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Mechanically Tunable Wire Medium Metamaterial in the Millimeter Wave Band

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Abstract—The paper is devoted to experimental and theoretical study of spectra zone characteristics of the wire medium metamaterial with mechanically tunable unit cell. We experimentally demonstrated the effective control possibility of the spectral characteristics of wire medium metamaterial by varying its elementary unit-cell geometry. We established conditions under which the experimental implementation of the wire medium metamaterial at microwaves possesses the properties of a plasma-like medium and the properties band gap structure. A good agreement between the experiment and theory is demonstrated.

1. INTRODUCTION

In recent years, the concept of design components for microwave devices and systems has been changed significantly. Such type of metamaterial as a wire medium is well known [1, 2] and seems to be a promising artificial tunable material. After Pendry et al. published the comprehensive research [3] of such metamaterials, a lot of attempts to implement them into high-frequency technology are undertaken.

The wire medium metamaterials (WMM) demonstrate unique electromagnetic properties which make them unrivalled for applications in spatially discriminatory and/or frequency-selective optical devices [4–6] and also demonstrate the prospects for manufacture of filters, polarizers, etc. [7]. Certain practical interest is presented in the possibility of such structures usage in nanoelectronics [5], antenna technology [6] and technologies of transmitting images with a subwavelength resolution [8].

One of the actual tasks of fundamental and applied sciences today is to create WMM with easily tunable constitutive parameters that may be tuned into a wide band. The significant attention of researchers has been paid to controllable properties of WMM via electric field [9–13]. Particularly, the controllability of photonic crystals [9] has been proposed with the periodic insertion of diodes along the rods of a two-dimensional (2D) wire medium. This enables the change of the metamaterial structure, dynamically tuning its electromagnetic properties. Unfortunately, most microwave metamaterials controlled by electrically provide functionality only within a narrow spectral range. In the same time, the mechanical adjustment of metamaterials parameters has several advantages among which is a greater spectral range of parameters variation [14–17].

In addition, the article [14] provides a wide overview of approaches and tuning techniques that change electromagnetic properties of metamaterial devices all the way from the RF through the optical regimes. In particular, [15] experimentally demonstrates the effective tunability of the resonance frequency at a wide spectral range, using metamaterial with highly elastomeric substrate. Such a metamaterial is formed by planar array of so called I-shaped resonant elements deposited on elastic substrates. It is frequency characteristics that can be tuned by up to 8.3% by mechanical stretching.

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The example of mechanically tunable metamaterial absorber performing as dielectric resonators located on conductive rubber planar layer is presented in [16]. Described configuration provides a near unity absorption around the magnetic Mie resonance of dielectric resonators. The authors were able to shift the absorption peak by 410 MHz through the strain on conductive rubber along H-field direction.

The above described designs are the result of well-proven approaches for the creation of a mechanically tunable planar metamaterials. In the given paper, we try to input the contribution to the general task of metamaterial technology. The novelty of our approach to research and formation of mechanically tunable metamaterials are as follows. First of all, we consider 3D WMM as a homogenized effective medium, where the dielectric matrix is removed. Therefore, the losses inherent to the matrix are also absent. Secondly, such an approach suggests a possibility of considering not only 2D structures, but also mainly 3D metamaterials. Note that 3D tunable metamaterials are of great importance at any applications, where the control of electromagnetic beam is necessary. Namely, it can be applied to design of optical computers, antenna technology, etc.

Thus, in this paper, a promising and easily implemented technique of manipulating spectra zone characteristics by mechanical adjustment geometrical parameters of the 3D WMM is suggested. The experimental and theoretical studies showing the capability of WMM controlled by elementary unite cell sizes are presented.

2. EXPERIMENTAL INVESTIGATION OF TUNABLE WIRE METAMATERIAL

To reach sufficient tunability, we developed and fabricated a 3D mechanically tunable wire medium (MTWM) performed according to principle of pantograph-like device (see Fig. 1(a)). The design of such a structure allows us synchronously increase or decrease the distance between wires for one of the directions simultaneously on all frames, as shown in Fig. 1(a).

