Jacek LEŚNIKOWSKI

Politechnika Łódzka, Katedra Odzieżownictwa i Tekstroniki

Dielectric permittivity measurement methods of textile substrate of textile transmission lines

Streszczenie. *W artykule opisano metody pomiaru przenikalności dielektrycznej, która jest jednym z najważniejszych parametrów podłoża nowego typu, tekstronicznych linii transmisyjnych. W artykule przedstawiono również podział tych metod oraz omówiono ich przydatność do pomiarów przenikalności dielektrycznej płaskich wyrobów włókienniczych. Przenikalność dielektryczna włókienniczego podłoża tekstronicznej linii transmisyjnej jest jednym z parametrów elektrycznych decydującym o przydatności takiej linii do transmisji sygnałów o szerokim widmie częstotliwości. W artykule omówiono główne problemy związane z pomiarem przenikalności dielektrycznej płaskich wyrobów włókienniczych. Zaprezentowano również przykładowe wyniki pomiarów przenikalności dielektrycznej materiałów włókienniczych wykonanych wybraną metodą. (**Metody pomiaru przenikalności dielektrycznej tekstylnego podłoża tekstylnej linii transmisyjnej**)*

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 determines their 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, tekstylne linie transmisyjne, tekstylne linie sygnałowe
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:

(1) $$\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

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:

(2) $$\tan\delta = \frac{\varepsilon_r^{''}}{\varepsilon_r^{'}}$$

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:

(3) $$C = \frac{\varepsilon_0 \varepsilon_r S}{d}$$

where ε_0 – dielectric constant of the vacuum, ε_r – relative dielectric constant, S - surface of the plates, d – distance between plates. From eq.3 we can obtain:

(4) $$\varepsilon_r = \frac{C \cdot d}{\varepsilon_0 \cdot S}$$

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

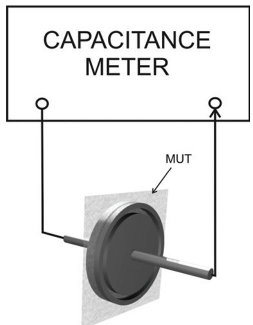

Fig.1 Parallel plate method probe

In the transmision 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]:

$$\varepsilon_r = \mu_r \frac{(1-\Gamma)^2}{(1+\Gamma)^2}\left(1-\frac{\lambda_o^2}{\lambda_c^2}\right)+\frac{\lambda_o^2}{\lambda_c^2}\frac{1}{\mu_r} \tag{5}$$

where μ_r – relative permeability, λ_o – free space wavelength, λ_c – cutoff wavelength. The reflection coefficent can be deduced as:

$$\Gamma = X \pm \sqrt{X^2-1} \tag{6}$$

where

$$|\Gamma| < 1$$

and

$$X = \frac{s_{11}^2 - s_{21}^2 + 1}{2s_{11}} \tag{7}$$

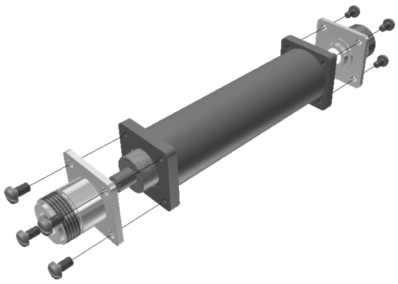

Fig.2 Transmision line method coaxial probe

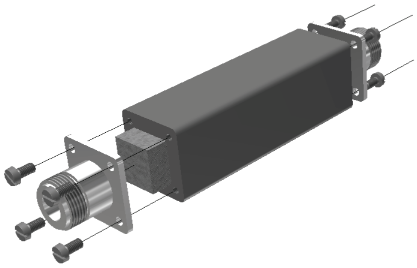

Fig.3 Example of transmision line method waveguide probe

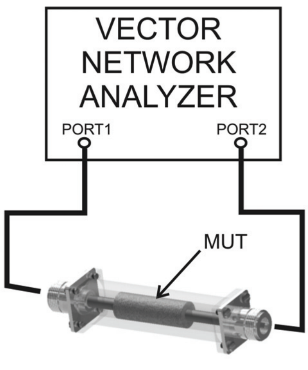

Fig.4 Measurement using transmission method and coaxial probe

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

$$\varepsilon_r = \frac{(1-\Gamma)^2}{(1+\Gamma)^2} \tag{8}$$

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 mehod dielectric permittivity is calculated from s_{11} parameter only. The method of attachment of the probe is shown in figure 5.

