Dielectric Property Measurement of PLA

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***Abstract*— 3D printing technology provides an affordable method of prototyping antennas. To design antennas with this technology it is necessary to characterize the materials used for printing precisely in terms of their permittivity and conductivity. Two major groups of materials for antenna design are dielectric and conductive materials. In this paper, we consider measurement of dielectric constants of three types of polylactic acid (PLA) plastic materials that can be used for 3D printing of antennas and other radio frequency (RF) devices.**

***Keywords*— 3D printing, dielectric constant, waveguide dielectric measurement**

I. Introduction

3D printers nowadays are more affordable and accessible to the public. This results in a good possibility of using 3D printers for prototyping antennas. The advantage of this technology is adding the third dimension in antenna design, opening a door to volumetric antenna design. Volumetric antenna design is not easily achieved by traditional milling methods. On the other hand, 3D printers are using specific materials that are new to antenna and electronic technology resulting in different antenna structures to meet antenna specifications.

3D printer uses polylactic acid (PLA), a biodegradable, high-strength thermoplastic [1]. For material characterization, the dielectric constant of the PLA needs to be determined by finding the complex permittivity. The real component of permittivity is the ability of a material to store electric energy, whereas the imaginary component is the loss factor of the material [2].

In this paper we show the results of application of two methods of material characterization to three different PLA materials that are candidates to be used in printing 3D antennas.

II. Material Characterization

A. Test Method Selection

There are many available test methods to characterize the electrical properties of the dielectric and conductor PLA materials. Each has advantages based on the available equipment, material sample shapes, material properties, and a multitude of other factors [2]. The transmission line was chosen due the advantages of being broadband, and best for lossy to low loss materials, and not requiring precision machining [3]. The result of this method are compared to the measurements done by Keysight dielectric probe 85070E [4].

B. Test Apparatus

Two different configurations of a transmission line apparatus were examined: a waveguide apparatus and a coaxial apparatus. The waveguide apparatus is shown in Fig. 1. This apparatus contains its own power source with a variable frequency from 9 GHz to 10 GHz. The power source generates an electromagnetic (EM) wave that travels through the main waveguide. Using the slotted line, the EM wave is then used to compute the voltage standing wave ratio (VSWR) and phase shift when a material sample is placed in the waveguide chamber. With these measurements, the permittivity and loss tangent values of the dielectric material can be calculated from the reflection coefficient and the impedance of the waveguide.

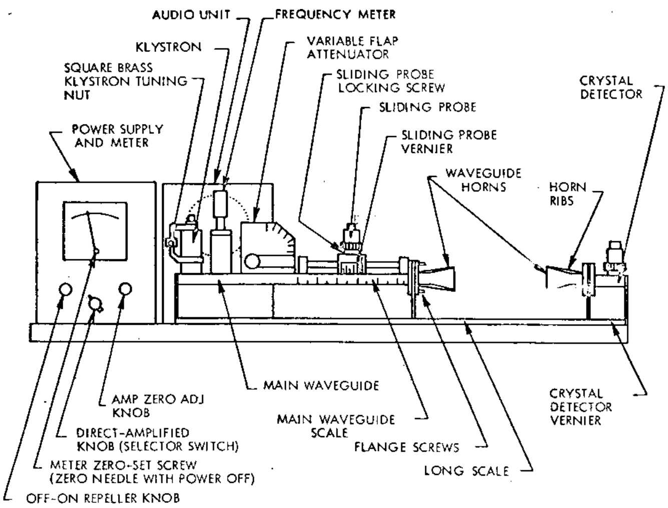
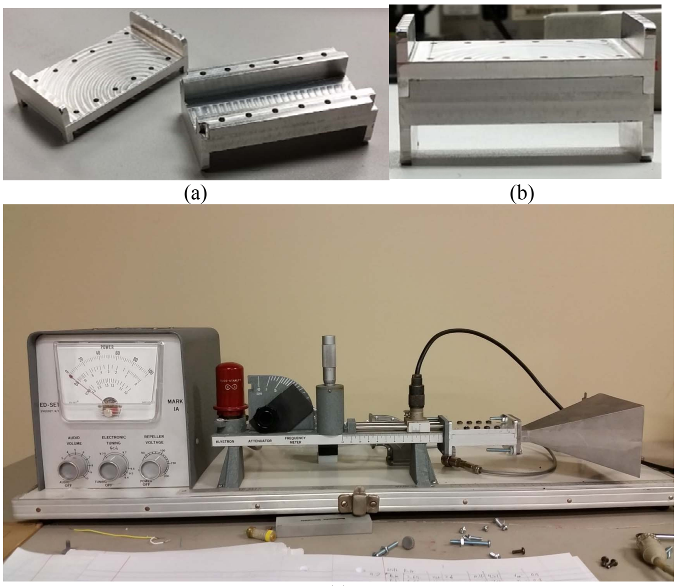