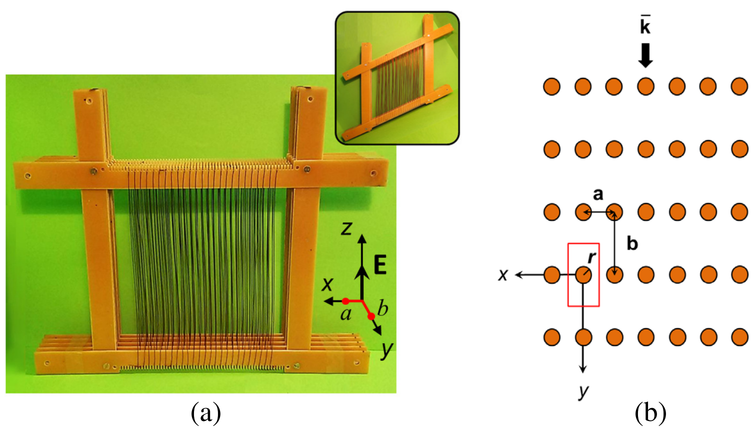
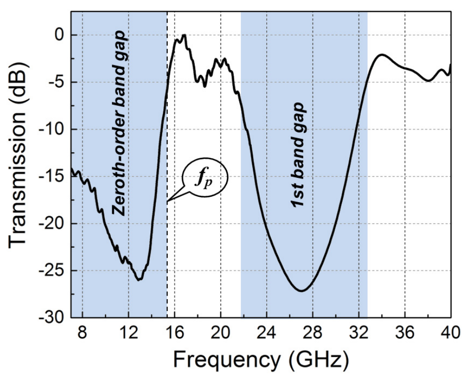


Figure 1. (a) 3D MTWM with rectangle unit-cell; (b) schematic representation of MTWM. The red box indicates unit-cell geometry ($a \neq b$).

The metamaterial under study is formed by an array of thin copper wires with a diameter $d_w = 0.315$ mm, which are wound on a fiberglass frame with a thickness of 1.5 mm (Fig. 1(a)). The wires are placed on a frame with a period a along the x-direction. Frames of identical thickness (5 pcs.) are fixed in succession one after the other along the y-direction at a distance b. Thus, the unit-cell of structure under study is presented in the form of a rectangle with different geometric dimensions, where $a \neq b$ (see Fig. 1(b)).

We are interested in studying the electromagnetic response of MTWM under z-directed electric field **E** (TM mode), where **E** field is parallel to the wires. We studied transmission through the structure under study at normal incidence at 10–40 GHz spectral range using Vector Network Analyzer Agilent (N5230A). The MTWM is located between the broadband horn antennas, which are the source and receiver of electromagnetic waves with a nearly plane wave front. The VNA N5230A generates an electromagnetic wave that passes through the whole system and detects experimental data as well. The measured transmission spectrum and FDTD, calculation for wire medium with rectangle unit cell (where $a \neq b$), are shown in Fig. 2(a) and Fig. 2(b).

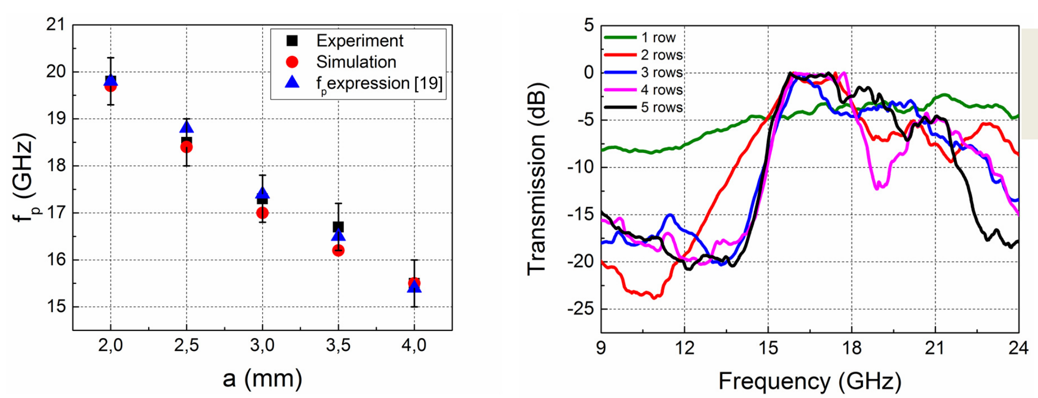


(a) (b)