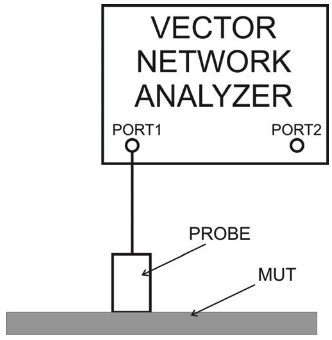

Fig.5 Reflection method of dielectric permittivity measurement

The method is less accurate in comparison with transmision/reflection methods. It also need the time consuming computation of ε_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.

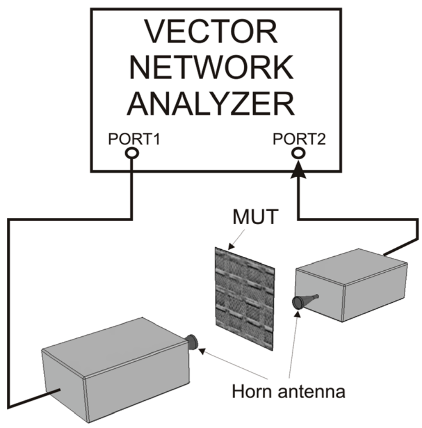

Fig.6 Free-space method for high frequency dielectric permittivity measurement

The Resonant (Cavity) Technique uses a special class of measurement cells that are especially useful for measurements of very low loss materials with highest possible accuracy of real permittivity [2]. The more detailed informations 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].

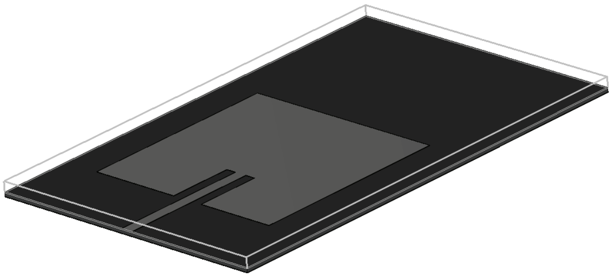

Fig.7 Microstrip patch antenna covered with the flat, tested sample

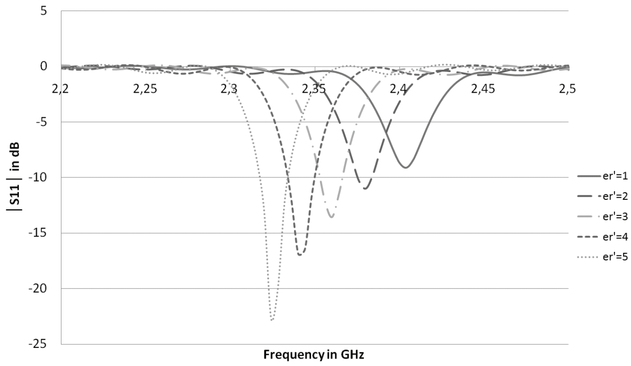

Fig.8 Changes in resonant frequency of antenna caused by changing the real part of permittivity (lossless MUT)

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 1 The comparison of the permittivity measurement methods

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

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 2 Parameters of textile materials and measurement results

No of sample	Material	Weave	Thickness	Surface mass	Apparent density	Open porosity	ε_r	$tg\delta$
			mm	g/m^2	kg/m^3	%	-	-
1	Cotton	twill	0,62	287	428	78,03	2,231	0,0366
2	Cotton	plain	0,48	203	390	74,35	2,077	0,0314
3	Wool	plain	0,42	287	250	76,99	1,865	0,0079
4	Elano-wool	twill	0,64	188	427	79,72	2,053	0,0076
5	Elano-wool	plain	1,26	266	391	79,36	1,670	0,0073
6	Wool + PA	twill	1,47	331	292	79,1	1,529	0,0052
7	Polyester	plain	0,36	158	416	79,55	1,748	0,0044
8	Viscose + PE	twill	0,52	224	400	77,05	1,707	0,0079
9	Polyester	plain	0,08	56	466	77,20	2,122	0,0035

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.

This work is (partially) supported by Structural Founds in the frame of the project titled „Development of research infrastructure of innovative techniques and technologies of textile clothing industry" CLO–2IN–TEX, financed by Operational Programme Innovative Economy, 2007-2013, Action 2.1.

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***Autor**: dr inż. Jacek Leśnikowski, Politechnika Łódzka, Katedra Odzieżownictwa i Tekstroniki, ul. Żeromskiego 116, 90-924 Łódź, E-mail: lesnik@p.lodz.pl;*