Fig. 1. Test apparatus for transmission line test [5].

To isolate the sample material during testing, a waveguide test chamber was required. The waveguide was designed using AutoCAD and fabricated using a CNC milling machine. The waveguide was then inserted after the slotted line, prior to the waveguide horns. The inner dimensions of the waveguide, 0.9 inches by 0.4 inches, were matched to the dimensions of the slotted line, and the length of the waveguide was set to 3 inches to ensure that a significant change in the reference plane of the reflection coefficient could be calculated. The length of the material samples was 1 inch so that they were larger than half the wavelength. The waveguide is shown in Fig. 2.



(a) (b)

(c)

Fig. 2. (a) Waveguide components, (b) assembled waveguide, (c) measurement waveguide apparatus.

Calibration testing was performed using a sample of ultra-high-molecular-weight (UHMW) polyethylene, which has a known material characteristics, to verify the accuracy of the apparatus. To calculate the permitivity, the load impedance is required. First the cutoff frequency f_c was found using:

$$f_c = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \tag{1}$$

where μ is the permeability, ε is the permittivity, $m = 1$ and $n = 0$ for a TE_{10} mode, and a and b are the inner dimensions of the waveguide. Then, the frequency was found by taking the inverse of the wavelength calculated using:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-(\frac{f_c}{f})^2}} \tag{2}$$

where λ_g is the wavelength between the nulls of the waveguide and λ_o and f are the wavelength and frequency respectively in an unbounded medium. The impedance Z_o of the waveguide was calculated by applying the cutoff frequency. Finally, the VSWR was found from E_{max} and E_{min}, which are the maximum and minimum electric fields at the peak and null of the slotted line. The VSWR was applied to (4) and was used to find the reflection coefficient and the load impedance, Z_l [6].

$$Z_0 = \frac{\sqrt{\mu/\epsilon}}{\sqrt{1-(\frac{f_c}{f})^2}} \tag{3}$$

$$|\Gamma| = \frac{\sqrt{\frac{E_{max}}{E_{min}}}-1}{\sqrt{\frac{E_{max}}{E_{min}}}+1} = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{4}$$

After the load impedance and reflection coefficient were calculated for free space, sample blocks of PLA, magnetic PLA, and conductive PLA were placed within the waveguide one at a time. The presence of a material sample in the waveguide will result in a shift in matching that can be found using a Smith Chart. By calculating the load impedance from the slotted line for each material, the permittivity and loss tangent can be found by calculating the shift in reflection coefficient through the waveguide over a range of frequencies.

During the data collection phase, the location and voltage value of the peaks and the nulls were found from the slotted line and network analyser, respectively. In order to find a specific null location, the average of the locations of the 3 dB points surrounding the nulls were calculated. These values were then used in the calculation of the VSWR and phase shift.

