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Triple-Debye Composite Dielectric Modeling and Multi-Layer Finite-Difference Time-Domain Simulation of Terahertz Pulse Reflection for Breast Cancer Detection

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ABSTRACT

Introduction: Terahertz (THz) time-domain spectroscopy enables non-invasive breast cancer detection by exploiting the dielectric contrast between healthy and malignant tissues, which is largely governed by water content and molecular binding. In this study, a broadband THz pulse generated via laser-plasma interaction is used.

Materials and Methods: To improve tissue discrimination, we introduce an enhanced Triple-Debye dielectric model that captures multiple water-related relaxation processes relevant to breast tissue composition. The Triple-Debye model was fitted to in vivo refractive index and absorption data from freshly excised breast tissues, achieving $R^2 > 0.98$. Heterogeneous regions within the tissue were represented using a Bruggeman effective-medium model, which combines adipose tissue ($\varepsilon \approx 2.5$), fibrous tissue ($\varepsilon \approx 5.2$), and tumor tissue ($\varepsilon \approx 6.8$). Pulse propagation was simulated using a multi-layer finite-difference time-domain (FDTD)–auxiliary differential equation framework for a stack consisting of quartz, adipose tissue, tumor, and muscle.

Results and Discussion: The Triple-Debye model provided significantly improved permittivity fitting compared to double-Debye formulations, especially below 0.5 THz. FDTD simulations showed tumor-induced pulse broadening (full width at half maximum: 0.96 ps vs. 0.81 ps) and >18% amplitude reduction due to higher water content in malignant tissue. By analyzing pulse-shape parameters, the integrated model achieved >92% accuracy in distinguishing tumor from healthy tissue, highlighting its potential for intraoperative margin evaluation.

Conclusion: By combining Triple-Debye modeling, effective-medium theory, and FDTD simulations, this work provides a robust computational framework for THz-based breast cancer detection. The observed pulse broadening and attenuation serve as reliable diagnostic markers, supporting real-time intraoperative imaging applications.

Keywords: Breast cancer detection, FDTD simulation, Terahertz spectroscopy, Triple-Debye model

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