Determination of the Complex Permittivity of Textiles and Leather in the 14-40 GHz, mm wave band using a Free-Wave Transmittance Only Method

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Abstract – A free wave, transmission only technique for the determination of complex permittivity in the mm wave band 14 – 40 GHz of planar samples of textiles is presented. With this method accurate alignment of source and detector horns is not required and time gating methods to reduce or remove standing wave interference between horns is replaced by a data smoothing process. Transmittance measurements are taken at discrete angles of incidence (0 to 65 degrees) for TE (*s*) polarised mm waves and the data is then smoothed to remove standing wave interference effects between transmitter and receiver horns. The resulting data is fitted to a mathematical model of an infinite planar sheet of isotropic complex permittivity in air and the permittivity parameters that best fit the data to the model are presented. The textiles investigated here are denim (cotton) and cow leather (two colours, Red and Beige). This method is shown to be simple to set up, easy to use and fast when compared with other methods such as free wave reflectance and transmittance or Fabry-Perot cavity and gives results which are accurate enough for most practical applications. Significant difference in the absorption of mm-wave power between the two leather samples is observed. This can be explained by the different chemical composition of the two leather samples, investigated using a Scanning Electron Microscope with Electron Dispersive Spectrometry, which is almost certainly a result of the colouring process employed.

1 Introduction

The determination of the complex permittivity of textiles in the mm-wave spectral region is becoming increasingly necessary as technologies as varied as personal antennas (Body-Centric Wireless) and security applications require more detailed information on the electromagnetic properties of clothing materials in the mm-wave band. There is a paucity of such data in literature, notable exceptions to this are [1,2]. There are several methods commonly employed in the determination of the complex permittivity of media in the mm-wave band, each with its own advantages and drawbacks. Three widely used and published methods are:

1. Fabry-Perot cavities [3,4,5,6,7,8,9]
2. Filled or partially filled waveguides [10,11,12]
3. Free-wave, reflectance and transmittance [13,14,15,16,17]

In each case the theoretical model must be known in order to extract permittivity from the measured physical quantities. In the case of the free space method, this takes the simple and well known Fresnel equations for an isotropic layer in air. This, combined with prior data smoothing and subsequent non-linear regression gives a simple and easy to use method for determining the complex permittivity from oblique transmittance only measurement. It is noted that phase information from the transmitted wave would further help to determine the permittivity but the added complexity of the non-linear regression of two dependent variables and the ability to satisfactorily determine the complex permittivity from transmittance magnitude alone renders this “extra” information unnecessary. For a discussion and comparison of the common methods of complex permittivity determination in the mm-wave band see *Janezic* [18].

2 Experimental Apparatus and Operation

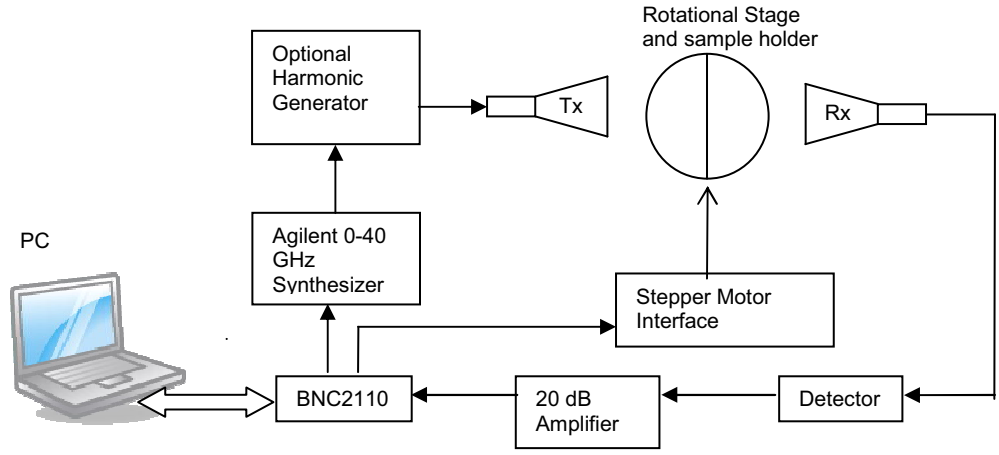

Figure 1. A block diagram of the millimetre wave system for determining the complex permittivity of fabrics.

