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Ceramics to 100 GHz: Including a novel free space dielectric measurement technique

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Abstract

Data are presented for transmission measurements on ceramic coplanar lines over the frequency range 50 MHz to 100 GHz. The data has been analysed to separate the loss due to the conductor and the loss due to the dielectric. The results of a novel technique to reduce surface losses by flash etching the surfaces of the conductors are also presented. In addition, a new free-space technique for measuring the loss tangent and relative permittivity of dielectric layers at high millimetre-wave frequencies is introduced.

Keywords: Dielectric properties; Electrical conductivity; Alumina oxide

1. Introduction

The commercialization of the millimetre-wave frequency band for wireless applications has created a need for new circuit technologies, and new techniques for evaluating the performance of these circuits.[1] At millimetre-wave frequencies the most convenient form of circuit interconnection is the coplanar line. Simple transmission measurements on coplanar lines, using a vector network analyser, will provide information on the line loss and the velocity of propagation.[2] There will be various sources of line loss, and these can be separated into conductor losses and dielectric losses. Furthermore, the conductor loss can be divided into the loss due to the bulk metal and the loss due to the surface roughness. It is this latter loss that is likely to become very significant at higher millimetre-wave frequencies, where the skin depth may be comparable to the rms surface roughness. If the total loss is measured, analytic techniques can be used to determine the proportion of loss in the conductor and dielectric, if the conductor geometry is known along with the surface roughness and the resistivity of the conductor. In this paper we have provided information on the relative magnitude of these losses, for a gold thick-film line on LTCC over the frequency range 50 MHz to 100 GHz.

It is useful to have a separate technique for properties of the dielectric material alone. At lower frequencies, the traditional method of measuring dielectrics is to use a waveguide resonant cavity. The difficulty with using cavity-based techniques at high millimetre-wave frequencies is that the dimensions of rectangular waveguide become very small as the frequency approaches 100 GHz, and there is a practical problem in preparing samples of the correct size. Overmoded circular cavities can be used at millimetre-wave frequencies, but again the dimensions become inconveniently small as the frequencies approach 100 GHz. In this paper we are proposing a novel free-space method that does not involve any metallic resonator. However, our method differs significantly from other published free-space techniques that involve simple transmission and reflection measurements,[3] in that we are essentially setting up a dielectric resonator in free-space. The key benefits of the new technique are that it is simple, does not involve any errors due to cavity loading, and does not require elaborate calibration. We have evaluated the new technique using samples of alumina and LTCC, and have obtained results that agree very well with other published data.

1.1. Line loss measurements

Transmission measurements were made on FGCPW (finite ground plane coplanar waveguide) lines fabricated in gold on LTCC substrates. The geometry of the test lines is shown in Fig. 1. It can be seen that the test pattern consisted of a 50 Ω

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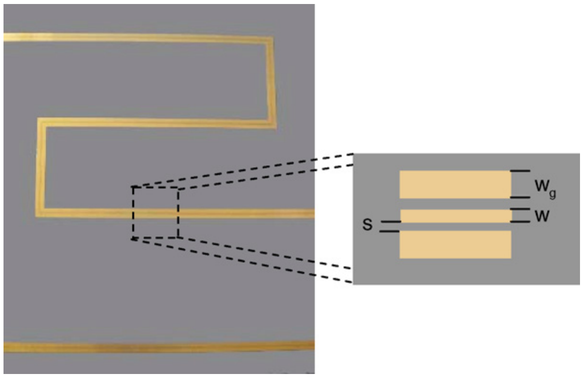

Fig. 1. Test circuit showing the straight and meander FGCPW lines.

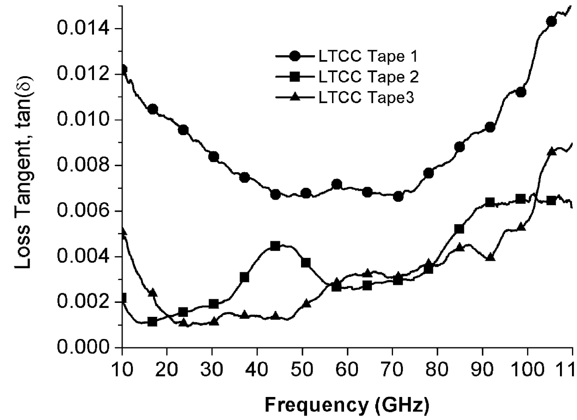

Fig. 3. Variation of loss tangent with frequency for a typical LTCC.

