Dielectric permittivity measurement methods of textile substrate of textile transmission lines

Abstract

The article describes measurement methods of the dielectric permittivity which is the most important parameter of the substrate of new kind, textronic, transmission lines. The paper also presents the classification and short description of these methods and discusses their suitability for dielectric permittivity measurement of textile substrates. The substrate permittivity of the textile transmission line is one of electrical parameters which determine the suitability for the transmission of signals with a wide frequency spectrum. The paper discusses the main difficulties related to the dielectric permittivity measurement of flat textiles. The paper also presents examples of permittivity measurements of textile substrate line using selected method.

Słowa kluczowe: Tekstronika, przenikalność dielektryczna, tekstylnie linie transmisyjne, tekstylnie linie sygnalowe

Keywords: Textronics, dielectric permittivity, textile transmission line, textile signal line

Introduction

In the recent years we have seen rapid development of intelligent materials applicable in the construction of smart garments. These kind of garments often use a different kind of transmission line usually made of conventional metal wires. In order to improve ergonomics of the garment, a lot of designers around the world working on new kind of transmission lines named textile (textronics) transmission lines. The new field of science dealing with the implementation of these types of transmission lines, and various types of modern electronic systems for textiles is called Textronics [4]. The substrate of these lines is made from different kind of flat textiles eg woven fabric, knitted fabric or nonwoven. The complex dielectric permittivity of this textile substrate is one of the most important parameters affecting the ability to transmit fast changing signals across the textile transmission line. For example, complex dielectric permittivity has an impact on the impedance of the wave line and this has an impact on the reflections and distortions of an electromagnetic wave in the line. This phenomenon has an impact on return loss in the transmission line. The complex permittivity is defined as:

\[
\varepsilon_r' = \varepsilon_r' - j\varepsilon_r''
\]

(1)

where real part of permittivity is traditionally called the dielectric constant, while the imaginary part is related to the dissipation factor. From complex permittivity we can also obtain the tangent of the loss angle:

\[
\tan \delta = \frac{\varepsilon_r''}{\varepsilon_r'}
\]

(2)

This term relates to losses in transmission lines.

Methods of dielectric permittivity measurement

Currently, there are several methods for measuring permittivity:

- Parallel plate method
- Transmission/reflection line method
- Open-ended probe method
- Free space method
- Resonant (Cavity) Technique

Microstrip patch antenna covered with the material under test

In the parallel plate the material under test (MUT) is sandwiched between two parallel plates as shown in fig.1. This structure creates a capacitor which capacity is measured by RLC meter. The capacity of the capacitor is expressed by the formula:

\[
C = \frac{\varepsilon_0 \varepsilon_r S}{d}
\]

(3)

where \(\varepsilon_0\) – dielectric constant of the vacuum, \(\varepsilon_r\) – relative dielectric constant, \(S\) - surface of the plates, \(d\) – distance between plates. From eq.3 we can obtain:

\[
\varepsilon_r = \frac{C \cdot d}{\varepsilon_0 \cdot S}
\]

(4)

The main disadvantage of the method is small frequency range of the permittivity measurement simply limited to 1 GHz.

![Fig.1 Parallel plate method probe](image)

In the transmission line method material under test (MUT) is inserted in to the coaxial, air cell as shown in fig.2 or in to the waveguide cell as shown in fig.3. The probe is connected to the Vector Network Analyzer (VNA) (fig. 4).

Assuming the four pole model of coaxial probe with MUT [4] the Vector Network Analyzer measures all parameters of matrix \(s\) from which we can calculate the complex permittivity of the MUT. There are various approaches for obtaining the permittivity from s-parameters widely described in literature [5], [6], [7]. In the transmission
method, the most popular is Nicholson-Ross-Weir Method [5],[6],[7]. From the procedure proposed by NRW method, permittivity can be computed from following equation [6]:

\[
\varepsilon_r = \mu_r \left( \frac{(1-\Gamma)^2}{(1+\Gamma)^2} \right) \left( 1 - \frac{\lambda_0^2}{\lambda_c^2} \right) + \frac{\lambda_0^2}{\lambda_c^2} \frac{1}{\mu_r}.
\]

where \( \mu_r \) – relative permeability, \( \lambda_0 \) – free space wavelength, \( \lambda_c \) – cutoff wavelength. The reflection coefficient can be deduced as:

\[
\Gamma = X \pm \sqrt{X^2 - 1}
\]

where \( |\Gamma| < 1 \) and

\[
X = \frac{s_{11}^2 - s_{22}^1 + 1}{2s_{11}}
\]

determines the minimum frequency value where we can obtain the dielectric permittivity. The method is dedicated for high frequency measurements only. The other disadvantage is complicated sample preparation especially in case of textiles. In the coaxial probe, however, the material must also be prepared, but the tested textile material can be rolled into a roll around inner conductor.

