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Dielectric Characterization of PCL-Based Thermoplastic Materials for Microwave Diagnostic and Therapeutic Applications

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Abstract

We propose the use of a polycaprolactone (PCL)-based thermoplastic mesh as a tissue-immobilization interface for microwave imaging and microwave hyperthermia treatment. An investigation of the dielectric properties of two PCL-based thermoplastic materials in the frequency range of 0.5 – 3.5 GHz is presented. The frequency-dependent dielectric constant and effective conductivity of the PCL-based thermoplastics are characterized using measurements of microstrip transmission lines fabricated on substrates comprised of the thermoplastic meshes. We also examine the impact of the presence of a PCL-based thermoplastic mesh on microwave breast imaging. We use a numerical test bed comprised of a previously reported three-dimensional anatomically realistic breast phantom and a multi-frequency microwave inverse scattering algorithm. We demonstrate that the PCL-based thermoplastic material and the assumed biocompatible medium of vegetable oil are sufficiently well matched such that the PCL layer may be neglected by the imaging solution without sacrificing imaging quality. Our results suggest that PCL-based thermoplastics are promising materials as tissue immobilization structures for microwave diagnostic and therapeutic applications.

Index Terms

dielectric characterization; thermoplastics; microwave imaging; microwave hyperthermia; transmission line measurement; tissue immobilization

I. Introduction

There is a growing interest in the development of microwave diagnostic and therapeutic techniques in medicine. For example, microwave breast imaging (e.g., [1]–[7]) and microwave hyperthermia treatment of breast cancer (e.g., [8]–[9]) have been the subject of numerous recent research studies. Microwave breast imaging, an exploratory technique for improving breast cancer screening and diagnosis [10], involves transmitting low-power microwave signals into the breast using an array of antennas. An immersion medium is used to improve the coupling efficiency of the low-power microwave signals into and out of the

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breast. The measured scattered signals are used to reconstruct the spatial distribution of the dielectric properties, or some related characteristic such as scattering strength, throughout the breast volume. Rigorous validation of microwave imaging using a clinical benchmark such as magnetic resonance imaging (MRI) technology requires precise co-registration. A patient interface that immobilizes the breast so that the same position is maintained during both the MRI and microwave scans would enable straightforward co-registration and an objective and unambiguous comparison. This type of patient interface would also potentially benefit microwave-induced hyperthermia treatment of breast cancer, which is a well-known thermotherapy approach that uses an antenna array to focus high-power microwave signals at the site of a tumor and elevate its temperature to 40–45°C, typically for 60–90 minutes. As in other cancer treatment modalities, immobilizing the breast for the duration of the hyperthermia treatment is critical to prevent movement that could degrade the selectivity of the treatment zone and potentially damage healthy tissue.

The material used for this purpose should be sufficiently malleable to conform to the tissue and yet rigid enough to prevent movement during the medical procedure. In addition, the material should be relatively low-loss to allow for adequate penetration of the microwave signals into the tissue to achieve the desired results and be well-matched to either the immersion medium or skin to prevent mismatch reflection loss. Several low-loss materials, including liquid crystal polymers [11], polymer-ceramic composites [12], and Parylene-N [13], have been proposed as flexible microwave substrates for conformal applications in microwave engineering. However, while these materials are flexible, they do not retain their shape unless bound or held in place. Thus they are not suitable for our proposed application.

Meshes constructed from perforated thermoplastic materials, such as the one shown in Fig. 1(a), have been used as immobilization devices in interventional breast MRI applications such as MR-guided preoperative localization or MR-guided needle biopsy [14]–[15]. One example of a thermoplastic polymer is polycaprolactone (PCL). This thermoplastic material is rigid at room temperature but softens and becomes malleable upon being immersed in a warm water bath of 57°C. In its malleable state, a thermoplastic mesh easily conforms to the pendulous breast. Once the material cools back down to room temperature, its rigidity is restored. PCL-based polymers are also low cost and biodegradable [16]. Such material characteristics are important for the intended application wherein the patient-conformed thermoplastic mesh would be discarded after a single use. PCL-based materials and films have been characterized at low frequencies up to 10 MHz [17]–[19] and shown to exhibit stable dielectric properties in terms of their pre-heated and cooled-down states [17].

