Sławomir Hausman,
Łukasz Januszkiewicz,
***Marina Michalak,**
Tomasz Kacprzak,
***Izabella Krucińska**

Technical University of Łódź
Institute of Electronics
ul. Wólczańska 211/215, 90-924 Łódź, Poland
E-mail: slawomir.hausman@p.lodz.pl

***Department of Fibre Physics and Textile Metrology**
ul. Żeromskiego 116, 90-924 Łódź, Poland

High Frequency Dielectric Permittivity of Nonwovens

Abstract
In this paper, selected direct-current and high-frequency properties of dielectric textile materials for application to textronics are presented. Textronics deals, among other matters, with designing and manufacturing devices which are at the boundaries of electronic and textile science and technology. Textronic materials may be applied to accomplish the wireless transmission of signals between various subsystems integrated into textile products, or transmission to systems in the user's environment. This research concentrates on nonwoven textile materials for applications where the need exists to integrate antenna systems with textile products. Body-worn antenna systems embedded in clothes provide the greatest degree of integration of the electronic and textile parts into a textronic product. To design such antennas, a knowledge of nonwovens' high frequency electrical parameters is required, namely the complex dielectric permittivity of textile materials. In this paper, we present the measurement results of dielectric permittivity as well as the through-resistance and surface resistance for several samples of nonwovens. The knowledge of these parameters' values is required to design textile antennas and their supply systems. The measurements were carried out for some variants of stitched nonwovens manufactured with the use of various raw materials, maintaining the same technological parameters. The particular variants of nonwovens were manufactured from fibres with typical properties for common applications and for slow-burning fibres.

Key words*: dielectric textile materials, nonvovers, high ferquency dielectric permittivity, surface resistance, through resistance, textronic materials, wireless signal transmission, antenna.*

Introduction

The development of the electronic integrated circuit technology at present allows very complex, and at the same time very small devices to be designed, which may be integrated with textile products. Therefore, clothing can perform new functions which may improve the living standards of both healthy and disabled people. Textronics deals with the design and manufacture of such devices, which are at the boundaries of electronics and textile technology. The field of textronic applications may be significantly broadened by using radio communication between various subsystems, including sensors and microprocessor controllers embedded in clothes, or communication with systems which are in the user's environment. In such applications, the need exists to integrate antenna systems with textile products. For this purpose, designers require a knowledge of nonwovens' electrical parameters, such as the dielectric permittivity and dielectric loss of textile materials in the range of high frequencies. At present, such data is still not available in literature, even for relatively popular textile materials. In this paper, the measurement results of dielectric permittivity, through-resistance and surface resistance for several samples of nonwovens are presented for the ISM (Industrial, Scientific and Medical) frequency band, i.e. 2.4 GHz. This band is convenient for many applications because it is not licensed.

Textronic products may be applied in protective clothing for persons working in extreme environmental conditions, such as fire or toxic substances. The need for constant communication with persons who are in conditions hazardous to life creates special demands for the design and elaboration of wireless systems, allowing for fast and constant contact with them. For this purpose, sensors (e.g. body temperature probes) can be placed into textile products, and their signals transmitted by an antenna to supervision centres. Since in this case electromagnetic waves propagate partly through the textile medium, knowledge of their electrical parameters is necessary. The authors have undertaken research into this issue for a range of materials devoted to use in nonwoven textronic products. Therefore the first tests have been carried out for these materials which may fulfil these demands, that is, nonwovens manufactured from traditional polyester fibres and special slow-burning fibres.

Test materials

Several nonwoven materials manufactured by the stitching method were tested. The selection of fibres follows from their suitability for special protective clothes as designed by the authors. The following fibres were used to obtain the test nonwovens: commonly used polyester fibres - PES (polyethylene terephtalate fibres - PET), slow-burning polyimide-amide fibres of the Kermel trade-name, and P84 polyimide fibres. Considering the possibility of applying the thermal method for joining nonwoven layers, the LMF biocomponent polyester fibres (LMF – low melting fibres) were additionally selected.