straight section and a 50 Ω meandered section. By measuring the transmission loss and transmission phase through each section, and then taking the difference between the results, we can evaluate the loss per unit length, and the phase change per unit length, in the coplanar lines. It should be noted that the only function of the meandered section was to create a longer length of line on the test substrate. Care was taken to ensure that the corners of the meander did not contribute errors to the measurement. By observing the variation of reflection coefficient with frequency for the meandered section, we could see if the corners were causing errors, as these would have been evident as a periodic ripple in the reflection coefficient response.

1.1.1. Extraction of loss data

The results of the line loss measurements are shown in Fig. 2. Three curves are presented for total loss for three different types of LTCC. Also in the figure are the loss values due to the conductor alone. This conductor loss was calculated theoretically using the known resistivity of the gold metallization and the measured rms surface roughness. The surface roughness was obtained from an SEM scan of the conductor surface. It can be seen that the loss increases with increasing frequency, as would be expected. Also it can be seen that the rate of change of loss increases as the frequency approaches 100 GHz. Again, this would be expected from theory, since the skin depth becomes comparable with the rms surface roughness in the vicinity of 100 GHz.

Having calculated the conductor loss, and knowing the dielectric constant of the substrate we were able to determine the loss tangent of the substrate material as a function of frequency. The results are shown in Fig. 3. The variation of loss tangent with frequency follows the expected form, with a rather high value at low frequencies, and minimum values occurring in the middle of the millimetre-wave range. Similar trends in loss tangent values have been reported by other authors,[4,5] although the exact variation of loss tangent with frequency will vary from one material to another, as this parameter is very material dependant.

All of the data is summarized in Fig. 4, which shows the total measured loss, and the contributions from the various loss sources. From an analysis of the error sources the following error bounds were established for all measured parameters: (1) for LTCC Tape #1, ±1.5%; for LTCC Tape #2, ±0.8%; for LTCC Tape #3, ±1.25%.

1.1.2. Flash etching

It follows from considerations of skin depth that surface losses will become significant at high millimetre-wave frequencies, when the rms surface roughness is comparable to the skin

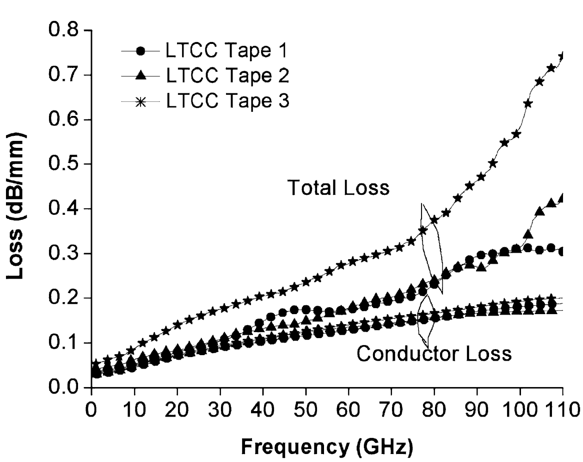

Fig. 2. Total loss and conductor loss in a typical LTCC.

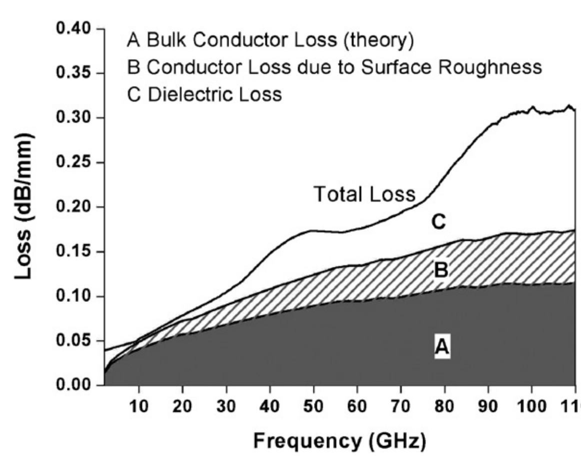

Fig. 4. Contribution from various loss sources in a typical LTCC.