In this paper, we propose the use of a PCL-based thermoplastic material as a tissue-immobilization interface for microwave breast imaging. First, we present an experimental microwave-frequency characterization of the dielectric properties of two commercially available PCL-based thermoplastic materials (shown in Fig. 1(b),(c)) in the frequency range of 0.5–3.5 GHz. The frequency range of our study corresponds to the range of interest in current microwave inverse scattering algorithms for breast imaging (e.g., [1]–[6]). The operating frequencies of clinical microwave hyperthermia treatment applicators also fall roughly in this range (e.g., [8]). To the best of our knowledge, this paper represents the first study of the frequency-dependent microwave dielectric properties of a PCL-based thermoplastic. This data is important because it enables an investigation of the potential impact of the immobilization mesh on microwave imaging performance as well as a determination of system features, such as the immersion medium, that minimize that impact. In the second part of the paper, we discuss a suitable immersion medium that is approximately impedance matched to the thermoplastic material and present a numerical study of microwave breast imaging using a realistic numerical breast phantom [20] with and without the presence of a thin thermoplastic material layer enveloping the breast. We apply a

microwave inverse scattering algorithm that does not account for the presence of the thermoplastic in the forward solver to both scattered-field data sets and show that there is no discernible difference in the reconstructed images. This suggests that the use of a thermoplastic mesh together with a suitable immersion medium is a viable strategy for immobilizing the breast without increasing the complexity of the image reconstruction procedure.

II. Method of Dielectric Characterization

We acquired samples of the following two PCL-based thermoplastic materials from Orfit Industries of America: Efficast® 8333Y.3/R and U-Plast™ 8338BL.S02+/R. These perforated thermoplastic sheets are designed for patient fixation in radiation oncology. The Efficast® sample, shown in Fig. 1(b), is a 2.0-mm-thick dielectric sheet perforated with 2.8-mm-diameter air holes. The U-Plast™ sample, shown in Fig. 1(c), is a 2.4-mm-thick dielectric sheet perforated with 1.4-mm-diameter air holes.

Transmission-line methods [21]–[28] are well suited for characterizing the wideband dielectric properties of thin, rigid material sheets. In such methods, the material under test is used as the substrate in a microstrip transmission line and its dielectric properties are extracted from electrical measurements performed on the line. We adopted this approach to characterize the dielectric properties of the PCL-based thermoplastic materials from 0.5 to 3.5 GHz. We fabricated a total of ten microstrip transmission lines of two different widths (five of each width) on each thermoplastic substrate. We chose transmission line lengths that spanned the entire length of the acquired sample boards. This was done to minimize the influence of the connector and parasitic parameters on the overall measurement accuracy. The transmission line widths were chosen to cover 2–3 air holes in the transverse direction, thereby ensuring that the measured properties represented volume averages of the bulk material and the air holes. For the Efficast® samples, the widths of the transmission lines were 10 mm and 15 mm; the length of each line was 265 mm. For the U-Plast™ samples, the widths were 5 mm and 10 mm while the common length was 205 mm. Printed-circuit-board (PCB) edge-mount connectors were soldered at the end of each line. Two-port scattering (S-) parameter measurements were carried out over the 0.5–3.5 GHz frequency range using an Agilent E8364 vector network analyzer (VNA).

We developed equivalent circuit models of the transmission lines that take into account the presence of the connectors as well as the parasitic effects of the transitions between the connectors and the transmission lines (see Fig. 2). Agilent's Advanced Design System (ADS) [29] was used to simulate these equivalent circuit models. The internal optimization engine in ADS was used to extract parameter values by matching simulated performance to measurement values [30]. The dielectric constant and loss tangent of the substrate in the model were optimized within ADS to achieve a good agreement between the measured S-parameters and those predicted by the equivalent circuits over the frequency range of interest.

