Woven metamaterials with an electromagnetic phase-advance for selective shielding

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Abstract. This study deals with the development of a large woven metamaterial surface for applications in the submillimeter frequency band. Before weaving, design of the metamaterial textile is investigated to obtain a phase-advance near 500 GHz. Then, a large sample is produced by semi-industrial machine and characterized in terms of dimensional homogeneity and electromagnetic behaviours in the frequency band [325 – 700 GHz]. Dimensional heterogeneity is measured to be less than 2% and shows that weaving process is well controlled. A phase-advance and high-pass filter behaviors are experimentally evidenced by electromagnetic characterizations with potential applications for selective shielding and phase manipulation of the wave.

1. Introduction

In the middle of the 1990s, the scientific field of metamaterials has appeared with the emergence of technologies permitting to produce new materials with electromagnetic or optical properties which can not be found in nature [1]. Metamaterials are produced by arranging metallic and/or dielectric structures with a specific organisation (slotted rings, metal cylinders, fishnets, arrays of planar or dielectric resonators…)[2]–[6]. While natural materials have only values of the electromagnetic parameters (permittivity ε and permeability μ) greater than one, such a metamaterial can act as an equivalent material with effective electromagnetic parameters which can have any positive or negative values. Then new applications have been considered as perfect lens previously theoretically proposed by Veselago [7], perfect electromagnetic absorbers [2], or the invisibility cloak to hide objects surrounded by a metamaterial [8]. A lab scale textile inspired technology has been proposed [9], and negative refractive index appearing as a phase-advance of the electromagnetic wave transmitted through a textile metamaterial have been measured [10].

This study deals with the development of a more realistic woven metamaterial in terms of flexibility and of the type of yarns available on the market. Metamaterials will be produced by the intrinsic ripple of plain wave woven yarns and not by addition of wires, by coating, printing or embroidery, as it is currently considered in literature. Firstly, we propose to study the homogeneity of woven metamaterial produced with semi-industrial machine. In a second part, electromagnectic characterization will be proposed showing a phase-advance of the transmission through the structure.

2. Materials and experimental method

2.1. Simulation

Figure 1 shows a 3D schematic of the basic cell of the fabric used for the simulation of electromagnetic responses of woven metamaterials with HFSS software by Ansys. Metallic wires (in orange/green) are composed of a copper (in orange) monofilament with a varnished dielectric cladding (in green), and dielectric monofilaments (in blue) are considered. Relative permittivity of dielectric materials (yarns and varnish) is fixed to ε = 3.3 (1 - i 0.02) [11]. For simulation, an electric field polarization parallel to conductive copper yarns is considered.

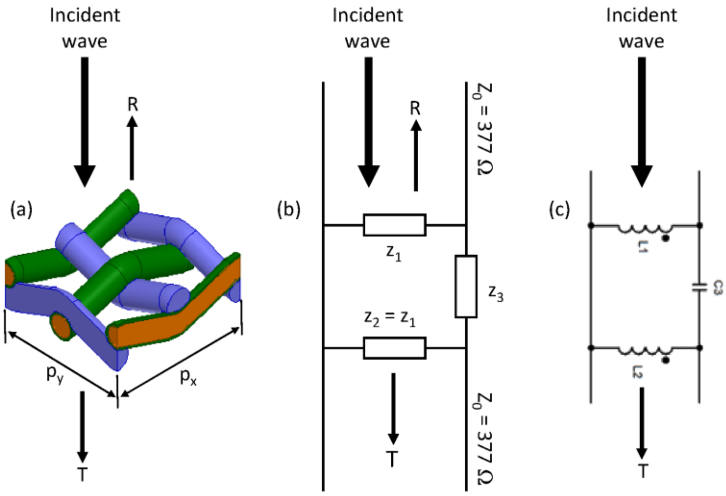

Figure 1. Basic cell of the fabric used for simulation (a), equivalent electric circuit of woven metamaterial (b), and equivalent electric circuit for phase-advance behavior (c).

2.2. Materials and woven structure

Textile metamaterial (30 x 30 cm^2, Figure 2) was produced by a weaving loom CCI SL8900S with parameter settings permitting to respect the geometrical dimensions of the basic cell previously defined by electromagnetic simulations with the goal to obtain a phase-advance in the frequency response around 500 GHz. Thus plain weave was selected with metallic wires in weft direction and dielectric yarns in wrap direction. According to simulations and weaving machine possibility, a warp density of 18 $yarns.cm^{-1}$ was used. Dielectric yarns were polyethylene terephthalate monofilament with diameter of 100 µm, and copper yarns, of diameter 81 µm, vanished with dielectric material of thickness estimated to 6 µm, were used for weft direction.

