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Nonwovens with Implanted Split Rings for Barriers Against Electromagnetic Radiation

Abstract
This work is a continuation of our investigations into nonwoven structures designed as barriers against electromagnetic radiation. The needled nonwovens were manufactured from polypropylene fibres. On the basis of the measured electric resistance of the fibres and the properties of the nonwovens manufactured from these fibres, we forecasted the behaviour of the nonwoven products in electromagnetic fields. The results obtained were verified experimentally by testing the nonwoven elements in a microwave electromagnetic field. In order to reduce the microwave transmission through the tested products, electroconductive elements of special shape were introduced into the nonwoven structure. The geometry, properties, and spatial configuration of these elements were selected according to the results obtained during our previous investigations into the attenuation of electromagnetic radiation within the range of 7.0 – 10.0 GHz.

Key words: *textile barriers, electromagnetic radiation, nonwoven modelling, polypropylene, wave transmission, wave attenuation, wire rings.*

Introduction

A perfect barrier against electromagnetic radiation needs to be a grounded thick-wall metal container, with both the electric conductivity and magnetic permeability of the metal as high as possible (in order to minimise the wall thickness required to prevent electric and magnetic fields from penetrating into the container). However, such barriers would exhibit none of the air permeability required for protecting workers, and so their applicability would be limited to protecting equipment. It is impossible to protect against the whole range of electromagnetic radiation, including low-frequency fields, microwaves, infrared, visible, ultraviolet, X- and gamma rays. Barriers should therefore be designed for specific, rather narrow frequency bands. The growing market of microwave devices (mobile phones and telecommunication systems, microwave ovens, traffic control radars) challenges scientists to search for barriers that meet the requirements of air permeability, low mass density, high flexibility, etc.

Textiles, including nonwovens, may be priority materials for creating human-friendly barriers against microwave radiation.

This work is a continuation of investigations conducted at the Department of Fibre Physics and Textile Metrology of the Technical University of Łódź within the scope of a research concerned with the barrier properties of textile materials against electromagnetic radiation [1 – 9]. This problem was undertaken in cooperation with a research team from Lithuania.

For the previous investigations [1], nonwovens were manufactured from polypropylene (PP) and electroconductive fibres. The electrical resistances of the fibres and nonwovens were tested, and the fibres' and products' ability to become electrically charged, i.e. an estimation of the accumulated electrostatic charges, were measured. The results obtained indicated that introducing small amounts of electroconductive fibres (0.5%) lead to a decrease in the through- and surface-conductivity by as much as 7 orders of magnitude. The blended nonwovens were characterised by a smaller susceptibility to become electrically charged.

For our next research work [2], multilayer nonwoven structures were manufactured on the basis of polypropylene fibres with a content of electroconductive fibres. We chose multilayer nonwoven structures for our investigation as they offered broader possibilities of application for barrier products in technical applications, and of more widespread use than homogenous products. In multilayer systems it is possible to change the physico-mechanical parameters of the product, and at the same time change their usage properties, by selecting and changing the barrier features. The layers were made as nonwovens from PP fibres and nonwovens from a blend of PP fibres and electroconductive fibres, these latter in a content of 10%. The through and surface resistances were checked, among other properties. We found that an appropriate arrangement of the layers with the carrier fibres (in this case PP fibres) and the fibres' blend with content of electroconductive fibres allowed us to obtain not only a higher through conductivity, but also a higher surface conductivity, at the same percentage content of electroconductive fibres (albeit with a changed fibre arrangement). This result is significant when modelling systems according to their final destination. In the work considered [2], the nonwovens manufactured were characterised by parallel arrangement of the fibres.

The work [8] was devoted to modelling and manufacturing multilayer nonwovens on the basis of PP fibres with the addition of electroconductive fibres. An attempt was undertaken to obtain by modelling the smallest resistivity of the ready-made nonwovens, and at the same time by minimising the electroconductive fibre content. The intention was to apply such a number of layers of such properties that the ready-made nonwonen products would have a smaller area mass than those obtained within the scope of work [2]. The nonwovens were manufactured at a crosswise fibre arrangement and at various values of stitching numbers.

Within the scope of work [9], nonwoven structures with the content of flax fibres were tested.

