TEM Cell for 3 GHz Pulsed Microwave Exposure and Monitoring of the Thermoelastic Response of Tissue: Aperture Design and Characterization

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***Abstract*—Microwave pulse absorption in tissue results in multiple bioeffects including micro- to macro-scale heating and mechanical changes via the thermoelastic (TE) effect. We present the development of a custom 3 GHz TEM cell featuring an aperture in the base that enables simultaneous pulsed plane-wave exposure and microscope-based monitoring of the TE response of tissue in a single unified system architecture. We evaluated two aperture covering designs through both simulation and experiment: a borosilicate glass covering with and without a conductive ITO coating. We found the non-conductive transparent glass covering to be more suitable for the investigation of pulsed microwave heating and the subsequent TE response of biological tissue.**

I. INTRODUCTION

Pulsed microwave-based technologies for medical diagnosis and treatment include microwave-induced thermoacoustic imaging for use in cancer detection (e.g. [1]), and pulsed microwave ablation for treating tumors (e.g. [2]). Further research is needed to elucidate the thermoelastic (TE) response that arises from microwave-induced thermal changes in tissues. A comprehensive understanding of this multi-physics effect will ensure the safety and efficacy of these technologies as well as other forms of intentional or unintended microwave (MW) pulse exposure.

Transverse electromagnetic (TEM) cells are versatile dosimetry devices that have been utilized and customized for a variety of bioelectromagnetics studies (e.g. [3]). They provide plane-wave illumination to tissue under test that simplifies the electromagnetic (EM) wave exposure conditions and facilitates direct comparison between dosage, i.e. total power absorption, and measured tissue response. A full characterization of the MW-induced TE response of tissue requires capturing tissue deformation during pulsed MW illumination.

Our initial 1 GHz TEM cell design introduced in [4] included a viewing aperture in the base for observing tissue deformation. The enhanced design presented in this paper offers several improvements: 1) a higher operating frequency (3 GHz) for a more compact TEM cell footprint, making it compatible for placement on the stage of an inverted microscope, 2) an open, side wall-free design to allow for contactless thermal imaging with a thermal camera and simplified access to the tissue sample, and 3) top and septum holes to enable laser illumination for enhanced lighting during high-speed imaging of the TE response. In this study, we characterized the thermal response of the aperture coverings and their impact on EM absorption in tissue during pulsed MW transmission. These insights yield an additional design improvement: an uncoated covering that improves tissue power absorption while maintaining controlled thermal conditions to prevent indirect tissue heating.

II. METHODS

A photograph of the constructed TEM cell is shown in Fig. 1. The dimensions are chosen for 3-GHz operation. Using the COMSOL Multiphysics software suite, we analyzed the EM and thermal performance of the custom TEM cell. The source was defined as continuous-wave since EM power absorption reaches steady state on a much shorter timescale than the duration of the microsecond-scale pulse envelopes. The tissue sample was defined as a 1-mm-thick, 1-cm-radius cylinder of homogeneous gray matter (ϵ_r = 48, σ = 2.2 S/m) [5]. Non-conductive borosilicate glass (BG) (ϵ_r = 4.8) was compared to conductive indium-tin-oxide-coated borosilicate glass (BG + ITO) (ϵ_r = 4.8, σ = 1.3e5 S/m) for the aperture coverings. Thermal conductivity and heat capacity for BG were 1.1 W/mK and 800 J/kgK, respectively [5].

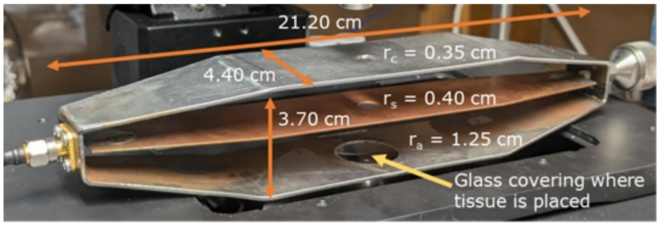

Fig. 1. Photo of a custom 3 GHz open TEM cell with viewing aperture (radius, r_a) in the bottom plate and laser illumination holes in the top (r_c) and septum (r_s).

Scattering parameters for the 3 GHz TEM cell were measured using a two-port vector network analyzer (Agilent N5221A). Simulated and measured parameters were in close agreement at the operating frequency. We also observed minimal differences in S11 and S21 for the TEM cell with the two aperture coverings. In all cases, the magnitude of S11 was below -25 dB, while the magnitude of S21 ranged between -0.25 and -0.5 dB. The 3-GHz pulsed MW generator (H6 Systems, Nashua, NH, USA) operated at 30 kW peak power with 1 μs pulse duration and 500 Hz pulse repetition frequency (PRF). The thermal response of the aperture coverings during MW transmission was assessed using a FLIR E50 thermal imaging camera.

