TEXTILE METAMATERIALS

Michalak M[1], **Brazis R**[2], **Schabek D**[1], **Krucińska I**[1]
[1] *Lodz University of Technology, Department of Material Commodity Science and Textile Metrology, Żeromskiego 116, Lodz, Poland*
[2] *Nacionalinis fizinių ir technologijos mokslų centras, Saulėtekio al. 3, Vilnius 10257, Lithuania*
izabella.krucinska@p.lodz.pl

ABSTRACT

Metamaterials are media whose properties result more from the distribution of elements than from the chemical composition. Their structural parts need to be smaller than the wavelength. This publication presents the results of the development of metamaterials based on a nonwoven fabric made of polypropylene and flax fibres and their blends. The structural elements were copper split ring resonators (SRR) with dimensions and position on the nonwoven fabric's surface enabling the reaction to an electromagnetic wave with a frequency around 10 GHz. One- and multiple-layer metamaterials with SRR arrays, imitating the crystal lattice band were studied. The calculation results coincided with the experimental ones.
Key Words: metamaterial, nonwoven fabrics, split-rings, resonance, electromagnetic radiation.

1. INTRODUCTION

Metamaterials are media whose properties result more from the distribution of elements than from the chemical composition. In a metamaterial, its structural parts need to be usually smaller than the wavelength. Word 'meta' means 'beyond' in Greek, and in this sense the name 'metamaterials' refers to 'beyond conventional materials'. Metamaterials are typically man-made and have properties that are hardly found in nature. What is so magical about this simple merging of 'meta' and 'materials' that has attracted so much attention from researchers and has resulted in exponential growth in the number of publications in this area [1]?
Electromagnetic waves affect the medium's electrical charges forcing their vibrating motion (by the electric field **E**) and circular motion (by the magnetic field **H**). The linear reactions of the medium to the **E** and **H** fields are described by the electric and magnetic permittivities ε and μ. Dielectrics are a group of media in which both the parameters are positive - DPM (Double Positive Materials). The media with negative values ε and μ belong to the group of DNM (Double Negative Materials) [1, 2]. In them, the refractive index is negative. They are rarely found in nature. The first theoretical reflections on materials with a negative refractive index appeared in 1968 [3], and in 2002 a model construction of DNM for the microwave area $f = 5$ GHz was announced [4], which turned out to be a breakthrough.
The research of fibrous metamaterials has been started in 2004, in the Department of Commodity Science, Materials Science and Textile Metrology of Lodz University of Technology, aiming at the development of barrier materials for human protection against electromagnetic radiation [5-9].
In the initial phase, the study has been focused on the influence of fibre type on the barrier properties of the nonwoven fabrics. Research in the field of super-high frequency (i.e. in the microwave range) has shown that the power transmission coefficient of all nonwoven fabric samples was virtually close to 100% [6]. In order to increase the barrier properties of the fibrous materials, the tests were carried out using the nonwoven fabric's modification by implanting metal elements with suitably selected shape and parameters. Thus, the first textile metamaterials have been developed.
For this purpose, nonwoven fabrics consisting of a run carried needled polypropylene (PP) fibres with implanted copper split rings were elaborated. A single split ring resembles the

letter "C". The effectiveness of the material developed was assessed on the basis of the resonant frequency of the elaborated system.
On the other hand, in [10,11] it was proposed a pair of split rings inserted into each other, with slits on opposite sides of the diametric line, aiming to mimic the „pure" magnetic dipole. Our considerations lead to the conclusion that this complicated solution does not bring anything significant. When the wave falls perpendicular to the plane, the substitute capacity and inductance of the system decrease. The value of the resonant frequency will change. The same effect is obtained by changing the dimensions of individual split rings.
The aim of the work presented in this paper was to create the textile metamaterials using split metal rings implanted in nonwoven model fabrics manufactured on the basis of polypropylene and flax fibres and their blends and investigate the resonance frequency of electromagnetic radiation. The resonance frequency was estimated by attenuation of electromagnetic radiation. Some parts of our earlier works were used in the article.

