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# Biomedical Sensing with Hydroxyapatite Ceramics in GHz Frequency Range

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**Keywords:** Hydroxyapatite, GHz frequency range, biocompatible sensor, real-time pressure sensing in medical applications, piezoelectic and pyroelectric properties, powder and films.

**Abstract.** Hydroxyapatite (HA) is a leading biocompatible material extensively used for bone implants as a porous ceramic graft and as a bioactive coating. Electrical characteristics of HA can be employed in implantable devices for real-time in vivo pressure sensor applications such as in knee or hip prosthesis. In particular, high piezo and pyroelectricity of HA, its polarisation by electron beam and selective adsorption of proteins on polarised domains indicate the potential for real-time biosensing applications of HA. For this purpose, a comprehensive understanding of the dielectric behaviour of different forms of HA over a frequency range relevant for biomedical sensing is critical. Such information for HA, especially its frequency dependent dielectric behaviour over the GHz range, is rare. To this end, we report on novel investigations of properties of HA in powder and film forms in the GHz frequency range.

## Introduction

Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is a leading biocompatible material that is extensively used for bone implants as a porous ceramic graft and as a bioactive coating. Hydroxyapatite (HA) is also known for its electret properties [1], piezoelectricity [2-4] and pyroelectricity [3, 5]. While electret properties mean that space charge can be introduced and/or dipoles can be aligned by means of an external electric field [4], piezo and pyroelectric properties indicate that hydroxyapatite is naturally polar, confirming a prediction made from quantum mechanical simulation [6]. Piezo- and pyroelectric nature of HA in its thick film form were also confirmed [2]. High piezo and pyroelectricity of HA, its polarisation by electron beam and selective adsorption of proteins on polarised domains indicate the potential biosensing applications of HA [3].

It has been recently revealed that high temperature treatment alone and a combination of high temperature and high voltage, i.e. poling, can cause pyroelectric behaviour being recorded from the surface of HA [2]. HA thick films too can behave as piezoelectric, since reversible pressure-induced changes in the values of their capacitance were recorded in real time. These electrical characteristics have direct impact on the development of advanced implantable devices, such as knee and hip prosthesis, with continuous self-monitoring option for pressure distribution. Notably, poling has been reported [7] to result in an increased deposition of bone like apatite on negatively poled (N-poled) surfaces as well as improved osteoblast adhesion, spreading, proliferation or extracellular matrix deposition on N-poled surfaces [8].

To further exploit the properties of HA materials for biomedical sensing applications, a novel investigation of HA powder and HA film mixed with polyvinyl alcohol (PVA) in the GHz frequency range using resonant microwaves cavities is presented.

## Investigating properties of materials using microwave cavities

The principle of investigating dielectric properties of materials using electromagnetic waves in the GHz frequency range is based on the fact that an object under test, when placed into a microwave cavity, interacts with the electromagnetic waves in a unique manner, which can be specifically correlated with the properties of this material. The test object changes the velocity of the signal by attenuating, reflecting it or by causing a phase shift. The major advantage of the technique using microwave cavities is the capability to measure materials non-destructively, without contact from a short distance, using penetrating waves, without health hazards to personnel. Disadvantages are the usually high degree of specialization and the simultaneous existence of several variables affecting the microwave measurement (temperature, density, moisture, structure, etc.) in material measurements [9].

A microwave resonator is made of a section of transmission line with open or shorted ends. Depending on the type of transmission line, the resonators can be for example coaxial, microstrip, stripline, slotline, or cavity resonators. When the resonator is used as a sensor, the object to be measured is brought into contact with at least some part of the electromagnetic field in the resonator. As a consequence, the resonant frequency and the quality factor will change in relation to the permittivity of the object. Due to the large variety of possible structures, sensors can be designed for measurement of almost any kind of object.

## Experimental Setup

Depending on the form of the sample under test, i.e. powder or a film, different microwave cavities can be used to explore the properties of the materials. Thus, HA powder and HA powder mixed with PVA fluid samples were placed into quartz NMR tubes, with the sample volume required for the measurement being 0.6 ml. These tubes were then tested in a purpose built 2-port resonant microwave cavity which has the dimensions that match the size of these tubes. For this particular experimental setup, which is shown in Fig. 1, the fundamental mode ($TM_{010}$) occurs at approximately 1.75 GHz when empty.

To investigate the properties of HA in a form of coating, namely as a film, the following procedure was employed. A 20% solution of PVA solvent was prepared by slowly adding and mixing 40 g of PVA powder (Polyvinyl alcohol 87-89%; average molecular weight: 13,000-23,000) with 200 ml of cold deionised water. Once the powder was fully dispersed, the mix was heated (90 °C) and stirred using a hot plate magnetic stirrer. Afterwards, a 10% solution of hydroxyapatite was prepared by mixing 4.5 g of calcined hydroxyapatite with 45 ml of PVA solution. A microscopic glass slide was used as a substrate for the HA films, which were made by dip coating the slides into a solution and subsequent heating at 150 °C for 5 mins. Samples prepared in this manner were more suitable for an analysis in a rectangular-shaped resonant cavity, which is depicted in Fig. 2. Notably, the sample is placed inside the cavity, which has an opening with matching dimensions.

