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Textiles Embroidered with Split-Rings as Barriers Against Microwave Radiation

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Abstract
Barriers protecting humans against electromagnetic microwave radiation were manufactured from polyester and flax fabrics with embroidered electro-conductive elements so as to enhance the wave attenuation. The shape, material properties and spatial distribution of the elements were chosen taking into account previous experiments on electromagnetic barrier structures for a range of 7 - 10 GHz. The significant attenuation of microwaves by the embroidery designed for a pre-defined frequency band was experimentally confirmed.

Key words: *textile, embroidery, split-ring, resonator, microwave X-band.*

Introduction

Increasing environmental pollution caused by electromagnetic radiation emitted by mobile phones, telecommunication systems, microwave ovens, car-control radars and ultrafast personal computers creates challenges for working out barriers protecting against such radiation. The barriers should be wearable, implemented in clothing, meet the requirements of air permeability, possess low mass density and high flexibility, present aesthetic values, etc.

Textiles, including nonwovens, possess some screening properties against electromagnetic radiation, and research on such properties is within the scope of the Department of Textile Metrology of the Technical University of Łódź, cooperating with a research group in Lithuania [1, 2]. Among the variety of element shapes, special attention was paid to metal split rings, which were used in the past for manufacturing chainmail - armour material protecting against mechanical shock. Since the discovery of electromagnetism in the XIX century, open metal rings soon became textbook illustrations of elementary electromagnetic circuits, and in the XX century they found broad application in radio-electronics. Considering split-ring implantation in textiles, our investigation meets XXI-century challenges for creating "chainmail" against electromagnetic hazards. The possibility of manufacturing excellent barrier materials for a pre-defined frequency range was demonstrated by implanting rigid split metal rings into high-resistance polypropylene or natural fibres [3, 4]. However, it remained unclear whether the barrier properties will be satisfactory when the rings are flexible. The last option would be of great value for practical applications of the rings in textiles as basic materials for human-friendly barriers against microwave radiation.

This article presents experimental results concerning the barrier properties of textiles embroidered with thin copper wires so as to create a pattern of rings.

Resonance model

Insight into the resonance-frequency correlation with the sample dimensions can be obtained without solving complicated problems of electromagnetic wave scattering on the split metal ring. If the sample is small compared to the wave length, then quasistatic approximation can be used for its response to alternate electric and magnetic fields. As the resonance is observed in both round samples and in ones with irregular shapes, one can compare the square frame and the rings made of wire (***Figure 1***).

The frame capacitance, calculated with the use of a model flat capacitor, is

$$C \approx \varepsilon_0 \, \varepsilon_r \, [tw / g + tl / (l - 2w)] \qquad (1)$$

Here the external size of the square is l, its internal size is $l - 2w$, the thickness is t, and g is the gap width. The first term in the sum of Equation (1) stands for the gap's contribution [6], and the second one (that is not accounted for in Ref. [6], but it has been proved here to be essential in determining the resonance frequency) is for contribution of the upper-lower beam pair to the capacitance; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the electric constant, and ε_r is the effective relative dielectric constant of the ring-supporting medium (textile). The inductance is approximated as that of a one-turn solenoid of the cross-section area $S = l^2$ and length (thickness) t; which is

$$L \approx \mu_0 \, l^2 / t \qquad (2)$$

Here $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic constant, and the sample components are supposed to be non-magnetic. As a result of this, when one substitutes $l \rightarrow 2R$, $w \rightarrow 2r$ and $t \rightarrow 2r$ for the ring inscribed in the square, the resonance frequency is

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \\ = \frac{c}{4\pi R \sqrt{[2r/g + 1/(1 - 2r/R)]\varepsilon_r}} \qquad (3)$$

Here R stands for the external radius of the ring, r is the wire radius, and $c = 1/\sqrt{\varepsilon_0 \mu_0}$. The effective value of ε_r does not differ much from the unity for the soft textile layer suspended in the air. Equation (3) shows the resonance frequency dependence on the ring dimensions and gap width.

