Metamaterials Applications in Radiocommunication and Biomedical Engineering

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ABSTRACT

Metamaterials are complex materials with artificial structure which have special features. These features attract many scientists to use metamaterial structure in many research areas [1]. The metamaterials can enhance properties of microwave and optical passive and active components and also to exceed some limitation of devices used in technical practice [1]. Examples of scientific and technical fields which are concerned are electrical engineering, micro- and nanotechnology, microwave engineering, optics, optoelectronics, and semiconductor technologies, biomedical engineering [1]. In plasmonics, the interplay between propagating electromagnetic waves and free-electron oscillations in materials are exploited to create new components and applications [1]. On the other hand, metamaterials refer to artificial composites in which small artificial elements, through their collective interaction, create a desired and unexpected macroscopic response function that is not present in the constituent materials [1].

Categories and Subject Descriptors

J.2 [**Physical sciences and engineering**]: *engineering, physics.*

General Terms

Measurement, Design, Experimentation.

Keywords

Metamaterials, microwave frequencies, biomedical engineering, sensors, radiocommunication.

1. INTRODUCTION

Metamaterials are artificial electromagnetic composites, which are typically made of highly conducting metals. The metamaterial structure responds to electromagnetic waves in ways that atoms in natural materials do not [2]. Metamaterials which are defined as effectively homogeneous electromagnetic structures exhibiting unusual electromagnetic properties especially the backward wave, negative index of refraction not readily available in nature, perfect lensing, perfect absorbers and invisibility cloaks [2]. The metamaterials using represents a new paradigm in electronics and photonics. The typical feature of metamaterials construction is the possibility to achieve the user defined electromagnetic response at a precisely controlled target frequency [2].

2. METAMATERIALS THEORY

The modern development and understanding of metamaterials began in 1966 when Viktor Veselago, a Russian scientist introduced some fundamentally new questions about electromagnetic wave propagation [3-5]. He considered what would happen if the fundamental electromagnetic material parameters, permittivity ε and permeability μ, were both simultaneously negative [3-5]. When they are both positive, an electromagnetic wave will propagate though the medium in the normal manner [3-5]. If either parameter is negative then the wave will cease [3]. Since metals have a negative permittivity at optical wavelengths this is why light reflects off of metals [3]. Veselago showed that if both parameters are negative, the material is so - called 'double-negative' material [3]. Veselago applied negative parameters to Maxwell's equations and discovered that electromagnetic waves will propagate with opposite direction of phase and group velocity [3]. Veselago`s ideas remained as proposals for over three decades, in part because of a lack of knowledge as to how a material with simultaneously negative permittivity and permeability could be created [3].

In 2000, Sir John Pendry of Imperial College resurrected the concept of negative refraction as proposed by Veselago [3], [6]. He showed how a lens made of such a material could boost the resolution of imaging systems to well beyond that given by the Rayleigh criterion, long considered to be the ultimate resolution limit of an imaging system [3]. However, in a negative refractive material, waves propagate with a phase opposite to that in a normal material [3]. Consequently, exponentially decaying evanescent waves become exponentially growing waves within a negative refractive material [1-3]. Thus, it should be possible to perfectly restore the subwavelength evanescent components at the image plane by amplifying them within the negative refracting material, independent of the imaging wavelength [1-3]. Figure 1 illustrates imaging with and without a negative refractive index (NRI) material and shows that amplification of the evanescent wave components results in an image with improved detail [3].

In conventional imaging Fig. 1a), the wavelength of the imaging source determines the quality of the image produced [3]. The reproduced image of the surface is smoother than the surface itself because the subwavelength details are lost [3].

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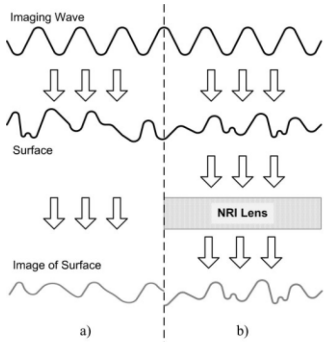


Figure 1. a) Conventional imaging and b) imaging with negative refractive index material using [3].

