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Dielectric studies of polyvinyl-acetate-based phantom for applications in microwave medical imaging

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Abstract Phantoms that exhibit complex dielectric properties similar to low water content biological tissues over the electromagnetic spectrum of 2–3 GHz have been synthesized from carbon black powder, graphite powder and polyvinyl-acetate-based adhesive. The materials overcome various problems that are inherent in conventional phantoms such as decomposition and deterioration due to the invasion of bacteria or mold. The absorption coefficients of the materials for various compositions of carbon black and graphite powder are studied. A combination of 50% polyvinyl-acetate-based adhesive, 20% carbon black powder and 30% graphite powder exhibits high absorption coefficient, which suggests another application of the material as good microwave absorber for interior lining of tomographic chamber in microwave imaging. Cavity perturbation technique is adopted to study the dielectric properties of the material.

Introduction

Materials suitable for use in vivo as artificial organs and tissues have been an intriguing topic of research for the past few years. There have been studies on the microwave dielectric properties of materials forming urinary calcifications [1] and various body fluids [2, 3]. Microwave tomographic imaging has gathered momentum in recent years due to the characterization of tissues in terms of its complex permittivity [4]. Microwave images are maps of the electrical property distributions in the body. At microwave frequencies, biological tissue interactions with the fields are defined by their complex permittivity. The bound water content of the tissue is a major factor in determining the permittivity.

Many prototypes of active microwave imaging setups have been presented [5, 6]. Evaluation of the performance of these prototypes requires imaging and interpretation of test objects or phantoms [7]. These could be simple uniform blocks or steps, or more complex designs containing embedded objects to provide tests of resolution or shape detection. It is desirable that the material should respond to microwaves in a similar fashion to the anatomical areas they represent, particularly in tests which measure or calibrate microwave exposures, or when used for optimization of system parameters over the required frequency range. The dielectric properties of the tissue-equivalent materials should yield a close match to the actual tissue conditions. Also the material should be well adapted when intermediate compositions are desired.

Various types of phantoms are already in use as tissue substitutes for microwave medical imaging [8, 9]. These compounds are constructed in one of the two ways; the first consists of jelly agent, polyethylene powder, sodium chloride and water; and the second consists of agar, sodium chloride and water. The disadvantage of constructing phantoms using these materials is that they cannot be used repeatedly as they

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dry out and decompose over time. To avoid this, non-hydrated phantoms are made of ceramic [10] to simulate muscle tissue. However these phantoms require specific adhesive made of ceramic powder whose function is to remove any air gaps between adjacent pieces of ceramic. Unfortunately, the adhesive is difficult to use and the hard ceramic material cannot be cut or reshaped easily.

This paper presents a non-hydrated phantom that overcomes the shortcomings of conventional phantoms. The material is composed of polyvinyl-acetate-based adhesive, carbon black powder and graphite powder. The complex permittivity of the phantom can be controlled by adjusting the composition ratio in order to simulate various biological tissues. The absorption coefficient of the material is studied for its feasibility of using as microwave absorber for interior coating of tomographic chamber in microwave imaging applications. A frequency of 2–3 GHz is selected for the study to conveniently include the Industrial, Scientific and Medical Applications (ISM) band of 2.45 GHz.

Experimental set-up and procedure

The samples are prepared by mixing polyvinyl-acetate-based adhesive (PVA), carbon black powder and graphite powder in different known proportions of weight.

Diamond and graphite are the two natural crystalline allotropes of carbon. Both of them are extracted from nature by conventional mining techniques. Diamond has a three-dimensional structure, while graphite is composed of a series of parallel planes. The structure of carbon black powder is intermediate between these two forms and is termed ''quasi-graphitic'', as a series of layers are formed during the nucleation process. Carbon black powder is intensely black in color, and is manufactured by subjecting natural gas to extremely high temperatures in carefully controlled combustion process. Natural gas is composed of 80–95% of methane, and the balance is composed of varying amounts of ethane, propane, butane and other hydrocarbon compounds.