The parameters of the two PCB edge-mount connectors were optimized to within $\pm 10\%$ of the values provided by the manufacturer. We modeled the parasitic effects of the coaxial-connector-to-microstrip transition and connector assembly imperfections using a shunt capacitance, C , a series inductance, L , and a series resistance, R , on each side of the line, as shown in Fig. 2. Assembly imperfections give rise to a small air gap that exists between the edge of the connector and the edge of the substrate. This gap contains a portion of the center conductor of the edge-mount connector with average dimensions of 1 mm both in diameter and length. Typical values for parasitic impedances of such short wires at microwave frequencies have been reported in [31]–[32]. Estimates for the fringing capacitance of a

microstrip line located at the edge of a dielectric substrate are also reported in [33]. From these studies, we obtained initial approximate values for the parasitic R , L , and C elements used in the circuit model. These parameters were optimized in ADS and the resulting parasitic element values were found to be $R = 0.05 \, \Omega$, $C = 0.07 \, \text{pF}$, and $L = 0.28 \, \text{nH}$.

The substrate dielectric properties extracted from the ADS simulation of the transmission line models include the effects of the air-hole perforations; hence, we refer to the ADS-optimized dielectric constant and loss tangent as ϵ_{avg} and $\tan \delta_{\text{avg}}$, respectively. The ADS optimization was performed using both the magnitude and the phase of the S_{21} and S_{11} measurements. The S_{21} fit was given a 10:1 priority weighting relative to the S_{11} fit because the imperfect symmetry in the assembly of the connectors on each side of the line gives rise to unequal reflection coefficients (e.g. S_{22} and S_{11}) from the two ports. The values of the substrate dielectric properties in each transmission line model were swept using the internal optimization engine of ADS until the best achievable optimization goal was obtained. Values for the dielectric properties were extracted for frequency bands of 0.5 GHz across the desired frequency range of 0.5–3.5 GHz.

The dielectric properties of the bulk thermoplastic are of greater fundamental importance than the volume-averaged properties of the mesh for two reasons. First, it is unlikely that the holes in the thermoplastic mesh will remain air-filled in the intended application involving an immersion liquid. Second, several different hole patterns are available from manufacturers of PCL-based thermoplastic meshes, and the volume-averaged dielectric properties depend on the hole pattern. Knowledge of the dielectric properties of the bulk thermoplastic enables one to predict the average dielectric properties of any mesh configuration.

We extracted the dielectric properties of the bulk thermoplastic material from the average dielectric properties using a volumetric averaging principle [34]. The hole patterns in the thermoplastic meshes repeat themselves in unit cells as shown in Fig. 1(b) and (c). The unit cells are triangular (equilateral) for the Efficast® sample and rectangular for the U-Plast™ sample. Thus, the relationship between the measured volume-averaged properties of the perforated Efficast® sample and the underlying properties of the bulk thermoplastic material, ϵ_r and $\tan \delta$, is as follows:

$$\epsilon_{\text{avg}} = \frac{\pi}{2\sqrt{3}} \left(\frac{D}{a} \right)^2 + \epsilon_r \left(1 - \frac{\pi}{2\sqrt{3}} \left(\frac{D}{a} \right)^2 \right) \quad (1)$$

$$\tan \delta_{\text{avg}} = \tan \delta \left(1 - \frac{\pi}{2\sqrt{3}} \left(\frac{D}{a} \right)^2 \right) \quad (2)$$

where $D = 2.88 \, \text{mm}$ is the hole diameter and $a = 5.8 \, \text{mm}$ is the length of the side of the unit cell triangle. Similarly, the average properties of the U-Plast™ sample are related to the properties of the thermoplastic material as follows:

$$\epsilon_{\text{avg}} = \frac{\pi}{2} \left(\frac{D^2}{w_1 \times w_2} \right) + \epsilon_r \left(1 - \frac{\pi}{2} \frac{D^2}{w_1 \times w_2} \right) \quad (3)$$

$$\tan \delta_{\text{avg}} = \tan \delta \left(1 - \frac{\pi}{2} \frac{D^2}{w_1 \times w_2} \right) \quad (4)$$

where $D = 1.4$ mm is the hole diameter and $w_1 = 2.88$ mm and $w_2 = 5.6$ mm are the sides of the rectangle. The loss tangent of the thermoplastic material was converted to an effective conductivity, σ .

III. Validation and Results

Our equivalent circuit model was tested and validated using S-parameter measurements taken of transmission lines patterned on a known Rogers 5880 board. The resulting extracted dielectric properties for the Rogers 5880 board were $\epsilon_r = 2.203$ and $\tan \delta = 0.00099$ for the frequency range of 0.5–3.5 GHz. The manufacturer specifies values of $\epsilon_r = 2.20 \pm 0.02$ and $\tan \delta = 0.0009$ for frequencies up to 10 GHz. This high level of agreement in the dielectric properties confirms the validity of the equivalent circuit model—namely, the connector parameters as well as the values of the parasitic elements—used in the ADS-based dielectric-properties optimization scheme.