In the Open-ended probe method dielectric permittivity is calculated from \( s_{11} \) parameter only. The method of attachment of the probe is shown in figure 5.

\[
\text{Fig.5 Reflection method of dielectric permittivity measurement}
\]

The main disadvantage of the transmission method using waveguide is cutoff frequency of the waveguide which determines the minimum frequency value where we can obtain the dielectric permittivity. The method is dedicated for high frequency measurements only. The other disadvantage is complicated sample preparation especially in case of textiles. In the coaxial probe, however, the material must also be prepared, but the tested textile material can be rolled into a roll around inner conductor.

In the Open-ended probe method dielectric permittivity is calculated from \( s_{11} \) parameter only. The method of attachment of the probe is shown in figure 5.

\[
\text{Fig.6 Free-space method for high frequency dielectric permittivity measurement}
\]

The method is less accurate in comparison with transmission/reflection methods. It also need the time consuming computation of \( \varepsilon_r \) and complicated calibration of the probe. The calibration process need to use permittivity standards like distilled water, methanol.

The free-space method stand is shown in figure 6. Typically it consisting of two horn antennas, MUT in sample holder, and Vector Network Analyzer. The free-space technique, widely described in literature [12], [13] has several advantages. Main, measurements using these techniques are contactless and nondestructive, so free-space methods can be used under different environmental conditions, such as high temperature. The main disadvantage of the method is that it needs large area of the sample for low frequency measurement. Therefore the method is most appropriate for high frequency measurements. The other drawback is that it needs expensive positioning antenna system assuring precise antenna movement for accurate system calibration.

For coaxial line probe \( \lambda_c \rightarrow \infty \). Additionally assuming \( \mu_r = 1 \) (measured textiles are non magnetic materials) from equation (5) we can obtain:

\[
\varepsilon_r = \left( \frac{(1-\Gamma)^2}{(1+\Gamma)^2} \right) \left( 1 - \frac{\lambda_0^2}{\lambda_c^2} \right)
\]

The main disadvantage of the transmission method using waveguide is cutoff frequency of the waveguide which
possible accuracy of real permittivity [2]. The more detailed
information about the method are described in [14].
The microstrip patch antenna covered with the material
under test is another method for permittivity measurement.
In this method microstrip patch antenna shown in figure 7 is
covered with the tested sample. This causes a change in
the resonant frequency of the antenna as shown in figure 8.
On the basis of the frequency change, the value of the
permittivity can be calculated (fig.8). A more detailed
description of the method can be found in [1],[8],[9].

![Fig.7 Microstrip patch antenna covered with the flat, tested sample](image)

Fig.8 Changes in resonant frequency of antenna caused by changing the real part of permittivity (lossless MUT)

The comparison of properties of the methods described
above and their suitability for measuring of the dielectric
permittivity of flat textiles is presented in table 1.
The first column of the table contains some of the
features affecting the suitability of a particular method for
measuring dielectric permittivity of flat textiles. The last line
of table 2 contains the final result of the comparison.

