Preparation and Dielectric Characterization of Arrowroot-Chitosan Film for Microwave Phantom Applications

Ullas G. Kalappura, Paulbert Thomas, Cyriac M. Odackal and K. T. Mathew

Abstract – **Arrowroot (Maranta arundinacea) and Chitosan are two well-known materials used in medical and scientific applications. Both materials possess medicinal properties and have the ability to form thick gels. Chitosan-reinforced Arrowroot film was developed and its dielectric characterization was performed at microwave frequencies. Cavity perturbation method was used for the measurement. The study proposes the use of Arrowroot-Chitosan film as phantom material representing human body counterparts in microwave imaging applications.**

Keywords – **Arrowroot-Chitosan film; Microwave Phantoms; Cavity perturbation; Complex permittivity;S-band.**

I. INTRODUCTION

The quest for thin, tough and transparent biocompatible films led to the development of new materials in medical field [1-3]. Arrowroot has been traditionally used as a medicinal herb and is most commonly used as a chief ingredient in baby food, as substitute for talcum in baby powder and body powder. A preliminary study on dielectric characterization of Arrowroot film was done by the authors [4]. Chitosan (poly [β-1-4]) D-glucosamine) is a biopolymer which is commonly used in medical field as implant material. It is also used in purification, food, chromatography, pharmaceutical and many other diverse fields [5, 6].

Microwave phantoms are usually used to evaluate quantitative performance of imaging systems [7]. The purpose and use of a phantom is to explore the interaction between body tissues and electromagnetic fields. It is also used in vitro for Specific Absorption Rate (SAR) studies. All biomaterials are prone to microwaves. Mariya Lazebnik *et al* characterized oil-in-gelatin dispersions that approximate the dispersive dielectric properties of a variety of human soft tissues over the microwave frequency range from 500 MHz to 20 GHz [8]. Polyvinyl-acetate-based phantoms were developed by G. Bindu *et al* [9] for medical imaging applications. In this paper we present the preparation and dielectric characterization of Arrowroot-Chitosan film. The possibility of the film for use as phantom material is explored. The dielectric properties of the film at S-band frequencies are measured with the aid of Vector Network Analyzer.

Ullas G. Kalappura, Paulbert Thomas and Cyriac M. Odackal are with Cochin University of Science and Technology, Cochin, Kerala, India, E-mail: ullasgk@gmail.com, paulbertthomas@gmail.com, cyriacpala@yahoo.co.uk
K. T. Mathew is with Viswajyothi College of Engineering & Technology, Vazhakulam, Kerala, India, E-mail: kattackalmathew@gmail.com

II. SAMPLE PREPARATION

The preparation of Arrowroot-Chitosan film involves the mixing of respective gels of both and drying its cast in room temperature. Arrowroot gel and Chitosan gel were prepared as the first step. Arrowroot powder (10g) was dissolved in water (100ml) and then heated in a glass tumbler. Around 80°C, the solution turned into a transparent gel. The Solute: Solvent ratio was determined experimentally. After reaching a saturation level, the solute particles tend to coagulate, thereby spoiling a clean gel. If the amount of solute is far below the optimal value, the gel wouldn't achieve sufficient viscosity for film formation. Conventional heating is more prone to coagulation due to inherent anisotropy in temperature distribution. If a conventional heater is used to heat the solution, then it is necessary to stir the solution to avoid coagulation of particles. In order to avoid the coagulation problem microwave heating can be used. Although the penetration depth of microwave limits the uniformity of heating, the faster heating rate ensures less coagulation. We were able to obtain a clean gel easily when microwave heating was used.