The experimental apparatus consists of an Agilent Technologies E8257D Microwave Synthesizer working from 250 KHz to 40 GHz, a rotational stage from Time and Precision, Model A4757-TSP, a sample holder, an RS stepper motor interface RS2173611, two horns used as transmitter and receiver, a Hewlett Packard 11585A detector, an amplifier, a NI interface BNC-2110 and a National Instrument card PCI-6132. For the control of the system and data collection a PC is used in conjunction with a program written in LabView 8.2.

Typically, the Agilent microwave synthesizer is set to trigger externally. The start and stop frequencies are set at 14 and 40 GHz respectively, the power to 20 dBm and the number of points per scan to 64. The output of the microwave source or the harmonic generator is then connected to the transmitter horn. The transmitted signal is detected by a 20 dB gain receiver horn and the detector, amplified and then digitised by an A/D port of the National Instrument PCI-6132 card.

The fabric samples (sizes are approximately that of A4 paper) are attached to a holder which is fixed to the top of the rotational stage which is situated between the

transmitting and receiving horns. The rotational stage and holder is rotated with a step angle of 5° from 0° to 65° using a stepper motor. The program controls the scan of the synthesised microwave source by sending pulses to its external trigger and the rotational stage by sending full steps to the stepper motor. The program then acquires and displays the data as amplitude (arbitrary units) against frequency.

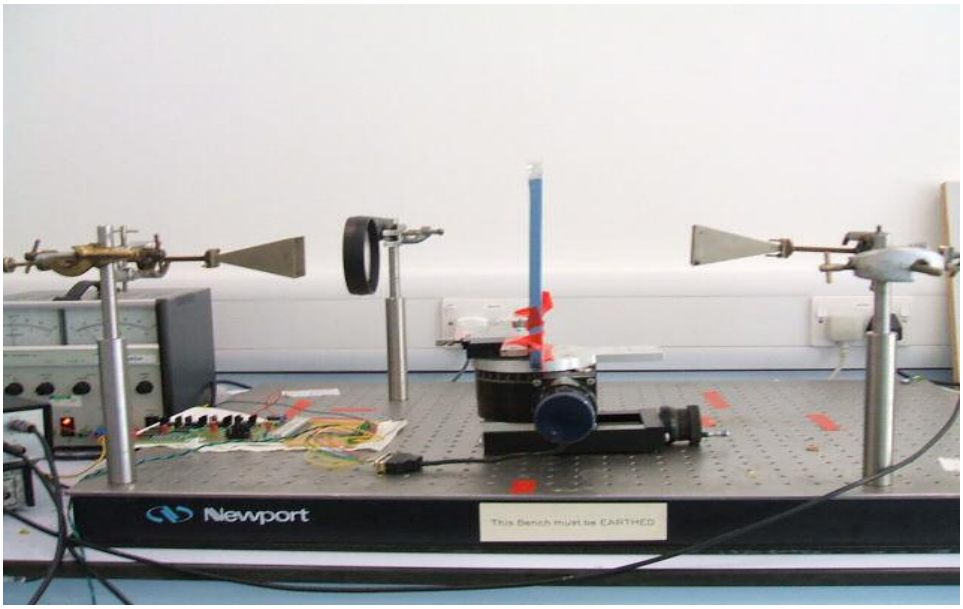

Figure 2. The transmitter, sample and receiver horn as used

3 Theory

Measuring the oblique transmittance of a planar sample is a simple and fairly sensitive method for determining the complex permittivity ε, of the medium, where $\varepsilon = \varepsilon' + i\varepsilon''$,. The transmittance of the planar sample is easily measured and is a function of the frequency ν, sample thickness *h*, angle of incidence θ and the complex permittivity of the medium. In this case we use waves that are TE polarised and the layer is situated in air with permittivity ~ 1.