The propagation of reflection coefficient can be used to calculate the change in reflection coefficient when a dielectric material is placed in the waveguide. By taking the complex reflection coefficient found from free space using [6]:

$$\Gamma = |\Gamma| e^{j(2X_m\beta \pm \pi)} \tag{5}$$

$$\Gamma_{shifted} = \Gamma e^{-j2\beta l} \tag{6}$$

where $|\Gamma|$ is the magnitude of the reflection coefficient, X_m is the location of the null, $\beta = \frac{2\pi}{\lambda_g}$, and l is the length needed to travel. $|\Gamma_{shifted}|$ is the reflection coefficient shifted to the end of the waveguide. The reflection is then converted to an impedance using [6]:

$$Z = \frac{\Gamma_{shifted}+1}{1-\Gamma_{shifted}} \tag{7}$$

Because impedance value changes as the wave moves through the dielectric material, the impedance is recalculated using [6]:

$$Z_{0\,diel} = \frac{2\pi f \eta}{\beta_{diel} v_{prop}\sqrt{\varepsilon_r}} \tag{8}$$

$$Z_{new} = \left(\frac{Z_{before\ dielectric}}{Z_{air}}\right) Z_{0\,diel} \tag{9}$$

where f is the frequency in an unbounded medium, η is the impedance of free space, β_{diel} is the new value of phase velocity within the material, v_{prop} is the propogation veloctiy in free space, ε_r is the dielectric constant of the material, $Z_{before\ dielectric}$ is the impedance at the location of the dielectric, and Z_{air} is the impedance of air in the waveguide. Additionally, the dielectric loss, which is the loss tangent value for the material, is found using [6]:

$$\alpha_d = 8.68\left(\frac{\varepsilon_e''}{\varepsilon_e'}\right)\left(\frac{\pi}{\lambda}\right)\left(\frac{\lambda_g}{\lambda}\right) \tag{10}$$

where λ_g is the wavelength between the nulls of the waveguide, λ is the wavelength in an unbounded medium, and $\frac{\varepsilon_e''}{\varepsilon_e'}$ is the loss tangent value. Using equations (6) and (7), the new impedance is adjusted to a new reflection coeffient and is shifted through the material. Using equations (7), (8), and (9), the new reflection coeffiecient is first converted back to impedance and is then converted back to free space impedance. Finally, using equation (6), the reflection coefficient is shifted back to the slotted line. By comparing the calculated reflection coefficient to the measured reflection coefficient when a sample material was placed in the waveguide, the properties of the material can be determined by finding a best-fit value. Additionally, measuring over a span of frequencies ensures a more accurate value.

C. *Measurement Results*

The waveguide method was used to characterize three types of materials: Dielectric PLA, conductive PLA and magnetic PLA. The magnetic and dielectric PLAs were obtained from www.proto-pasta.com. The conductive PLA has been reported to have volume resistivity of 115Ω/cm. The magnetic iron PLA is claimed to be ferromagnetic and responding to pure iron. These materials were picked due to the need of all three types in designing antennas.

Figs. 3-6 demonstrate the measured reflection coefficients compared to the calculated reflection coefficients using dielectric constant and loss tangent. Adjusting the dielectric constant and the loss tangent rotates and expands the calculated reflection coefficient around the Smith Chart. In Figs. 3 and 5, the calculated reflection coefficient follows the shape of the measured reflection coefficient. However, there are more errors in conductive PLA measurements (Fig. 4).