A smaller imaging wavelength allows smaller features to be reconstructed on the image plane [3]. Using a slab of negative refractive index material as a lens Fig. 1b), the evanescent waves can be amplified and a perfectly reconstructed image is created, including all subwavelength details [3].

3. BIOMEDICAL APPLICATIONS OF METAMATERIALS

The metamaterials structures are in present in the focus of many researchers in the field of biomedical engineering. They used metamaterials for wide frequency range - from microwave to optical frequencies and the metamaterials increasingly become a part of device like sensors, antennas and systems for imaging methods. In this part we mention some of latest biomedical applications.

3.1 Metamaterial Design for Energy Storage

National Institute for Standards and Technology (NIST) succeeded in tuning metamaterials to store energy using a particular frequency [2], [7]. The invention's primary aim would be an application as a biomedical sensor and other microwave devices [2], [7]. The scientists have used purified water in tuning the resonant frequency of metamaterials so that they can store energy which can then be utilized in other applications [2], [7]. NIST Researchers, with help of computer simulations have made a "kaleidoscope" of metamaterial using 18 copper squares of 10 mm size in this experiment, Fig. 2 [2], [7].

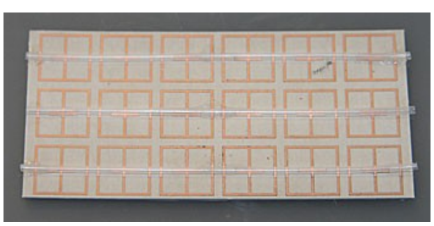


Figure 2. Metamaterial structure for energy storage [7].

The copper structure can be excited by microwaves [7]. The energy liberated thus, is stored in the "T" shaped gaps in between the copper structures [7]. The fluid is then packed in plastic tubes and the structure being placed in a waveguide [7]. This gives makes it perfectly synonymous to a kaleidoscope [7].

3.2 Metamaterial Silk Composites

Researchers at the Tufts University School of Engineering and Boston University have fabricated and characterized the first large area metamaterial structures patterned on implantable, bio-compatible silk substrates [2], [8]. The team focused on metamaterial silk composites that are resonant at the terahertz frequency [2], [8]. This is the frequency where many chemical and biological agents show unique "fingerprints," which could potentially be used for biosensing [2], [8]. The researchers sprayed gold-based metamaterial structures directly on pre-made silk films with micro-fabricated stencils using a shadow mask evaporation technique [2], [8]. Spraying the metamaterial onto the flexible silk films created a composite so pliable that it could be wrapped into small, capsule-like cylinders [2], [8].

Silk films are highly transparent at THz frequencies, so metamaterial silk composites display a strong resonant electromagnetic response [2], [8]. Each fabricated sample is 1 square centimeter and contained 10000 metamaterial resonators with unique resonant response at the desired frequencies [2], [8].

The metamaterial structure is like an array of small antennas that behave as one [2], [8]. The silk metamaterial composite is sensitive to the dielectric properties of the silk substrate and can monitor the interaction between the silk and the local environment [2], [8]. For example, the metamaterial might signal changes in a bioreactive silk substrate that has been doped with proteins or enzymes [2], [8]. The addition of a pure biological substrate such as silk to the gold metamaterial adds immense latitude and opportunity for unforeseen applications [2], [8]. The resonance response could be used as an implantable electromagnetic signature for contrast agents or bio-tracking applications [2], [8].

To demonstrate the concept, the researchers conducted a series of in vitro experiments that examined the electromagnetic response of the silk metamaterials when implanted under thin slices of muscle tissue [2], [8]. They found that the metamaterials retained their novel resonance properties while implanted one [2], [8]. The same process could be readily adapted to fabricate silk metamaterials at other frequencies [2], [8]. This new approach offers great promise for applications such as in situ bio-sensing with implanted medical devices and the transmission of medical information from within the human body [2], [8]. The benefits can be of monitoring the rate of drug delivery from a drug-eluting cardiac stent, making a perfect absorber that can be implanted to attack diseased tissue by heat, or wrapping an invisibility cloak around an organ to examine the tissue behind it [2], [8].