In the present study, we used commercially available carbon black powder, graphite powder and PVA. PVA is easily available in the brand name Fevicol. Carbon black and graphite powder are mixed in various composition ratios (C:G) of 50:0, 40:10, 30:20, 20:30, 10:40 and 0:50 with the PVA content in all the samples fixed as 50%. It is found that if the PVA content is more than 50% there is difficulty in setting the compound.

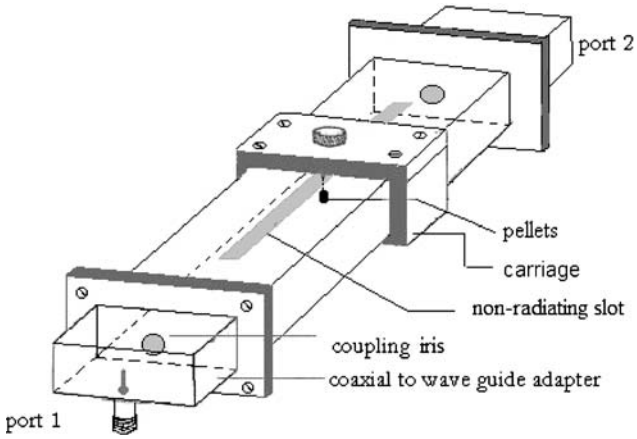

Fig. 1 Schematic diagram of the cavity resonator

Cylindrical pellets of diameter 3 mm, height 2 mm and volume 0.014 cm-cubed are made for all the mixture samples by compressing them in a 3 mm die using a laboratory press. The bulk density and specific gravity of the carbon black powder, graphite powder and PVA are 0.56 and 1.9 g/cm-cubed, 0.56 and 1.8 g/cm-cubed, and 0.62 and 2.1 g/cm-cubed, respectively. Microwave studies of the pellets are done using cavity perturbation technique [11].

The experimental set-up consists of a transmission type S-band rectangular cavity resonator of dimension 34×4 cm, HP 8714 ET network analyzer and an interfacing computer. The cavity is excited in the TE_{10p} mode. In the frequency range of 2–3 GHz, the empty cavity exhibits three positions of maximum of electric field and hence shows three resonant peaks at 2.438, 2.683 and 2.985 GHz. The schematic diagram of the cavity resonator and the resonant frequency spectrum of the cavity are shown in Figs. 1 and 2. These resonant frequencies f_cs and the corresponding quality factors Q_cs of the empty cavity are noted. The cavity is then perturbed by introducing a single pellet into the cavity through the non-radiating slot. The position of the pellet is adjusted for maximum perturbation at each of the three resonant peaks (i.e. maximum shift of resonant frequencies with minimum amplitude for the peaks). Thus three new values of resonant frequencies f_ss and the quality factors Q_ss are obtained. This procedure is repeated for pellets of all the C:G combinations.

Theory of cavity perturbation

The meaning of the term *perturbation* is disturbance or slight change. Perturbation methods are simple and

