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Dielectric Properties of Substrates for InkJet Technology in GHz Area

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Abstract

This paper is focused on investigation of dielectric properties of various substrates for InkJet printing technology. In addition this paper included investigation of dielectric properties' homogeneity. Dielectric constant and loss tangent of polymeric flexible substrates (Polyimide DuPont Kapton HN, PET Mylar A, PEN Teonex Q51) and insulation paper (Nomex 410) were measured in GHz frequency area. Measurements were done by combination of vector network analyzer and split cylinder resonator. This measuring method provides dielectric properties at frequency around 10 GHz, the exact value of frequency may vary depends on specific material and its resonant frequency. Experiments included two types of samples, 6 x 6 cm which is recommended area for measurements of dielectric properties by split cylinder resonator and 12 x 12 cm for measurements of dielectric properties' homogeneity (one sheet contains 9 overlapping measuring areas 6 x 6 cm). All measured values of dielectric constant and dielectric losses were statistically processed and depicted by SigmaPlot software. The paper shows values of dielectric properties at GHz frequency area as they are lacking in datasheets from manufacturers and evaluate homogeneity of measured substrates.

Keywords

dielectric constant, homogeneity, InkJet printing, loss tangent, polymeric substrates, GHz frequency

1 Introduction

Increasing of frequencies in electronic applications to process greater volume of data and to provide greater transfer speed is more than actual nowadays. Increasing of frequencies goes hand by hand with increasing requirements on stabile dielectric properties of the substrates in GHz area. Different types of substrates are used in GHz applications the most common are PCB (Printed Circuit Boards) and LTCC (Low Temperature Co-fire Ceramics) substrates but in recent years polymeric flexible substrates and insulating papers were used for GHz applications too [1–5].

Flexible substrates and insulating paper are used in combination with the InkJet printing technology when conductive material is deposited on one or both sides of substrates or papers. It is a relatively new technology at the field of electronics [6]. The InkJet printing technology brings a lot of possibilities to create small precise electronic circuits which request high accuracy of conductive layout speaking of InkJet printing it means high accuracy of deposited nano-inks [6–8].

High accuracy of printed conductive pattern was requested by miniaturization of electronic devices. Miniaturization is caused by increasing frequencies and dielectric constant of used substrates. It is well known fact that wavelength in free space is ratio between velocity of light and frequency, with higher frequency wavelength decreases [9]. The second well known fact is that wavelength of signal in transmission is ratio between wavelength of signal in free space and square root of dielectric constant, the higher dialectic constant the smaller wavelength of signal in transmission line [10].

Dielectric constant has influence on the size of electronic device and on the performance as well [11, 12]. Mismatch between expected and real dielectric constant can lead to detuning and could decrease performance. Dielectric losses has crucial impact on strength and quality of transmitted signal, with higher losses signal is interfered and more noisy.

As it was mentioned impact of dielectric properties on electronic devices is significant, for that reason

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homogeneity of these properties is very important too. Different values at different areas of substrates or papers can decrease performance of the electronic device. Size and shape of polymeric substrate or insulating paper depend on the specific application, it begins at dimensions of a few millimeters squared and can rise to a few centimeters squared. Different values at different parts of substrates or papers can have significant influence on quality and strength of signal.

Measurements of dielectric properties are very complex problem and several methods exist. Most of the methods for GHz area work on principle of tuned resonator or cavities where measured material is inserted into resonator or cavity. Afterwards impact of inserted material on resonance frequency of resonator or cavity is investigating and mathematically processed to calculate the values of dielectric constant and dielectric losses [13, 14].

2 Experimental

The investigations of dielectric properties and their homogeneity were done on four different substrates suitable for the InkJet printing technology with equal thickness 0.127 um (5 mil). Three polymeric substrates polyethylene terephthalate (PET) Mylar A, polyethylene naphthalate (PEN) Teonex Q51, polyimide (PI) DuPont Kapton HN and insulating paper Nomex 410 were measured. Dielectric properties of these substrates are listed in Table 1, all values are from datasheets of manufacturers [15–18].