The TE transmittance is given as,

$$T = \left| \frac{(1-\Gamma)^2 \exp[i\kappa h]}{1-\Gamma^2 \exp[i2\kappa h]} \right|^2 \quad (1)$$

where $\kappa = \frac{2\pi\nu}{c}\sqrt{\varepsilon - \sin^2(\theta)}$, $\Gamma = \frac{\cos(\theta) - \sqrt{\varepsilon - \sin^2(\theta)}}{\cos(\theta) + \sqrt{\varepsilon - \sin^2(\theta)}}$ and *c* is the speed of light in a vacuum.

Note: The effective magnetic permeability of the sample is assumed to be unity.

4 Data Smoothing and Fitting

The detector output signal is linear with received power over the range used, thus the output voltage is proportional to the power incident on the receiving horn. The transmittance of the sample can be obtained by dividing the signal with sample, at a given frequency, by the signal at the same frequency with no sample. When a sample is present an oscillation is seen in the signal with frequency. This is due to standing waves between transmitter and receiver. The frequency change between peaks in this pattern is related to the distance between horns and is a much more rapid oscillation with frequency than is the signal due to thin film interference in the sample. Smoothing is achieved by convolution integral technique, which is achieved by Fourier transforming the data and multiplying by the Fourier transform of a function appropriate for removing the high frequency oscillations from the data, forming a low pass filter. The authors used a Gaussian function in this instance, and then applying the inverse Fourier transform on the product. An example of a data set before and after the smoothing process is shown in figure 3.

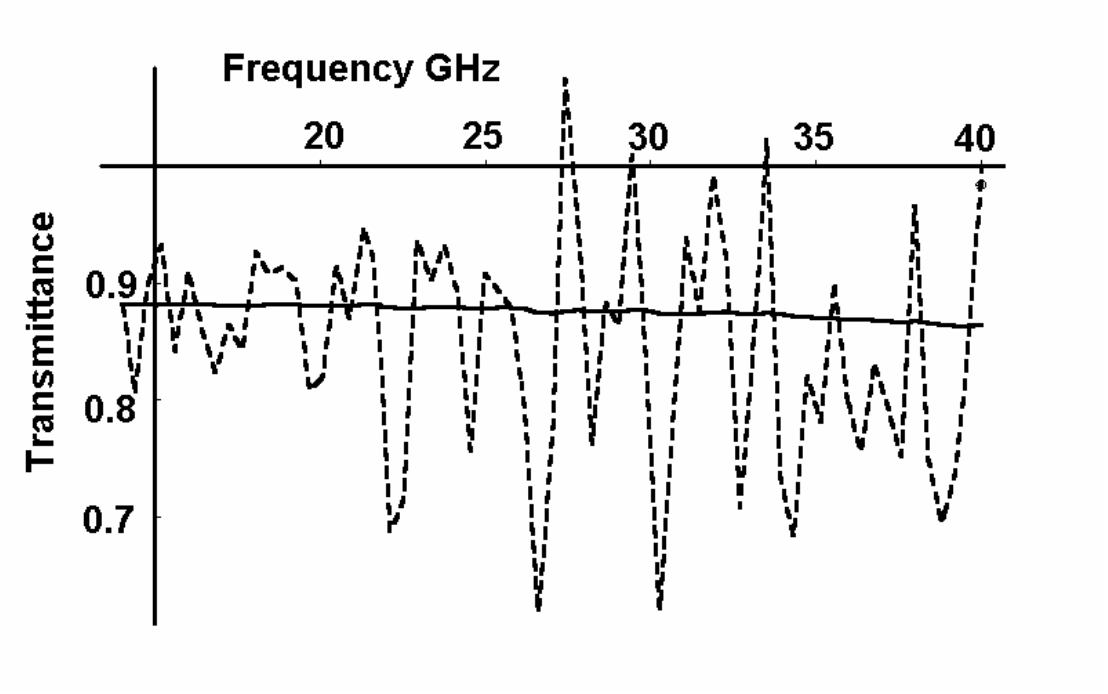

Figure 3. A plot of raw data (dashed line) and smoothed data for beige leather sample at normal incidence. The rapid oscillations in the raw data are due to standing wave interference between horns.