Polyester fibres belong to the group of thermoplastic fibres. They are characterised by relatively high values of thermal resistance factors. They have a melting temperature within the range of 253 °C – 256 °C and a softening temperature within the range of 230 °C – 240 °C. The polyester fibres are distinguished by very good dielectric properties, and are poor conductors of direct current. Their resistivity is within the range of 10^{11} Ω·m [1].

Kermel fibres are high-tech polyimide-amide fibres. They are provided for specific applications, such as in protective clothing used by people working at high temperatures, e.g. in the metallurgical industry and for firemen. The Kermel fibres have a tenacity of 25 –35 cN/tex and elongation at break of 30 – 35% [2].

The P84 fibres are characterised by high thermal stability. Because of their physical properties and their resistance to chemicals, they are manufactured for use in fabrics and products resistant to high temperatures, for example flame resistant protective clothing. As their glass transition temperature is 315 °C, and the temperature of carbonisation 370 °C, they can be used up to the temperature of 260 °C (depending on the environmental conditions). They have a tenacity of 38 cN/tex, and elongation at break of 30%.

LMF fibres are special polyester fibres manufactured by Huvis (Korea). These are two component fibres, manufactured from basic polyester fibres and modified polyester fibres. They have a considerably lower melt temperature than conventional polyester fibres, and they may be easily thermally joined with other fibres. The LMF fibres selected for our tests were characterised by a melting temperature of 110 °C [4].

The nominal parameters of all the fibres investigated in this research are listed in Table 1.

Table 1. Nominal parameters of fibres used in the research.

Fibre	Linear density, dtex	Cut length, mm
Kermel	1.7	60
P84	1.7	50
LMF	4.4	51
PES	3.3	57

Blends of Kermel fibres, polyester fibres, and P84 fibres with LMF fibres were prepared for manufacturing the nonwovens. In all blends, the content of LMF fibres was 5%. In the initial stage of the research, webs were obtained by feeding the carding machine with a mass of fibre mixtures of 50 g, and were produced with parallel-arranged fibres. The area mass of each web was about 100 g/m^2. Next, the webs were stitched, and the nonwovens obtained were arranged layer by layer and stitched again using needles of the type 15×18×40×3 ″ BB. A stitching number of 40 stitchings per cm^2 was applied with a stitching depth of 12 mm.

Parallel to the nonwovens obtained, according to the above-mentioned method, nonwoven variants were obtained by applying thermal processing. In order to obtain such nonwovens, they were pressed with a clothing pressure machine for 1.5 minutes, at a temperature of 150 °C.

Test methods

The morphological and physical features of nonwovens after stitching, before and after thermal processing were determined. All the morphological features were tested according to the appropriate standards. The following nonwoven properties were selected for tests:

1. Area mass (M_p) in accordance with Polish Standard PN-EN 29073-1: 'Textiles. Testing methods for nonwovens. Determination of area mass'.
2. Thickness (d) in accordance with Polish Standard PN-EN 29073-2: Textiles. Testing methods for nonwovens. Thickness determination'.
3. Air permeability (P_p) in accordance with Polish Standard PN-EN ISO 9237: 'Determination of air permeability of textile products'.
4. Thermal conductivity (λ) and thermal resistance (R_c) with use of the Alambeta device, made in Czech Republic, by Sensora.
5. The electrical through-resistance (R_s) and surface resistance (R_p) in accordance with Polish Standard PN-91/P-04871:'Textiles. Determination of electrical resistivity'.

When determining the electrical properties, in order to eliminate calculation errors, the sample resistivity values were not calculated, and only the resistance values obtained from indications were analysed. While doing so, the geometrical arrangement of the measuring cell used must be considered, and the values analysed are valid only for this arrangement. If a need arises, then it is possible to calculate the resistances knowing the geometry of the cell, dimensions of the electrodes, and the sample thickness,.

The electrical surface resistance was tested on both surfaces of the singular nonwoven samples, and the result is the average value.