In the work [7], the aim was to determine the absorption of electromagnetic radiation of super-high frequency and infrared radiations in nonwovens manufactured from hemp fibres, and compare them with the absorption ability of similar materials but with a content of electroconductive fibres, as well as nonwovens manufactured from chemical fibres. The results obtained led to the conclusion that electroconductive fibres and hemp fibres are characterised by the attenuation of electromagnetic radiation within a broad frequency range up to about 10^{11} Hz, justifying the usefulness of conducting further investigations into applying these raw materials for manufacturing barrier materials protecting against electromagnetic radiation. Within the scope of work [9], nonwoven structures with the content of other natural (flax) fibres were tested. Research has shown that, in spite of the enormous increase of electric conductivity related to the admixture of electro-conductive fibres, artificial and natural fibre blendsare still weak barriers to super-high frequency radiation. Suppressing the magnetic component of radiation proved to be one of the main problems related to barrier design.

On the basis of the research results obtained in [10], considering the strong attenuation bands of electromagnetic waves observed in a three-dimensional array of split copper rings suspended on transparent plastic foils, we assumed that such an effect could also be achieved in nonwovens if electro-conductive fibres were spatially organised in a special way so as to create rings, slits, or other features improving the electromagnetic wave coupling to the nonwoven blends. A system of rings (loops) made from optimum electro-conducting fibres would require the optimum dimensions and their spatial arrangement (symmetrical or random) to be established. This is rather a broad research programme, which we are initiating with the first step of implanting metal split rings with already known properties into the nonwovens.

The aim of the work presented in this paper was to investigate the barrier effect against electromagnetic radiation of split metal rings implanted in nonwoven model samples manufactured on the basis of polypropylene fibres. The research work was conducted on the basis of results obtained by the above-mentioned investigations.

Part of the tests was carried out with the use of a measuring stand at the Semiconductor Physics Institute in Vilnius, Lithuania, which enabled the checking of the transmission and attenuation of electromagnetic waves within the frequency range of about 10 GHz.

Test material

The soft irregular structure of nonwovens offers many degrees of freedom for implant split rings. Therefore nonwovens with low electric conductivity have been selected for these primary experiments, in order to reduce perturbations of the fields related to rings.

Nonwovens from polypropylene staple fibres (PP) were manufactured for our tests. The nominal linear mass of the PP fibres was 7 dtex, with a staple length of 60 mm.

Two variants of webs were prepared for tests, both with an area mass of about 50g/m^2, which were formed with the use with a take-up web drum of the 3KA laboratory carding machine made by Befama, Bielsko-Biała, Poland. The webs were stitched by 15×16×403.5RB push-through needles, at the following stitching parameters: stitching number – 40/cm^2, stitching depth - 12 mm.

The above-mentioned webs were used for manufacturing nonwovens which were composed of 17 layers.

As the investigation within the scope of this work was conducted as a continuation of the experiments carried out by the authors of work [9], we manufactured the nonwoven samples with dimensions similar to these used in that same work.

Methods

Testing the nonwovens' morphological features

All the morphological features were tested in accordance with appropriate standards. The following nonwoven features were selected for testing:

- area mass and its unevenness, in accordance with Polish Standard PN-EN 29073-1: 'Textiles. Methods for testing nonwovens. Determination of area mass';
- thickness and its unevenness, in accordance with Polish Standard PN-EN 29073-2: 'Textiles. Methods for testing nonwovens. Determination of thickness';
- air permeability and its unevenness, in accordance with Polish Standard PN-EN ISO 0237: 'Determination of air permeability of textile products'.

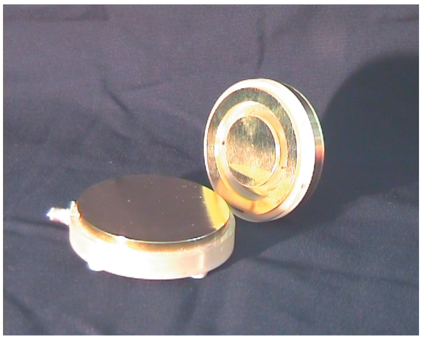

Figure 1. View of the measuring cell for flat textile products.

The tests of the nonwovens' thicknesses were conducted with use of a bridge thickness meter, designed and built at the Textile Research Institute, Łódź, Poland. The load acting on the sample was selected in such a way that the pressure acting on the nonwoven during the test was equal to the pressure acting while testing the electrical resistance of the nonwovens, a pressure of 100 kN/m^2.