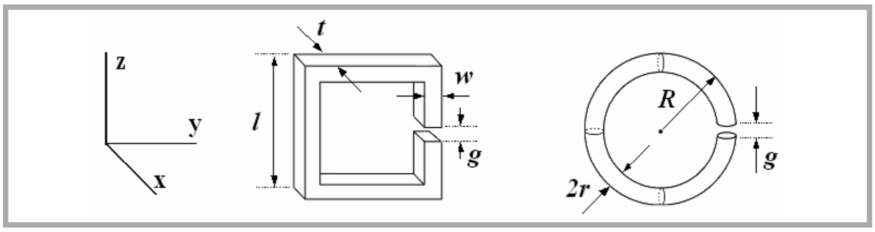

Figure 1. *Resonators in the form of a square frame and ring made of wire in an electric field* **E** *of waves propagating along the x-axis and polarised parallel either to the z (E-excitation) or y-axis (no excitation).*

Sample preparation

Pure flax (LI) and polyester (PES) woven fabrics of plain weave from a yarn of 100 tex linear density were used used (***Table 1***).

*Table 1. Textile sample parameters; *measured according to the Polish Standard PN-P-04637, **measured according to the Polish Standard PN-85/P-04613, ***measured according to the Polish Standard PN-91/P-04871.*

Textile symbol	Contents	Thread number*		Area mass** m_p, g/m^2	Resistance***, GOhm	
		warp	weft		through	surface
LI	100% flax	160	124	259.1	84.1	13.4
PES	100% polyester	160	128	329.1	97.1	181.9

Textile samples were embroidered with varnished copper-wire thread so as to create a pattern of C–shaped rings with all the gaps oriented in the same direction. The pattern was selected on the basis of our earlier investigations. The two-dimensional arrays of rings manufactured are displayed in ***Figure 2***, showing the irregularities of the embroidery stitching. The nominal diameter of the rings is 5 mm, and the nominal gap is 1.3 mm, nevertheless, there were random deviations from these nominal values.

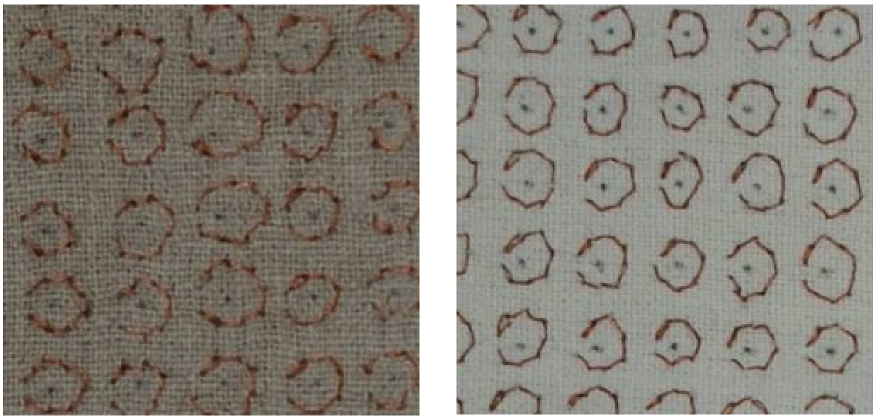

Figure 2. *The two-dimensional arrays of copper-wire rings embroidered in flax (sample LI, left) and polyester (sample PES, right) fabric samples. The distance between the nearest ring centres is 10 mm.*

Besides the arrays, probe single rings were embroidered for inserting the microwave waveguide. The ring dimensions were determined using digital photography and computer analysis. Seeking to account for the shape irregularities, the mean values of five measurements were taken and recorded in ***Table 2***. The standard deviation of the diameter is estimated to be ±1 mm, and that of the gap is 0.25 mm (equal to the wire diameter, which is $r = 0.125$ mm).