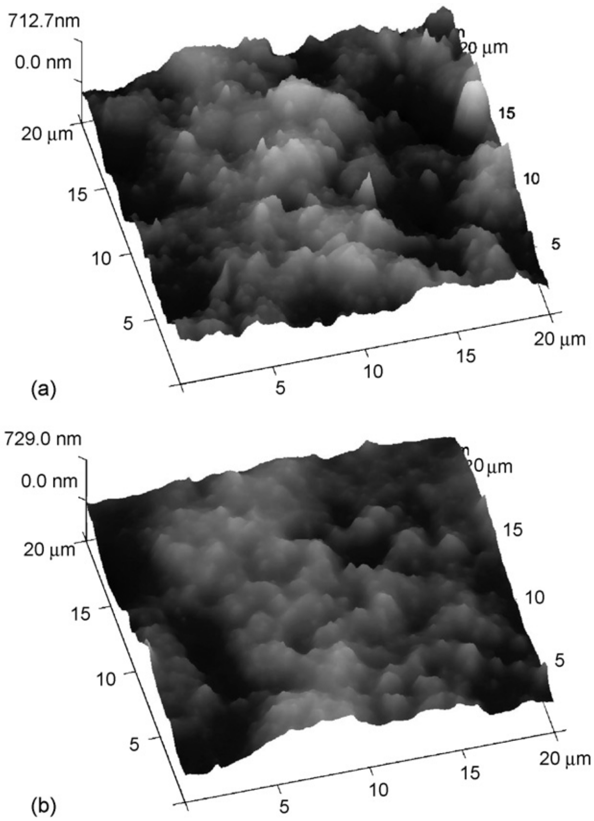

Fig. 5. SEM data showing the conductor surface (a) prior to etching and (b) after etching for 5 min.

depth for the conductor material. For example, the skin depth in gold at 100 GHz is 0.2 mm, and this is very close to the measured rms surface roughness of 0.17 mm. This means that the majority of the conductor current will be flowing in a relatively high resistance region. Clearly if the surface roughness can be reduced, this will lead to a significant reduction in surface losses. We have investigated a simple technique, whereby the surface of the conductor is flash-etched to reduce the peaks. The reasoning behind the method is that if the etching time is small, then the peaks on the surface will be etched preferentially. This proposition is supported by the measured SEM data presented in Fig. 5a and b; Fig. 5a shows the surface prior to etching, and it can be seen that there are significant peaks present, and Fig. 5b shows the same surface after 5 min of etching. Clearly there has been some substantial improvement in the smoothness of the surface. Obviously the amount of etching time will depend on a number of factors, but in particular the strength of the etching solution and its temperature. In this experiment the etchant was iodine in potassium iodide.

Also, the line loss was measured before etching the surface, and periodically after etching for a given time. The results for line loss, as a function of etching time are shown in Fig. 6. It can be seen that improving the smoothness of the surface through etching results in a significant reduction in line loss. The greatest reduction occurred at the high end of the frequency band, where the surface roughness would be expected to be comparable with the skin depth.

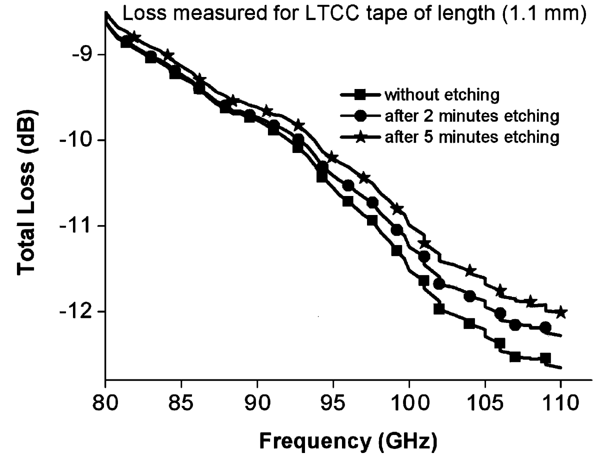

Fig. 6. Line loss responses as a function of etching time.

Fig. 7 shows the measured loss data plotted as a function of the etching time, at different frequencies, and this further supports the predicted beneficial effects. It should be noted in this figure that the change in loss, in dB/mm, has been plotted and only small changes are evident since the line loss in dB/mm is relatively small.