Testing electrical resistance

The electrical resistance was tested in accordance with Polish Standard PN-91/P-04871: 'Textiles. Determination of the electrical resistance.'

The electrical resistances of fibres and nonwovens were tested (in atmospheric conditions of 23 ± 1 °C, and a relative humidity of 35%), but in order to avoid errors which may occur while calculating the electrical resistivity of the fibres, in this work only the values of electrical resistance taken from measuring device indications were analysed. To avoid misunderstandings when analysing the values of electrical resistance, Figure 1 shows the measuring cell used for flat products, whereas its dimensions and the dimensions of measuring cell for fibres are listed below.

dimensions of measuring cell for flat products:
diameter of the inner electrode: 0.05 m,
width of the ring: 0.01 m,
distance between the rings: 0.01 m
diameter of the lower electrode: 0.09 m;

dimensions of measuring cell for fibres:
distance between the electrodes in the cell: 0.02 m,
width of the electrode in the cell: 0.06 m,
filling height of the tested material: 0.05 m.

The samples were weighed with an accuracy of 0.005 g; the mass of the samples is indicated in the standard for each kind of fibre.

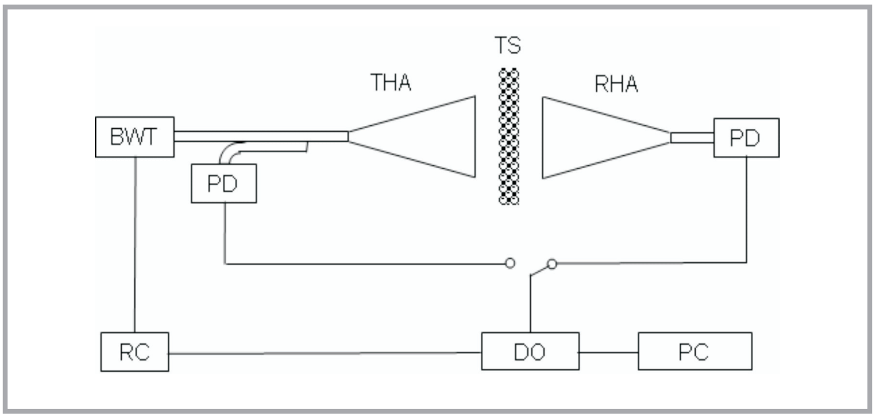

***Figure 2.** Brief scheme of the microwave testing system: BWT – backward wave tube, THA - transmitting horn antenna, RHA – receiving horn antenna, TS – textile sample, PD – point detector, RC - resistance-capacitance circuit, DO – digital oscilloscope, PC – personal computers.*

The nonwovens' electrical resistance was tested in the perpendicular direction (through resistance) and the longitudinal direction (surface resistance). Special electrodes were prepared for these measurements. The nonwovens were conditioned before the electrical resistance measurements in the same way as the fibres (temperature of 23±1 °C, relative humidity of 35%), and the same measuring device was used (Teralog, made in Germany).

Textile testing with super-high-frequency electromagnetic waves

After proofing the high DC resistivity of the PP nonwovens and their high microwave transparency, the nonwovens were deemed suitable to serve as substrates for manufacturing model samples with split rings for microwave testing. The testing system (Figure 2) is similar to that used in [10], apart from the additional means for measuring the wave reflection coefficient. The system includes a generator (backward wave tube - BWT) with waveguide output to a transmitting horn antenna (THA), the tested sample (TS), a transmitted-wave receiving horn antenna (RHA) with input to a point detector (PD). The wave frequency was tuned by discharging a capacitor of the resistance-capacitance circuit (RC) through the anode circuit of the BWT. The anode voltage and detector signal, recorded by a digital oscilloscope (DO), are stored and processed by the personal computer (PC). The directional coupler inserted between the BWT and THA served to measure the wave reflection coefficient.

This technique required prior calibration of the BWT output frequency dependence on the anode voltage $f=f(U_a)$, and the point-detector voltage dependence on the incident power $U_d(P_i)$. Both these dependencies turned out to be non-linear but smooth. The PD was tuned so as to achieve a nearly flat output-voltage dependence on the frequency in the BWT operation range (6-11 GHz). The point detector dynamic range was 50 dB, and the rise/decay time was about 10 ns. The output power of BWT exhibited a stable, but rather complex dependence on frequency. It was stored in the PC memory for further data processing. The RC constant was chosen as about 50 ms, enabling one set of measurements to be completed in around 30 s. The system repeatability was tested by performing 10 measurements in 10 minutes under unchanged conditions. The detector voltage U_d's dependence on frequency was found to be sufficiently stable: the standard deviation ratio to the average voltage did not exceed one per cent.