Microwave spectrometry

The microwave spectrometer (***Figure 3***) implies both the standard X-band waveguide components and special horn components for expanding the waveguide aperture from the standard 10 × 23 mm to 80 × 80 mm so as to cover nearly all the ring elements of the 100 × 100 mm samples. Antenna-like horns act here similar to the oversized waveguide sections. Laborious examination The advantage of the set-up was performed seeking to minimize the influence of standing waves arising between the horns. Reflected and transmitted waves were measured at various inter-horn distances and sample positions between the horns. It was proved that the standing-wave effects are minor when the transmission through the sample is measured close to the generator-side horn.

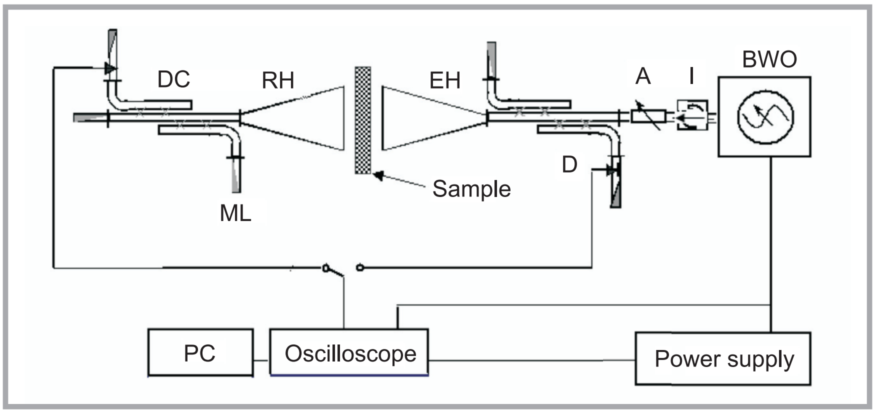

Figure 3. *Microwave spectrometer scheme including BWO − generator (backward-wave oscillator), I − unidirectional transmitting device (isolator), A − variable attenuator, 10 × 23 mm cross-section metal waveguides, DC − directional couplers, D − detectors, EH − emitting horn, RH − receiving horn, ML − matched loads, variable-voltage power supply, digital oscilloscope, personal computer, and the sample.*

Table 2. *Experimental ring parameters.*

Sample #	Ring external diameter 2R, mm	Gap width g, mm
R1	6	2.2
R2	5.2	1
R3	5	1.5
R4	6.5	2
R5	4.4	1.8
R6	4.3	1.48

The output frequency is controlled by discharging a capacitor through the anode circuit of the microwave generator tube. The two-channel digital oscilloscope stores data for both the anode voltage and microwave detector output voltage and sends the data set to the PC. With the use of a generator and detector calibration functions (which are determined prior to measurements), the computer transforms the measured data to the detected microwave power dependence on frequency.

For the two-dimensional array testing, the 120 × 120 mm square embroidery samples were stretched on 100 × 100 mm textolite square frames positioned between the horns. The transmission coefficient was determined as a ratio of the microwave power transmitted through the sample to the power transmitted through the empty set-up. The reflection coefficient was determined as the ratio of the power reflected from the sample to the power reflected from the copper plane positioned in the place of the sample [5].