1.2. Free space dielectric measurement

A new method for measuring the dielectric properties of substrate materials at high millimetre frequencies has been proposed and validated through practical measurement. Essentially, the method involves propagating the signal through thin dielectric samples, where the thickness of the sample is some integer multiple of half of the wavelength in the material. Thus there will be a resonance effect, with the signal being reflected between the two material–air interfaces. This effect can be observed as a reduction in the transmitted signal at the resonant frequency. Moreover, by monitoring the change in received signal around he resonance frequency, a Q-curve can be plotted. The system set-up for our experiment is shown in Fig. 8. The

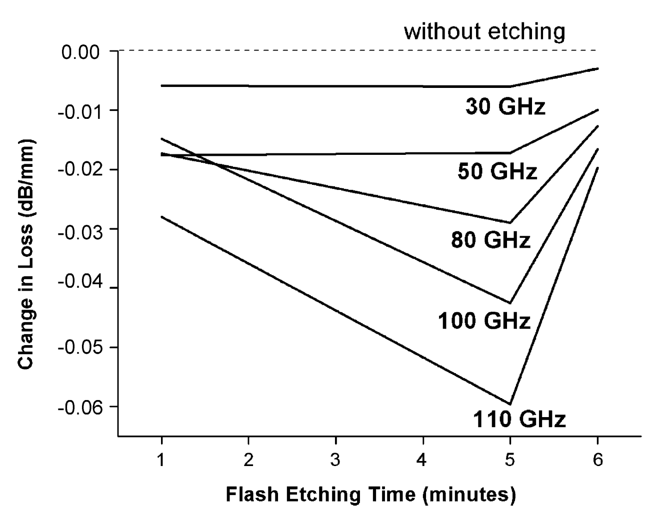

Fig. 7. Change in line loss as a function of etching time.

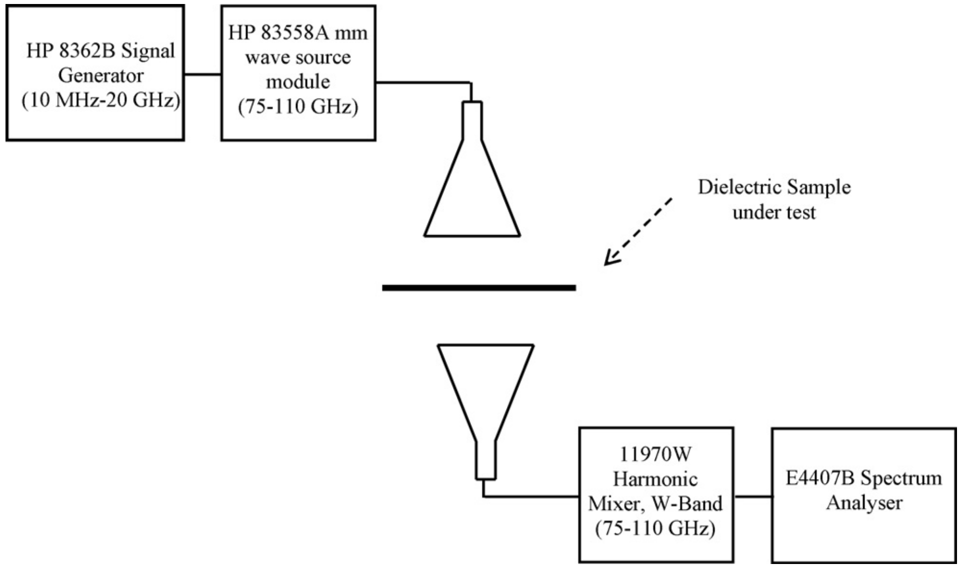

Fig. 8. Experimental setup for free space dielectric measurement.

