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Investigation of Metamaterial Structure Influence on Selective Properties of Microwave Waveguide Sensor

Abstract. *The paper proposes the possibility of double negative metamaterial structure using for the transmission properties of open waveguide probe changing and the possibility of microwave open waveguide sensor tuning with metamaterial structure to be used for non-destructive testing of dielectric materials properties changing. The aim of our work was to develop a frequency selective sensor in microwave frequency band sensitive to changing of dielectric properties of investigated dielectric material.*

Streszczenie. *Opisano możliwość zastosowania struktury metamaterialnej posiadającej właściwości zmiany transmisji falowodu i możliwość srttrojenia czujnika falowodowego mikrofalowego. Czujnik można wykorzystać do badań nieniszczących materiałów dielektrycznych. Opracowano czujnik mikrofalowy o selektywnie zmienianej częstotliwości. (**Badania struktury metamaterialnej w zastosowaniu do mikrofalowego falowodowego czujnika**)*

Keywords: complex permittivity, metamaterial, microwave frequencies, waveguide sensor.
Słowa kluczowe: czujnik mikrofalowy, przenikalność zespolona, falowód.

Introduction

Microwave waveguide sensors can measure properties of materials based on microwaves interaction with matter, and they can be used to provide information about dielectric properties of investigated dielectric material characterized with complex permittivity, and with that knowledge can afford information about moisture content, density, structure, and even chemical reaction [1]. Microwave sensor offers many advantages in comparison with conventional sensor such as rapid and nondestructive measurement [1, 2]. Nowadays, a great interest has been devoted to the sensing applications of metamaterials [1] to increase the sensing properties of conventional waveguide sensor.

Not only absolute value of complex permittivity can be in interest – in some technological processes it is needed information about changing dielectric properties of processed materials and also some pathological processes are connected with dielectric properties of biological tissues changing.

In our paper we have used in the process of the increasing of sensor sensitivity the approach connected with the implementation of artificial metamaterial structure into the classical waveguide sensor volume for frequencies from X-band. This performance of sensitivity increasing is connected with adjusting frequency selective properties of open waveguide sensor by incorporation of designed metamaterial structure to the volume of waveguide sensor.

Sensing and metamaterials

Recently a great deal of interest has been devoted to the potential sensing applications of metamaterials [3]. For example, He *et al.* studied the resonant modes of a 2D subwavelength resonator, and showed it was suitable for biosensing. Jakšić *et al.* investigated some peculiarities of electromagnetic metamaterials convenient for plasmon-based chemical sensing with enhanced sensitivity, and it was believed that metamaterial sensor may have potential applications in environmental sensing, homeland security and biosensing [3, 4]. Alù *et al.* proposed a method of dielectric sensing using *ε* near-zero narrow waveguide channels. Shreiber *et al.* developed a novel microwave non-destructive evaluation sensor using metamaterial lens for detection of material defects small relative to a wavelength. Zheludev analysed the road ahead for metamaterials, and pointed out that sensor applications are another growth area in metamaterials research [3]. Among various applications matamaterials can be used also to improve sensing of classical microwave devices and in such way metramaterials open new degrees of freedom in sensor design like a sensitivity increasing [3].

Metamaterials are defined as artificial effectively homogeneous electromagnetic structure exhibiting unusual electromagnetic properties especially the backward wave and negative refraction not readily available in nature and represent a new paradigm in electronics and photonics [4]. One of the most important features of the metamaterial is the enhancement of the evanescent field [5, 4], which has been used to enhance the properties of near field sensors. The resonant nature of metamaterial artificial structure results in frequency dispersion and narrow bandwidth operation where the center frequency is fixed by the geometry, dimensions of the elements comprising the metamaterial composite [4] and their placement in the one, two or three dimensions space.

Sensor for dielectric properties investigation

A lot of methods have been proposed for dielectric properties of materials investigation [6, 7]. In our paper we describe the design of microwave waveguide sensor tuned with metamaterial structure (MMS), which is capable to the material dielectric properties changes.

Our approach at sensor suggestion was to design sensor capable to complex permittivity change. This fact can be observed via changes of distribution parameter *α* in Cole - Cole equation

(1) $$\dot{\varepsilon}_{\mathrm{r}} = \varepsilon_{\infty} + \frac{\varepsilon_{\mathrm{s}} - \varepsilon_{\infty}}{1+\left(\mathrm{j}\omega\tau\right)^{1-\alpha}},$$

where ε_{s} and ε_{∞}, are static and infinite permittivity, respectively, ω is angular frequency, τ is the mean relaxation time for dielectric and distribution parameter α is a constant for dielectric, having a value $0 \le \alpha \le 1$.