Chitosan is a biopolymer which is obtained from the shells of sea crustaceans like shrimp and crab, and is commercially available. It is soluble in weak acids due to the low value of pKa (acid dissociation constant). Chitosan powder (5g) was dissolved in 100 ml glacial acetic acid (99-100%) which was diluted with 10ml of water. The obtained gel was added to Arrowroot gel in different ratios (1:5, 2:5, 3:5) and mixed thoroughly. The mixes were casted and dried in shadow to obtain thin films of varying thickness. The films were uniform in thickness without any air gaps or pores on the surface. The thickness of the films ranged from 0.15mm to 0.8mm. The films were then cut into thin strips of 3-5 mm width and 50mm length for measurement purpose. Three methods were used to dry the cast - conventional shadow drying, microwave drying and hot air drying. Among these methods, shadow drying was found to be the best method to obtain a uniform film. Microwave and hot air drying can also produce good films. But if the temperature given to the cast is even slightly high, it will result in a deformed film. Hence we have to reduce the temperature and increase the drying time. But it will consume more electricity. Choosing the appropriate drying method demands a trade-off between time and economy.

III. EXPERIMENTAL SETUP AND THEORY

Microwave characterization of Arrowroot (Arrow) and Arrowroot-Chitosan (Arrow-Ch) films was performed using Agilent 8714 ET vector network analyzer. Cavity perturbation technique [10, 11] was employed for the purpose. This method was adopted because it gives more precise results for materials with low permittivity values. Small strips of film were used for the measurement. The properties such as Complex permittivity, Conductivity, Skin depth, Microwave heating coefficient and Attenuation constant were calculated. The experimental setup is as shown in Fig.1.

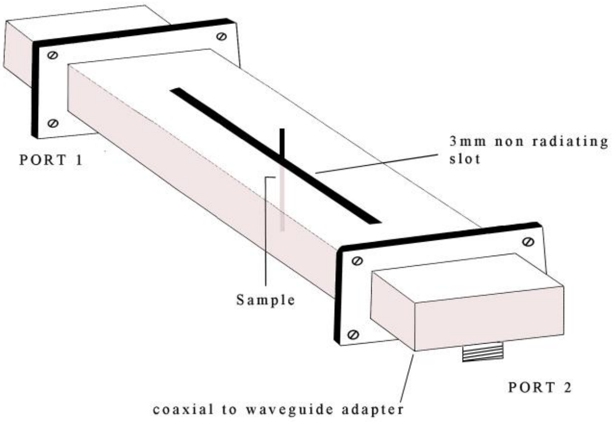

Fig. 1 Cavity perturbation setup for dielectric property measurement at S-band

The resonator was excited in TE_{10p} mode by connecting it to Agilent 8714ET vector network analyzer. The resonant frequency and Q factor of the cavity are changed due to the perturbation of the sample within the cavity. However, the cavity perturbation method for small objects requires that the electric field outside the inserted sample does not change. The dielectric properties of the samples were evaluated from the variation of resonant frequencies and quality factors of empty and loaded cavities. The resonant frequency f_0 and quality factor Q_0 of each resonant peaks of unloaded cavity (without sample) are determined first. Then the sample is inserted via the non-radiating slot along the major axis of the cavity and its position is adjusted for maximum perturbation. For each resonant peak, the new value for resonant frequency f_s and Q factor Q_s for maximum perturbation are noted. These values are used in Eqs. (1) and (2) to find ε_r' and ε_r", the real and imaginary parts of the relative complex permittivity of the inserted sample. The real part of the relative complex permittivity is known as dielectric constant and the imaginary part, loss factor.

The complex permittivity can be obtained from the measured data as [11],

$$\varepsilon_r' = \frac{f_0 - f_s}{2f_s}\left(\frac{V_c}{V_s}\right) + 1 \qquad (1)$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{Q_0 - Q_s}{Q_0 Q_s}\right) \qquad (2)$$

Where V_c and V_s are the volumes of the cavity and sample respectively. The microwave conductivity can be found as

$$\sigma = \omega\varepsilon'' = 2\pi f_s \varepsilon_0 \varepsilon_r'' \qquad (3)$$