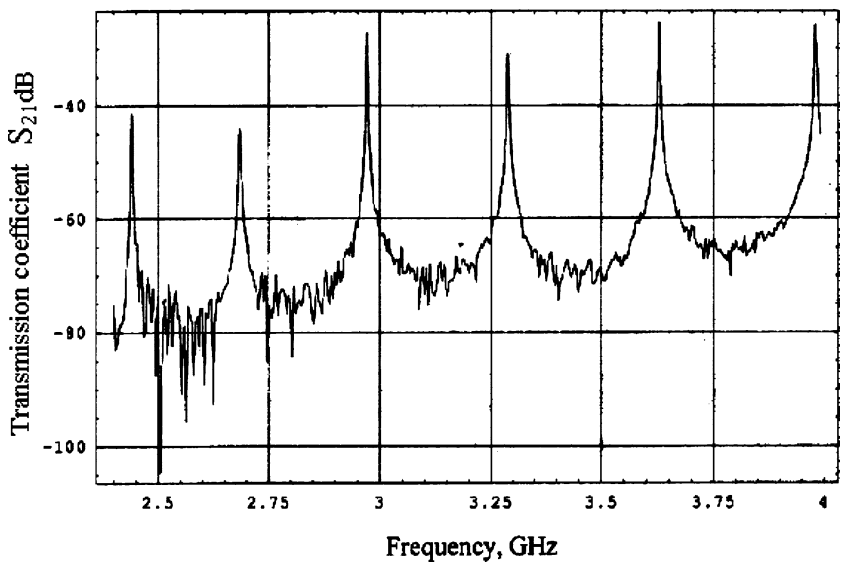

Fig. 2 Resonant frequency spectrum of the S-band rectangular cavity

accurate for calculating changes in some quantity due to small changes in the problem. Many of the electromagnetic field problems can be very effectively solved by this method. The perturbation method involves two situations, namely, the ''unperturbed'' and ''perturbed'' states.

Cavity resonator is a simple device to measure the dielectric properties of an object by studying the perturbation created by the object inside the cavity. A conducting surface enclosing a loss less region forms a cavity resonator. It can be of coaxial, rectangular shape with the propagation mode as transmission or reflection.

For the transmission type rectangular cavity resonator shown in Fig. 1, the electromagnetic energy is coupled to the cavity through coupling irises at the cavity ends. A non-radiating slot is provided at the broad wall of the cavity for the introduction of the sample. On exciting the cavity resonator, a typical resonant frequency spectrum is obtained, depending on the cavity dimensions. The basic principle involved in the technique is that, the field within the cavity resonator is perturbed by the introduction of a dielectric sample through the non-radiating slot. The resonant frequency and the quality factor of the cavity get shifted due to the perturbation. Dielectric properties of the sample are determined based on this theory of perturbation [11, 12]. When a dielectric sample is introduced into the cavity, the relative complex frequency shift of the resonator is given by,

$$-\frac{\mathrm{d}\Omega}{\omega_o} \approx \frac{(\varepsilon_r - 1)\int\limits_{Vs} E.E_o^* \mathrm{d}V + (\mu_r - 1)\mu_o \int\limits_{Vs} H.H_o^* \mathrm{d}V}{\int\limits_{Vc} (D_o.E_o^* + B_o.H_o^*)\mathrm{d}V} \tag{1}$$

where E_o is the electric field in the unperturbed cavity, E is the electric field in the perturbed cavity, D is the displacement current density and H_o, H, and B the respective magnetic quantities. ε_r is the relative complex permittivity of the sample. The dielectric material gets polarized by the electric field inside the cavity and hence its dielectric properties are complex due to the formation of both conduction and displacement currents. The conduction currents represent the current flow that is in phase with the applied voltage whereas the displacement currents are in phase quadrature with the applied voltage. The complex relative permittivity of the sample is represented as

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{2}$$

where ε_r' is the real part of complex relative permittivity known as the dielectric constant or permittivity and ε_r'' is the imaginary part known as the dielectric loss. The real and imaginary parts of complex relative permittivity represent the complimentary processes of energy storage and dissipation respectively. At the position of maximum electric field, the contribution of magnetic field is minimum. The field perturbation due to the introduction of the dielectric sample at the position of maximum electric field is related as,

$$-\frac{\mathrm{d}\Omega}{\omega_o} \approx \frac{(\varepsilon_r - 1)\int\limits_{Vs} E.E_{o\max}^* \,\mathrm{d}V}{2\int\limits_{Vc} |E_o^2|\mathrm{d}V} \tag{3}$$

where dΩ is the complex frequency shift, V_s and V_c are the volumes of the sample and the cavity resonator respectively. The complex frequency shift is related to the quality factor as