The distribution parameter *α* characterizes the width of relaxation spectra of investigated dielectric material [8]. The changes of investigated material permittivity induce also the changes of distribution parameter *α*.

It can be seen in Fig. 1a) and Fig. 1b) the simulation results for frequency dependence of real and imaginary part of material complex permittivity for various values of distribution parameter *α.*

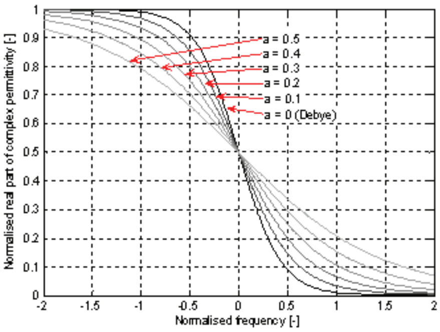


Fig.1a. The frequency dependence of real part of complex permittivity for various values of distribution parameter α in Cole – Cole equation

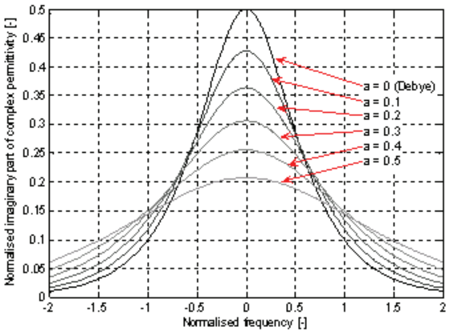
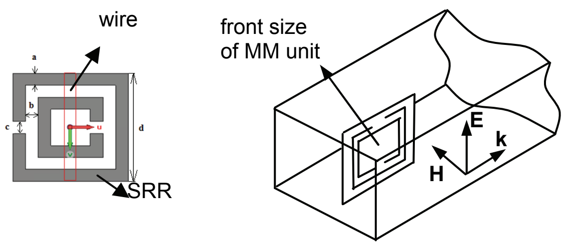


Fig.1b. The frequency dependence of imaginary part of complex permittivity for various values of distribution parameter α in Cole – Cole equation

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 starts work with another value of distribution parameter α of investigated dielectric material and the frequency band, to which is sensor capable, will be changed. The frequency spectrum of reflected signal from the investigated dielectric can be investigated and its changes we consider to be response to dielectric properties of investigated material.

Numerical and experimental results

The numerical simulations of electromagnetic wave propagation in rectangular sensor waveguide with metamaterial structure in the waveguide volume, Fig. 2 were performed by using the commercial software CST Microwave Studio, which is a three-dimensional (3D) full-wave solver that employs the finite integration technique [8]. The design of one double negative metamaterial unit and its principal placement and orientation in the waveguide volume is shown in Fig. 2.



a) b)

Fig.2. a) One metamaterial unit with SRR (front size) and wire (back side), b) the principal position of one metamaterial unit in rectangular waveguide

We have used the classical metamaterial structure with two kinds conductive elements - squared split ring resonators (SRR) and wires [5] (cuprum with thickness h_C = 35 μm) on the substrate. The SRR were designed on the front side of substrate ROGERS RT/DUROID 5870 (thickness h = 0.508mm, ε_r = 2.33, tanδ = 0.0012) and disrupted wires were placed on the back side of substrate. This type of metamaterial structure is one of most simple and most used metamaterial structure in microwave frequency band.

The resonant behaviour and band-stop properties of MMS were numerically simulated and experimentally observed by the transmission coefficient through the rectangular waveguide sensor in which volume were MMS inserted.

The proposed metamaterial unit interaction with electromagnetic field can be study through frequency dependence of scattering parameters S_{11} (reflection coefficient) a S_{21} (transmission coefficient). We have investigated the influence of metamaterial units number on the with of stop-band filter proposed by insertion of metamaterial to the waveguide volume. Figure 3 shows the band-stop properties of waveguide sensor with one metamaterial unit - the bandwidth is Δf = 0.99 GHz (low frequency f_l = 10.78 GHz, high frequency f_h = 11.76 GHz)

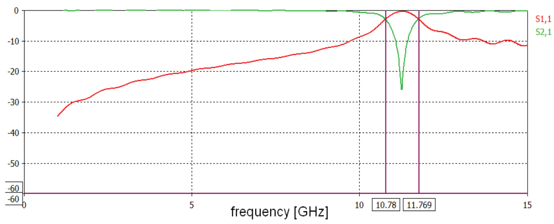


Fig.3. The S_{11} and S_{21} – parameters of band-stop filter characteristics for one metamaterial unit

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. The optimal number of metamaterial units on substrate for chosen frequency band-stop is 6. The dependence of band-stop width on number of metamaterial units is in Fig. 4.