Body-worn antenna systems [5] embedded in clothes provide the greatest degree of integration of the electronic and textile parts into a textronic product. Their advantages are their light weight, easy usage of the clothing (fewer cables, quicker dressing), unobtrusiveness, and low cost. In order to design textile antennas and transmission lines, it is necessary to

Table 2. Denotations of the nonwoven samples tested (K – denotation of Kermel, T – denotation for thermal processing).

Denotation	Sample description
K+LMF	Stitched nonwovens obtained from the blend of Kermel and LMF fibres with content of 95% and 5% respectively, not thermal processed
P84+LMF	Stitched nonwovens obtained from the blend of P84 and LMF fibres with content of 95% and 5% respectively, not thermal processed
PES+LMF	Stitched nonwovens before thermal processing, obtained from the blend of PES and LMF fibres, with content of 95% and 5% respectively, not thermal processed
(K+LMF)/T	Stitched nonwovens obtained from the blend of Kermel and LMF fibres, with per content of 95% and 5% respectively; after thermal processing at 150^{0}C, over 1.5 minutes
(P84+LMF)/T	Stitched nonwovens obtained from the blend of P84 and LMF fibres, with content of 95% and 5% respectively; after thermal processing at 150 °C, over 1.5 minutes
(PES+LMF)/T	Stitched nonwovens obtained from the blend of PET and LMF fibres, with content of 95% and 5% respectively; after thermal processing at 150 °C, over 1.5 minutes.

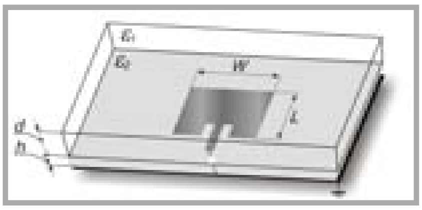

***Figure 1.** The patch antenna with a dielectric cover; L – length and W – width of the microstrip patch antenna; h – thickness of the substrate of the microstrip patch antenna; d – sample thickness; ε_1 and ε_2 – permittivities of samples used and antenna substrate respectively.*

know the complex dielectric permittivity of the antenna substrate and all its superstrata (typically all of them are textile materials) at the frequencies for which the system is being designed.

Several methods have been proposed for measuring permittivity, such as waveguide cells, resonant cavities, and coaxial or microstrip transmission lines. One method for the dielectric permittivity measurement is by means of covering a microstrip patch antenna with the material under test [7] (see Figure 1). In comparison to other measurement setups, the advantages of the microstrip patch antenna approach are small size, ease of fabrication, and low cost. The main disadvantage is that a given patch antenna in this method can be used for measurements at one (i.e. resonant) frequency only. The method involves a patch antenna that is designed to operate at a given f_{r1} frequency in the free space medium (permittivity equal to 1). The length L and width W of the microstrip patch antenna presented in Figure 1 has been calculated for the resonant frequency f_{r1} = 1.87567 GHz. In practical applications, this frequency can be measured as the minimum value of VSWR (voltage standing vawe ratio) versus frequency.

Test results and their analysis

Below are presented the test results of parameter determination for the following nonwovens: stitched nonwovens before thermal processing, and nonwoven structures after pressing and manufactured by thermal bonding.

The tested nonwoven samples are described in Table 2.

Table 3 presents the determined values of area mass (M_p), thickness (d), apparent density (g), and air permeability (P_p) of stitched nonwovens before thermal processing.

***Table 3.** Morphological properties and air permeability of stitched single-layer nonwovens before thermal processing; M_p - area mass, d – thickness, g – apparent density, P_p – air permeability.*

Parameter	Unit	K+LMF	P84+LMF	PES+LMF
M_p	g/m^2	283.5	196.7	322.2
d	mm	6.56	6.22	7.67
g	g/cm^3	0.0432	0.0155	0.042
P_p	dm^3/m^2·s	147.87	189.39	234.95

***Table 4.** Electrical and thermal properties of single-layer stitched nonwovens before thermal processing; R_s – through-resistance, R_p –surface resistance, R_c – thermal resistance.*