A non-linear fitting package is then used to best fit the smoothed transmittance data, as a function of angle of incidence (for constant frequency) to equation (1). The thickness of the layer is measured at ten points over the sample and the mean taken and used as the sample thickness in the equation. The real and imaginary parts of the permittivity are the parameters that are iterated until there is no change in the sum of squares of the deviation between theory and experiment. The starting values for the permittivity parameters are chosen as (0.1, 0.1) and then varied separately in steps of 0.1 to a maximum of (5, 5). Certain solutions can be discarded as they are not physical (i.e. negative imaginary part of permittivity) and others discounted as they are not consistent within small changes of frequency. For example, it is tacitly assumed that the permittivity varies reasonably slowly with frequency. Thus one can confidently select the parameters that describe the dielectric properties of the fabric samples. It is found often that best fit permittivity parameters converge upon the

same solution for a wide range of starting values. An example of the smoothed transmittance data with the best fit transmittance curve as calculated from equation 1 is presented in figure 4.

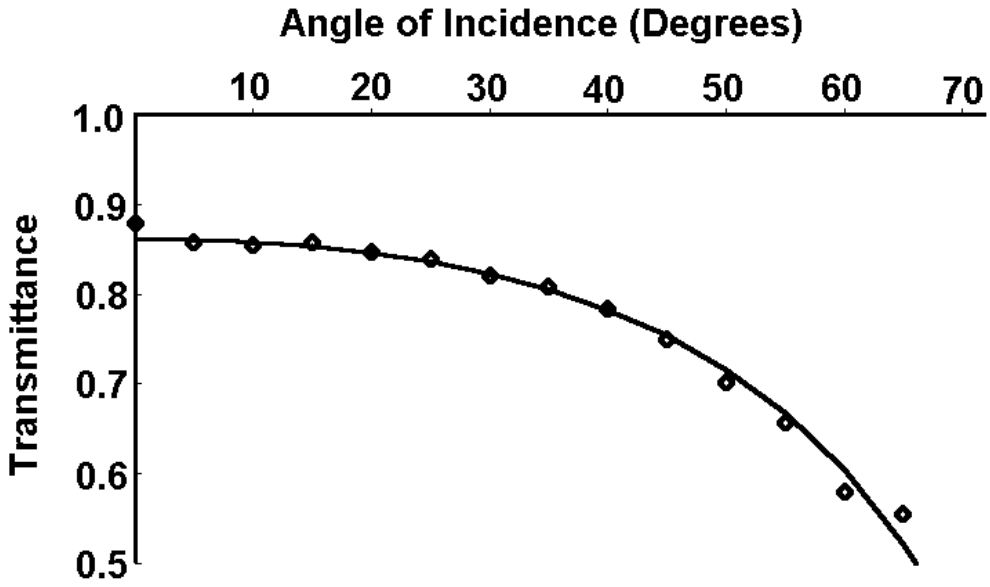

Figure 4. A plot of the smoothed transmittance data points (diamonds) for beige leather sample versus the transmittance curve predicted by equation (1) for best fit permittivity (2.13+*i* 0.0553). The frequency is 25 GHz.

5 Results and Discussion

The fabrics examined are denim and two coloured (red and beige) leather samples. These were chosen as they are more absorbing than most other commonly worn textiles and are a problem for mm wave imaging devices (security applications). For example Nylon, Polyester and other man made fibres are practically transparent to mm-wave radiation in the 14-40 GHz region, thus they do not lend themselves to measurement with a free-wave transmittance technique and would be better

measured using a resonant cavity method. It is supposed that the chosen materials are more lossy than other textiles as they readily absorb water from the atmosphere and it is well known that water has a high dielectric constant (~ 60+*i*35 at 10 GHz) in both real and imaginary parts, in this frequency range [19]. It is therefore probable that the permittivity of the samples taken is very strongly influenced by atmospheric humidity and that subsequent measurements upon the same samples might yield substantially different results as the water content of the samples changes [2,20].

The mean thickness of the Denim sample was 0.89 mm, the mean thickness of the beige and red leather samples was 1.49 and 1.09 mm respectively. The best fit permittivity parameters for the measured samples as determined by transmittance measurements are present in figures 5 and 6.