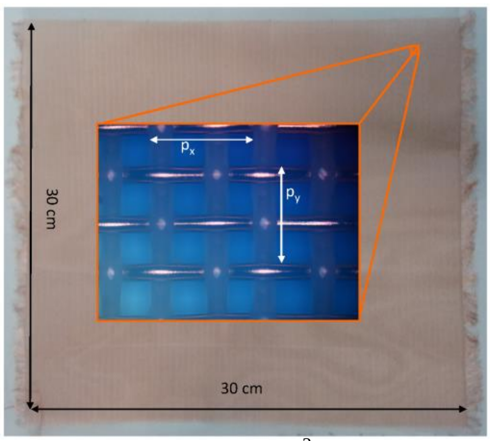

Figure 2.Textile metamaterial (30 x 30 cm^2) and close up view of weaving.

2.3. Dimensional characterization

The woven textile have been divided in 21 areas of 5 x 5 cm^2, and each area has been observed with an optical microscope to measure the real values of p_x and p_y periods. Thus 304 measurements were taken for p_x and 373 for p_y. From dimensional measurements, mean value, minimal value, maximal value and standard deviation have been calculated and reported in the Table 1.

2.4. Electromagnetic characterization

Complex transmission coefficient was measured in two frequency bands (325-500 GHz and 500-750 GHz) by a Vector Network Analyzer (VNA) Rohde & Schwarz ZNA 24. The experimental setup is shown in Figure 3. Fabric has been cut in samples of 20 x 12.5 cm^2 to fit in the sample holder which is fixed on a motorized XYZ displacement stage. It was positioned in the middle of the transmitting and receiving devices constituted by an antenna and a lens. The sample was illuminated by a collimated beam of about 1 cm of diameter, and the transmission (t_s) and reflection (r_s, not shown here) coefficients were measured by scanning the entire sample with an horizontal and vertical step of 1 cm. More than 200 electromagnetic measurements have been performed in each band. They permit the statistic evaluation of the rejection frequency f_R and of the frequency $f_{T\sim 1}$ with maximum transmission reported in the Table 2.

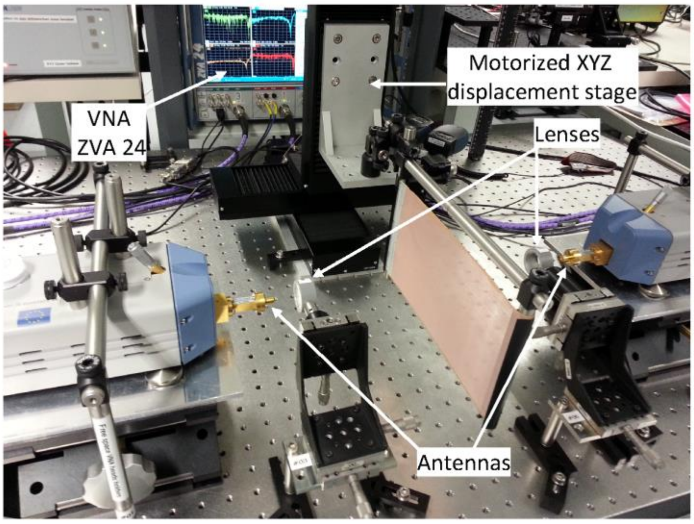

Figure 3. Manufactured textile metamaterial and experimental electromagnetic setup.

Finally, the transmission coefficient t_{ref} was also measured in the absence of the sample and it was used as a reference for calculating the transmission coefficient for a thickness of the woven metamaterial structure e = 0.18 mm by equation 1 [10].

$$t = \frac{t_s}{t_{ref}} \cdot exp\left(-i \cdot \frac{\omega e}{c}\right) \tag{1}$$

The set of measurement data is then post-processed by a Scilab code for (i) interpolating the frequency responses of each measured transmission by spline functions ; (ii) determining the frequency f_R and the value of the transmission t_{min}, both corresponding to a rejection, as well as the values corresponding to the quasi-unit transmission ($f_{T\sim 1}$, and t_{max}).

3. Results

3.1. Simulation

In the Figure 4, transmissions (T) simulated for a period p_x =0.55 mm with the period p_y as a parameter from 0.46 mm to 0.54 mm are plotted. We can note that the woven structure act as a high-pass filter. Under $f \sim 500$ GHz, less than 10% of the power ($T(dB) < -10$dB) is transmitted through the textile while quasi-unitary transmission band is observed at higher frequency, above a strong rejection appearing between 440 GHz and 480 GHz depending on the value of p_y. Between the rejection and

500 GHz, a phase-advance is observed just above a phase jump of near 180°. In this frequency band, the metamaterial textile is equivalent to a material with a negative refractive index.