Measuring dielectric properties in wide frequency range is very complicated and complex problem. There are several methods each of these methods have advantages and disadvantages [19, 20]. For the purpose of our experiments the split cylinder resonator method was chosen to measure dielectric constant and dielectric losses.

By the split cylinder resonator non-magnetic samples with minimal length or diameter 56 mm can be measured (recommended 60 mm). Typical uncertainty for dielectric constant is 1 % and ± 0.0001 for dielectric losses. Since thickness has significant influence on achieved results it was measured by built-in micrometer with resolution 0.001 mm (accuracy 0.01 mm) and confirmed by another mechanical micrometer. This method provides measuring of dielectric properties at various frequencies from 10 GHz to 28.2 GHz. Frequency of measurement is limited by frequency range of vector network analyzer, for that reason our experiments include measurements at frequency approx. 10 GHz (cavity mode TE_{O11}). The exact measuring frequency varies depending on specific material since each material has different impact on the resonant frequency of the split cylinder resonator. Dielectric properties are measured by comparison of resonance frequency of empty resonator and resonator with inserted measured material [19, 20].

Table 1 Dielectric properties of measured substrates

Substrate	Dielectric constant	Dielectric losses
PI DuPont Kapton HN 200	3.9*	0.0036*
PET Mylar A	3.25*	0.005*
PEN Teonex Q51	3*	0.003*
Insulation paper Nomex 410	2.4**	0.006**
* at 1 kHz	** at 60 Hz	

Homogeneity of dielectric substrates was evaluated by measuring dielectric properties in 9 overlapping areas (dimensions 6 × 6 cm) of the whole substrate (dimensions 12 × 12 cm) as it is shown in Fig. 1. Area 6 × 6 cm was chosen to cover major part of the measured substrate by the split cylinder resonator. To improve accuracy of measured results measurements were repeated twice and substrate had marked measured areas to provide measurements at the same position.

Measured dielectric constant and dielectric losses at each of 9 overlapping areas were joined to one complete sheet and statistically processed and interpreted using SigmaPlot software for scientific data analysis.

3 Results

This paper analyzes dielectric constant and dielectric losses at approx. 10 GHz in addition to that investigation of dielectric properties' homogeneity is included. Achieved results show values of dielectric constant and dielectric losses at 10 GHz, since the lack of these values in datasheets from manufacturers. In addition to that measured results evaluate homogeneity of these properties. Detailed results of dielectric properties and their homogeneity are described below.

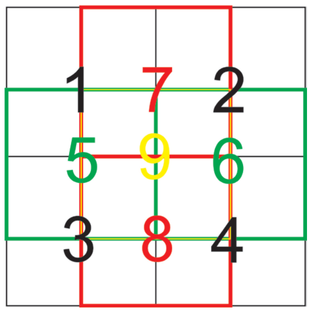

Fig. 1 9 overlapping areas for measuring homogeneity of dielectric properties

3.1 PET substrate Mylar® A

PET substrate Mylar® A transparent, flexible film offers special design options to the electrical industry due to excellent balance of its electrical properties with its physical, chemical and thermal properties. It has excellent resistance to moisture and most chemicals, can withstand temperatures extreme temperatures (-73 °C to 150°C) and does not become brittle with age [21].

It is difficult to compare measured dielectric properties (Table 2) with manufacturer stated since manufacturer does not provide measurement at GHz frequency. It can be compared with different type of flexible film from the same manufacturer Mylar® 24 C. Dielectric constant curve of Mylar® 24 C is slowly decreasing from 100 Hz with rising frequency, it is in correlation with measured and manufacturer stated values of Mylar® A as well as rising of dielectric losses with increased frequency [18].

Distribution of dielectric constant of Mylar® A is shown in the Fig. 2. Dielectric constant varies from 3.158 to 3.172 at substrate with dimension 12 × 12 cm.