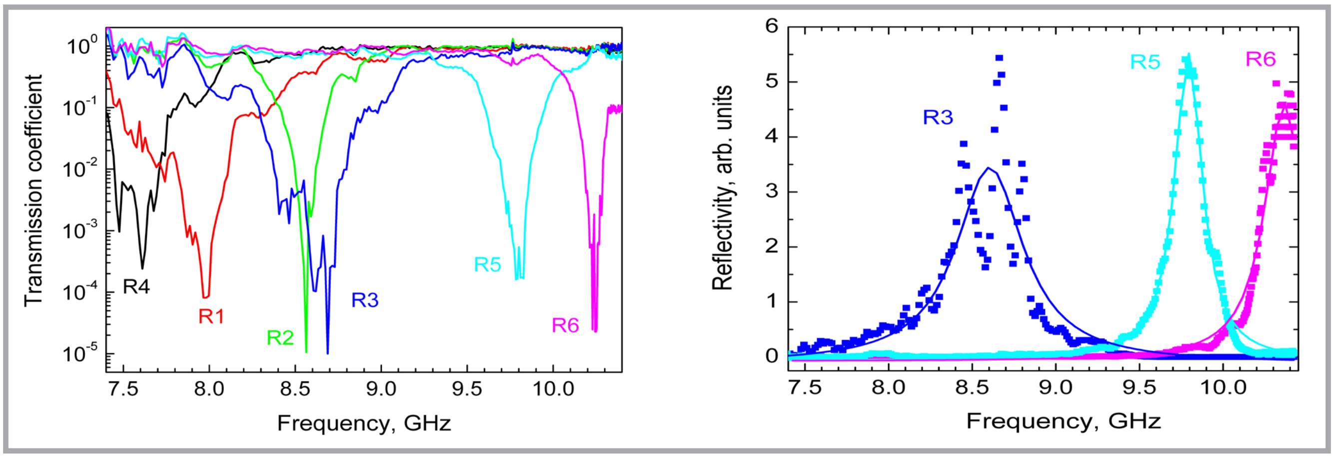

Figure 4. *a) Microwave transmission coefficient as a function of the wave frequency measured for the split-ring samples R1-R6; b) Microwave reflectivity as a function of the wave frequency measured for the split-ring samples R3, R5 and R6. Solid lines represent the Lorentzian function fit to experimental data points.*

In the case of single ring testing, the horns were not used. The single ring embroidered in the textile sample (8 × 8 mm) was fixed in a 10 × 10 × 23 mm styrofoam block plugged into a standard metal waveguide whose ends were tightly connected. Transmission coefficient was determined as the ratio of the microwave power transmitted through the waveguide with a sample to the power transmitted through the empty waveguide. In the case of reflection measurements, a 10 × 10 × 23 mm aluminum block was plugged into the waveguide instead of the sample, and the signal reflected from it was taken as a 100-percent reference reflection.

Results

a) Single ring measurements. Single ring measurements were made in order to examine the possibility of mathematical modelling the resonance of rings of imperfect shape using idealised concepts. Insertion of a single ring into the waveguide results in a quite large attenuation at resonance (***Table 2***). The resonance line and frequency (***Figure 4***) depends on the sample's dimensions.

A simple approximation (Equation 3) showing reasonable compatibility with experimental data (***Figure 5***) is convenient for selecting the size of embroidery elements designed for a pre-defined frequency band.

Table 2. *Insertion loss at resonance.*

Sample #	Insertion loss at resonance, dB
R1	-41
R2	-36
R3	-50
R4	-33
R5	-38
R6	-46

The correlation coefficient of experimental and theoretical values is equal to 0.988.

b) Two-dimensional arrays. If one neglects the irregularities of the samples (***Figure 1***) and imagines an ideal split ring and a two-dimensional array completed thereof, then one can notice an important property of the symmetry: it is the 2nd-order (*binary*) symmetry axis that is horizontal in ***Figures 1 and 2***. Let us denote it as unit vector **b**. Considering the symmetry, electromagnetic wave interaction with such a structure is expected to depend on whether the wave electric field **E** is parallel to the binary axis or perpendicular to it. It was proven experimentally (***Figure 6***): a non-transmission band between 8 and 8.25 GHz arises for **E** perpendicular to **b**, whereas for **E** parallel to **b** the sample is nearly completely transparent in the whole frequency range.

In order to mimic free-space wave penetration through the absorbing layer, the inter-horn distance needs to be as large as possible. This distance was limited by diffraction on the sample of rather small aperture (10 × 10 cm). It was proven that circumventing the sample (leakage) signal was negligible for an inter-horn distance up to 30 cm.