$$\frac{d\Omega}{\omega_o} = \frac{d\omega}{\omega_o} + \frac{j}{2}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right) \quad (4)$$

where Q_s and Q_c are the quality factors of cavity resonator with and without the sample. Quality factor Q is given by the equation

$$Q = \frac{f}{\Delta f} \quad (5)$$

where f is the resonant frequency and Δf is the corresponding 3 dB bandwidth. For a small sample, it is assumed that $E = E_o$, which is one of the assumptions taken in the theory of perturbation. When the cavity is excited in the dominant TE_{10p} mode of the rectangular cavity, the electric field inside the cavity can be written as

$$E_o = E_{o\,max} \sin\frac{\pi x}{a} \sin\frac{p\pi x}{d}, \quad p = 1, 2, 3 \ldots\ldots \quad (6)$$

where a and d represent the breadth and length of the cavity resonator.

From Eqs. (2–6), we get

$$\varepsilon_r' - 1 = \frac{f_c - f_s}{2f_s}\left[\frac{V_c}{V_s}\right] \quad (7)$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{Q_c - Q_s}{Q_c Q_s}\right) \quad (8)$$

where f_s and f_c are the resonant frequencies of the cavity with and without the sample. As heat production inside the dielectric sample is related to the product of frequency and the dielectric loss factor, these are combined to be known as the dielectric conductivity σ as,

$$\sigma = \omega\varepsilon_o\varepsilon_r'' \quad (9)$$

The absorption coefficient α of the material is related to its dielectric constant and dielectric loss by the equation

$$\alpha = \frac{\pi\varepsilon_r'' f}{c\sqrt{(\varepsilon_r' 2 + \varepsilon_r'' 2)}} \quad (10)$$

where c is the velocity of light in free space.

Results and discussions

To study the variations of dielectric constant and conductivity of the phantom samples compared to their elemental values, dielectric properties of carbon black, graphite powder and PVA are studied separately using cavity perturbation technique. Cylindrical pellets of same dimensions as the phantom samples are made for the study. In the frequency range of 2–3 GHz, carbon black powder exhibits dielectric constant variation from 3.8 to 2.67. The respective variation of graphite is from 4.8 to 3.87 and for PVA from 5.74 to 4.02. For the same frequency range, the conductivity variation for, carbon black powder is from 0.0024 to 0.0067, graphite is from 0.003 to –0.005 and for PVA from 0.003 to 0.015. When these materials are mixed in definite proportions, the dielectric constant and conductivity increases and behaves as an ideal simulant of low water content biological tissues.

The decrease of dielectric constant with increase in frequency is due to the orientation of the polarization in the microwave field. The higher the polarizability of the material greater will be the dielectric constant. In the case of orientation polarization, the applied field causes a net orientation of the dipoles parallel to the field. At sufficiently low frequencies all three types (electronic, atomic and orientation) of polarizations are taking place. As the frequency of the applied field is increased, the net polarization is reduced due to orientation polarization and total polarizability falls to α_T–α_O where α_T is the total polarizability and α_O is the polarizability of orientation polarization [13]. This fall in polarizability leads to dielectric relaxation, which in turn, leads to a decrease in dielectric constant. In other words at higher frequencies due to the rotational displacement of polar groups under the influence of the electric field, frictional loss increases and it reduces dielectric constant.

The conductivity of dielectric materials in a microwave field depends upon the dielectric loss factor ε_r''. As frequency increases the dielectric loss factor increases. The dielectric loss is a direct function of the relaxation process, which is due to the local motion of the polar groups. At high frequencies the friction between the molecular chains increases, which leads to a higher dielectric loss. This dielectric loss factor leads to the so called ''conductivity relaxation''. At the relaxation region, the polarization acquires a component out of phase with the field and a displacement current in phase with the field, resulting in thermal dissipation of energy. This generates dielectric loss, which in turn generates conductivity.