The polarisation of the electrical field of the wave in the vertical plane was ensured by using rectangular TE$_{10}$-mode waveguides which gradually expanded out from the initial dimensions (10×23 mm) to the final horn antenna aperture (8×8 cm), which was somewhat smaller than the textile sample size (10×10 cm). The fixed polarisation enabled us to test the anisotropy of the nonwoven's attenuation by revolving the sample in its plane around the axis which was parallel to the direction of wave propagation.

The sample tested was freely positioned between the antennas, and the dependence of the transmitted power P_t on the wave frequency was measured. The transmission coefficient T was determined as the quotient of the power P_t to the power P_{0t} transmitted and measured without the sample. The reflected power P_r was collected by the same transmitting antenna and sent through the directional coupler to the detector. The reflection coefficient R was determined as the quotient of the power P_r to the power P_{0r} reflected from a mirror (flat copper screen) which was inserted instead of the sample. During reflection calibration, special care was needed to suppress the standing waves between the highly reflecting mirror and the BWT. The influence of secondary waves penetrating to the detector from surrounding objects was minimised by choosing a small inter-horn distance (~10.5 cm). It was proved that neither a large-size object position in the laboratory nor the copper screen aside of the TS appreciably affected the measurement results.

The nonwoven samples with implanted split rings were prepared in such a way so as to allocate their barrier properties within the pre-determined frequency band defined by the available measuring system.

A single split-ring shape resembles the letter C. Owing to the split-ring capacity and wire turn inductance, it acts like a LC-circuit. The eigen-frequency of this elementary circuit is

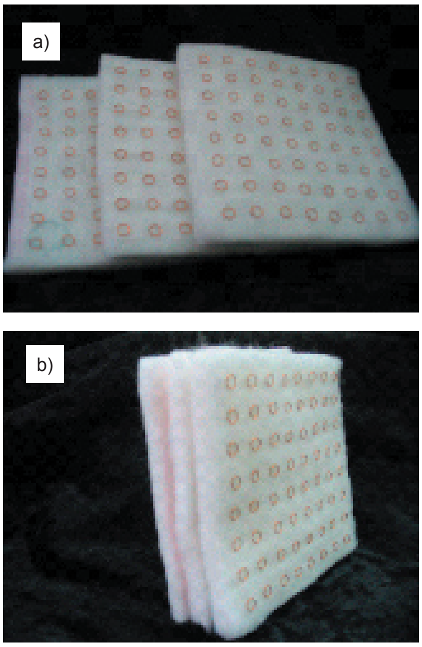

***Figure 3.** Photos of nonwoven structures with introduced rings; a) singular nonwoven layer, b) joined nonwoven structure.*