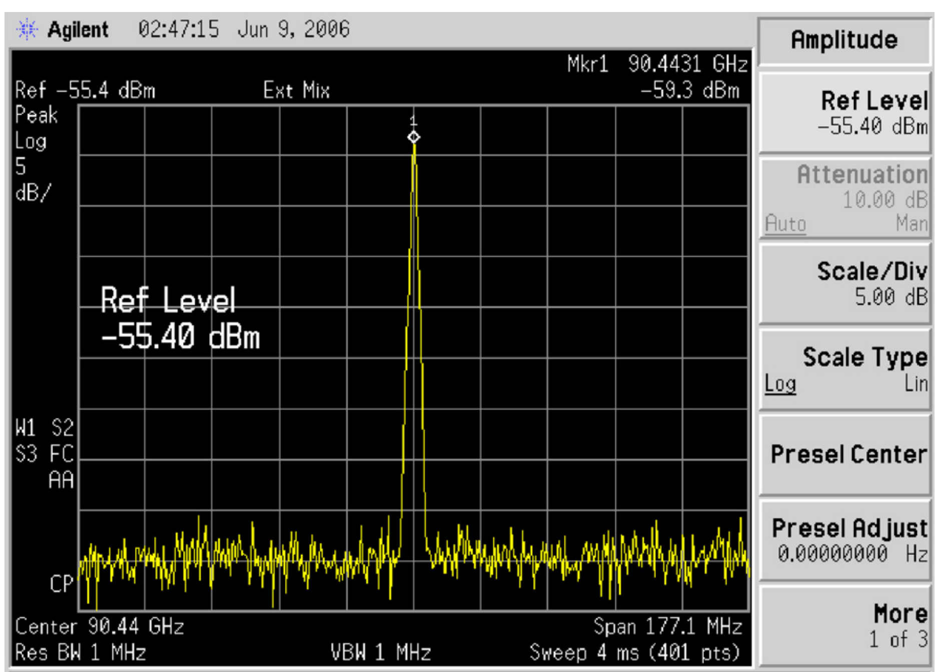

Fig. 9. Spectrum analyser output showing the received power as a function of frequency.

specimen under test is positioned mid-way between two horn antennas. The distances from the specimen to the horn antennas was chosen to ensure that the specimen was in the far field region.

The spectrum analyser was used to monitor the received signal as a function of transmitted frequency; a typical output is shown in Fig. 9. Thus we were able to obtain the Q-factor of the material, and hence the loss tangent, as the inverse of the Q-factor. Typical data for the measured received signal as a function of frequency are shown in Fig. 10.

The loss tangent obtained for alumina at frequency 90.22 GHz was 0.00541 and for a typical LTCC sample at a frequency of 93.90 GHz was 0.007918. These values agree well with typical measured data reported in the literature, and are also in agreement with the value obtained in the present work through line loss analysis.

The permittivity was calculated for the alumina and LTCC samples at these resonant frequencies, giving value of 9.82 and 6.7081, respectively.

2. Discussion

The line loss measurements, and subsequent analysis, gave useful information about the properties of the coplanar lines at

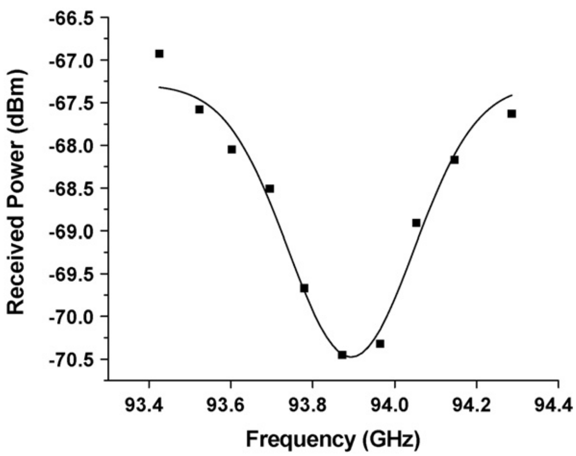

Fig. 10. The Q-factor plot for a typical sample.

high millimetre-wave frequencies. The measured data agreed well with data reported in the literature from the use of other measurement techniques. However, the benefit of the present approach is that is gives continuous information over a wide frequency range, whereas most of the other reported techniques involve resonant structures, and hence only give data at a restricted number of discrete frequencies.

The free-space technique for measuring thin dielectrics appears to have a number of useful advantages, when compared to other methods. It is simple, requires little sample preparation, and does not suffer from any loading effects, as are experienced with resonant cavity methods. Data was obtained for two different materials, and these agree well with those predicted both from theory, and from extrapolations of data reported in the literature.

3. Conclusion

There were two useful outcomes from the work. Firstly, it has been shown that chemical polishing of the conductor surface, in the form of flash etching, has a significant beneficial effect in reducing the line loss. Secondly, the free-space resonator technique has been shown to yield useful information about the essential properties of thin dielectric layers.

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