Fig. 3 shows distribution of dielectric losses of Mylar® A. Dielectric losses varies from 0.00291 to 0.00296 at substrate with dimension 12 × 12 cm.

3.2 PI substrate Kapton® HN 200

Polymeric PI substrate Kapton® HN possesses a unique combination of properties that make it ideal for variety of applications in many branches of industry. Kapton® HN polyimide film is a tough, aromatic polyimide film, providing an excellent balance of chemical, electrical and physical properties over a wide range of temperatures.

Manufacturer stated dielectric properties of PI substrate Kapton® HN 200 at frequency 1 KHz and does not provide values of dielectric properties for higher frequency. Manufacturer provides these values for different type of polymeric substrate Kapton® HN 100 with very similar properties. Measured values of Kapton® HN 200 (Table 3) are in correlation with Kapton® HN 100, where by rising frequency up to 10 GHz dielectric constant is decreasing and dielectric losses are increasing, which confirm correctness of facts mentioned above [19].

Table 2 Dielectric properties of PET Mylar® A

PET Mylar® A	Measured average value	Standard deviation
Dielectric constant	3.1665*	0.0046*
Dielectric losses	0.00703 *	0.00002*
*at 9.979 GHz		

Table 3 Dielectric properties of PI Kapton® HN 200

PI Kapton® HN 200	Measured average value	Standard deviation
Dielectric constant	3.3117*	0.0107*
Dielectric losses	0.01066 *	0.000097*
*at 9.975 GHz		

