 2180 kg m^{-3} for 25%CF-PTFE vs $\approx 1100 \text{ kg m}^{-3}$ for the three tissue layers, peak *SAR* generated in the tissue model at a given frequency and power density combination would be roughly four times greater than that generated in the CF-PTFE as a conservative estimate. A mechanism to estimate pulse duration is needed, either through direct analysis of the TA pulse waveform or through potential EMI related signal features, in order to recover EM exposure quantities from the TA piezo amplitude values. For an incident wave with a power density of 50 mW cm^{-2} , a basic thermal effects threshold associated with continuous wave exposure at prescribed continuous wave averaging times, the S-band piezo signals indicate a voltage amplitude on the order of 10s of mV is achievable at the charge and voltage gain settings used here, with some fraction of that signal driven by excitation of the PVDF sensor (Institute of Electrical and Electronics Engineers 2019). For this same incident power density, an approximate order of magnitude increase in gain, through more efficient mechanical coupling of the piezo sensor, refinement in signal conditioning parameters, or both, is needed in the mm Wave case to obtain a similar amplitude voltage signal under stress confinement conditions. From Fig. 5.8, the 50 mW cm^{-2} threshold corresponds to a peak *SAR* of approximately 220 W kg^{-1} in the 25% CF-PTFE absorber at 94 GHz.

5.5 Conclusions

The CF-PTFE HPM-induced TA signal chain model described here demonstrates some potential utility for use in operational exposure applications,

subject to key constraints that must be addressed in any practical implementation. For meaningful interpretation of the TA piezo voltage signal, which will be proportional to the peak *SA*, appropriate signal processing techniques must be performed to extract relevant beam parameter estimates such as pulse width and power penetration depth from the acquired waveforms in order to estimate *SAR*. The Cole-Cole permittivity approximation determined for 25% CF-PTFE provides a tool to predict the power penetration depth at a given microwave frequency, and by extension, the minimum thickness of absorber volume needed to ensure multiple reflection perturbations can be ignored during the analysis of the generated TA signal. As observed during mm Wave testing, HPM pulses at higher microwave frequencies will likely exceed the stress confinement ratio condition, so timing data is an important component in estimating pulse width efficiency through an appropriate response function. In addition to future work required to fully characterize the EMI susceptibility of the thin piezo film PVDF, empirical evaluation of the target assembly to calibrated acoustic excitation would permit greater flexibility in predicting TA signal conversion efficiency for a given set of pulsed beam parameters and provide necessary insight to optimize the mechanical coupling between the CF-PTFE sensitive volume and the acoustic sensor. Further optimization of the target could be explored via a dielectric mixing model such as the Maxwell-Garnett formula, which provides a mechanism to predict bulk behavior of homogenized composite samples but would require testing of CF-PTFE variants with intermediate values of percent fill to compute the EM properties of the

amorphous carbon constituent (Koledintseva et al. 2009). This semi-empirical fit, along with associated model fits for elastic and thermal material properties, would allow the calculation of frequency-dependent TA conversion yield at an arbitrary absorber fill and supports further optimization of the target material in terms of overall TA conversion yield. A thermoacoustic sensor employing cylindrical geometry, with a piezo cable inserted axially within a CF-PTFE rod, is one potential method to ensure sufficient EM thickness of the target while reducing the overall dimensions of the assembly and warrants further consideration in future studies.