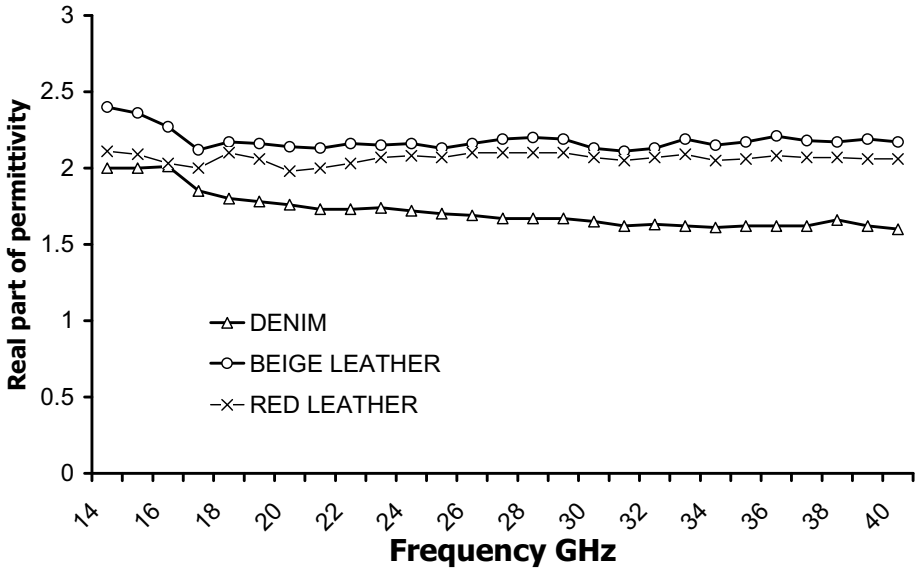

Figure 5. The real part of the permittivity for the three textiles

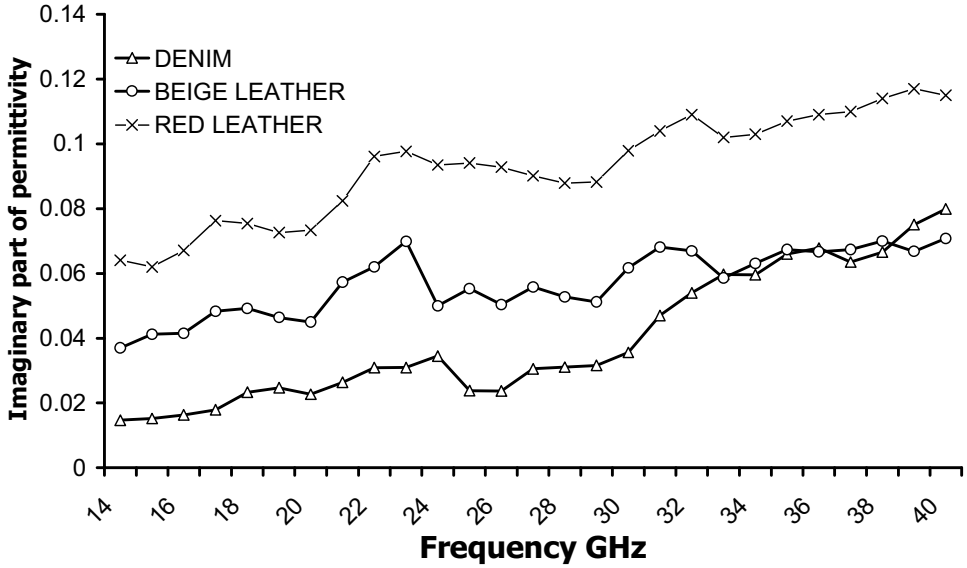

Figure 6. The imaginary part of the permittivity for the three textiles

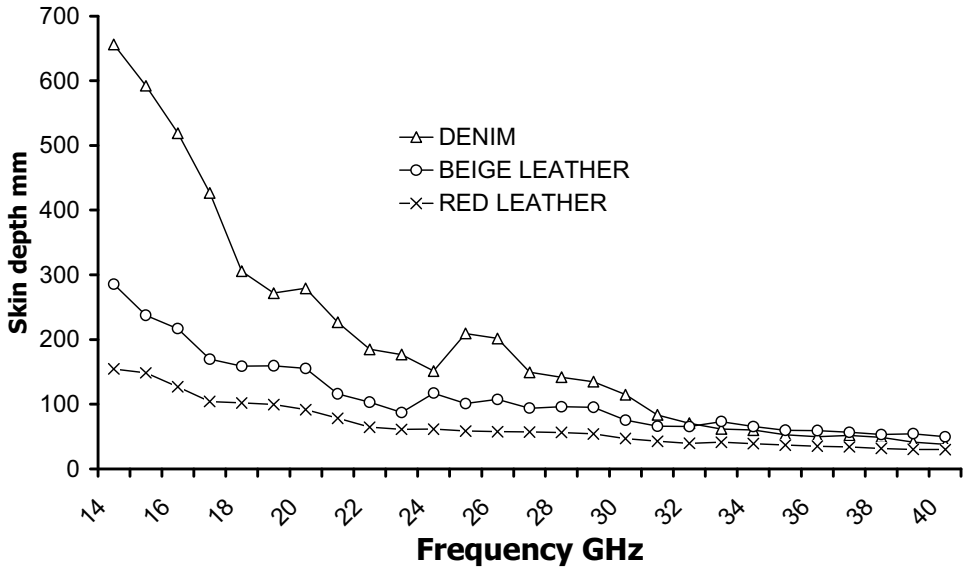

Figure 7. The skin depth of the textile samples

There is very little difference in the real parts of permittivity for the two leather samples and both show little variation with frequency over the range measured. Denim has a slightly lower real part of permittivity than the leather samples and does appear to fall slightly with increasing frequency. The Imaginary parts of the

permittivity, however, do show substantial difference and dependence upon frequency. The denim is the least lossy of the three media as is seen by the skin depth plots in figure 5, obtained from the expression

$$\delta = \frac{c\sqrt{\varepsilon'}}{\pi \nu \varepsilon''} \tag{2}$$

Equation 2 is valid for $\frac{\varepsilon''}{\varepsilon'} << 1$ as is the case for low loss dielectrics.

