Application of Meta-materials in the Ports of Conveyor Belt Microwave Heating Systems

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Abstract— The problem of improvement of input/output ports construction of conveyor belt microwave heating system is considered. Meta-materials can be applied for significant reducing of electromagnetic energy escape from microwave processing chamber. Meta-material considered in this paper consists of printed circuit boards with metallization as a set of split-ring resonators. Estimation of effective permittivity and permeability of the meta-material was performed by FDTD analysis of the microstructure following Nicolson-Ross-Wier approach. Numerical results show that both effective permittivity and permeability have negative values at the frequency 2.45 GHz at some sets of parameters of the geometry, and these values provide negative (left-handed) refraction, which can be used for preventing escape of microwave energy from processing chamber through conveyor belt port.

1. INTRODUCTION

Meta-materials can be considered as a promising resource of improvement of the existing technologies, as well as a key element of novel technologies due to unusual interaction with electromagnetic waves. In particular, negative values of effective permittivity and/or permeability of these materials allow obtaining such technically interesting electromagnetic effects as negative refraction [1], band gaps [2], magneto-electric coupling [3], etc..

In this paper meta-materials are investigated with the purpose of improvement of existing conveyor-belt microwave heating systems. Schematic design of the system is presented in Fig. 1.

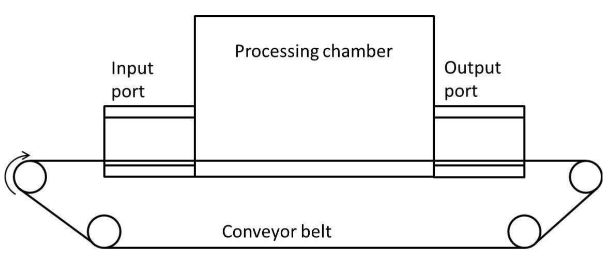


Figure 1: Conveyor belt microwave heating system.

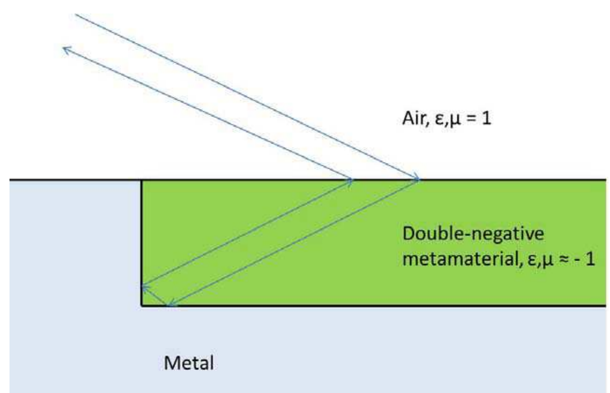


Figure 2: Application of negative refraction effect for back reflection of incident wave.

One of the actual tasks for these systems is construction of input/output ports for the conveyor belt, which do not allow electromagnetic energy to escape from the microwave processing volume. Existing methods dealing with this problem include following options: application of moving metal shields, using microwave attenuators, using chains of filters, conversion of the modes to one particular mode and filtering this mode, using corner reflectors. These methods do not provide attenuation of microwave energy in the case of large aperture of the ports, or suffers from arcing effect due to high power of microwaves (in case of corner reflectors). To this end the idea of application of meta-materials at the ports arises. The idea is illustrated in Fig. 2.

If the walls of input/output ports are equipped with a layer of double negative meta-material, then full back reflection of incident electromagnetic wave can be expected. In this paper, this idea is studied using numerical modeling on macro- and micro-level.

2. METHOD

In this paper, numerical modeling of the interaction of the electromagnetic field with the structure containing double-negative meta-material is performed using FDTD method, more specifically, using full-wave electromagnetic simulation software Quick Wave-3D [4]. Meta-materials consist of large number of small-size constructive elements, which require dense FDTD mesh for direct modeling, so, direct simulation of full structure of input/output port with meta-material layer seems to be impossible taking into account currently available computational resources. Instead of direct modeling, the simulation can be done in two steps. Firstly, the input/output port can be simulated on macro-level, with electromagnetic parameters of meta-material defined with Drude dispersion model. The output of this step is the dependence of performance of the port on the parameters of the meta-material layer. On the next step the aim is to find the micro-structure of meta-material which provides desired electromagnetic parameters. This step can be performed using direct modeling of small volume of meta-material inside metallic waveguide.