Figure 2. Transmission spectra of 3D MTWM ($a = 4$ mm, $b = 6.5$ mm): (a) experiment $f_p = 15.5$ GHz; (b) FDTD simulation $f_p = 15$ GHz.

Both the figures show that the MTWM is a plasmonic-type medium with plasma frequency, marked on both graphs as f_p. We observe a good propagation of electromagnetic waves with a frequency above f_p, so called zeroth-order band gap, when ε_{eff} of the structure is positive. It is a prerequisite when $a, b, r \ll \lambda$ (as shown in [3]) to ensure the presence of f_p on the spectra. The minimum acceptable aspect ratio of the unit cell dimensions relative to λ is the condition $\lambda_p/b = 3$ as shown in [1]. Note that it is stacked half wavelength for one of the geometric dimensions $b = 6.5$ mm in the considered structure at the frequency of 22 GHz, and this frequency domain is marked as the 1st band gap. We can conclude that the MTWM on 22 GHz is an electromagnetic band gap crystal, and as a result, we see extremely low level of power transmission in the structure.

In addition to experimental characterizations, the spectral properties of the MTWM were investigated by numerical simulation with the finite difference time domain (FDTD) method, using a freely available software package MEEP [18]. Fig. 3(a) presents a comparison of the plasma frequency f_p dependencies on the wire's period a for three cases: experiment, FDTD-calculation and plasma



(a) (b)

Figure 3. (a) Plasma frequency versus a for three cases: experiment, FDTD-calculation and plasma frequency expressions [19]; (b) transmission spectra of MTWM ($a = 4$ mm, $b = 6.5$ mm) for a different rows number (1 to 5).

frequency expression [19].

$$(2\pi f_p)^2 = \omega_p^2 = \frac{2\pi c^2}{ab\ln\left(\sqrt{ab}/r\right)}, \tag{1}$$

where ω_p is the plasma frequency, c the speed of light in vacuum, r the radius of the wire (a, $r \ll \lambda$), and a, b are periods of wires' location at the medium along x-direction and y-direction correspondingly.

Note that for experiment and numerical modeling with increasing of the period, f_p is shifted to lower frequencies. This phenomenon is explained by the fact that an increase of the distance between the wires decreases the density of metallic filling structure. Fig. 3(a) also shows confidence intervals for measured values of plasma frequency that is 0.5 GHz. It is clear that the measured value of f_p shows good agreement with the theoretical one calculated by the (FDTD) method. These results are obtained for the case that **k**-vector is directed along the y-direction, as shown on Fig. 1(b). The transmission spectra of MTWM with rectangle unit-cell ($a = 4$ mm, $b = 6.5$ mm) for a different rows number (1 to 5) are presented in Fig. 3(b). In the case of $N \geq 3$, we observe the same curves character and the presence of plasma frequency for all spectral curves, which separates domains with different signs of ε_{eff}. In these cases, MTWM is a plasmonic-type medium when condition $\lambda_p/b = 3$ is true.