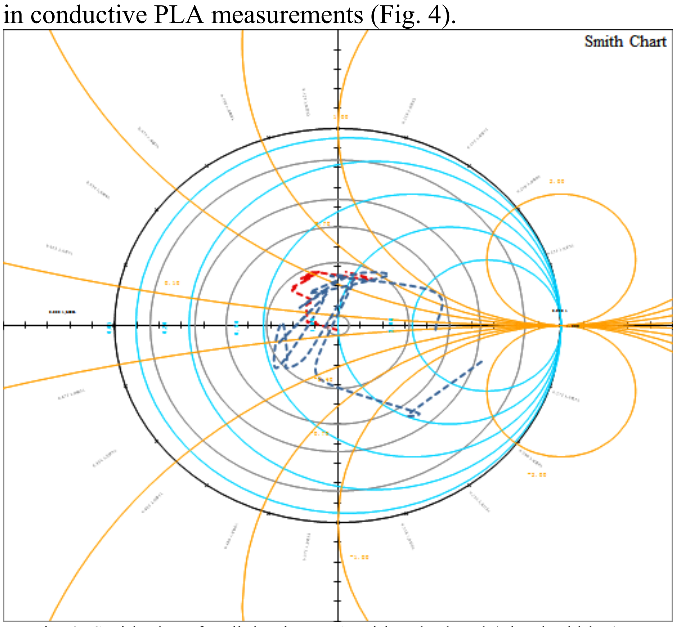


Fig. 3. Smith chart for dielectirc PLA with calculated (dasshed blue) vs measured (solid red) with dielectric constant of 3.549 and loss tangent of -0.001.

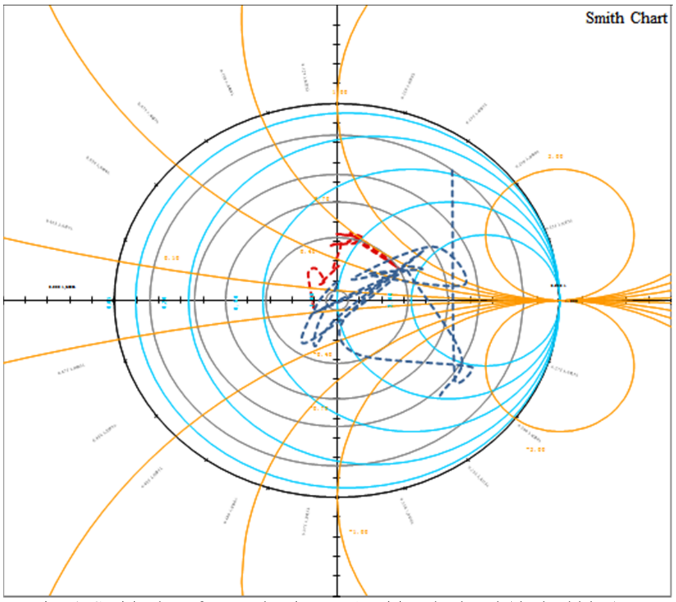


Fig. 4. Smith chart for conductive PLA with calculated (dashed blue) vs measured (solid red) with dielectric constant of 6.414 and loss tangent of 0.

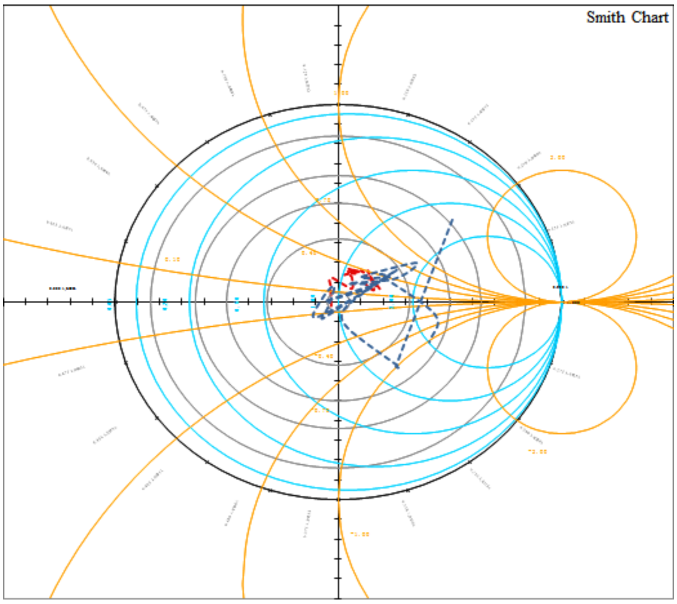


Fig. 5. Smith chart with for magnetic PLA calculated (dashed blue) vs measured (solid red) with dielectric constant of 3.637 and loss tangent of 0.