<table>
<thead>
<tr>
<th>Method/feature</th>
<th>Parallel plate</th>
<th>Transmission/reflection with coaxial probe</th>
<th>Transmission/reflection with waveguide probe</th>
<th>Open-ended probe</th>
<th>Free space</th>
<th>Resonant</th>
<th>Microstrip patch antenna covered with the MUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Permittivity measurement</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetic Permeability measurement</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency range</td>
<td>Average</td>
<td>Very good</td>
<td>Average</td>
<td>Very good</td>
<td>Average</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Very good</td>
<td>Medium good</td>
<td>Medium good</td>
<td>Medium</td>
<td>Medium good</td>
<td>Very good</td>
<td>Medium good</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>Fast</td>
<td>Medium</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
<td>Medium</td>
<td>Fast</td>
</tr>
<tr>
<td>Usefulness for measuring permittivity of textiles</td>
<td>Very good</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

Examples of permittivity measurements

For permittivity measurement the parallel plate method
was used. The choice of this method was caused by its
simplicity. Moreover, this method allows non-destructive
testing of the textiles with fast sample preparation. The
comparable method (table 1) is Free Space Method but in
this method creases of tested textiles may cause
measurement inaccuracies. The measuring probe with two
parallel plates was used. The distance between them is
regulated by micrometer screw. Parameters of the tested
fabrics, and permittivity measurement results are shown in
table 2. The measurement frequency was 200 kHz.
Parameters of the surrounding air were as follows: the
ambient temperature - 25°C, atmospheric pressure -
1001hPa and ambient RH - 32%. As a result of the
measurements obtained (table 3), the cotton fabrics is
characterized by the highest values of dielectric constant
and loss.

<table>
<thead>
<tr>
<th>No of sample</th>
<th>Material</th>
<th>Weave</th>
<th>Thickness (mm)</th>
<th>Surface mass (g/m²)</th>
<th>Apparent density (kg/m³)</th>
<th>Open porosity (%)</th>
<th>ϵr</th>
<th>tgδ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton</td>
<td>twill</td>
<td>0.62</td>
<td>287</td>
<td>428</td>
<td>78.03</td>
<td>2.231</td>
<td>0.0366</td>
</tr>
<tr>
<td>2</td>
<td>Cotton</td>
<td>plain</td>
<td>0.48</td>
<td>203</td>
<td>390</td>
<td>74.35</td>
<td>2.077</td>
<td>0.0314</td>
</tr>
<tr>
<td>3</td>
<td>Wool</td>
<td>plain</td>
<td>0.42</td>
<td>287</td>
<td>250</td>
<td>76.99</td>
<td>1.865</td>
<td>0.0079</td>
</tr>
<tr>
<td>4</td>
<td>Elano-wool</td>
<td>twill</td>
<td>0.64</td>
<td>186</td>
<td>427</td>
<td>79.72</td>
<td>2.053</td>
<td>0.0076</td>
</tr>
<tr>
<td>5</td>
<td>Elano-wool</td>
<td>plain</td>
<td>1.26</td>
<td>266</td>
<td>391</td>
<td>78.36</td>
<td>1.670</td>
<td>0.0073</td>
</tr>
<tr>
<td>6</td>
<td>Wool + PA</td>
<td>twill</td>
<td>1.47</td>
<td>331</td>
<td>292</td>
<td>79.1</td>
<td>1.529</td>
<td>0.0052</td>
</tr>
<tr>
<td>7</td>
<td>Polyester</td>
<td>plain</td>
<td>0.36</td>
<td>158</td>
<td>416</td>
<td>79.55</td>
<td>1.748</td>
<td>0.0044</td>
</tr>
<tr>
<td>8</td>
<td>Viscose + PE</td>
<td>twill</td>
<td>0.52</td>
<td>224</td>
<td>400</td>
<td>77.05</td>
<td>1.707</td>
<td>0.0079</td>
</tr>
<tr>
<td>9</td>
<td>Polyester</td>
<td>plain</td>
<td>0.08</td>
<td>56</td>
<td>466</td>
<td>77.20</td>
<td>2.122</td>
<td>0.0035</td>
</tr>
</tbody>
</table>
Conclusion

Currently, there are many methods to measure dielectric permittivity of textiles. For each of them we can use several different algorithms for determining the permittivity. The correct choice of one of them has an impact on accuracy, convenience, frequency range for which the permittivity was determined, measurement speed etc. Resonant (Cavity) method is preferred for measuring the permeability for high frequency signals. The other high accuracy, standardized method is parallel plate method. The main disadvantage of these methods is narrow measurement frequency range. This disadvantage considerably limits the use of these methods to study changes in the substrate dielectric constant of broadband textile transmission lines. As a result of preliminary measurements, we obtained, that the cotton fabric is characterized by the highest values of dielectric constant and loss.

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