3. CALCULATION OF DISPERSION DIAGRAM

Figure 4 shows the projected band dispersion diagram along the wave propagation direction with the first and second TM propagating modes of the infinite WMM with symmetry that corresponds to Fig. 1(b). Simulations were performed with FDTD-method using a package MEEP. Here we represent frequencies without any normalization for better ability of comparison with experimental data. But wave vector is normalized in usual manner for dispersion diagrams of the periodical structures. Different types of dispersion curves correspond to various values of parameter a (2.0; 2.5; 3.0; 3.5; 4.0) mm. Parameter b is fixed ($b = 6.5$ mm). Zeroth-order band gap (0–16 GHz), 1st band gap (22–35 GHz) and 2nd one are marked by shaded area (for the case $a = 4$ mm). These data are in good agreement with obtained experimental and theoretical results for the spatially restricted structure. (Fig. 2 and Fig. 3). As can be seen in Fig. 4, the width of band gaps increases with the parameter a decreasing. Moreover, dispersion curve becomes flatter. Under condition $a \to 0$, dispersion curves transform into straight lines. It is clear that in this case wire structure is the "condensed metal", and its band gap "character" of spectrum disappears. Indeed, the rows of wires along axis Ox transform into metal sheets that completely reflect the incident radiation. It should be noted that low-frequency boundaries of the first and second band gaps do not depend on parameter a. Additional numerical calculations show that these boundaries are shifted by varying parameter b. Therefore, the dispersion and spectral properties of the wire structure are controlled by geometrical sizes of the wire medium unit cell. For example, one can change the zeroth-order band gap width and accordingly effective plasma frequency by means of mechanical changing of the parameter a value (see Fig. 1(a)). Changing parameter b provides additional possibility for the WMM dispersion properties tuning.

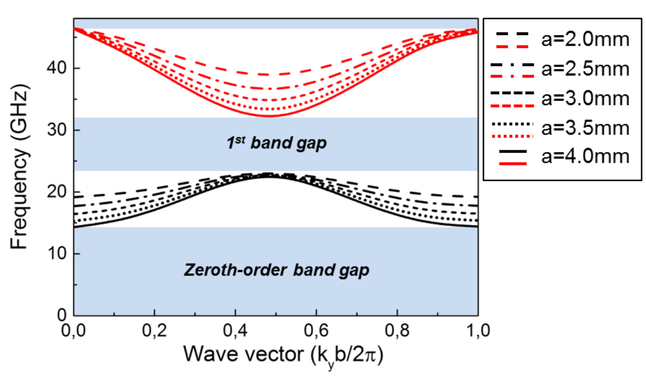


Figure 4. Evolution of dispersion curves of the MTWM with mechanical changing parameter a value.

4. CONCLUSIONS

In summary, both experimental and theoretical researches of MTWM are carried out in millimeter wave band. The effective control possibility of the MTWM spectral characteristics by varying 2D unit-cell dimensions is experimentally shown. We experimentally demonstrate that the MTWM with rectangular unit-cell is a plasmonic-type medium at $\lambda_p/b > 3$ at lower values, and the MTWM should be considered as the electromagnetic band gap structure. Also, it is experimentally shown that the periodic wire structure formed by N rows must be considered as an unbounded WMM under condition $N > 3$. The FDTD-calculation of the dispersion diagrams shows that the possibility of the position and width of band gaps varies due to tuning of the MTWM unit cell dimensions for the spectral range 7–40 GHz. Further search of additional abilities to control the dispersion and spectral properties of the WMM is under way. Offered implementation of the WMM with mechanical adjustment of unit cell sizes may simply, fast and visually help with understanding of wave propagation properties in such anisotropic media. It also suggests some improvements, which can be made in future filters designs. Thus in our opinion the performed research can be considered as a certain base for the design of spatial GHz, THz devices (filters, attenuators, etc.).