D. *Dielectric Probe Measurements*

To examine how good the waveguide measurements are a series of measurements were also conducted using Keysight Dielectric Probe 85070E. Blocks of materials with approximately 1 cm^3 were printed (Fig. 6). The measurements were done in the span of 2 GHz- 20 GHz. The results are shown in Figs 7-9. Keysight Dielectric Probe uses an open-end transmission line method. It is attached to a vector network analyser to measure S_{11} and calculate permittivity and conductivity.

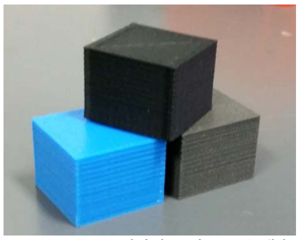


Fig. 7. Blocks for measurements: deielectric PLA (blue), conductive PLA (black), magnetic PLA (gray).

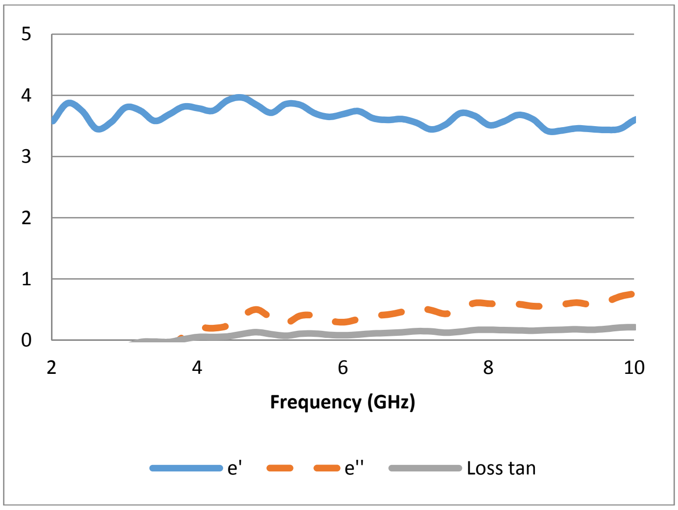


Fig. 8. Dielectric constant (real: e', imag: e'') and loss tangent for dielectric PLA.

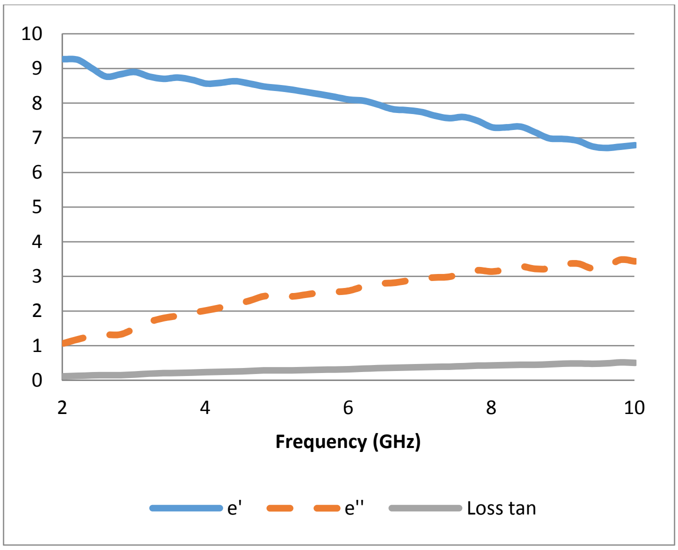


Fig. 9. Dielectric constant (real: e’, imag: e”) and loss tangent for conductive PLA.