3.3 Paper – Based Metamaterial Device

The same group in Tufts University designed paper-based metamaterial device, which can potentially be utilized for quantitative analysis in biochemical sensing applications, is introduced [8]. Proof-of-concept demonstrations are accomplished by patterning micrometer-sized metamaterial resonators on paper substrates, Fig. 3 and monitoring the resonance shift induced by placing different concentrations of glucose solution on the paper based metamaterial device [8].

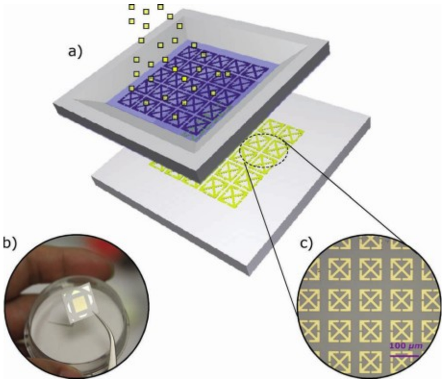


Figure 3. a) Schematic of the micrometer-sized metamaterial resonators sprayed on paper substrates with a predefined microstencil [8]. b) Photograph of paper-based terahertz metamaterial sample [8]. c) Optical microscopy image of one portion of an as-fabricated paper metamaterial sample [8].

3.4 Microwave Hyperthermia Improved with Metamaterial Lenses

As the metamamaterials lens can generate appropriate focusing spot in biological tissue as required in microwave hyperthermia treatment [9]. By using single flat metamaterial lens to concentrate microwave energy in a mass of tissue covered by water bolus, microwave hyperthermia scheme is proposed for superficial tumor hyperthermia [9]. Metamaterials provide a new prospect for microwave hyperthermia [9]. Flat metamaterial slab can be used as a lens to focus microwave energy emitted from the phase center of microwave antenna and acquire a subwavelength focusing resolution Fig. 4 [9].

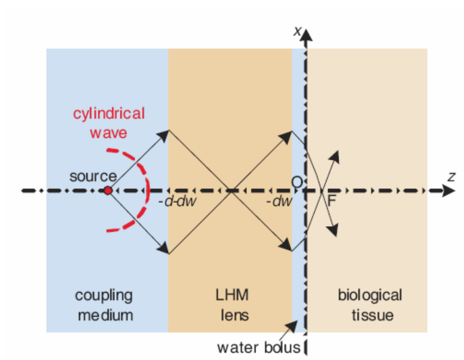


Figure 4. Microwave hyperthermia using flat metamaterial lens [9].

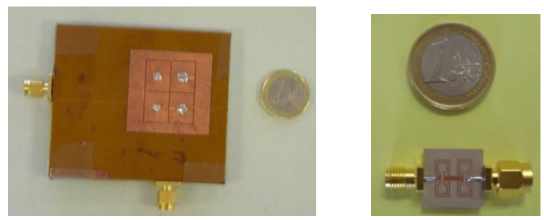
Flat metamaterial lenses have great potential for microwave hyperthermia due to the convenient adjustment of position of focusing or heating spot in tissue region [9]. The heating spot in tissue can be adjusted readily by moving the source, without any complex deployment and control system as required in the conventional array applicator [9]. In addition, microwave focusing spot of moderate size suitable for tumor hyperthermia can be achieved even in heterogeneous lossy medium [9]. The using of metamaterials lenses results to higher power deposition and thus the more effective microwave hyperthermia can be achieved in cancerous tissue [9].

4. METAMATERIALS APPLICATIONS IN RADIOCOMMUNICATIONS

The using of metamaterial structure in radiocommunication area is directed to the implementation of metamaterial structure to the antennas, sensors and waveguide devices such a high Q antennas, phase shifters, miniaturization of microwave devices. In this part we mention some of radiocommunication applications.

4.1 Patch Antenna and Filter Design with Metamaterial Structure

Due to the frequency selective response of metamaterial miniaturized filters have been developed [10]. The authors have proposed the use of conventional microstrip patches filled with metamaterial structures to achieve multi-frequency antenna operation [10-11]. The antenna is based on a square microstrip patch filled with metamaterial structures, Fig. 5a) [10]. The band-pass filter is connected to the antenna feeding microstrip lines to avoid undesired interferences, Fig. 5b) [10].