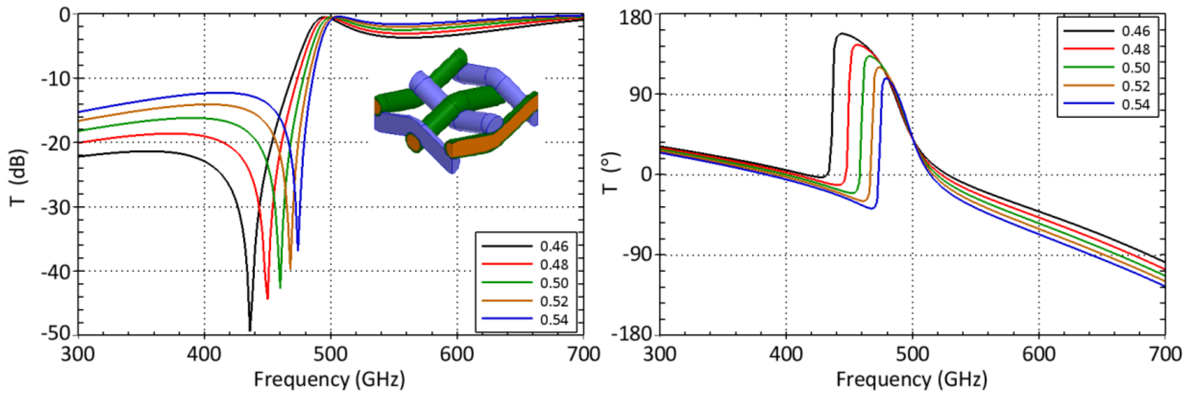

Figure 4. Simulated transmission through the woven metamaterial illustrated in insert.

To better understanding the frequency response of the Figure 1, the equivalent electric circuit of the weaving shown in the Figure 1b can be evaluated. By calculation, we can show that each impedance (z_i with i = 1 to 3) of the circuit corresponds to a parallel *RLC* circuit with a resonance appearing at the rejection frequency for z_3, and at around 560 GHz for $z_1 = z_2$. The latter frequency value corresponds to the second minimum of transmission observed in the Figure 4. Before the resonance, the impedance of a *RLC* circuit is inductive and above it is capacitive. Then, between the two resonances of impedances the woven metamaterial is equivalent to the high-pass filter circuit shown in the Figure 1c, and a phase-advance appears in the phase of the transmission coefficient. More extensive physical explanations about the origin of the phase-advance observed in woven metamaterials can also be found in the reference [12].

3.2. Dimensional characterization

From optical microscope observations, p_x and p_y periods and their statistical value are presented in Table 1. The plain weave is homogeneous in terms of yarn periods. The period p_x have a weak variation ($\sigma_{px} \sim 0.5$ %) while p_y have highest dispersion ($\sigma_{py} \sim 2$ %) in good accordance with the distributions of the measured periods plotted in the Figure 5.

Table 1. Statistical values from p_x and p_y periods measurements

	Moy (mm)	σ *(µm)*	*Min (mm)*	*Max (mm)*
p_x	0.548	2.46	0.542	0.554
p_y	0.512	10.58	0.491	0.531

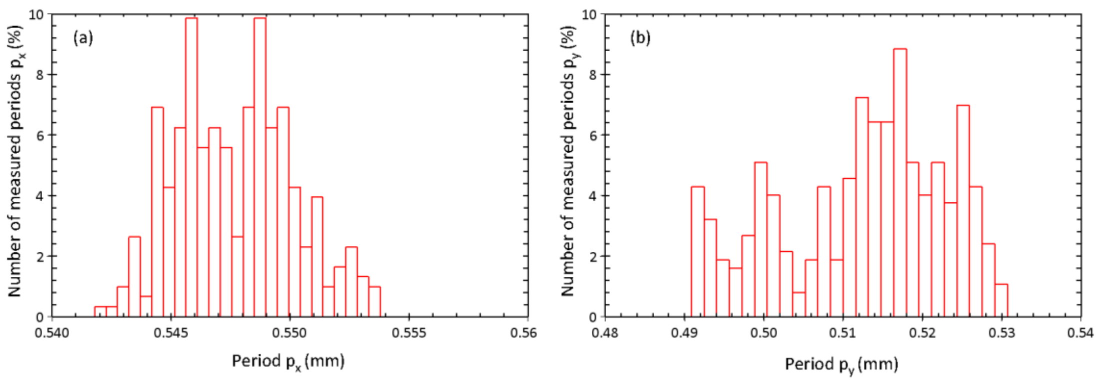

Figure 5. Distributions of the measured periods p_x and p_y in the entire woven sample.