2. MATERIALS AND METHODS

2.1. Materials

Nonwoven fabrics from polypropylene (PP) staple fibres, flax fibres and the blends (50/50) of PP and flax fibres were manufactured. The nominal linear density of the PP fibres was 7 dtex with a staple length of 80 mm, the linear density of flax fibres was 33 dtex and the staple length was 67 mm. For each fibre kind the webs were prepared for tests, both with area mass of about 50 g/m^2. The webs were stitched by the 15×16×403.5RB-pushthrough needles with the stitching number of $40/cm^2$, and the stitching depth of 12 mm. The above-mentioned webs were used for manufacturing nonwoven fabrics composed of 17 layers.
In order to obtain the resonance in the fibrous materials, the tests were carried out using the nonwoven fabric's modification by implanting metal elements with suitably selected shape and parameters. Specifically, the element shape of single split ring resembling the letter "C" has been tested. The split ring acts like LC contour. In the simplest approach, the inductance stems from the coiled wire whereas the capacitance from the slit. A deeper look reveals the need to add the stray- and the half-ring capacitance, etc. In real situation, inductance and capacitance of the split metal wire ring is complicated. Simplified approach to the evaluation of L and C implies the inductance to be proportional to the wire length, and the capacitance to be the sum of the three components: the half-rings', the slit's, and the stray capacitances. The copper split rings were used.

2.2 Methods

All the morphological features of nonwoven fabrics were tested in accordance with appropriate standards. Area mass and its unevenness were tested in accordance with Polish Standard PN-EN 29073-1: 'Textiles. Methods for testing nonwoven fabrics'; thickness and its unevenness were evaluated in accordance with Polish Standard PNEN 29073-2: 'Textiles. Determination of thickness' and air permeability and its unevenness were evaluated in accordance with Polish Standard PN-EN ISO 0237: 'Determination of air permeability of textile products'. The electrical resistance was tested in accordance with Polish Standard PN-91/P-04871: 'Textiles. Determination of the electrical resistance'.
Tests of the electromagnetic resonance receiving in the microwave range were carried out using the set-up presented in the Figure 1.

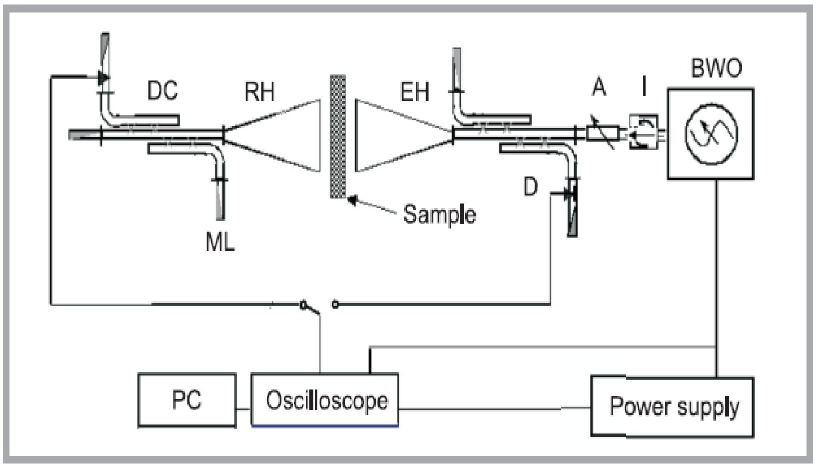

Figure 1. Microwave set-up for metamaterial testing

BWO − backward-wave oscillator, I − unidirectional transmitter (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.

The nonwoven samples with implanted split rings were prepared to allocate their resonance frequency in the pre-determined frequency band defined by the available measuring system. A single split ring acts like a LC-circuit with the own frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The effective inductance in magnetostatic approximation can be equalled to the ring inductance [12], and the capacitance in electrostatic approximation can be written including the slit-, the stray- and the half-ring capacitances [8]:

$$L \approx \mu_0\left(ln\frac{8R}{r} - \frac{7}{4}\right), \qquad C \approx \pi^2\varepsilon_0 R\left(ln\frac{8R}{r}\right)^{-1} + \frac{\pi\varepsilon_0 r^2}{d}\left[1 + \frac{d}{\pi r}\left(ln\frac{16\pi r}{d} - 1\right)\right] \tag{2}$$

Here R is the ring radius, r is the wire radius, the magnetic constant is $\mu_0 = 4\pi\times10^{-7}$ H/m, $\varepsilon_0 = 8.85\times10^{-12}$ F/m is the free-space dielectric constant. However, the nearest neighbour ring magnetic flux interpenetration changes the effective inductance. Therefore, we compared the resonance frequency of ring-implanted textile layers differing by the ring inter-centre distance; as for the capacitance, we include the effective relative dielectric permittivity ε_r of the medium surrounding the ring.