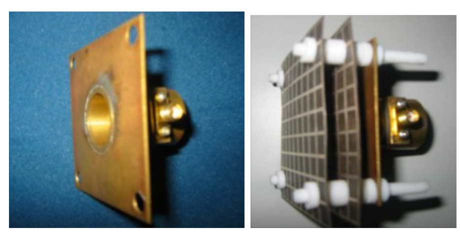


a) **b)**

Figure 5. a) Design of patch antenna tuned with metamaterial structure [10] and b) band-pass filter [10].

4.2 3D Metamaterial Structure for Circular Antenna Gain Increasing

Not only 2D metamaterial structures are used for antennas parameters' improvement, but also 3D structures are designed also for antenna applications. A new approach how to increase the gain of circular waveguide array is shown in Fig. 6 [12].



a) **b)**

Figure 6. Design of cylindrical antenna a) without [12] and b) with metamaterial structure [12].

The using of metamaterial structures is effective and metamaterial structure can realize congregating the radiation energy, so the gain of the antenna increases while the side lobe level decreases [12]. Moreover, a great improvement of gain can be obtained by using metamaterial structure on the array antenna in comparison with the conventional one [12]. It is also expected that the metamaterial structure can be applied in various antennas to improve their radiation performance [12].

4.3 Waveguide Band-Stop Filter Design

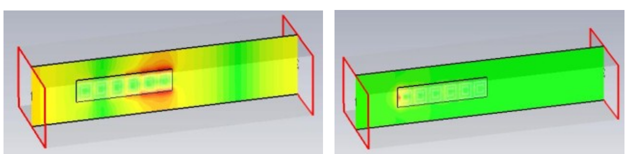
A lot of methods have been proposed for dielectric properties of materials investigation. In our paper we describe the design of microwave waveguide sensor tuned with metamaterial structure (MMS).

Our idea at sensor suggestion was to design sensor capable to complex permittivity changes. This fact can be observed via changes of distribution parameter α in Cole - Cole equation [13-15]. The changes of investigated material permittivity induce also the changes of distribution parameter α. The real and imaginary part of material complex permittivity for various values of distribution parameter α is frequency dependent [14-15].

We proposed the waveguide sensor with metamaterial structure which induces the band-stop properties sensor. The MMS can be designed for chosen frequency band to be capable to the value of investigated dielectric material complex permittivity. In the case, that dielectric characteristic of investigated material change, the sensor start work with another value of distribution parameter and will change the frequency band to which is sensor capable. The frequency spectrum of reflected signal from the investigated dielectric can be investigated and its changes respond to dielectric properties of investigated material.

4.3.1 Numerical Approach

The numerical results for transmission of microwave signal in new waveguide sensor tuned with MMS are in Fig. 7. Figure 7a) shows situation of state which respond to the dielectric properties of investigated material. In the case when dielectric properties of investigated material are changed, the sensor become insensitive and microwave signal is not transmitted, Fig. 7a) where is displayed situation of changed dielectric properties of investigated sample. It can be seen, that a new waveguide sensor is frequency selective and can be capable to the changes of material dielectric properties [13-15].



a) b)

Figure 7. The electromagnetic field distribution in waveguide sensor with metamaterial structure, a) nonzero and b) zero transmission.

4.3.2 The Bandstop Width Adjustment

The metamaterial structure was designed with the conventional spit ring resonators (SRR) on one side of substrate ROGERS RT/DUROID 5870 (ε_r = 2.33, tanδ = 0.0012) and with disrupted wires on the other side of substrate, Fig. 8.

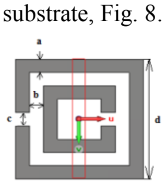


Figure 8. The SRR and wire on the substrate – conventional metamaterial unit.

The designed MMS is strongly resonant around the magnetic plasma frequency ω_m, which is induced by the currents and split, which imitates magnetic poles [16]. This resonant behaviour is due to the capacitive element such as splits, and in turn results in very high positive and negative values of permeability close to the magnetic plasma frequency [16].