VI. Conclusions

6.1 Summary of Findings

This research assessed the feasibility of thermoacoustic-based HPM exposure detection based on a particular variant of commercially-procured microwave absorbing polymer, demonstrating the validity of the approach while also identifying key constraints that must be addressed in any practical implementation. Applying a broad set of analytic techniques to the polymer resulted in an increased understanding of the material properties of CF-PTFE of relevance to TA wave generation not previously available in the literature, with a key focus on the complex permittivity over a ~100 GHz bandwidth. Incorporating these properties into a multi-physics finite element model enabled a numeric simulation of the response of an idealized TA detector chain to pulsed microwave excitation. The simulation allowed exploration of the various physical processes that ultimately contribute to elastic pulse magnitude, confirming the utility of CF-PTFE as a target material and identifying important boundary condition and material interface considerations that significantly influenced the physical design of the TA target assembly. The results of in-beam response testing of the completed detector chain further emphasized the importance of the empirical material property and signal conditioning component analysis conducted during this study, as both considerations are necessary to interpret TA response sensitivity in the context of personnel exposure assessment.

While the virgin PTFE used as the base sample matrix is well characterized in the literature, the material property measurements collected during this study provided insight into the impacts that the amorphous carbon fill had on EM coupling to the incident beam and the magnitude of the resulting TA pulse. A sufficient bandwidth of dispersive complex permittivity data obtained via free-space focused beam S-parameter analysis was derived to allow for the extrapolation to the full frequency range of interest of 2-110 GHz. This extrapolation was accomplished via the fitting of a Cole-Cole dielectric approximation taken from the literature and validated over the 60-67 GHz range, as described in subsection 5.3.1. As the time domain shape of the TA waveform is directly dependent on the power penetration depth during the incident microwave pulse, this power law approximation drives the length of the rising edge of the TA at any arbitrary microwave frequency across a > 100 GHz bandwidth. It also provides a bounding value for physical sample thickness of the CF-PTFE absorber plate in order to ensure an acceptable minimum energy absorption even at the lowest frequency of interest. Empirical elastic property values, derived from laser vibrometry modal analysis as described in subsection 4.3.2, were used to compute the longitudinal speed of sound in the CT-PTFE samples, setting an important time domain characteristic of all microwave-induced TA waveforms in these materials while providing a key component of the elastic pulse magnitude through its contribution to the Grüneisen parameter. From the dispersive EM and elastic material property data, the stress

confinement time was calculated, bounding the pulse width at which this criterion will be exceeded for a given microwave frequency.

The TA response of the configured detector chain, both in simulation and in-beam testing, demonstrated the needed functional relationships between TA signal characteristics and incident HPM beam parameters. Simulated waveforms, generated using the Solid Mechanics variant of the multistage COMSOL multiphysics model as presented in subsection 4.4.2, provided an early confirmation of the validity of the TA pulse magnitude relationships between predicted elastic stress and incident microwave power density as captured in eqn (4.28). This peak amplitude estimate was approximately $\frac{1}{2}$ of the maximum potential value, implicitly supporting the high-reflection acoustic boundary impedance mismatch assumption leveraged during in-beam HPM waveform analysis. Frequency domain analysis of the simulated waveform data was used to verify that the dominant modal frequency was within the response bandwidth of the conditioned piezo sensor chain, indicating that the signal conditioning approach used was a good match for the frequency characteristics of the signal. HPM response testing in the S-band and mm Wave regions described in subsection 5.3.2, bracketing the frequency continuum of interest, provided empirical confirmation of general trends noted during the simulation runs with respect to the frequency transfer function of the detector chain, as well as supplying a mechanism to address some of the limitations of the TA approach to HPM exposure assessment. As observed during mm Wave testing in particular, reduced pulse width sensitivity outside of the stress confinement region

significantly impacted the overall TA yield of the target assembly and must be considered via impulse response testing when interpreting the resulting waveforms, an approach successfully demonstrated in subsection 5.4.2.