2.1. Modeling On-macro-level

The input/output ports of the conveyor-belt system, depicted in Fig. 1, can be considered as large size rectangular metallic waveguides. In order to provide back reflection for a set of eigenmodes of the waveguides, the meta-material layer can be placed inset the walls, as shown in Fig. 3. The effective permittivity and permeability values for the meta-material layer are defined with Drude dispersion model

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{(2\pi f_p)^2}{(j\omega 2\pi v_c - \omega^2)}, \quad \mu_r(\omega) = \mu_\infty + \frac{(2\pi f_p)^2}{(j\omega 2\pi v_c - \omega^2)}, \tag{1}$$

with parameters providing values $\varepsilon_r = -1$, $\mu_r = -1$ at the frequency 2.45 GHz: permittivity and permeability at high (infinite) frequency $\varepsilon_\infty = \mu_\infty = 1$, plasma frequency $f_p = 3.465$ GHz, collision frequency $v_c = 0.0013$ GHz.

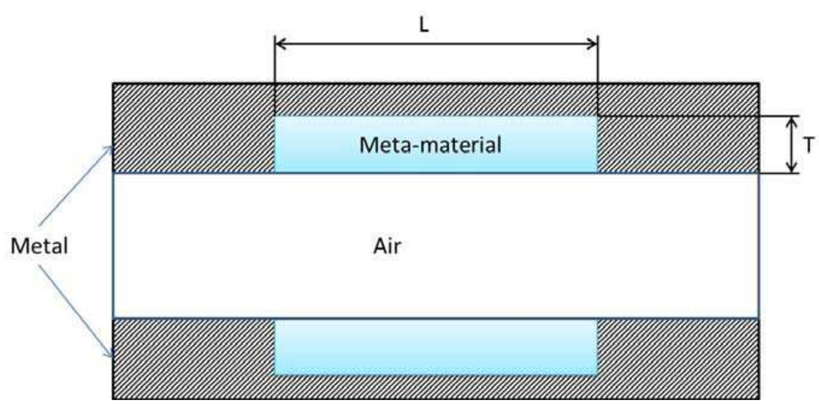


Figure 3: Waveguide section containing meta-material layer.

2.2. Modeling on Micro-level

In order to find geometry of the elements of the meta-materials, providing negative values for both effective permittivity and permeability, the procedure described in [5] and based on Nicolson-Ross-Wier approach can be applied. According to [5], effective permittivity and permeability of the artificial meta-material can be calculated numerically, using reflection S_{11} and transmission S_{21} coefficients of dominant mode in the section of rectangular waveguide containing section of meta-material. In this paper, the rectangular waveguide with cross-section 44×88 mm and length 260 mm, containing the section of meta-material with length 120 mm, was simulated numerically. The micro-structure of meta-material is simulated in this modeling directly, with application of dense FDTD mesh.

3. RESULTS

As a result of modeling on macro-level, the dependences of transmission coefficient S_{21} on frequency for several eigenmodes of waveguide (shown in Fig. 3) were calculated. All dependences demonstrate similar behavior, which is illustrated in Fig. 4 for mode TE_{10}.

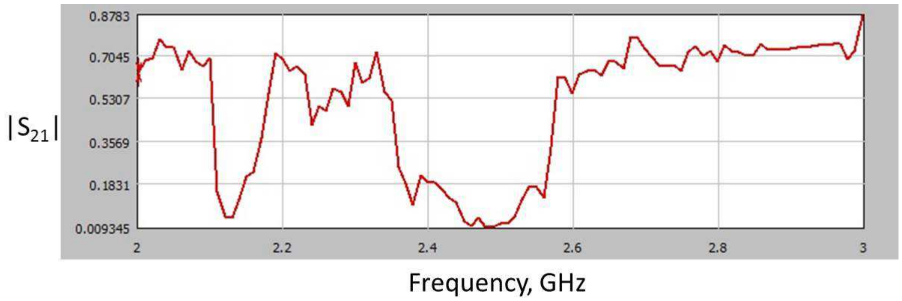


Figure 4: Dependence of transmission coefficient on frequency for mode TE_{10}.

The result was obtained with the following parameters: cross-section of the waveguide 500 mm × 200 mm, thickness of meta-material layer $T = 100$ mm, length of meta-material section $L = 1000$ mm, relative effective permittivity and permeability of the meta-material at the frequency 2.45 GHz are $\varepsilon_r = -1$, $\mu_r = -1$. It can be seen from Fig. 4, that there is a range aroung 2.45 GHz, where transmission coefficient has very low values. This can be explained by full reflection of the eigenmode back to waveguide. This conclusion is proved by modeling of the field structure inside waveguide with sinusoidal excitation at the port at 2.45 GHz. The result is shown at Fig. 5.