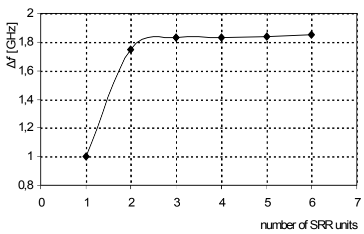


Fig.4. The optimization of waveguide sensor tuned with band-stop filter

In the next step we investigated by using software CST Microwave Studio the influence of metamaterial structures number with six metamaterial units on one substrate on the with of the stopband filter. Figure 5 shows the frequency dependence of scattering parameters and the width of stopband in the case of three metamaterial structures inserted in the volume of the waveguide.

It can be seen from Fig. 3 and Fig. 5, that the width of stopband properties of rectangular waveguide sensor can be stated and adjusted with the number of metamaterial units (Fig. 2a), on the substrate, Fig. 3 and also with the number of metamaterial structures, Fig. 5 inserted to the volume of waveguide sensor.

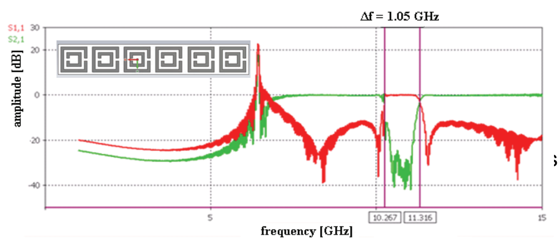


Fig.5. S_{11} and S_{21} – parameters of band-stop filter characteristics for three metamaterial structures in volume of waveguide

The bandstop properties of tuned senor we have used in the process at following the changes of materials dielectric properties.

We have used for experimental confirmation of the possibility of metamaterials using at tuning waveguide sensor two samples of wood, where the change of dielectric properties was achieved by increasing of sample humidity. First one sample was with the humidity 15% and the next one with the humidity 20%. Each sample has been inserted to the volume of waveguide tuned with MMS and the frequency dependence of transmission and reflection coefficient was investigated.

The comparison of the transmitted signal from wooden sample (humidity 15%) inserted in the volume of waveguide tuned with one, two and three metamaterial structure is in Fig. 6.

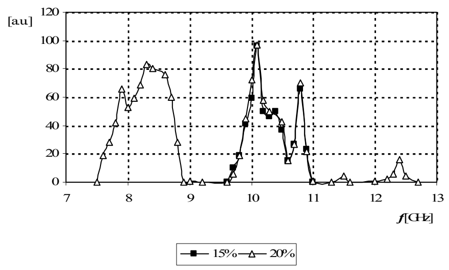


Fig.6. Frequency dependence of transmission coefficient amplitude for waveguide sensor tuned with one, two and three metamaterial structures

From the Fig. 6 it can be seen, that only one bandpass (from 9.6 GHz to 11 GHz) of waveguide sensor can be achieved by using three metamaterial structures. In the case of one or two metamaterial structures inserted to the waveguide volume another bandpass occurs from 7.5 GHz to 9.0 GHz.

In the next measurement we investigated the influence of wooden sample humidity increasing on frequency dependence of microwave signal transmission through the waveguide tuned with three metamaterial structures, the experimental results are in Fig. 7.

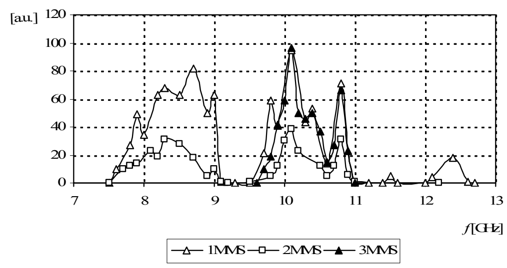


Fig.7. Frequency dependence of transmission coefficient amplitude for two wooden samples with different humidity

It can be seen from Fig.7, that in the case of wooden sample humidity increasing in 5% the second one bandpass will occurs – in this case the loss factor of dielectric sample was changed. It can be seen from Fig. 7 that the sensor tuned with metamaterial structure with appropriate design for desired permittivity of investigated material is capable to the dielectric properties changes.

Conclusion

The numerical and experimental results have shown the new approach to the investigation of material dielectric properties changing. We have shown that the waveguide sensor tuned with designed metamaterial structures has the frequency selective properties. The selective properties can be adjusted with the number of metamaterial units and with the number of metamaterial structures inserted in the volume of waveguide. The metamaterial structure is strongly frequency dependent and this fact allows to choose appropriate frequency region which is capable to variation of biological tissue dielectric properties. The tuned open waveguide sensor can be used in the technical practice in the technological process at the monitoring of dielectric properties changes and also in medical diagnostics of diseases to which symptoms appertains the change of dielectric properties of biological tissue, e.g. oncology diseases.

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