When carbon black, graphite and polyvinyl acetate are mixed in definite proportions, the conductivity and dielectric constant increase compared to their corresponding elemental values due to interfacial polarization. In heterogeneous dielectrics where a dielectric material is composed of two or more phases, space

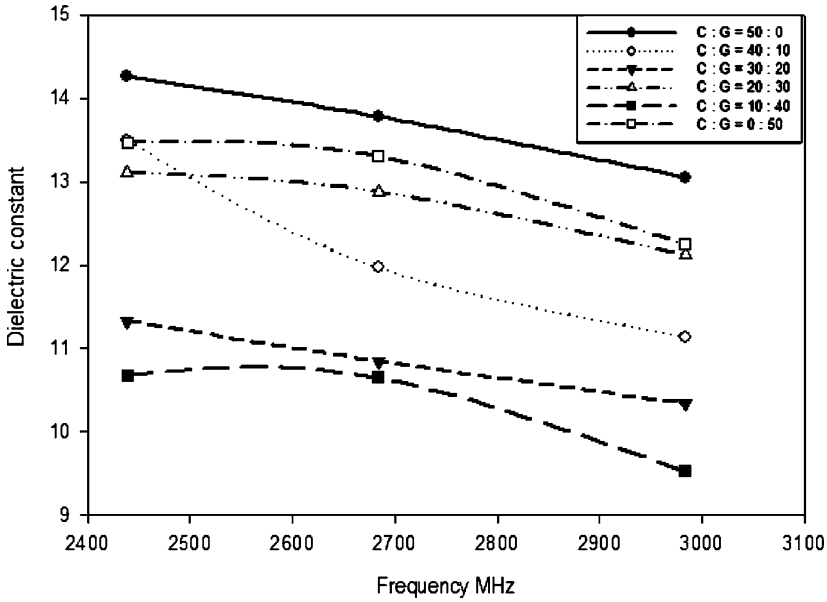

Fig. 3 Variation of dielectric constant with frequency for the phantom. (C—carbon black powder, G—graphite powder)

charge build up occurs at the macroscopic interface as a result of the differences in the conductivities and dielectric constants of the materials at the interface. This accumulation of space charge leads to field distortions and dielectric loss; this interfacial loss depends on the quantity of filler present as well as on the geometrical shape of its dispersion. The magnitude of the interfacial loss is particularly susceptible to the length of the dispersed phase geometry in the direction of the field. Due to this interfacial loss the conductivity increases [13]. Also, in the presence of microwave field, dielectric constant depends on the dipolar polarization. The accumulation of polar charges at the interface leads to dipolar polarization, which in turn increases the dielectric constant.

The variations of dielectric constant and conductivity with frequency for phantom samples are shown in Figs. 3 and 4. It is observed that for all the samples, the dielectric constant decreases and conductivity increases, with increase in frequency. This result coincides with the studies on dielectric properties of biological tissues [14]. The figures show that a combination of 50% PVA, 20% carbon black powder and 30% graphite powder exhibits higher conductivity