The SRR would yield a negative value of permeability and the wire structure a negative value of permittivity [17]. The resonant behaviour and band-stop properties of MMS were numerically simulated and experimentally observed by measuring the transmission through the waveguide with inserted MMS. The proposed metamaterial unit (Fig. 8) interaction with electromagnetic field can be study through frequency dependence of scattering parameters S_{11} a S_{21}, Fig. 9. Figure 9 shows the band-stop properties of one metamaterial unit.

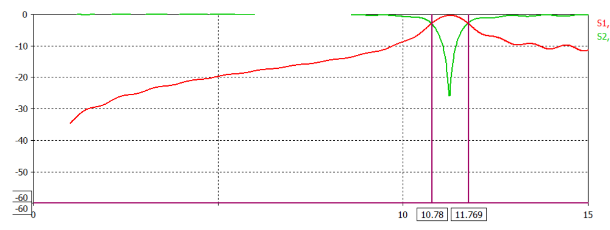


Figure 9. The S_{11} and S_{21} – parameters of band-stop filter characteristics for one metamaterial unit.

The number of metamaterial units was optimised for band-stop (the bandwidth Δf = 1.85 GHz, low frequency f_l = 10.48 GHz, high frequency f_h = 12.33 GHz) with numerical simulation of S – parameters, Fig. 10.

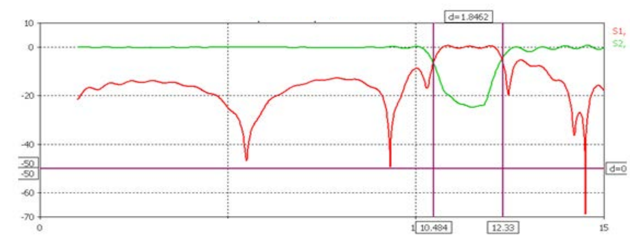


Figure 10. The S_{11} and S_{21} – parameters of band-stop filter characteristics for designed waveguide sensor.

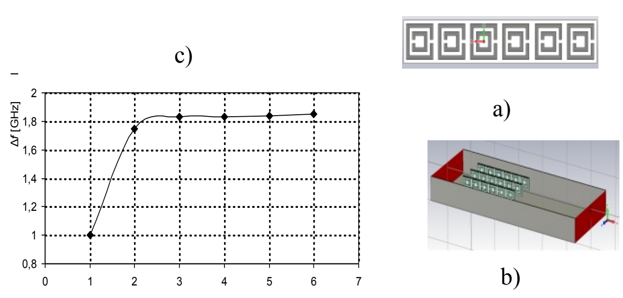


Figure 11. The optimization of waveguide sensor tuned with band-stop filter

The optimal number of metamaterial units on substrate for chosen frequency band-stop is 6, Fig. 11a); optimal number of substrates with MMS inserted to the volume of waveguide is 3, Fig. 11b)

[13-15]. The dependence of band-stop width on number of metamaterial units is in Fig. 11c).

4.3.3 Measurement Results

The measurements of sample dielectric properties changes were performed on the standard laboratory microwave measuring set in the X band frequency with 1 kHz modulation and the reflected signal from the dielectric sample was detected by the selective amplifier.

The dielectric sample was placed in the aperture of open waveguide sensor tuned with metamaterial structure and measurements of the standing wave ratio, position of the voltage minimum were done and also the amplitude of reflected signal was measured.

The experimental results have validated the numerical results and have confirmed that the new sensor tuned with metamaterial structure is possible to use for material dielectric properties changes investigation. Figure 12 shows the frequency dependence of reflected signal from the dielectric sample. It can be seen the band-stop properties of designed waveguide sensor around central band-stop frequency, f_c = 11.5 GHz [13-14].

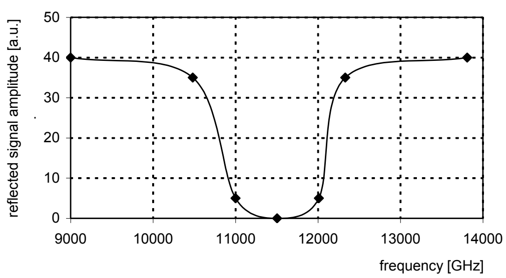


Figure 12. The frequency dependence of reflected signal from dielectric sample.