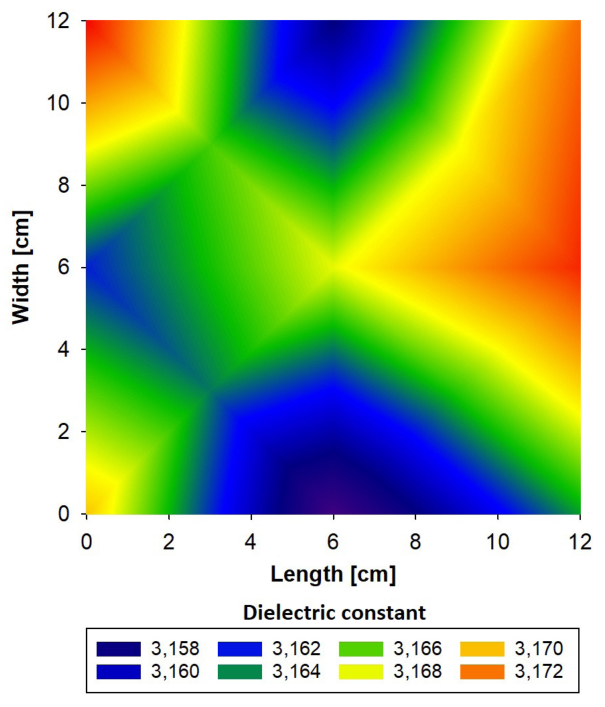

Fig. 2 Distribution of dielectric constatnt of Mylar® A

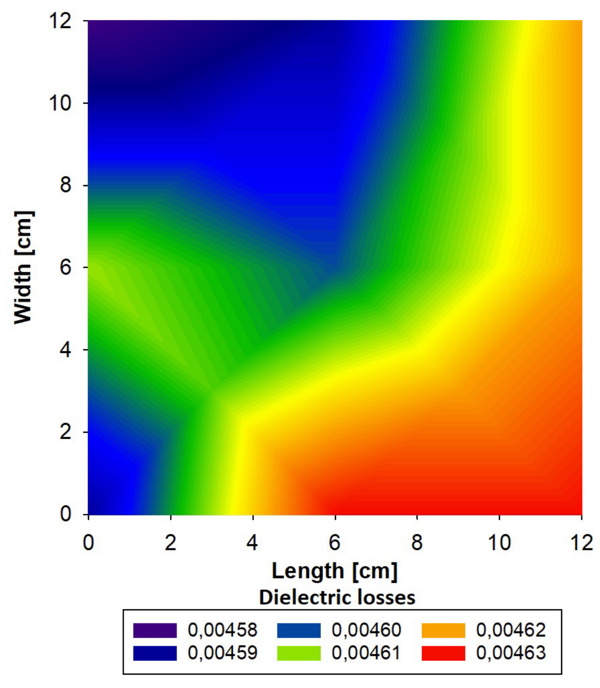

Fig. 3 Distribution of dielectric losses of Mylar® A

Fig. 4 shows distribution of dielectric constant of Kapton® HN 200. Dielectric constant varies from 3.29 to 3.33 at substrate with dimension 12 × 12 cm.

Fig. 5 shows distribution of dielectric losses of Kapton® HN 200. Dielectric losses vary from 0.01055 to 0.01075 at substrate with dimension 12 × 12 cm.

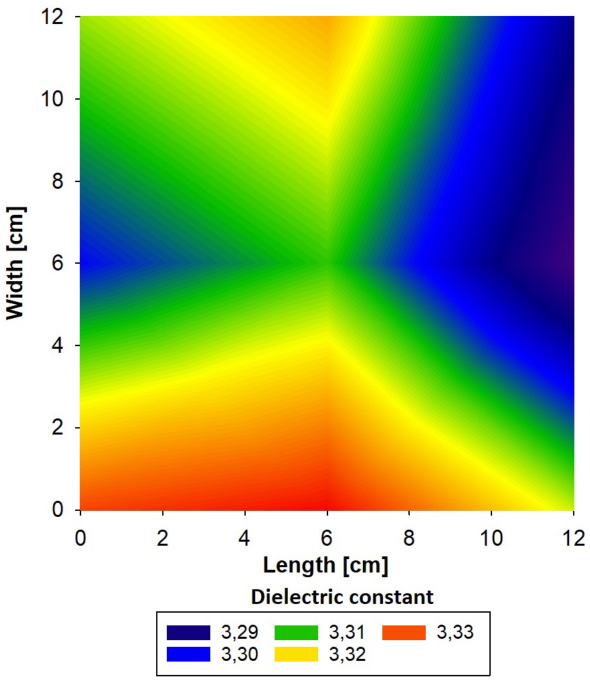

Fig. 4 Distribution of dielectric constant of Kapton® HN 200

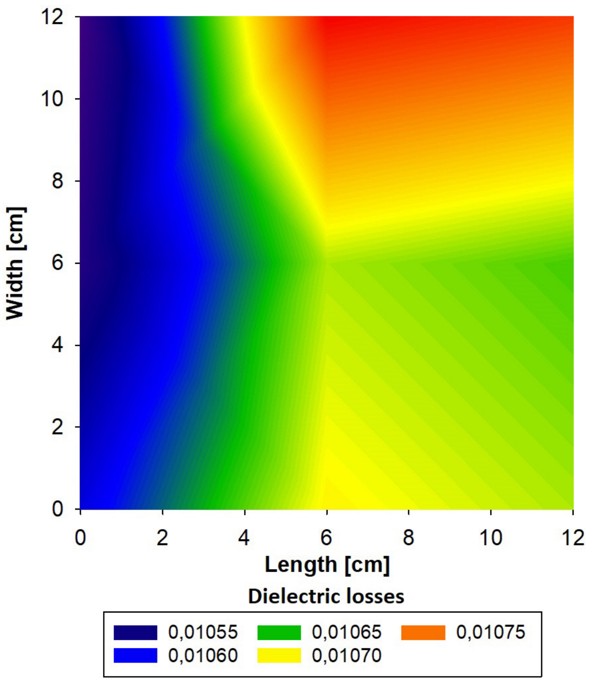

Fig. 5 Distribution of dielectric losses of Kapton® HN 200

3.3 PEN substrate Teonex® Q 51

PEN substrate Teonex® Q 51 has many superior properties such as heat resistance, strength, superb optical clarity, excellent dielectric strength, it is suitable for mild soldering etc. It is used in many various applications e.g. high density data storage tapes, IC card and automotive applications [20].