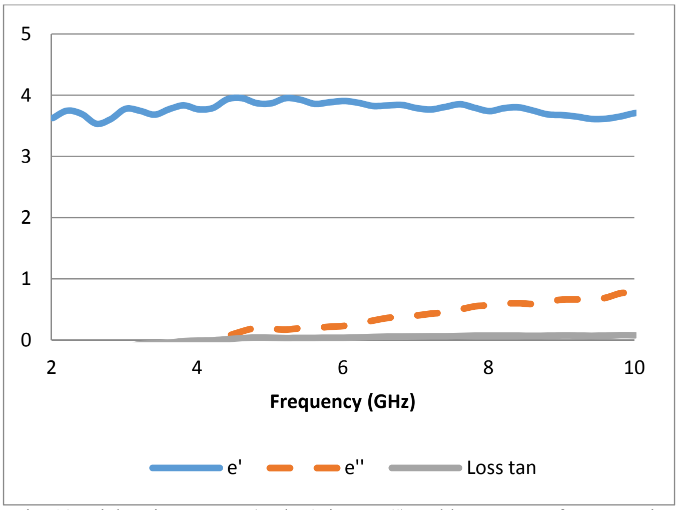


Fig. 10. Dielectric constant (real: e’, imag: e”) and loss tangent for magnetic PLA.

E. *Comparison*

When calculating the reflection coefficient, the material was first assumed to be lossless; however, this assumption has caused issues in calculating the reflection coefficient. After measuring the materials at high frequencies, the loss tangent could not be accurately determined. Table I shows the values of the dielectric constant and loss tangent averaged over 9 GHz to 10 GHz, using the waveguide method. Similarly, the values of measurements through dielectric probe were averaged for the frequency range of 9 GHz – 10 GHz. These are shown in Table II. The error for dielectric constant measurement were calculated as 2.2%, 5.8%, 0.4% for dielectric, conductive and magnetic PLA, respectively. Based on these results one may conclude that the waveguide method has enough accuracy for dielectric and magnetic PLA dielectric constant measurement. However, there is a larger error in measuring conductive PLA. Also by looking at Fig. 8, it can be seen that conductive PLA as a more range of variation than other two materials. Therefore, it is very sensitive to the frequency range of measurement.

TABLE I
VALUES FOR DIELECTRIC CONSTANT AND LOSS TANGENT AVERAGE OF 9 GHZ-10 GHZ.

Material	Dielectric Constant	Loss Tangent
PLA	3.549	-0.001
Conductive PLA	6.414	0.00
Magnetic PLA	3.637	0.00

TABLE III
VALUES FOR DIELECTRIC CONSTANT AND LOSS TANGENT PROBE METHOD AVERAGE OF 9 GHZ-10 GHZ.

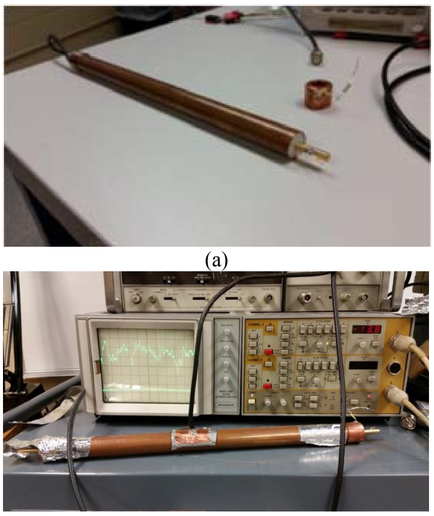
Material	Dielectric Constant	Loss Tangent
PLA	3.471	0.073
Conductive PLA	6.811	0.493
Magnetic PLA	3.653	0.187

F. *Coaxial Transmission Line*

For the conductive PLA, the dielectric constant may change dramatically by frequency. Conductive PLA needs accurate measurement at the working frequency. Given that many wireless systems are working at lower frequencies; we are building a slotted line coaxial apparatus. The measurement range of this new transmission line, shown in Fig. 10, will be 1.7 GHz to 4 GHz, which is within the range for WiFi antennas.

III. CONCLUSION

In conclusion, the dielectric constants for three types of PLAs were measured using waveguide method and was compared with the results from a commercial dielectric probe. The results for dielectric constant measurements were within 6% accuracy; however, there is low confidence in the loss tangent values calculated from transmission line method.



(a)

(b)

Fig. 10. (a) Coaxial cable slotted line, (b) measurement setup.

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