REFERENCES

1. Brown, J., "Artificial dielectrics," *Progress in Dielectrics*, Vol. 2, 195–225, 1960.
2. Nicorovichi, N. A., R. C. McPhedran, and L. C. Botten, "Photonic band gaps for arrays of perfectly conducting cylinders," *Phys. Rev. E*, Vol. 52, No. 1, 1135–1145, 1995.
3. Pendry, J. B., A. J. Holden, W. J. Stewart, et al., "Extremely low frequency plasmons in metallic mesostructures," *Phys. Rev. Lett.*, Vol. 76, No. 25, 4773–4776, 1996.
4. Boutayeb, H., A.-C. Tarot, and K. Mahdjoubi, "Focusing characteristics of a metallic cylindrical electromagnetic band gap structure with defects," *Progress In Electromagnetics Research*, Vol. 66, 89–103, 2006.
5. Vasilantonakis, N., M. E. Nasir, W. Dickson, G. A. Wurtz, and A. V. Zayats, "Bulk plasmon-polaritons in hyperbolic nanorod metamaterial waveguides," *Laser Photonics Rev.*, Vol. 9, No. 3, 345–353, 2015.
6. Wu, B.-I., W. Wang, J. Pacheco, X. Chen, T. M. Grzegorczyk, and J. A. Kong, "A study of using metamaterials as antenna substrate to enhance gain," *Progress In Electromagnetics Research*, Vol. 51, 295–328, 2005.
7. Wu, D. M., N. Fang, C. Sun, et al., "Terahertz plasmonic high pass filter," *Appl. Phys. Lett.*, Vol. 83, 201–203, 2003.
8. Belov, P. A., C. R. Simovski, P. Ikonen, et al., "Image transmission with the subwavelength resolution in microwave, terahertz and optical frequency bands," *J. Commun. Technol. Electron.*, Vol. 52, 1009, 2007.
9. Lourtioz, M., A. De Lustrac, F. Gadot, and D. Lippens, "Toward controllable photonic crystals for centimeter and millimeter wave devices," *J. Lightwave Tech.*, Vol. 17, 2025–2031, 1999.
10. Boutayeb, H., T. A. Denidni, A. R. Sebak, and L. Talbi, "Band structure analysis of crystals with discontinuous metallic wires," *IEEE Microwave and Wireless Components Letters*, Vol. 15, No. 7, 2005.
11. Belov, P. A. and C. R. Simovski, "Subwavelength metallic waveguides loaded by uniaxial resonant scatterers," *Phys. Rev. E*, Vol. 72, 036618, 2005.
12. Ikonen, P., M. Karkkainen, C. Simovski, et al., "Light-weight base station antenna with artificial wire medium lens," *IEE Proc. Microwaves, Antennas and Propag.*, Vol. 153, No. 2, 163–170, 2006.
13. Ikonen, P., P. Belov, C. Simovski, and S. Maslovski, "Experimental demonstration of subwavelength field channeling at microwave frequencies using a capacitive loaded wire medium," *Phys. Rev. B*, Vol. 73, 073102, 2006.

14. Turpin, J. P., J. A. Bossard, K. L. Morgan, D. H. Werner, and P. L. Werner, "Reconfigurable and tunable metamaterials: A review of the theory and applications," *International Journal of Antennas and Propagation*, Vol. 2014, Article ID 429837.
15. Li, J., C. M. Shah, W. Withayachumnankul, and D. Abbott, "Mechanically tunable terahertz metamaterials," *Appl. Phys. Lett.*, Vol. 102, 121101, 2013.
16. Zhang, F., S. Feng, K. Qiu, Z. Liu, Y. Fan, W. Zhang, Q. Zhao, and J. Zhou, "Mechanically stretchable and tunable metamaterial absorber," *Appl. Phys. Lett.*, Vol. 106, 091907, 2015.
17. Shadrivov, I. V., D. A. Powell, S. K. Morrison, and Y. S. Kivshar, "Scattering of electromagnetic waves in metamaterial superlattices," *Appl. Phys. Lett.*, Vol. 90, 201919, 2007.
18. Oskooi, A. F., D. Roundy, M. Ibanescu, P. Bermel, J. Joannopoulos, and S. G. Johnson, "MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method," *Computer Physics Communications*, Vol. 181, 687–702, 2010.
19. But'ko, L. N., A. P. Anzulevich, D. S. Liharev, and S. Moiseev, "Electrodynamics properties of media formed by regular lattices of conducting wires," *CSU Bulletin, Physics*, Vol. 16, No. 9, 11–17, 1996 (in Russian).