Manufacturer stated dielectric properties of PEN Teonex® Q 51 at three frequencies: 60 Hz; 1 KHz and 1 GHz, by rising frequency dielectric constant is decreasing and dielectric losses are increasing. This trend is in conflict with measured values of dielectric properties (Table 4). Measured dielectric constant at 9.974 GHz is higher (3.3874) and dielectric losses is lower (0.00294) than dielectric constant at lower frequencies.

Distribution of dielectric constant of PEN Teonex® Q 51 is shown in the Fig. 6. Dielectric constant varies from 3.37 to 3.40 at substrate with dimension 12 × 12 cm.

Fig. 7 shows distribution of dielectric losses of PEN Teonex® Q 51. Dielectric losses vary from 0.00291 to 0.00296 at substrate with dimension 12 × 12 cm.

Table 4 Dielectric properties of Teonex® Q 51

PEN Teonex® Q 51	Measured average value	Standard deviation
Dielectric constant	3.3874*	0.0184*
Dielectric losses	0.00294 *	0.00002*
*at 9.974 GHz		

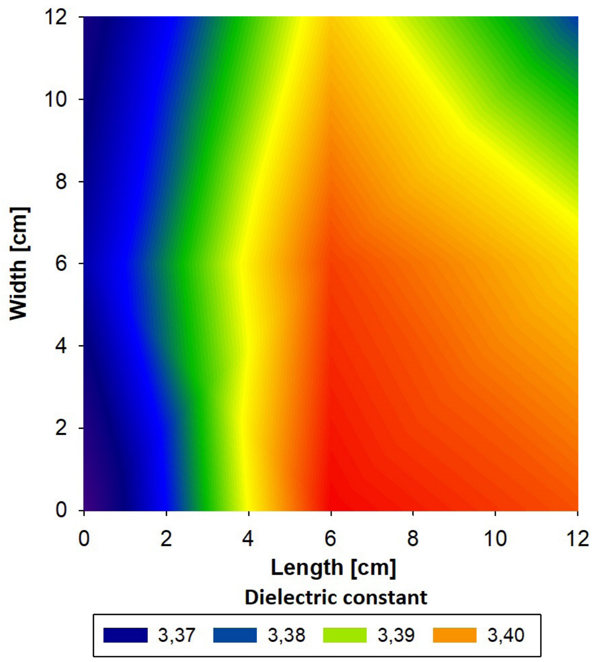

Fig. 6 Distribution of dielectric constant of Teonex® Q 51

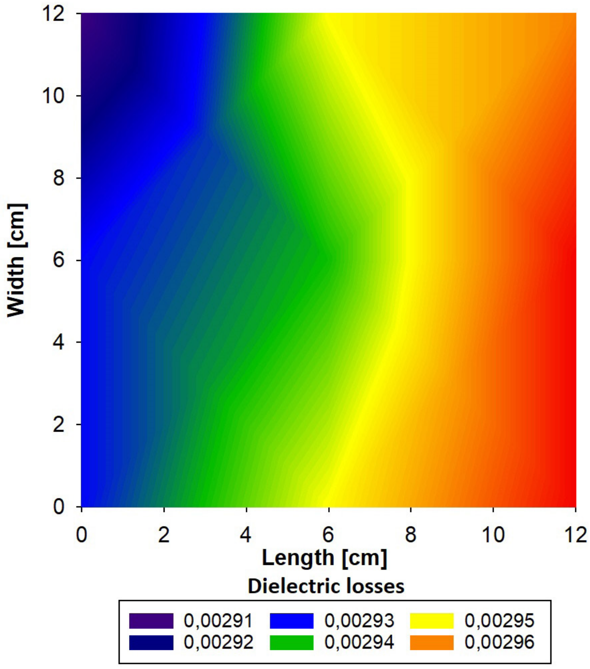

Fig. 7 Distribution of dielectric losses of Teonex® Q 51

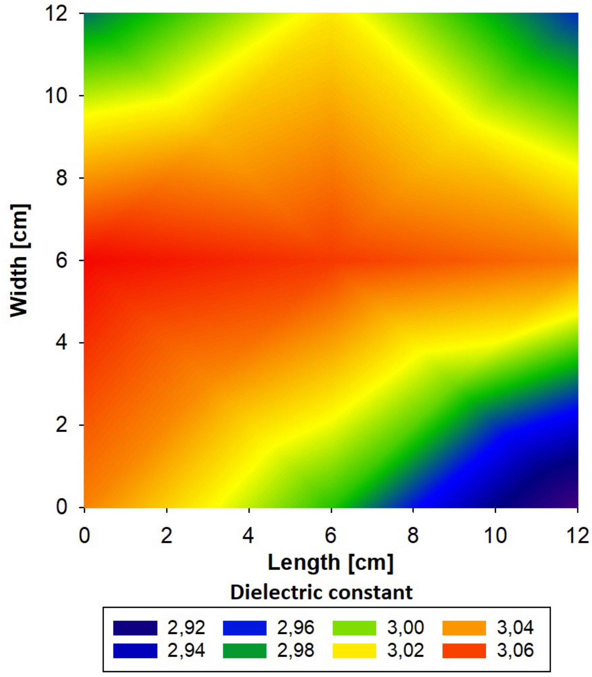

Fig. 8 Distribution of dielectric constatnt of Nomex® 410

3.4 Insulation paper Nomex® 410