The measured and simulated S_{21} curves for one of the 205-mm-long, 10-mm-wide transmission lines on the Efficast® sample are shown in Fig. 3. This representative example illustrates the excellent agreement obtained between measurement and simulation for all of the transmission line samples. The resulting dielectric properties, ϵ_r and σ , of both PCL-based thermoplastic materials are presented in Fig. 4. Each data point represents the mean value of the results (dielectric constant or effective conductivity) from the ten transmission lines fabricated on each of the two material samples. The vertical bars span the maximum and minimum values at specific frequencies.

The mean value of the dielectric constant of the Efficast® PCL-based material ranges between 3.23 and 3.24 over the 0.5–3.5 GHz frequency range. For the U-Plast™ material, the mean dielectric constant ranges between 3.20 and 3.22. The mean conductivity ranges from 0.014 (S/m) at 0.5 GHz to 0.048 (S/m) at 3.5 GHz for Efficast® and from 0.013 (S/m) (0.5 GHz) to 0.049 (S/m) (3.5 GHz) for U-Plast™. The variation about the mean dielectric constant is less than 1.4% for Efficast® and 3.5% for U-Plast™ over the entire frequency range of interest. This measurement variability is attributed to small differences in the assembly processes for each of the transmission lines used to extract these properties.

IV. Impact of the Thermoplastic Mesh on Microwave Breast Imaging

During the measurement of a breast by a microwave imaging system, any surrounding objects illuminated by the array may scatter the waves strongly enough to introduce artifacts in the resulting images if those objects are not properly accounted for. In general, any materials used for tissue immobilization must be imaged along with the breast, redacted from the data via some calibration scheme, or included in the propagation model of the imaging solution. All of these options add significant complexity to the imaging algorithm. However, if the dielectric properties of the immobilizer are closely matched to the immersion medium into which the array and breast are placed, the scattering from the immobilizer may fall below the sensitivity of the measurements making any resulting imaging artifacts negligible.

We investigated the impact on microwave breast imaging of a PCL-based thermoplastic material used to immobilize the breast in an immersion medium comprised of vegetable oil. We used a numerical test bed in order to isolate the effect of the thermoplastic immobilizer; such an investigation cannot be conducted in the less-controlled environment of an experimental test bed. The numerical test bed was based on the down-sampled Class 2 (scattered fibroglandular) breast phantom and dipole array described in a previous imaging study [6]. In addition, a conformal layer of 2-mm-thick thermoplastic material was placed over the surface of the skin region of this phantom. The dielectric properties of the

thermoplastic material were assumed to be $\epsilon_r = 3.24$ and $\delta = 0.031$ S/m. The dielectric properties of the oil immersion were assumed to be dispersive with single-pole Debye parameters $\epsilon_s = 2.97$, $\epsilon_\infty = 2.72$, and $\tau_p = 15$ ps [35]. This Debye model gives a dielectric constant of 2.97 and a conductivity of 0.0003 S/m at 0.5 GHz and a dielectric constant of 2.95 and a conductivity of 0.0145 S/m at 3.5 GHz. We modeled the thermoplastic immobilizer as a solid layer without any perforations. We consider this to be a worst-case test bed because it creates the largest expected impedance mismatch between the immersion medium and the immobilizer. In practice, the average dielectric properties of a perforated thermoplastic layer (with either air- or oil-filled holes) will provide a better match to the properties of the oil immersion than that assumed here.

We applied the inverse scattering algorithm described in [6] to the data acquired from the numerical phantom with and without the conformal thermoplastic layer. In both cases we excluded the thermoplastic in the forward model of the imaging solution and instead assumed that the immersion medium extended to the skin surface. Under these forward-model assumptions, any scattering from the thermoplastic layer that is on the order of the level of scattering from the interior breast tissue structures will manifest as artifacts in the image of the interior volume. Such artifacts would occur because the imaging algorithm seeks to minimize any residual scattering between measurements of the reconstruction and the actual object.