On the other hand, it is necessary to reduce the influence of standing waves arising in the open cavity created by the horns and perturbed by the sample. It was discovered that standing waves do not necessarily manifest when the sample is positioned near the sender horn. The frequency dependence of the transmission coefficient (***Figure 7.a***) was not essentially influenced by the horn-sample distance in a distance range up to 50 mm, which is approximately equal to the electromagnetic wave length in the free

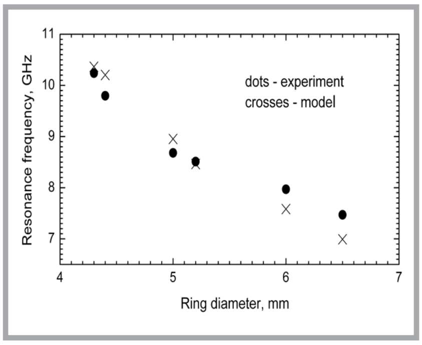

Figure 5. *Correlation between the ring diameter and its resonance frequency measured for samples R1 - R6 (dots) and calculated using the model Equations (1 - 3).*

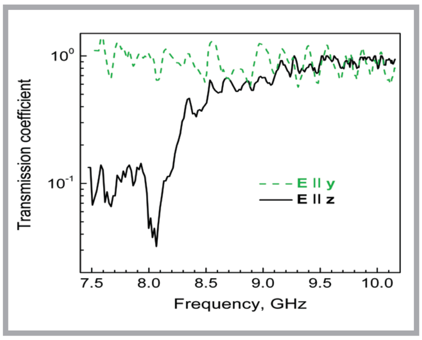

Figure 6. *Transmission coefficient of the two-dimensional array sample as a function of the wave frequency for a wave electric field polarized parallel to the 2nd-order symmetry axis (dashed green line) and transverse to it (solid black line). Sample PES.*

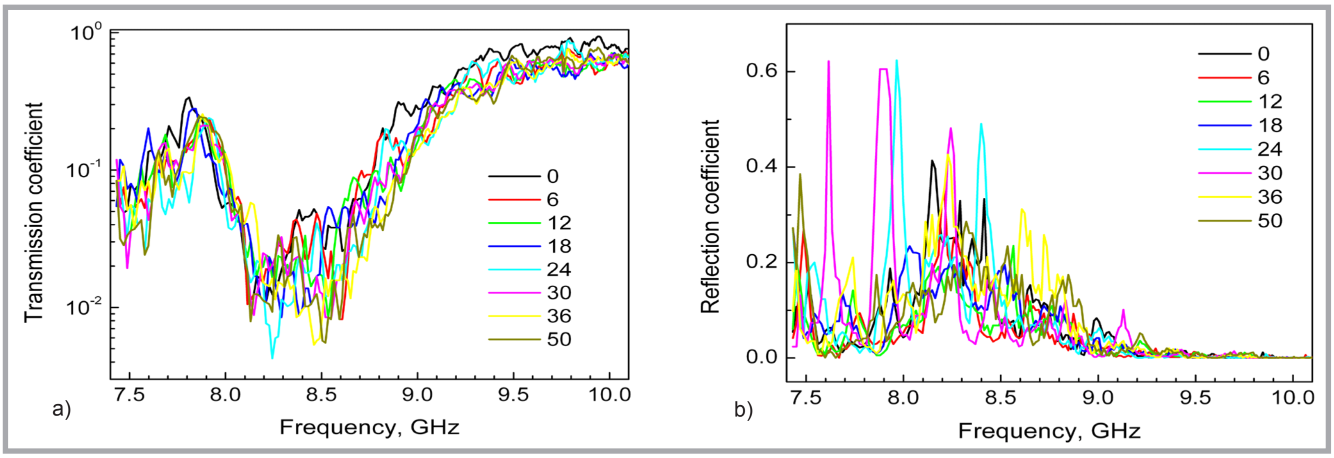

Figure 7. *Transmission (a) and reflection (b) spectra for the two-dimensional array sample PES at various distances (in millimeters) between the sample and sending horn. The inter-horn distance is 30 cm.*