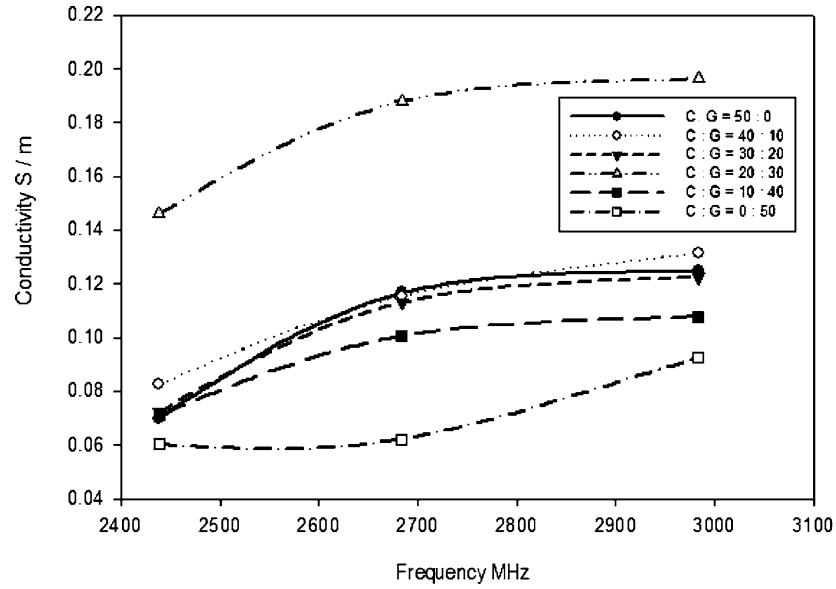

Fig. 4 Variation of conductivity with frequency for phantom

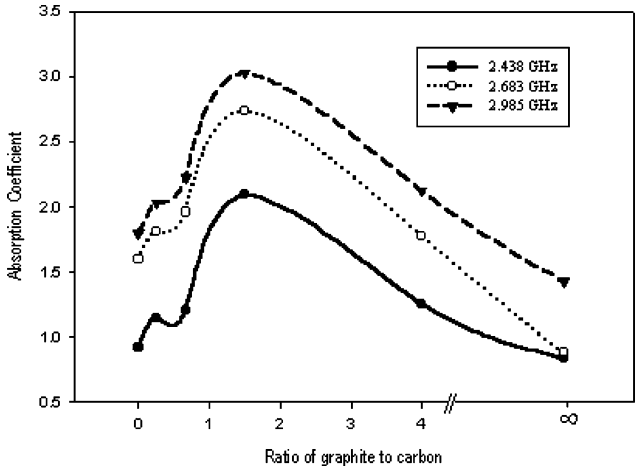

Fig. 5 Variation of absorption coefficient for different compositions of carbon black powder and graphite powder. In all the samples PVA constitutes 50% of the composition

than all other combinations while the values of dielectric constants are comparable.

The absorption coefficient of a dielectric material depends on dielectric constant, conductivity and resonant frequency f_s as given in Eq. (10). The absorption coefficients of the phantom samples are plotted against the composition ratios of graphite to carbon black powder in Fig. 5. It is observed that a combination of 50% PVA, 20% carbon black powder and 30% graphite powder exhibits good absorption rate due to its high value of conductivity. Hence the material is ideal to use as absorbing material in microwave tomographic imaging.

The equivalent phantoms for various low water content biological samples [15] in the frequency range of 2–3 GHz are given in Table 1. It is observed that, mixing carbon black powder and graphite powder in definite proportions with PVA can simulate phantoms of any of these biological tissues.

Conclusion

Polyvinyl-acetate-based composite of carbon black and graphite powder is identified as suitable phantom for low water content biological tissue in microwave medical imaging. The dielectric constant and conductivity of the phantom samples exhibit good matching with the available literature data on biological tissues. High value of absorption coefficients of the samples suggest their another application as microwave absorbing material in medical imaging.

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Table 1 Equivalent phantoms of various biological tissues in the frequency range of 2–3 GHz

Biological sample	Range of dielectric constant	Range of conductivity S m^{-1}	Equivalent ratio of carbon black:graphite with 50% PVA
Bladder, Human	13.5–13.1	0.21–0.215	C:G = 40:10, C:G = 0:50
Breast Fat, Human	10.2–9.8	0.052–0.062	C:G = 10:40
Bone, Cancellous, Human	12.6–12.14	0.15–0.17	C:G = 20:30
Bone, Cortical, Ovine	11.78–11.299	0.17–0.23	C:G = 30:20
Bone, Cortical, Human	12.44–10.96	0.068–0.71	C:G = 20:30
Bone marrow (infiltrated), Ovine	13.31–14.76	0.175–0.182	C:G = 50:0