Coronal cross-sections of the resulting three-dimensional images of the phantom with and without the thermoplastic layer are shown in Fig. 5. Any differences between the reconstructed dielectric-properties profiles for the two cases are imperceptible. This result suggests that the PCL-based thermoplastic material and vegetable oil are sufficiently well matched such that the thermoplastic layer presents a negligible amount of scattering and may therefore be neglected by the imaging solution.

V. Conclusion

The dielectric properties of commercially available PCL-based thermoplastic materials have been experimentally characterized in the microwave range of 0.5–3.5 GHz using transmission line measurements. We determined that the dielectric constant of the PCL-based thermoplastics is 3.22 ± 0.02 over the entire frequency range and the conductivity ranges from 0.0133 ± 0.0004 (S/m) at 0.5 GHz to 0.0485 ± 0.0008 (S/m) at 3.5 GHz. We have also conducted a numerical study of microwave breast imaging to investigate the impact of using a thin PCL-based thermoplastic material to immobilize the breast in a vegetable-oil-based immersion medium. We found that introducing the thermoplastic layer to immobilize the breast without accounting for its presence in the image reconstruction algorithm results in images that are essentially identical to those obtained without the tissue immobilizer. The results of this imaging study suggest that PCL-based thermoplastic meshes are promising candidates for use as tissue-immobilizing materials in medical microwave imaging.

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References

1. Meaney PM, Fanning MW, Raynolds T, Fox CJ, Fang QQ, Kogel CA, Poplack SP, Paulsen KD. Initial clinical experience with microwave breast imaging in women with normal mammography. *Academic Radiology*. 2007 Feb.; vol. 14(no. 2):207–218. [PubMed: 17236994]