The Skin depth gives a measure of the depth of penetration of electromagnetic wave inside the material. At a depth of δ, the wave amplitude decreases by a factor e^{-1}. Skin depth is found from the basic relation,

$$\delta = \frac{1}{\sqrt{\pi f_s \mu \sigma}} \qquad (4)$$

Where μ is the permeability of the sample ($\mu = \mu_0\mu_r$)

The microwave heating coefficient (J) represents the power dissipation properties of the material. It is inversely proportional to loss factor. The attenuation constant (α) represents the spatial rate of decay of the wave within the medium. When the wave moves along the z axis, its amplitude decays by a factor $e^{-\alpha z}$. The microwave heating coefficient and attenuation constant are found using the formulae

$$J = \frac{1}{\varepsilon_r' \tan(\delta)} \qquad (5)$$

$$\alpha = \frac{\varepsilon_r'' f_s}{\sqrt{(\varepsilon_r' + \varepsilon_r'')} \times c} \qquad (6)$$

Where tan (δ) is the loss tangent of the medium and c, the velocity of light.

IV. RESULTS AND DISCUSSIONS

The cavity perturbation technique gives the permittivity and loss factor at microwave frequencies as a function of shift in resonant frequency and variation in quality factor of the wave guide cavity. The dielectric properties of a material define its interaction with microwaves. It is independent of the volume or thickness of the material, but depends on the relaxation time of the molecules constituting the material.

Fig. 2 depicts the variation of real part of relative complex permittivity with respect to frequency. The dielectric constant of standalone Chitosan film is low when compared to Arrow and Arrow-Ch films. The Arrow-Ch films used for measurements were prepared by the addition of 5% Chitosan gel to 10% Arrowroot gel. The dielectric constant of Arrow-Ch film can be further lowered to the desired value by increasing the amount of Chitosan in the film. The overall low value of the real part of complex permittivity is an indication of the lack of water content in the film. The presence of moisture would have increased the value of dielectric constant. Due to the low dielectric constant, the charge holding capacity of the films will be nominal. Hence the films are non-polar in nature.

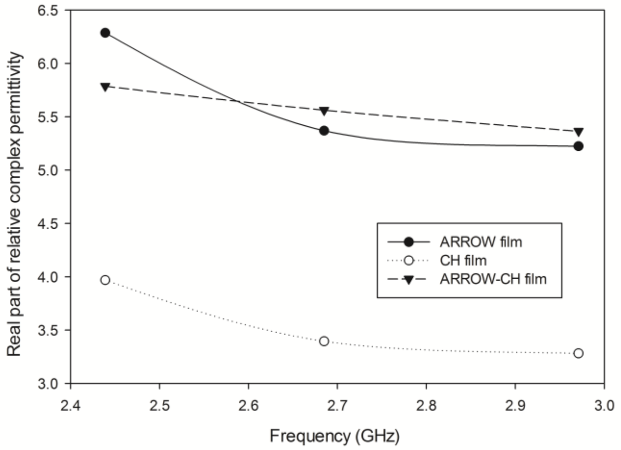

Fig. 2 Variation of dielectric constant with frequency

The dielectric properties of the prepared film are the same as that of certain biological constituents of human body. A comparative study of human tissues (37°C) at 3GHz [12] and their equivalent phantoms is shown in Table 1. The dielectric constant of the film can be fine-tuned by varying the amount of Chitosan in the film. This is one of the advantages of using Arrow-Ch film rather than standalone Arrow film. Another advantage is the inability to hold charges. If the material accumulates charges on its surface, it can affect the measurement results significantly. Hence Arrow-Ch film can function as a phantom material representing human body tissues in scientific/medical applications.