The two leather samples show a distinct difference, with the red leather being substantially more attenuating than the beige sample. This difference might be explained by the colouring process that the leather has undergone. To investigate this, the surface chemistry of the two leather samples were examined by an Analytical Scanning Electron Microscope, model Jeol JSM 6300, operated at 20 Kev and fitted with an Oxford Instrument Energy Dispersive X-ray Spectroscope (EDS). The data were collected using INCA Energy 300 system. X-ray spectra and also X-ray elemental maps were obtained from a representative area of each sample.

It was found that both specimens were composed of C, O, Na, Al, Si, S and Cl elements. In addition, the red leather specimen contained a small amount of Cr (~1%, by normalised Oxygen stoichiometry method), Ti (~7% of oxide content), and relatively significant amount of Fe (~21% of oxide content). On the other hand, the beige leather sample also contained a small amount of P (~2%), Ca (~1.4%), significant amount of Cr (~ 28% of oxide content), but showed no presence of Fe and Ti elements.

The individual X-ray spectra of the two samples are shown in figures 8 and 9.

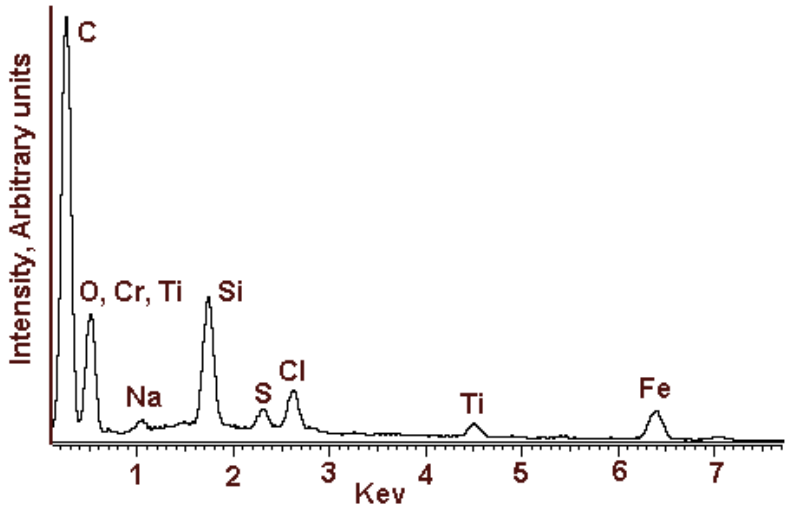

Figure 8. EDS spectrum of a red leather specimen.