Insulation paper Nomex® 410 is family of insulations papers that offer high mechanical toughness, flexibility, high dielectric strength, broad chemical compatibility and excellent flame resistance. It is widely used in most of electrical equipment applications [21].

Dielectric properties are stated by manufacturer at two frequencies; 60 Hz and 1 kHz. No further information about values at higher frequencies exist but the same conclusion as for above mentioned substrates (PI, PET and PEN) from the dielectric losses point of view can be made from graph of temperature dependence where dielectric losses for four different frequencies are stated. By increasing frequency dielectric losses increase as well. Unfortunately, there is a lack of information about dielectric constant of insulation paper Nomex® 410 in GHz area and cannot be compared with measured results (Table 5).

Fig. 8 shows distribution of dielectric constant of insulation paper Nomex® 410. Dielectric constant varies from 2.92 to 3.06 at substrate with dimension 12 × 12 cm.

Table 5 Dielectric properties of Nomex® 410

Nomex® 410	Measured average value	Standard deviation
Dielectric constant	3.0073*	0.0223*
Dielectric losses	0.0571 *	0.00019*
*at 9.97 GHz		

Fig. 9 shows distribution of dielectric losses of insulation paper Nomex® 410. Dielectric losses vary from 0.0219 to 0.0224 at substrate with dimension 12 × 12 cm.

4 Discussion

The aim of this paper is to investigate dielectric constant and dielectric losses of substrates suitable for the InkJet