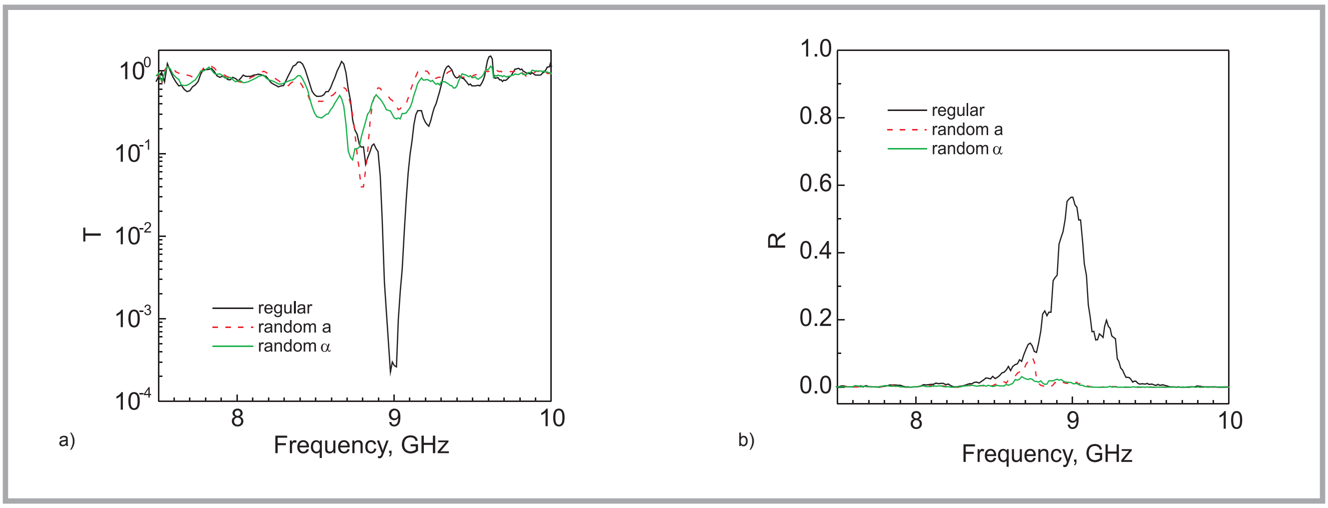

Figure 4. *Power transmission T - (a) and reflection coefficients R - (b), for a single PP nonwoven with regular and irregular distribution of the rings on the nonwoven substrate.* ***Remark:*** *This figure is presented in colour in the internet-edition of the journal (www.fibtex.lodz.pl).*

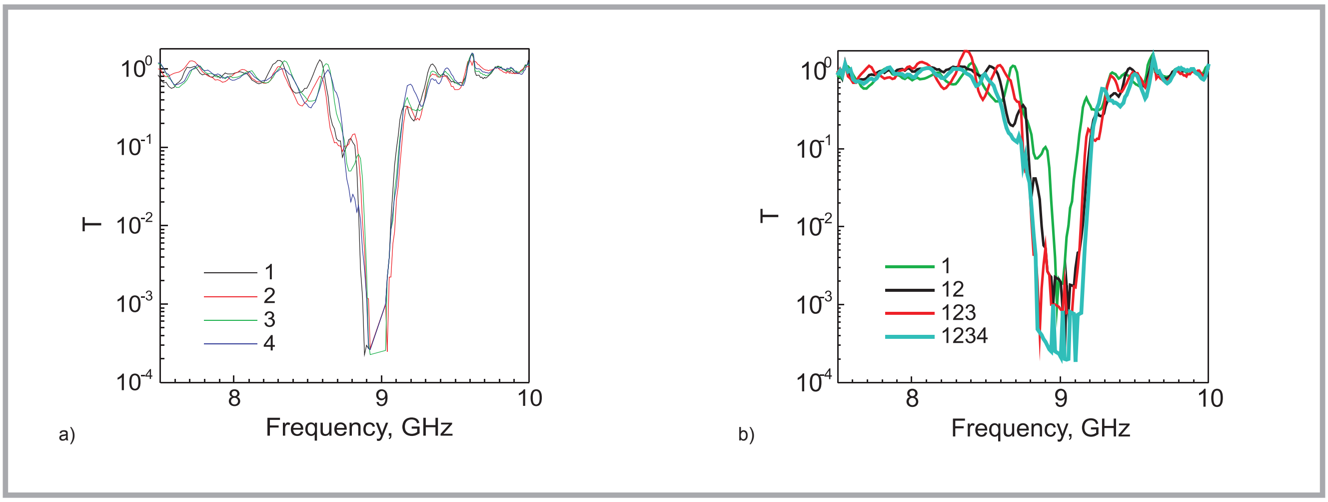

Figure 5. *Power transmission coefficient (T) dependence on frequency: (a) - for single layers numbered 1, 2, 3, 4; (b) – for the same one, two, three, and four layers positioned in stack.* ***Remark:*** *This figure is presented in colour in the internet-edition of the journal (www.fibtex.lodz.pl).*

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \qquad (1)$$

Here, the inductance L for non-magnetic materials can be written as a function of the ring radius R and the wire radius r [11],

$$L \approx \mu_0 R\left(\ln\frac{8R}{r} - \frac{7}{4}\right), \qquad (2)$$

with the magnetic constant

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m},$$

and the capacitance can be written as the sum of the two main terms:

$$C \approx \pi^2 \varepsilon_0 R\left(3\ln\frac{R}{r}\right)^{-1} + \frac{\pi\varepsilon_0 r^2}{d}\left[1+\frac{d}{\pi r}\left(\ln\frac{16\pi r}{d}-1\right)\right] \qquad (3)$$