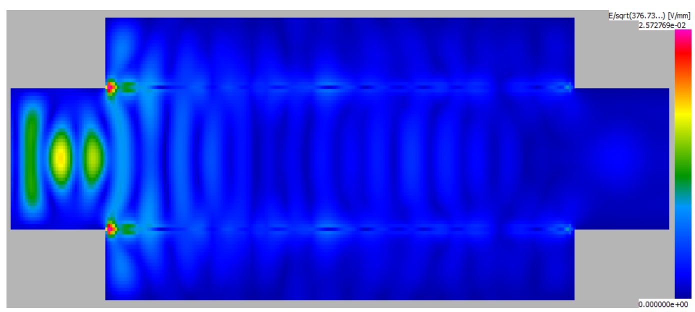
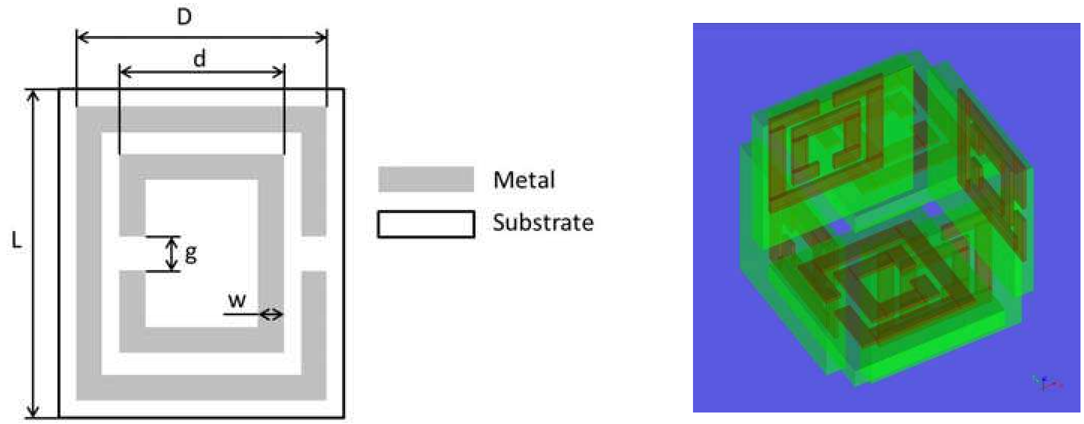


Figure 5: Distribution of intensity if the electric field inside waveguide.

It is obvious, that the picture correspond to staying wave pattern at the input port of waveguide, while the energy at the output port is near zero. This means that the energy of the eigenmode reflects back to input port.

The next step is to find a microstructure of the meta-material, which provides double-negative effective electromagnetic parameters. In the literature, the following options for construction of double-negative meta-material were mentioned: a matrix of spherical magneto-dielectric particles [3], a set of helices with different orientations [6], a set of metallic rods and split rings [7], a set of printed board circuits with metallic strips and split rings [8]. Taking into account the demand of no arcing effect and simplicity of fabrication, the structures on printed board circuits are most attractive from the options above.

In this paper, the structure, shown at Fig. 6, was studied numerically. Effective permittivity and permeability of the meta-materials are calculated using micro-modeling approach described in the previous section. The following parameters of the structure were constant in all calculations: thickness of substrate 1 mm, material of substrate FR-4 ($\varepsilon = 4.4$), number of cells of the printed board along coordinate axes $4 \times 8 \times 12$. Other parameters, which are depicted in Fig. 6(a), were variable. It was found as a results of micro-level modeling, that meta-material with parameters $L = 10$ mm, $D = 6$ mm, $d = 3.6$ mm, $w = 0.8$ mm, $g = 0.4$ mm provides effective permittivity and permeability values $\varepsilon^* = -1.770 + 0.065i$, $\mu^* = -0.604 - 0.022i$. The absolute value of refraction coefficient of meta-material in this case is equal to 1.034, and this is close to refraction coefficient of air, so we can expect small reflection of electromagnetic energy from the boundary of air and meta-material. Of course, round design of split rings also can be applied in this approach, but it requires numerical adjustment of the parameters of the microstructure.



(a) (b)

Figure 6: Microstructure of the meta-material: (a) split rings on printed circuit board; (b) three-dimensional cell of printed circuit boards.

4. CONCLUSION

In this paper, the possibility of energy leakage reducing from microwave processing chamber through the ports of conveyor-belt heating system was numerically studied. Modeling on macro-level shown the effect of back reflection of the eigenmode from the meta-material section with negative values of effective permittivity and permeability. Modeling on micro-level permitted to find the parameters of meta-material microstructure, which provides both negative values for effective permittivity and permeability. So, the possibility of application of the meta-materials in the problem was proved by numerical analysis.

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