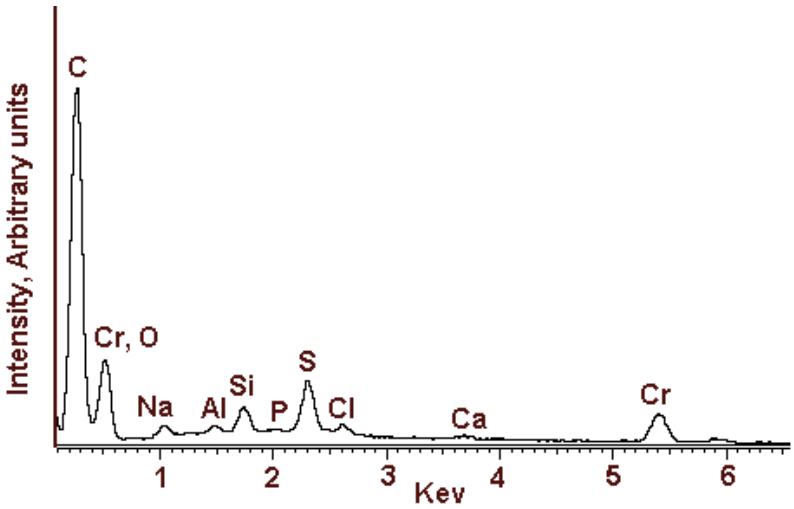

Figure 9. EDS spectrum of a beige leather specimen.

The SEM secondary electron images of the red and beige leather surface morphologies and their equivalent elemental maps of Fe, Cr and Ti elements are presented in figures 10 and 11 respectively.

Both specimens showed even distribution of the elements, which is demonstrated in the maps by bright spots. This is a qualitative technique where intensity of a signal over the scanned surface is directly related to a content of the element being

mapped. In case of the red leather specimen a few small regions showed higher concentration of iron in relation to the overall area.

It would appear that the surfaces of both specimens are covered with oxides. In case of the red specimen, iron oxide is likely to be responsible for the colour of the leather surface.