2.3 Results

In the case of ring positioning at interfaces of the composite structures the effective dielectric constant is modified including partial contributions of neighbour media. In spite of long history of solving inductance problems in relation, e.g., to loop (magnetic dipole) antennas [13] the split ring resonator problems remained unsolved for a long time, perhaps because the split ring manifests quite complicated behaviour exhibiting both the electric and magnetic dipole resonances. Generally, the resonance can be excited either by the linearly polarised microwave electric field (electric field **E** is along the ends of split wire), or magnetic field (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. In the present work the split rings have been oriented to allow excitation by the wave electric field only. The dependence of the resonance frequency on the ring parameters: the rings radius *R*, the slit *d* and wire diameter *r* was calculated and shown in the Figure 2.

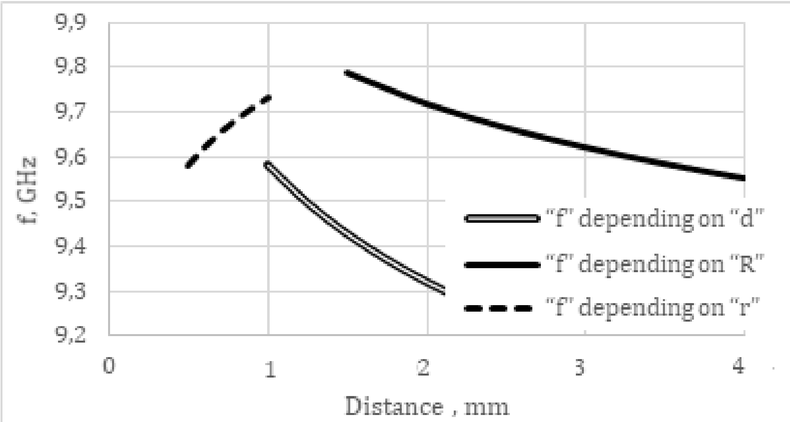

Figure 2. The calculated resonance frequency for different parameters of the split rings
For "f" depending on "r": R = 3.5 mm, d = 0.6 mm
For "f" depending on "R": r = 1 mm, d = 0.6 mm
For "f" depending on "d": R = 3.5 mm, r = 1 mm

With the increase of wire and ring diameter the resonance frequency decreases. With the slit width increase the resonance frequency increases.

The experimental tests were carried out using nonwoven fabrics. The parameters of nonwoven fabrics determined by the tests were as follows: the area mass of the flax nonwoven fabric - 487.72 g/m^2, the thickness - 9.3 mm, the air permeability - 1091.7 dm^3/m^{2}s, the electrical resistance - $5.25 \cdot 10^{11}$ Ohm; for the PP nonwoven fabric area mass - 571.0 g/m^2, its thickness - 10.5 mm, its air permeability - 495 dm^3/m^{2}s, its electrical resistance - $1.06 \cdot 10^{13}$ Ohm; for the 50 Flax/50 PP nonwoven fabric area mass - 632.25 g/m^2, its thickness - 10.7 mm, its air permeability - 386.7dm^3/m^{2}s, and the electrical resistance - $1.63 \cdot 10^{12}$ Ohm. Parameters of split rings used in the investigation were follows: the diameter of wires - 0.5 mm, inner diameter of the rings - 4.5 mm, the slit width - 1.1 mm, the distance between the centres - 14 mm x 14 mm.

The experimental resonance frequency for flax substrate was equal to *f* = 8.5 GHz, for 50flax/50PP *f* = 8.55 GHz and for PP substrate *f* = 8.6 GHz. The calculated resonance frequency for all substrates was equal to 8.89 GHz.

As the tests did not indicate any attenuation of waves in the ring-free PP substrates, our assumption in Equation (3) that the nonwoven fabric's 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.

In the nonwoven fabrics with rings, shown in the photos of Figure 3, the ring distribution is regular. The ring centres are equidistant, and the slits 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. The reflection coefficient reaches its maximum at the same resonance frequency of nearly 9 GHz. The influence of ring distribution irregularities on the transmission and reflection spectral

bands was investigated. 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. Returning to regular structures again, we may note that the non-transmission band changes slightly from sample to sample due to manufacturing imperfections. Adding the layers consecutively, we observe gradual formation of the forbidden band, as in photonic crystals [14].
Further tests were carried out on a polypropylene nonwoven fabric. Four single layers were examined. The laying the layers with rings in a stack (rings arranged one above the other imitate the induction cell) is shown in Figure 3.