Parameter	Unit	Multiplier	K+LMF	P84+LMF	PES+LMF
R_s	Ω	10^8	5.95	1.75	7.5
R_p	Ω	10^8	11.0	1.7	11.0
λ	W/m·K	10^{-3}	39.1	40.8	40.9
R_c	m^2·K/W	10^{-3}	203.5	174.0	223.5

***Table 5.** Morphological properties and air permeability of single-layer nonwovens after thermal processing; M_p – area mass, d – thickness, g – apparent density, P_p – air permeability.*

Parameter	Unit	(K+LMF)/T	(P84+LMF)/T	(PES+LMF)/T
M_p	g/m^2	264.86	188.08	322.22
d	mm	3.17	3.35	1.26
g	g/cm^3	0.0835	0.0561	0.0256
P_p	dm^3/m^2·s	100.72	158.04	77.27

***Table 6.** Electrical parameters and thermal resistance of single-layer nonwovens after thermal processing; R_s – through-resistance, R_p – surface resistance, R_c –thermal resistance.*

Parameter	Unit	Multiplier	(K+LMF)/T	(P84+LMF)/T	(PES+LMF)/T
R_s	Ω	10^9	3.7	0.33	1.6
R_p	Ω	10^9	3.9	0.39	4.5
λ	W/m·K	10^{-3}	35.6	37.4	42.1
R_c	m^2·K/W	10^{-3}	105	104	30.8

The results obtained in the preliminary tests of the morphological features of the nonwovens and their air permeability indicated the correctness of selection of these fibres for use in the nonwovens, as the obtained samples made from blends of PES fibres were characterised by the highest air permeability, despite having the highest values of thickness and area mass. In contrast, the nonwoven manufactured from the blend of P84 and LMF fibres was characterised by the smallest value of air permeability, at the lowest value of the area mass.

Table 4 presents the values of through-resistance (R_s), surface resistance (R_p), thermal conductivity (λ), and thermal resistance (R_c) determined for stitched nonwovens before thermal processing.

The analysis of the electrical and thermal property results obtained for the preliminary nonwovens indicates that all nonwovens are characterised by high values of electrical resistance, and similar values of thermal conductivity and thermal resistance.

Table 5 presents the values of area mass (M_p), thickness (d), apparent density (g), and air permeability of stitched nonwovens after thermal processing.

The morphological nonwovens parameters changed after thermal processing, according to the former assumptions. The thickness decreased, whereas the apparent density of the nonwovens increased at unchanging area mass. The air permeability of nonwovens with Kermel and PES fibres decreased significantly, whereas they remained unchanged after pressing the nonwoven manufactured from the blend of P84 and LMF thermoplastic fibres.

Table 6 presents the parameters of the through-resistance (R_s), the surface resistance (R_p) the thermal conductivity (λ), and the thermal resistance (Rc) obtained for stitched single-layer nonwovens after thermal processing.

The applied thermal processing, generally changed all the electrical and thermal parameters. The through-resistance changed in some cases by almost as much as one order of magnitude.

Results of high frequency measurements

Covering the antenna with the sample of a dielectric material results in a reduction of the resonant frequency to f_{r2} as shown in Figure 2. The f_{r1}- f_{r2} shift of the resonant frequency is caused by the difference of the electromagnetic wave length for the uncovered antenna (as is assumed in the procedure for designing the antenna) and the antenna covered with a sample of dielectric material of unknown permittivity ε_1 (see Figure 1). The frequency shift depends on covering material permittivity ε_1 and its thickness d. If the frequency shift f_{r1} - f_{r2} is measured, the permittivity can be found from a theoretical analysis of the patch antenna's resonant frequency. In general, the resonant frequency f_r can be represented as function (1).