III. RESULTS

MW-induced thermal effects of both BG and BG + ITO coverings are shown in Fig. 2. The simulation results in the top four images indicate the thermal invariance of BG (top-most row) when exposed to pulsed MWs and the susceptibility to a temperature rise of the conductive BG + ITO (2nd row). The experimental results in the bottom four images confirm this prediction. The thermal response of BG + ITO to pulsed MWs risks creating a multi-modal heating scenario for the tissue and complicating the analysis of the pulsed MW-induced TE behavior of the samples.

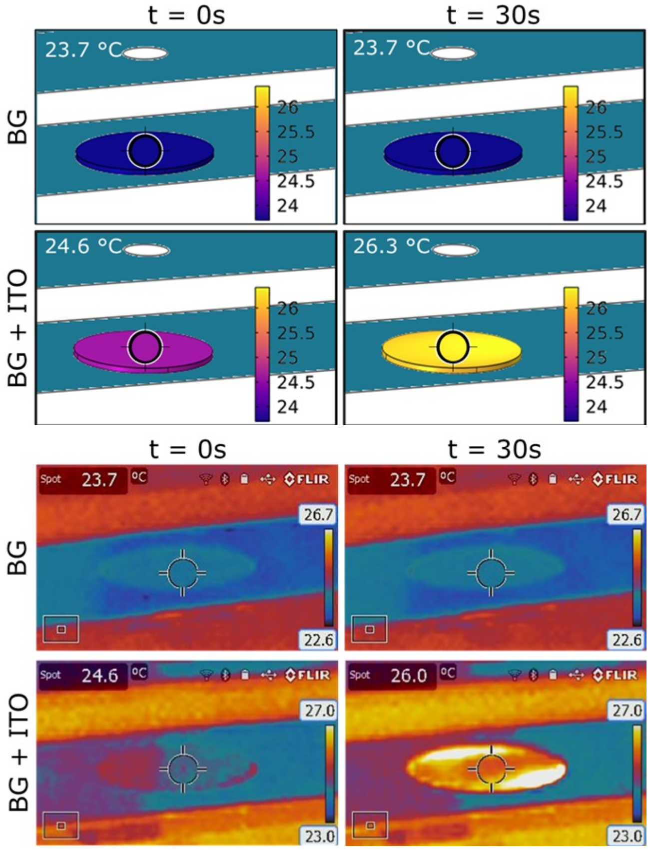

Fig. 2. Simulated (top) and measured (bottom) temperature rise of the BG and BG + ITO aperture coverings when exposed to pulsed MWs for 30 seconds. Transmitted pulses are 1 μs duration at 500 Hz PRF with peak power of 30 kW.

The power absorption efficiency (PAE) and power absorption homogeneity in a tissue sample resting on the aperture covering are presented in Fig. 3. The PAE is the total power absorbed in the tissue sample divided by the total power transmitted into the TEM cell. Power absorption homogeneity is quantified by the coefficient of variation (CV): the ratio of standard deviation to the mean of the power absorption density. BG + ITO shows a more uniform power absorption across the tissue, but at the expense of efficiency. With BG + ITO, only 0.02% of the power transmitted into the TEM cell is absorbed by the tissue. This is in stark contrast to the 20x higher PAE in the BG-covered aperture configuration. BG provides fairly homogeneous power absorption in the interior of the tissue sample, which can be leveraged when observing the tissue expansion with a microscope.

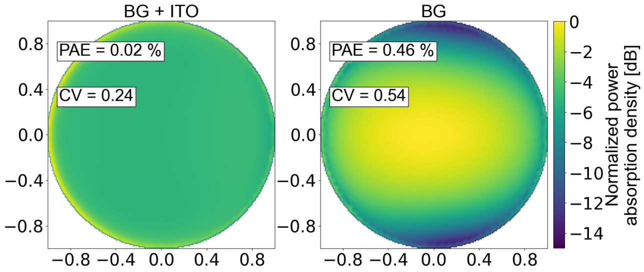

Fig. 3. Normalized power absorption density at 3 GHz for 1-cm-radius, 1-mm thick tissue samples positioned on the bottom surface of a TEM cell, evaluated for two different viewing aperture coverings: borosilicate glass (BG) with (left) and without (right) an ITO coating. Axes are labeled in centimeters. The PAE and CV are noted for each scenario.

IV. CONCLUSION

This study examined the MW and thermal characteristics of a custom 3 GHz TEM cell for evaluating tissue undergoing MW plane-wave illumination. By evaluating transmission properties, power absorption homogeneity, power absorption efficiency, and temperature dynamics, we verified the TEM cell design's suitability for investigating MW-induced TE responses in biological tissues. Our research demonstrates the benefits of a non-conductive aperture covering: higher power absorption efficiency, thermal isolation of the tissue sample, and comparable power absorption uniformity within the field of view of a microscope.

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