6.2 Future Work

6.2.1 Material Properties

Electromagnetic, thermal, and elastic material property characterization of the CF-PTFE samples used in these studies formed a necessary foundation which enabled TA response testing. However, material property data from additional CF-PTFE variants is needed in order to determine a more general model of TA behavior as a function of microwave absorber fill percent. With the exception of the aggregate mass density, non-trivial variations in material property values were noted across the 0%, 15%, and 25% CF-PTFE target plates, particularly in regards to complex permittivity. Mixing models, such as the Maxwell-Garnett formula expressed in eqn (2.24), provide mechanisms to predict bulk behavior of homogenized composite samples but require reference values for both constituents. As the EM and elastic measurement techniques presented in Chapters 3 and 4 are not suited for the analysis of pure amorphous carbon samples, testing of CF-PTFE variants with intermediate values of percent fill obtained via more refined procurement methods would allow curve fitting to appropriate mixing models for each material property of interest. These empirical fits would allow the calculation of frequency-dependent TA conversion yield at an

arbitrary absorber fill and support further optimization of the target material in terms of overall TA conversion yield.

6.2.2 Modeling and Simulation

The planar target approach used for this project was initially selected due to sample availability and mounting requirements of the focus beam systems, but the flexibility of the multiphysics FEM modeling approach detailed in Chapter 4 would easily allow the exploration of alternate 2-D absorber geometries. As COMSOL supports dynamic remeshing of model components during parametric geometry sweeps, this process would also permit a more detailed accounting of the multi-reflection contributions to the stationary EM solution and hence target plate thickness threshold determination. Cylindrical and spherical absorber geometries present another route towards potential enhancement of the TA relative sensitivity, although modeling such curvilinear TA detector chains would require some appropriate application of axisymmetric solution and piezoelectric coordinate axis transformations. The culmination of such modeling refinement inquiries should be a full transient modeling of the microwave hearing effect outlined in Chapter 2, linking the TA output of a potential pulsed HPM detector chain to induce pressure in a representative numeric computational skull phantom.

6.2.3 Thermoacoustic Response

For in-beam response testing, a cylindrical absorber target represents the alternative geometry most easily realizable using commercially available

components. Preliminary testing using axially-drilled CF-PTFE rod stock and PVDF piezo cable indicates that effective mechanical coupling of the TA pulse from absorber to sensor presents a challenge. This challenge would be mitigated to some extent by an anticipated geometric focusing of the elastic pulse as it approaches the absorber axis and the relative ease of meeting the PTFE EM thickness requirements previously described. For this and the planar target assembly, further HPM response testing at additional beam frequencies would allow a more robust sensitivity analysis of the acoustic efficiency of the PVDF sensor, as well as quantification of the EMI direct-excitation sensitivity of the signal chain as the power penetration depth decreases. Further optimization of the conditioning electronics is also needed in order to support self-triggering of the waveform capture process instead of the averaging acquisition used here, likely requiring the insertion of additional hardware high-pass filtering into the chain to further attenuate the substantial acoustic background noise that results from the wide bandwidth of the PVDF sensors as implied by eqn (2.32).

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14. ABSTRACT A feasibility analysis for the use of microwave-induced thermoacoustic (TA) wave generation in lossy dielectric media to detect pulsed high power microwave directed energy weapons in force health protection applications was conducted based on a series of empirical and computational investigations. A potential target volume material, carbon-loaded polytetrafluoroethylene, was identified for further study based on anticipated complex dielectric properties, with laboratory measurements of select electromagnetic (EM), thermal, and elastic material properties of relevance to the TA effect conducted to determine parameter values. A planar geometry TA-based signal chain model using thin film piezoelectric sensors was developed for both finite element method based numerical simulation and in-beam response testing, with TA signal output evaluated in the time and frequency domain using both approaches. Based on empirically-derived complex permittivity values, a single-term Cole-Cole dielectric relaxation model approximation was developed over the 2-110 GHz microwave frequency region to permit a more general evaluation of EM coupling efficiency of the material. Modeling and simulation of the idealized signal chain allowed the analysis of TA waveform dependency on microwave beam parameters not otherwise accessible during in-beam response testing. High frequency TA signal data was suitably fit to a pulse width sensitivity impulse response function model for the target geometry and found to be in good agreement for personnel exposure applications.					
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