TABLE 1
DIELECTRIC PROPERTIES OF HUMAN TISSUES AT 3 GHZ AND THEIR EQUIVALENT PHANTOMS

Biological tissue at 37°C	Dielectric constant of standard sample	Equivalent phantoms in terms of ratio of gels used in preparation (Arrowroot: Chitosan)
Collagen	5.5-6.5	5:1
Bone marrow	4.2-5.8	5:1
Fat	5.28	5:2
Breast fat	5.15	5:2
Human abdominal wall fat	4.92	5:3

Fig. 3 shows the variation of loss factor with frequency. When an electromagnetic wave is applied to a dielectric material, it tries to polarize the material. As the films we prepared are relatively non-polar, the molecules will return to their initial state as soon as the applied field is withdrawn. Hence the dielectric relaxation time will be quite small. The dielectric loss highly depends on the relaxation process which involves local motion of polar groups. The loss occurs due to the friction between the molecular chains during this process. In the case of biomaterial films, the friction between the chains will be nominal. Hence the films exhibit low loss factor value.

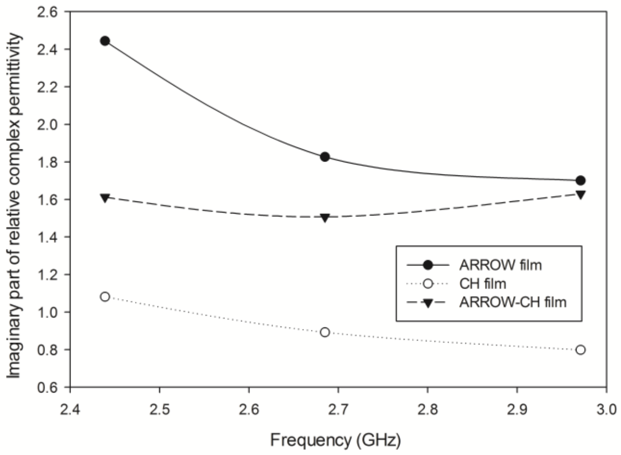

Fig. 3 Variation of loss factor with frequency

The conductivity of the Arrow-Ch film varies as a function of frequency and dielectric loss of the material. Hence it shows same variation as with the loss factor (Table 2). As the film is non-polar, an increase in frequency lowers the capacitive reactance of the film which in turn increases conductivity. The Skin depth gives a measure of the depth of penetration of the microwave signal. For a conducting material, the Skin depth will be low due to the reflection from the surface. The penetration depth varies inversely with conductivity. A high value of the heating coefficient means that the material is poor for dielectric heating applications.

TABLE 2
VARIATION OF CONDUCTIVITY, SKIN DEPTH, HEATING COEFFICIENT AND ATTENUATION CONSTANT OF ARROW-CH FILM WITH FREQUENCY

Frequency (GHz)	Conductivity (S/m)	Skin depth (m)	Heating coefficient	Attenuation constant
2.44	0.21	0.02	0.62	45.87
2.68	0.22	0.02	0.66	48.78
2.97	0.26	0.01	0.61	56.15

The Arrow-Ch film has low value of dielectric loss which implies that the dielectric heating of the material is low. Attenuation occurs due to the collision between molecular chains resulting in dielectric loss. The attenuation constant is high at 2.97GHz. For a highly attenuating material, the depth of penetration will be low. This can be verified from the value of Skin depth from Table 2. It is clear that Arrow-Ch film could be used for microwave phantom applications. It is observed from Fig. 2 that the dielectric constants of Arrow and Arrow-Ch films are close to each other. But as far as fine tuning of dielectric properties are considered, Arrow-Ch film proves to be a better choice.

V. CONCLUSIONS

Arrowroot-Chitosan biomaterial film was developed. The microwave properties of the film were studied. It was found that the film could be used as phantom material in microwave imaging applications and in SAR studies. The dielectric properties of the film can be tuned to the desired value by adjusting the percentage composition of Chitosan in the film. The film is also devoid of air gaps and pores. The films prepared are biodegradable as both Chitosan and Arrowroot are edible. With its unique dielectric, mechanical and morphological characteristics, Arrow-Ch film proves to be a versatile material and can find use in many diverse fields.

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