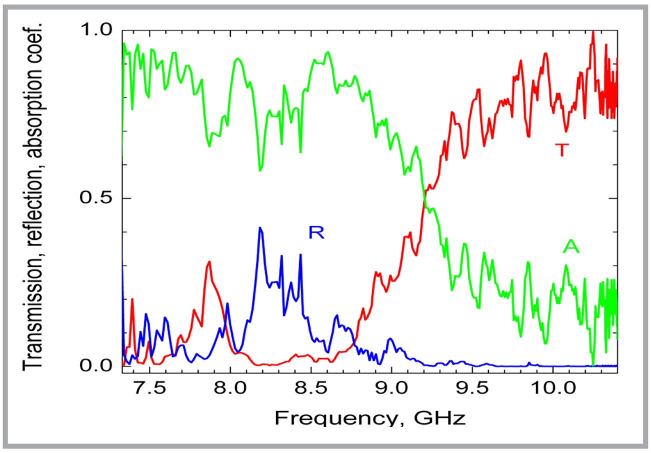

Figure 8. *Coefficients of transmission T, reflection R, and absorption A = 1 - R - T as a function of the wave frequency for the two-dimensional array, sample PES, at an interhorn distance of 30 cm.*

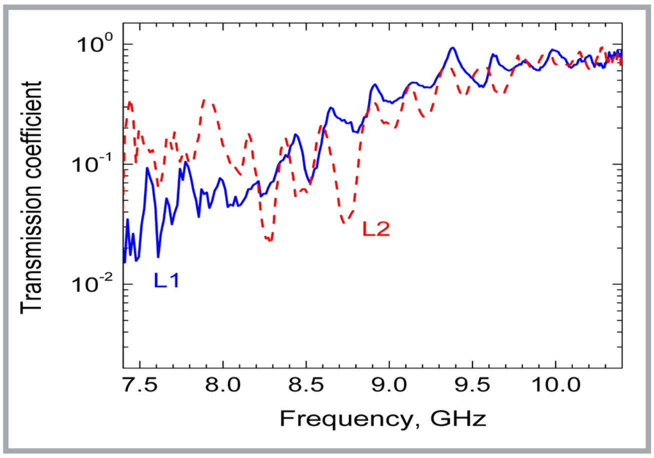

Figure 9. *Transmission coefficient for a two-dimensional array of rings on the flax substrate (samples LI). The inter-horn distance is 30 cm.*

space. The series of maxima on the lower-frequency side of the reflection spectrum (***Figure 7.b***) is a sign that standing waves were still present in the system.

As a result of the ring size and shape spread, the absorptivity of the embroidery is quite high in the whole lower-frequency range up to 9 GHz (***Figure 8***).

Within the range of 8.25 - 8.5 GHz (in the forbidden-frequency band of the two-dimensional array), the transmission is suppressed due mainly to the enhanced reflection. This property is valuable in cases when the electromagnetic power should be rejected rather than absorbed by the barrier, i.e., when barrier heating is undesired.

Compared to the polypropylene-ring structures, the flax-ring structures seem to suppress the wave transmission in a somewhat broader frequency range (***Figure 9***). This correlates with the appreciable broad-band absorption in flax textiles [2], although the ring shape spread does not allow for quantitative comparison at this stage.

The efficiency of the barrier properties may be increased by increasing the number of layers with rings of differently oriented gaps.

Conclusions

Fabrics designed and embroidered with split rings can be highly efficient barriers protecting against electromagnetic radiation. The dimensions of the embroidered pattern prepared in the first experiments made it possible to attenuate wave transmission within the range of 7 to 10 GHz. For a change in the desired range of electromagnetic wave frequency, a simple convenient model for selecting split ring dimensions is proposed. Textile products embroidered with electroconductive threads may have various non-electroconductive fibre substrates (e.g., nonwovens, knited fabrics).

The irregularities of the rings implemented were found to be negligible for the electromagnetic barrier band formation, as demonstrated in the experiments. This is of great importance for designing embroidered products for clothing protecting against electromagnetic radiation.

The technology of embroidery implemented in microwave textile photonics broadens the application horizons of pure theoretical considerations [7, 8], which up to now have been aimed towards quantum electronics [6] and medicine [9].

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