2. Gilmore C, Abubakar A, Hu W, Habashy TM, van den Berg PM. Microwave biomedical data inversion using the finite-difference contrast source inversion method. *IEEE Transactions on Antennas and Propagation*. 2009 May; vol. 57(no. 5):1528–1538.
3. Winters DW, Shea JD, Kosmas P, Van Veen BD, Hagness SC. Three-dimensional microwave breast imaging: Dispersive dielectric properties estimation using patient-specific basis functions. *IEEE Transactions on Medical Imaging*. 2009 July; vol. 28(no. 7):969–981. [PubMed: 19211350]
4. Rubaek T, Kim OS, Meincke P. Computational validation of a 3-D microwave imaging system for breast cancer screening. *IEEE Transactions on Antennas and Propagation*. 2009 July; vol. 57(no. 7):2105–2115.
5. Shea JD, Kosmas P, Hagness SC, Van Veen BD. Contrast enhanced microwave imaging of breast tumors: A computational study using 3-D realistic numerical phantoms. *Inverse Problems*. 2010 Apr.vol. 26:22. 074009.
6. Shea JD, Kosmas P, Hagness SC, Van Veen BD. Three-dimensional microwave imaging of realistic numerical breast phantoms via a multiple-frequency inverse scattering technique. *Medical Physics*. 2010 Aug.; vol. 37(no. 8):4210–4226. [PubMed: 20879582]
7. Li X, Bond EJ, Van Veen BD, Hagness SC. An overview of ultrawideband microwave imaging via space-time beamforming for early-stage breast cancer detection. *IEEE Antennas and Propagation Magazine*. 2005 Feb.; vol. 47(no. 1):19–34.
8. Vargas HI, Dooley WC, Gardner RA, Gonzalez KD, Venegas R, Heywang-Kobrunner SH, Fenn AJ. Focused microwave phased array thermotherapy for ablation of early-stage breast cancer: Results of thermal dose escalation. *Annals of Surgical Oncology*. 2004; vol. 11(no. 2):139–146. [PubMed: 14761916]
9. Zastrow E, Hagness SC, Van Veen BD. 3D computational study of non-invasive patient-specific microwave hyperthermia treatment of breast cancer. *Physics in Medicine and Biology*. 2010; vol. 55(no. 13):3611–3629. [PubMed: 20526033]
10. Joy, JE.; Penhoet, EE.; Petitti, DB., editors. *Saving Women's Lives: Strategies for Improving Breast Cancer Detection and Diagnosis*. Washington, DC: National Academies Press, Institute of Medicine; 2005.
11. Thompson DC, Tantot O, Jallageas H, Ponchak GE, Tentzeris MM, Papapolymerou J. Characterization of liquid crystal polymer (LCP) material and transmission lines on LCP substrates from 30 to 110 GHz. *IEEE Transactions on Microwave Theory and Techniques*. 2004 Apr; vol. 52(no. 4):1343–1352.
12. Koulouridis S, Kiziltas G, Zhou Y, Hansford DJ, Volakis JL. Polymer–ceramic composites for microwave applications: fabrication and performance assessment. *IEEE Transactions on Microwave Theory and Techniques*. 2006 Dec.; vol. 54(no. 12):4202–4208.
13. Sharifi H, Lahiji RR, Han-Chung Lin PD, Katehi LPB, Mohammadi S. Characterization of Parylene-N as flexible substrate and passivation layer for microwave and millimeter-wave integrated circuits. *IEEE Transactions on Advanced Packaging*. 2009 Feb.; vol. 32(no. 1):84–92.
14. Heywang-Koebrunner SH, Heinig A, Pickuth D, Alberich T, Spielmann R. Interventional MRI of the breast: lesion localisation and biopsy. *Eur Radiol*. 2000; vol. 10:36–45.
15. de Souza NM, Kormos DW, Krausz T. MR-guided biopsy of the breast after lumpectomy and radiation therapy using two methods of immobilization in the lateral decubitus position. *J. Magnetic Resonance Imaging*. 1995 Oct.; vol. 5(no. 5):525–528.
16. Armani DK, Liu C. Microfabrication technology for polycaprolactone, a biodegradable polymer. *J. Micromechanics Microengineering*. 2000 Jan..vol. 10:80–84.
17. Wurm A, Soliman R, Schick C. Early stages of polymer crystallization—a dielectric study. *Polymer*. 2003 Nov.; vol. 44(no. 24):7467–7476.
18. Bello A, Laredo E, Grima M. Comparison of analysis of dielectric spectra of PCL in the ϵ^* and the M^* formalism. *J. of Non-Crystalline Solids*. 2007 Oct..vol. 353:4283–4287.
19. Capps RN, Stack GM, Samuels MQ, Beumel LL. Dielectric and viscoelastic properties of some meta-tetramethyl xylene diisocyanate-based polyurethanes as a function of sample composition. *J. of Applied Polymer Science*. 1992 July; vol. 45(no. 7):1175–1188.
20. Zastrow E, Davis SK, Lazebnik M, Kelcz F, Van Veen BD, Hagness SC. Development of anatomically realistic numerical breast phantoms with accurate dielectric properties for modeling