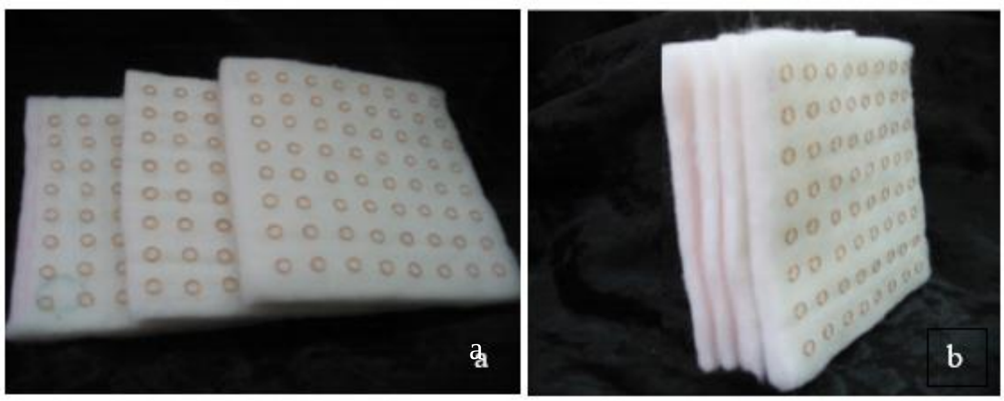

Figure 3. The layers with rings
a – the single layer, b – four layers positioned in a stack

The individual layers were characterized by the same values of the frequency of the resonance *f* = 9.0 GHz. If the two or more nonwoven fabric samples with the implanted lattices of two-dimensional split rings are positioned in stack, then the wave non-transmission band is found to broaden. The resonant frequency of four-layer structure is in the frequency band from f = 8.75 GHz to *f* = 9.24 GHz.
The intercentre distance of split rings was investigated. It was obtained that distance between centres of split rings affected the resonant frequency (Figure 4a).
The results of electromagnetic radiation attenuation dependences on number of layers for four layers positioned in stack are shown in the Figure 4b. The attenuation level for both cases was chosen on –20 dB.

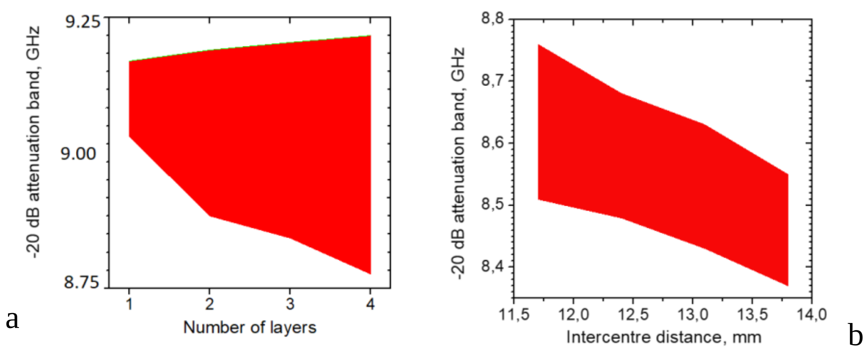

Figure 4. The dependence of resonance frequency on number of layers (a)
and the split ring inter-centre distance (b)

3. CONCLUSIONS

- Implementation of the split rings in textile structures makes it possible to produce metamaterials with excellent barrier properties to electromagnetic radiation.
- The frequency and bandwidth of the reduced transmission of the wave depend on the distance between the centres of the rings and their orientation with respect to the direction of propagation of electromagnetic wave.
- The band of dramatic attenuation can be positioned in the required frequency range by implanting the split rings of proper dimensions, at optimised inter-ring distances, to create two-dimensional lattice, and using multiple-layer structures.
- The three-dimensional structures obtained in this way mimic the microwave photonic crystals. Natural (flax) substrate exhibits somewhat higher attenuation than the polypropylene one at the same other conditions. Effective dielectric constant of the flax substrates is also somewhat higher than that of the polypropylene. These are promising features for the metamaterials created from natural fibres and solid-state elements.

3. REFERENCES

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