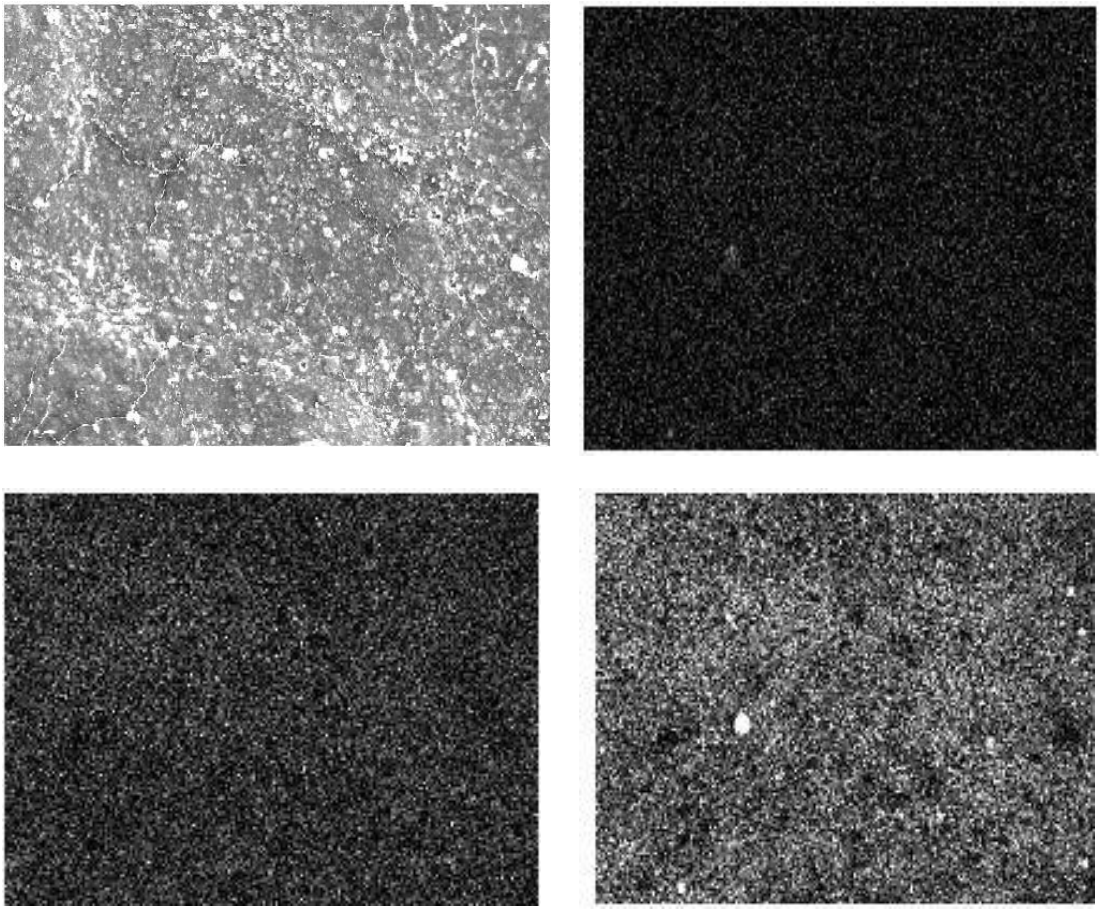

Figure 10. SEM image of the red leather sample (top left) and its elemental X-ray maps of Cr, Ti and Fe. (top right, bottom left and bottom right)

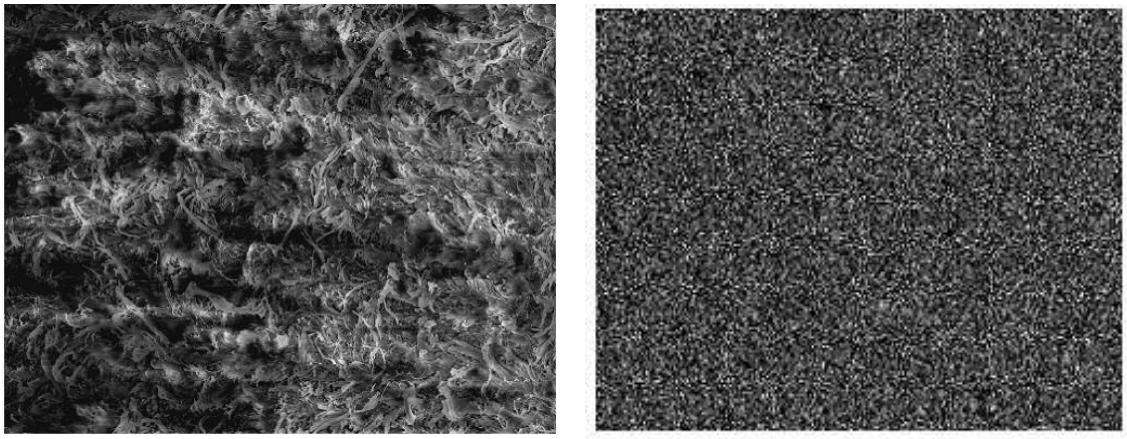

Figure 11. SEM image of the beige leather sample (left) and an elemental X-ray map of Cr (right).

Although the moisture content of the samples is very important in determining the complex permittivity, some difference is observed, between the two coloured leather samples at least, as a result of the tanning and colouring process. It is probable that natural fibres, such as cotton (denim) and leather are more attenuating in the 14-40 GHz frequency range than are man made fibres like Nylon because their fibres can hydrogen bond with water and thus they will retain moisture more readily. Since both the beige and red leather samples have been stored together it is reasonable to state that the differences in their complex permittivity across the 14-40 GHz frequency band is due to the colouring treatment they have undergone. This assertion is borne out in the EDS analysis of the two samples. The presence of relatively large concentrations of iron and titanium oxides in the red leather sample and their absence from the beige leather sample may well explain the difference in the imaginary part of the permittivity of the samples.

However we may conclude that even these natural fibres are fairly transparent in the frequency range studied and for layers that are the order of a wavelength thick (as is

to be expected) such materials can be treated as being lossless for most applications.

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