We can see that the distribution of the period p_x follows a narrow Gaussian shape centered on 0.548 mm, while the distribution for the period p_y is rather uniform and more extended from 0.49 and 0.53 mm. These behaviors can be explained by the weaving process. Indeed, the spacing between wrap yarns is quite constant because it is imposed by comb, whereas weft yarns are packed with a force which may not be constant during the textile production.

3.3. Electromagnetic characterization

Table 2 summarizes the statistical values calculated from about 200 and 370 measured transmissions used to determine f_R and $f_{T\sim 1}$ respectively. Despite the relatively strong dispersion of the p_y values shown above, it appears that the rejection frequency is relatively stable with a low standard deviation (σ = 0.55%) and values centered around 478.8 GHz. On the other hand, the value of the minimum transmission at rejection varies greatly in a ratio 2 (in dB).

Table 2. Statistical measured values for f_R and $f_{T\sim 1}$ and for transmission levels in dB

	Moy	σ	*Min*	*Max*
f_R *(GHz)*	478.8	2.61	471.2	485.0
t_{min} *(dB)*	-29.7	3.37	-41.6	-23.1
$f_{T\sim 1}$ *(GHz)*	509.8	11.4	494.8	546.0
t_{max} *(dB)*	-2.85	0.650	-4.55	-1.69

A selection of deembedded experimental transmissions measured at three positions on the sample and corresponding to minimal, mean, and maximal values of the rejection frequency f_R are plotted in the Figure 6. A phase-advance is clearly evidenced between the rejection at around 480 GHz and the highest transmission level at 500 GHz. Results show a strong rejection down to $T \sim$ -30 dB, and a phase jump of more than 100° at the rejection.

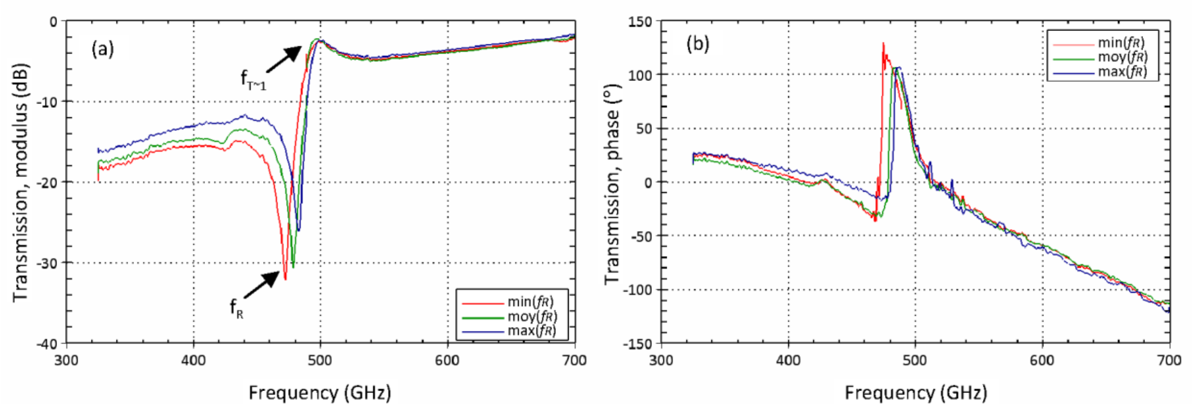

Figure 6: Experimental transmission, modulus (a) and phase (b), measured at three positions on the sample corresponding to the extreme and mean values of the rejection frequency f_R.

On the Figure 6, the sensitivity of the rejection frequency f_R is visible and a quasi-insensitivity of $f_{T\sim 1}$ with a maximum transmission value (about -2 dB) is observed. These sensitivities are also observed on the phase of the transmission which shows a phase shift at the rejection preceding a phase-advance frequency band. It is noted that the low sensitivity of the frequency $f_{T\sim 1}$ makes it possible to obtain a phase-advance which is almost identical and not very sensitive to the position of the measurement on the sample. Finally, experiments compare favorably with the simulated results plotted in the Figure 4 which shows identical transmission phases around the maximum transmission.
Beyond the phase-advance, we can mention that such textile behaves as a high-pass filter, with an attenuated band lower than -12 dB and a higher transmission above 490 GHz. Such an electromagnetic characteristic could be a good feature for selecting the frequency band of electromagnetic shielding.

4. Conclusion

A textile metamaterial has been produced by weaving metallic and dielectric yarns with specific dimensions, and it has been electromagnetically characterized in the frequency band 325 - 700 GHz.

Experiments have been favorably compared with simulated results. Phase-advance and high-pass filter behaviors have been measured with potential applications in metamaterial and electromagnetic shielding domains.

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