- microwave interactions with the human breast. *IEEE Transactions on Biomedical Engineering*. 2008 Dec.; vol. 55(no. 12):2792–2800. [PubMed: 19126460]
21. Lee M-Q, Sangwook N. An accurate broadband measurement of substrate dielectric constant. *IEEE Microwave and Guided Wave Letters*. 1996 Apr.; vol. 6(no. 4):168–170.
 22. Barot, SF.; Bernhard, JT. *IEEE Antennas and Propagation Society International Symposium*. San Diego, CA: 2008. Permittivity measurement of layered media using a microstrip test bed; p. 1-4.
 23. Chang S-H, Kuan H, Wu H-W, Yang R-Y, Weng M-H. Determination of microwave dielectric constant by two microstrip line method combined with EM simulation. *Microwave and Optical Technology Letters*. 2006 Nov.; vol. 48(no. 11):2199–2201.
 24. Baker J, Janezic M, Degroot D. High-frequency dielectric measurements. *IEEE Instrumentation & Measurement Magazine*. 2010 Apr.; vol. 13(no. 2):24–31.
 25. Djordjevi AR, Biljic RM, Likar-Smiljanic VD, Sarkar TK. Wideband frequency-domain characterization of FR-4 and time-domain causality. *IEEE Transactions on Electromagnetic Compatibility*. 2001 Nov.; vol. 43(no. 4):662–667.
 26. Cauwe M, De Baets J. Broadband material parameter characterization for practical high-speed interconnects on printed circuit board. *IEEE Transactions on Advanced Packaging*. 2008 Aug.; vol. 31(no. 3):649–656.
 27. Queffelec P, Gelin P, Gieraltowski J, Loaec J. A microstrip device for the broad band simultaneous measurement of complex permeability and permittivity. *IEEE Transactions on Magnetics*. 1994 Mar.; vol. 30(no. 2):224–231.
 28. Chung J-Y, Sertel K, Volakis JL. Broadband characterization of bulk and thin magnetic composites using stripline structures. *IEEE Transactions on Microwave Theory and Techniques*. 2010 Nov.; vol. 58(no. 11):2960–2967.
 29. Agilent Advanced Design System 2009 User Manual. Santa Clara, CA: Agilent Technologies; 2009. (see, e.g., "Distributed Components - Microstrip Components - Microstrip Line")
 30. Ramazani M, Miladi H, Shahabadi M, Mohajerzadeh S. Loss measurement of aluminum thin-film coplanar waveguide (CPW) lines at microwave frequencies. *IEEE Transactions on Electron Devices*. 2010 Aug.; vol. 57(no. 8):2037–2040.
 31. Lee H-Y. Wideband characterization of a typical bonding wire for microwave and millimeter-wave integrated circuits. *IEEE Transactions on Microwave Theory and Techniques*. 1995 Jan.; vol. 43(no. 1):63–68.
 32. Yun SK, Lee HY. Parasitic impedance analysis of double bonding wire for high frequency integrated circuits packaging. *IEEE Microwave Guided Wave Letters*. 1995 Sept.; vol. 5:296–298.
 33. Yamashita E, Ohashi H, Atsuki K. Characterization of microstrip lines near a substrate edge and design formulas of edge-compensated microstrip lines. *IEEE Transactions on Microwave Theory and Techniques*. 1989 May; vol. 37(no. 5):890–896.
 34. Muldavin JB, Rebeiz GM. Millimeter-wave tapered-slot antennas on synthesized low permittivity substrates. *IEEE Transactions on Antennas and Propagation*. 1999 Aug.; vol. 47(no. 8):1276–1280.
 35. Al-Joumayly MA, Aguilar SM, Behdad N, Hagness SC. Dual-band miniaturized patch antennas for microwave breast imaging. *IEEE Antennas and Wireless Propagation Letters*. 2010 Mar.; vol. 9:268–271. [PubMed: 21866218]

Fig. 1. Photographs of PCL-based thermoplastic meshes characterized in this study. (a) A U-Plast™ 8338BL.SO2+/R thermoplastic mesh molded to a physical breast phantom. (b) An Efficast® 8333Y.3/R 2.0-mm-thick mesh with 2.8-mm-diameter holes created on a hexagonal lattice with $a = 5.8$ mm. (c) A U-Plast™ 8338BL.SO2+/R 2.4-mm-thick mesh with 1.4-mm-diameter holes created on a rectangular lattice with $w_1 = 5.6$ mm and $w_2 = 2.8$ mm.

Fig. 2. Equivalent circuit model of the transmission line configuration. The parasitic elements associated with the coaxial-to-microstrip transition are contained inside the dash-dot-dash boxes ($L = 0.28$ nH, $R = 0.05$ Ω , $C = 0.07$ pF).

Fig. 3. Measured S_{21} for a microstrip transmission line (width of 10 mm, length of 265 mm) fabricated on a substrate comprised of a perforated PCL-based thermoplastic (Efficast® 8333Y.3/R), compared with the ADS-computed S_{21} for a model of the microstrip with optimized substrate dielectric properties.

(a)

(b)

Figure 4.

Dielectric properties of two PCL-based thermoplastic materials, as a function of frequency, obtained from microstrip transmission-line measurements. The properties correspond to those of the bulk thermoplastic, after accounting for the air holes (i.e., perforations) in the commercial samples of (a) Efficast® 8333Y.3/R and (b) U-Plast™ 8338BL.SO2+/R.

Figure 5.

Coronal cross-sections of reconstructed three-dimensional dielectric profiles of a Class 2 (scattered fibroglandular) breast phantom. (a)–(b) Images of the phantom with no thermoplastic sheet. (c)–(d) Images of the phantom with the thermoplastic sheet at the skin surface. Dielectric constant, left, and effective conductivity (S/m), right, at 2.0 GHz. (Color version of this figure is available online.)