$$f_r = f(W, L, \varepsilon_1, \varepsilon_2, d, h) \qquad (1)$$

No exact analytical form of (1) is known, but some approximations exist [6 - 9]. In this research, an approach involving the variational method in the spectral domain was adopted from [7]. Figure 3 presents a computer simulation of the relative frequency shift

$$\Delta f_r = (f_{r1} - f_{r2}) / f_{r1}$$

as a function of the relative permittivity of the tested material ε_1 for values of sample thickness d appropriate for the tested nonwoven samples. Values of ε_2, W, L, and h are fixed for the particular patch antenna used. The results of the permittivity measurements obtained with the use of the method described for the samples considered are presented in Table 7. All materials have values of ε_1 between 1.012 and 1.175. As could be predicted, permittivity increased significantly for nonwovens after thermal processing. The method described is suitable for measuring the properties of thin samples $d < \lambda$ as it involves the so-called effective dielectric permittivity [e.g. 7]. This assumption has been satisfied for all the samples tested.

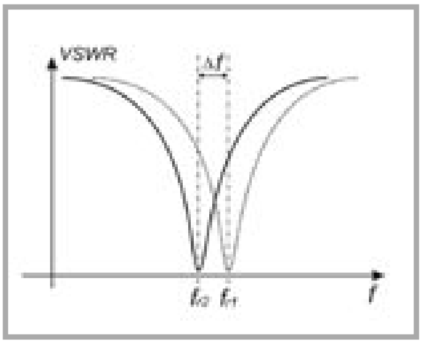

Figure 2. *The shift of the resonance frequency of the covered patch antenna; VSWR - voltage standing wave ratio.*

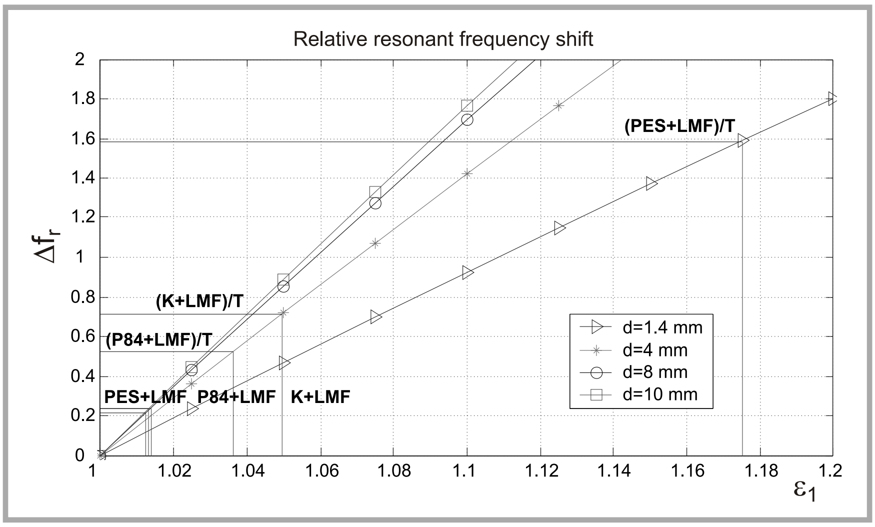

Figure 3. *Computer simulation of relative resonant frequency shift Δf_r as a function of relative permittivity of the tested material ε_1 for different thickness d of the sample.*

Table 7. *Dielectric permittivity of nonwovens.*

Parameter	PES+LMF	P84+LMF	K+LMF	(PES+LMF)/T	(P84+LMF)/T	(K+LMF)/T
thickness d, mm	10	8	8	1.4	4	4
dielectric permittivity ε_1	1.013	1.012	1.014	1.175	1.036	1.050

Conclusions

In the research described, a method using a microstrip patch antenna has been implemented and used to measure the high-frequency dielectric permittivity of nonwovens. The permittivity of selected nonwovens has been measured at a frequency of about 1.9 GHz, and the values obtained have been presented and briefly discussed. The results can be used not only in the design of textile antennas with nonwovens as their substrate, but additionally to account for such materials as superstrata (for instance layers of garment) covering the antenna.

The research will be continued in order to find a similar methodology for the measurement of the complex dielectric constant in order to include material losses.

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