Here, the first term is the closed-ring contribution [12], the second term is the slit contribution with an account for edge effects [11], and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, is the free-space dielectric constant. In spite of a long history of solving inductance problems in relations, such as to loop (magnetic dipole) antennas [12], the split-ring resonator problems remained unsolved for a long time, perhaps because the split ring manifests quite complex behaviour, exhibiting both electric and magnetic dipolar resonances. Generally, it can be excited either by the linearly polarised microwave electric field (the electric field E is along the ends of the split wire), the magnetic field (the magnetic field H is along the ring axis), or both fields simultaneously, depending on the ring orientation relative to the fields and wave propagation direction [10]. In the present work, the split rings have been oriented so as to allow excitation by the wave electric field.

Test results and their analysis

The parameters of fibres and nonwovens determined by the tests are listed below:

- area mass – 571 g/m^2,
- thickness – 10 mm,
- air permeability – 495 dm^3/m^{2}s,
- electrical through resistance of fibres – 2.6×10^{13} Ω,
- electrical through resistance of nonwovens – 1.06×10^{15} Ω,
- thermal resistance – 21.5 K m^2 W^{-1}.

As the tests did not indicate any attenuation of waves in the ring-free PP substrates, our assumption in Equation (3) that the nonwovens effective dielectric permittivity is equal to unity is reasonable. We had expected that split ring implantation would dramatically change the effective index of refraction of the composite structure in the a priori selected frequency range.

The dimensions of the rings and their geometrical arrangement are given below:

- diameter of the wire used for rings $2r = 0.5$ mm,
- inner diameter of the rings, $2(R\text{-}r) = 4.5$ mm,
- width of the splits $d = 1.1$ mm,
- distances between the ring centres in rectangular coordinates – 14 mm × 14 mm,
- distance between the nonwoven planes with rings – about 10 mm.

In the nonwoven structures with rings, shown in the photos of Figure 3, the ring distribution is regular. The ring centres are equidistant, and the splits are oriented at the same angle in the plane.

If the wave is normally incident to such a sample plane, it can only excite the rings' resonance with an electric field. The microwave non-transmission band is then sharp (Figure 4, see page 67). The reflection coefficient reaches its maximum at the same resonance frequency of nearly 9 GHz. Note that nearly 60 percent of radiation power is reflected by the single layer manifesting a dramatic increase of the reflection index of the composite structure.

We investigated the influence of ring distribution irregularities on the transmission and reflection spectral bands. In the two-dimensional system, there are two variable parameters: the distance a between the neighbour ring centres, and the angle α of slit orientation in the sample plane. Randomisation of a or α results in a dramatic weakening of absorption (Figure 4, see page 67).

Returning to regular structures again, we may note that the non-transmission band changes slightly from sample to sample (Figure 5.a, see page 67). This is due to manufacturing imperfections. Adding the layers consecutively, we observe gradual formation of the forbidden band (Figure 5.b, see page 67), as in photonic crystals [10].

Sharp lines are still present in the non-transmission band, manifesting the influence on the barrier's properties of a finite number of layers. Nevertheless, the band position observed is quite close to that calculated from Equations 1-3 for the given set of single split ring parameters: the calculated eigen-frequency equals 9.18 GHz. The somewhat lower experimental frequency is attributable to interaction between the rings, and to the effective refraction index of the nonwoven matrix, which of course slightly exceeds unity.

Conclusions

The split rings of metal implanted in the nonwoven textiles ensure that excellent barriers can be created against pre-defined bands of electromagnetic radiation. Particularly, the 9 GHz band is assigned to many applications such as civil traffic radar, military radar & countermeasures, and international telecommunication [14]. The simple oscillator model predicts that larger-diameter rings will provide the possibility of constructing barriers suppressing power leakage from widely-used microwave ovens, which operate at the lower frequency of ~2.45 GHz. Shifting the barrier band to higher frequencies is also feasible by using smaller-diameter rings [15]. Aside from the feasibility of these applications in textile technology, this work provides empirical material for modelling electromagnetic processes in disordered and regular nanometer-scale structures for photonics. Observation presented in this work opens new directions in textile barrier structure engineering. Further refinement of the barrier-band evaluation model will include coupling the fields induced by implanted rings when changing the inter-centre distance and ring orientation, as well as an evaluation of the complex dielectric constant of (electro-conductive) nonwoven matrix.

Acknowledgements

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