5. CONCLUSIONS

In paper has been done short overview of metamaterial principle and their possibilities using in two fields: in biomedical and radiocommunication engineering. We have shown that metamaterial structure can improve the properties of classical devices in microwave, terahertz and optical frequency range.

In the paper we also discus our approach to the design of new waveguide sensor assigned for changes of dielectric properties technical and biological materials investigation.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Zouhdi, S., Sihvola, A. and Vinogradov, A. P. (Eds.). 2008. Metamaterials and Plasmonics: Fundamentals, Modelling, Applications. In *Proceedings of the NATO Advanced Research Workshop on Metamaterials for Secure Information and Communication Technologies* (Marrakech Marocco, May 07-10, 2008).

[2] Tao, B. H., Amsden, J. J., Strikwerda A. C., Fan, K., Kaplan, D. L., Zhang, X., Averitt, R. D. and Omenetto, F. G. 2010. Metamaterial silk composites at terahertz frequencies. *Adv. Mater.* 22 (July 2010), 3527-3531.

[3] Wright, D. W. and Cobbold, R. S. C. 2009. The characteristics and applications of metamaterials. *Ultrasound* 17, 2 (May 2009), 68-73.

[4] Veselago, V. G. and Narimanov, E. E. 2006. The left hand of brightness: past, present and future of negative index materials. *Nat. Mater*. 5 (2006), 759–762.

[5] Veselago, V. G. and Narimanov, E. E. 2006. The left hand of brightness: past, present and future of negative index materials. *Nat. Mater*. 5 (2006), 759–762.

[6] Pendry, J. B. 2000. Negative refraction makes a perfect lens. *Phys. Rev. Lett*. 85 (2000), 3966–3969.

[7] http://www.crazyengineers.com/kaleidoscope-made-up-of-metamaterials-can-be-used-in-biomedical-sensors-466/ (September 21, 2011).

[8] Tao, B. H., Chieffo, L. R., Brenckle, M. A., Siebert, S. M., Liu, M., Strikwerda, A. C., Fan K., Kaplan, D. L., Zhang, X., Averitt, R. D., Omenetto, F. G. Metamaterials on paper as a sensing platform. *Adv. Mater.* 23, 28 (July 2011), 3197-3201.

[9] Gong, Y. and Wang, G. 2009. Superficial tumor hyperthermia with flat left-handed metamaterial lens. *Progress In Electromagnetics Research* 98 (2009), 389-405.

[10] Ugarte-Munoz, E., Herraiz-Martinez, J., González-Posadas, V., Segovia-Vargas, D. 2010. Patch antenna based on metamaterials for a RFID transponder. *Journal of Telecomm.* 23, 2 (July 2010), 66-71.

[11] Faktorová, D., Omelka, P. and Isteníková, K. 2010. Antenna parameters enhancement by using artificial magnetic structure. *Journal of Electrical Engineering* 61, 7/s. (2010), 156-159.

[12] Li B., Wu B., and Liang C.-H. 2006. Study on high gain circular waveguide array antenna with metamaterial structure. *Progress In Electromagnetics Research* 60 (2006), 207-219.

[13] Burokur, S. N., Latrach, M. and Toutain, S. 2007. Influence of split ring resonators on the properties of propagating structures. *IET Microw. Antenna Propag.* 1, 1 (2007), 94-99.

[14] Faktorová, D. 2011. Dielectric materials parameters characterization using waveguide probe tuned with metamaterial. In *Proceedings of the Conference ISMOT 2011* (Prague, Czech Republic, June 20-23, 2011).

[15] Faktorová, D., Černek, R. and Isteníková, K. 2011. Design of frequency selective sensor with metamaterial structure for dielectric properties determination. In *Proceedings of the Conference ISEM 2011* (Napoli, Italy, September 07-09, 2011).

[16] Aydin, K. and Ozbay, E. 2006. Identifying magnetic response of split-ring resonators at microwave frequencies. *Opto-Electronic Review* 14, 3 (2006), 193-199.

[17] Majid, H. A., Rahim, M. K. A. and Masri, T. 2009. Microstrip antenna`s gain enhancement using left-handed metamaterial structure. *Progress In Electromagnetics Research M* 8 (2009), 235-247.