A Rohde and Schwarz ZVA24 vector network analyser (VNA) was used for the purposes of data acquisition from both cavities, with this unit being appropriately calibrated according to manufacturer specifications. The data (60,000 points for each measurement) was captured in the frequency range of 1-16 GHz for both reflected ($S_{11}$) and transmitted ($S_{21}$) powers. Post processing of the data identified a number of interest regions which are indicative of the materials being tested and thus can be used as a sensing indicator for these materials.

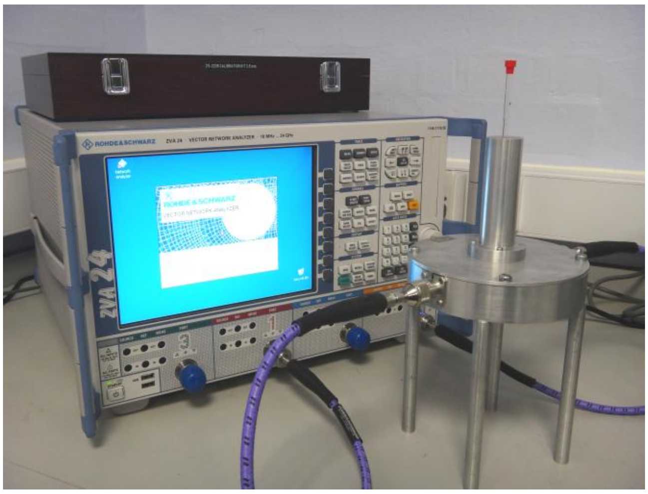

*Fig. 1. Experimental setup showing VNA and the microwave resonant cavity with a sample in NMR tube.*

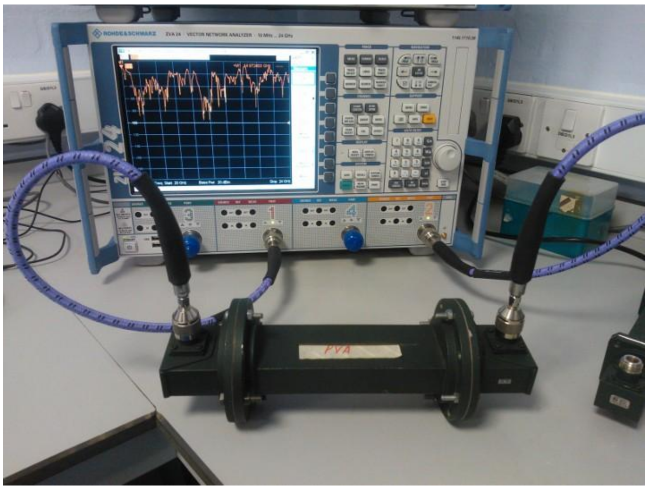

*Fig. 2. Experimental setup showing VNA and rectangular-shaped microwave resonant cavity with HA sample on a glass substrate inside the cavity.*

## Results and Discussion

Fig. 3 and Fig. 4 show the $S_{11}$ and $S_{21}$ spectra responses of HA powder alone, PVA solution alone and a mixture of HA and PVA to microwaves when placed in a cylindrically shaped resonant cavity in NMR tubes. On the other hand, Fig. 5 and Fig. 6 depict the normalised $S_{11}$ and $S_{21}$ signals for HA film samples on glass substrates in square cavity. Notably, these spectra clearly indicate that HA powder responds to microwaves in a unique manner, different from the response of PVA and even a mixture of PVA and HA, which can be used as an indicator for sensing purposes. These spectra will be further analysed to determine the dielectric constant of HA at GHz frequencies and how different forms affect these properties.