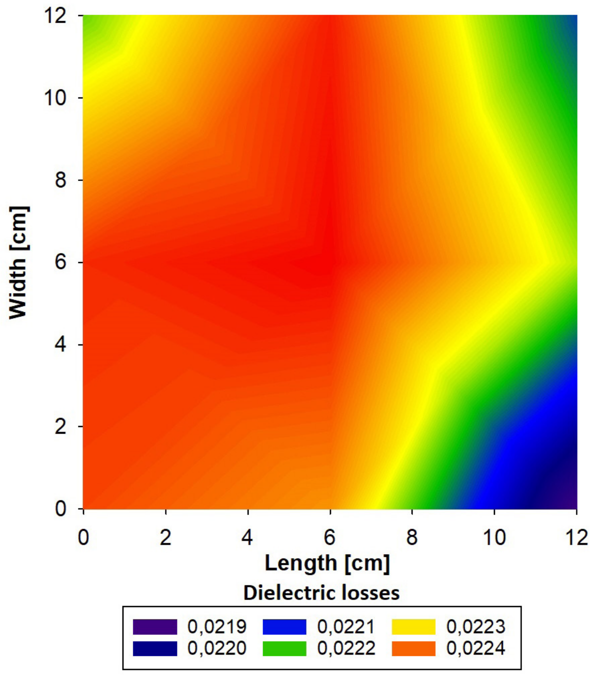

Fig. 9 Distribution of dielectric losses of Nomex® 410

printing technology in GHz frequency area to predict possibility of using these substrates for various application at this frequency area. Nowadays, measured substrates are used in lower frequency range and for that reason manufacturers stated dielectric properties at frequencies in range from 60 Hz to 100 kHz, rarely at 1 GHz. This fact and lack of any similar researches related to this topic incite the necessity of these measurements.

Dielectric properties have key role in design of high frequency applications as well as in their final performance. Even minimal mismatch between real and expected values of dielectric properties can decrease performance of final electronic device or can lead to malfunction of electronic device. It is well known that dimensions of e.g. filters, antennas etc. are strongly dependent on dielectric constant. Design of electronic device with wrong value of dielectric constant can detune final product and device will not work properly in specific frequency range because the working frequency can be shifted to lower or higher frequencies. Dielectric losses have major impact on quality and strength of transmitted signal, higher dielectric losses can lead to not adequate level of signal and malfunction of electronic device.

The measured results show common pattern in behavior of polymeric substrates. Increasing of working frequency causes decreasing of dielectric constant and increasing of dielectric losses. The same pattern can be observed speaking of insulation paper and dielectric losses. On the other hand increasing of frequency significantly increase dielectric constant of insulation paper.

In addition to above mentioned experiments this paper includes investigation of dielectric properties' homogeneity. Homogeneity of substrates is very important to achieve stable performance of electronic devices. Polymeric substrates and insulation paper are used in form of sheets. Conductive inks are deposited on these sheets to create conductive paths which represent final layout of electronic device. Different values of dielectric properties in different spots / areas of used substrate can decrease performance of electronic device. Therefore it is important to investigate homogeneity of dielectric constant and dielectric losses to prevent problems caused by unequal values or to predict behavior of designed electronic device.

Measured results show that polymeric substrates are homogeneous from the point of dielectric properties view in GHz area. On the other hand dielectric constant of insulation paper varies more than 6 % what can lead to detuning of electronic device, dielectric losses oscillate in the same range as polymeric substrates.

5 Conclusion

In this article insulation paper and three polymeric substrates (PI, PET and PEN) which are usually used for InkJet printing technology were investigated from dielectric properties point of view. In addition homogeneity of these properties were investigated as well.

The achieved results show that rising frequency has not the same impact on all substrates, speaking in manner of dielectric properties. For that reason it is important to take this fact into account by designers of electronic devices to choose suitable substrate for high frequency applications. Increased frequency has different impact on dielectric constant of each measured substrate: slight decrease of Mylar® A, significant decrease of Kapton® HN 200, slight increase of Teonex® Q 51 and significant increase of Nomex® 410. Increased frequency has no influence on dielectric losses of Teonex® Q 51, but influenced dielectric losses of remaining substrates: slight increase of Mylar® A, significant increase of Kapton® HN 200 and Nomex® 410. Measurements of dielectric properties show homogeneity of dielectric properties of all substrates except Nomex® 410 whose dielectric constant varies from 2.89 to 3.07 (approx. 6 %).

This paper shows possibility of measuring dielectric properties' homogeneity by the split cylinder resonator. Polymeric substrates are more suitable for applications sensitive to change of dielectric properties at different parts of substrate.

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