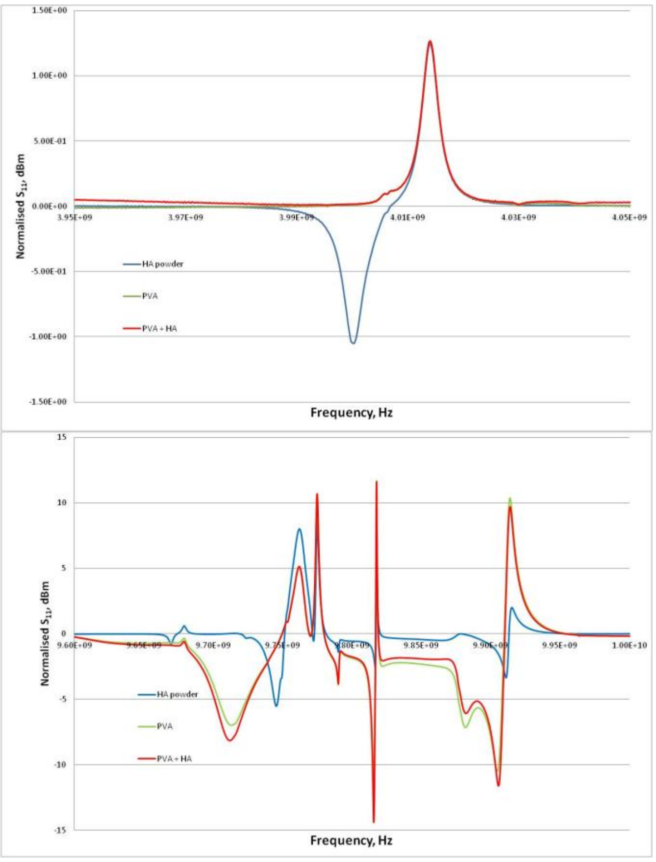

*Fig. 3. Normalised $S_{11}$ for samples in NMR tubes.*

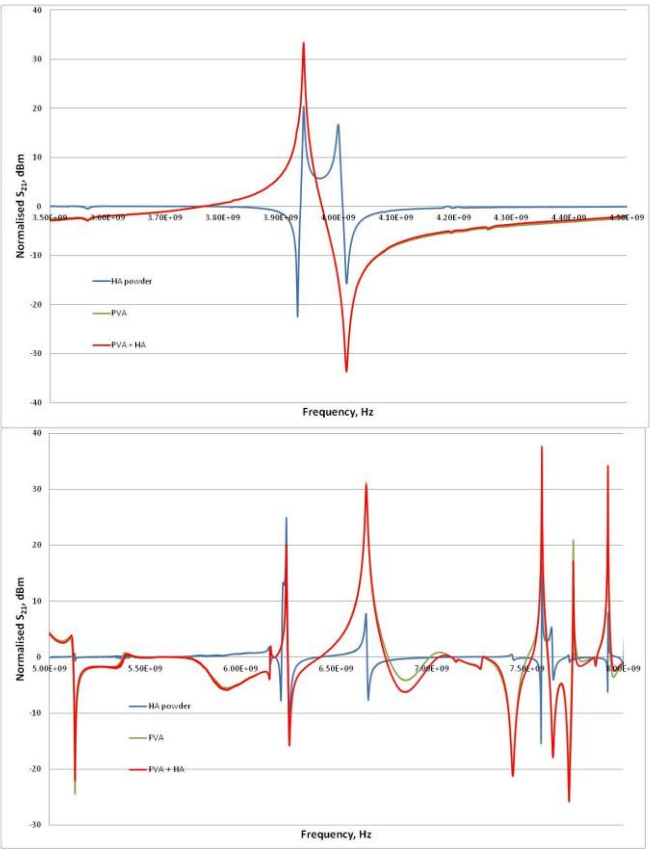

*Fig. 4. Normalised $S_{21}$ for samples in NMR tubes.*

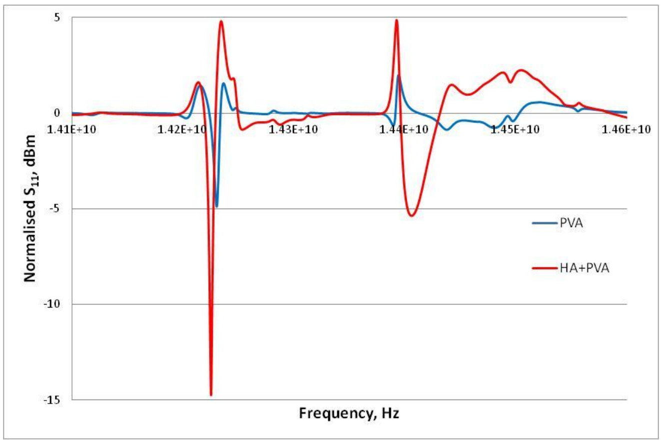

*Fig. 5. Normalised $S_{11}$ for samples on glass substrates in square cavity.*

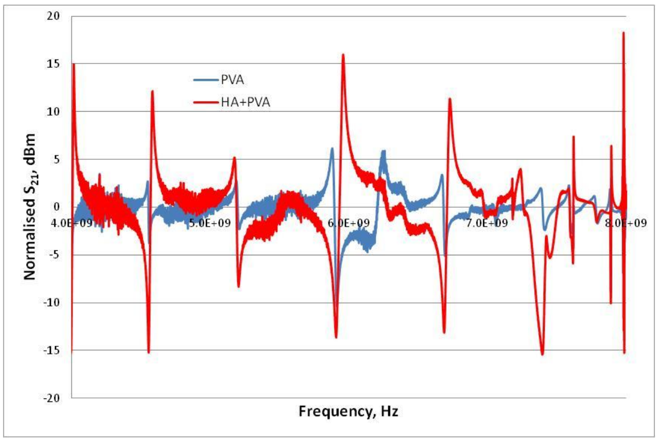

*Fig. 6. Normalised $S_{21}$ for samples on glass substrates in square cavity.*

## Summary

The investigation of the dielectric properties of HA thick films is vital for the understanding of their bioactive characteristics for effective application in medical industry. Thus, the response of both HA powder and thick films suggests that their interaction with EM waves in GHz frequency range resulted in some unique spectra specifically attributable only to HA material and accordingly can be used as an identification, or sensing method specifically for biomolecule interaction investigations, as well as implant performance monitoring.

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