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MICROWAVE NONDESTRUCTIVE TESTING OF CONDUCTIVE MATERIALS USING SENSOR TUNED WITH NEGATIVE PERMEABILITY AND PERMITTIVITY STRUCTURE

Dagmar Faktorová* — Adrina Savin — Raimond Grimberg****

Microwave nondestructive testing methods become nowadays ever more exploited electromagnetic evaluation method not only dielectric but also metal materials surface and volume homogeneity. A novel microwave sensor created from open waveguide with metamaterial structure for non-destructive testing was developed in an attempt to increase the sensitivity of the microwave nondestructive evaluation method for detection of defects in metal and dielectric materials. In the paper we describe the new approach with implementation of metamaterial structure with negative permittivity and negative permeability over the open waveguide sensor in order to increase the gain and achieve the optimal radiation pattern of designed waveguide sensor with metamaterial structure in microwave X-band.

Keywords: waveguide sensor, metamaterial, filled defect, microwave frequencies

1 INTRODUCTION

The published information about the metamaterial structure (MMS) properties in microwave frequencies band [1-3] inspired an interest in their use also in microwave non-destructive testing particularly from the standpoint of the sensitivity increase at the scanning of the defect. In this regard the experiments presented in this paper were directed. From many existing microwave measuring methods a more accurate open waveguide reflection method was chosen. The reflected signal was monitored from the point of view the frequency dependence and the different distances the probe from the empty defect. Also the amplitude of reflected signal from defect with dielectric filling [4] was measured. The amplitude of reflected signals detected by the waveguide probe with the metamaterial and without it are compared. The impedance of the designed metamaterial structure was measured too.

2 INTEGRATION WAVEGUIDE SENSOR WITH METAMATERIAL

Often used approach how to increase the sensitivity of microwave waveguide probe is to increase the excitation frequency, which reduces diffraction limit of the conventional probe but this comes with a reduction in the depth of penetration in the volume of investigated material [5, 6]. Another approach for increasing the sensitivity of waveguide probe which we described in paper is using of metamaterial structure incorporated to the open waveguide probe.

Metamaterials which are defined as effectively homogeneous electromagnetic structure exhibiting unusual electromagnetic properties especially the backward wave and negative refraction not readily available in nature, represent a new paradigm in electronics and photonics. One of the most important features of the negative material is the enhancement of the evanescence field [7], which has been used to enhance the near field sensors.

The currently available artificial structures are realized by using planar structures with specific topology in *x-y* plane. These planar structures provide enhanced permeability only in the direction normal to the plane of the MMS and enhanced permittivity in the directions tangent to the plane [7]. In our paper we study the influence of negative permeability medium on the performances of a waveguide probe. Metamaterial structure which we used for waveguide probe tuning consists of arrays of unit cells of split resonators (SR), which was designed by Pendry et al. [1, 2] and of wires. Split resonators behave as LC resonant circuits which can be excited by a time-varying electromagnetic field with a non-negligible component applied parallel to the split resonator axis.

The metamaterial cover of waveguide probe plays a role of controlling the electromagnetic wave propagation direction. In the far-field view, the sideward radiation is reduced and forward radiation can be enhanced in the radiation patterns and in the near field view, the sensitivity of probe is increased. As a result, a more directional and higher gain probe will be obtained.

The metamaterial plate with cell units at face side and wires at back side Fig. 1a was designed and optimized for conventional waveguide probe tuning [9]. The improvement in sensitivity and resolution was achieved by using double negative material in conjunction with the classical waveguide probe. The cell units and wires are placed on dielectric substrate ROGERS RT/DUROID 5870 with relative permittivity $\varepsilon = 2.33$ in the form of a 2–D and provide negative reflection of electromagnetic wave.

Figure 1b shows the metamaterial structure incorporated with the waveguide probe. The optimisation of parameters of new probe was done by using software CST Microwave Studio. The metamaterial structure is placed in the front of waveguide probe. The number of unit resonant cells and wires along the *x* and *y* axis is $N_x = 7$ and $N_y = 7$ and the distance between units is 5 mm, the same distance is between the wires on the other side of used substrate. The incident electromagnetic wave propagates along the *z* direction, while

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the vector of electric intensity $\bar{E}$ is oriented along the x direction, and magnetic intensity $\bar{H}$ is oriented along the y direction.

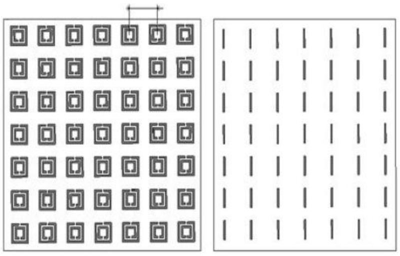

Fig. 1a. Face (left) and back (right) side of designed metamaterial structure

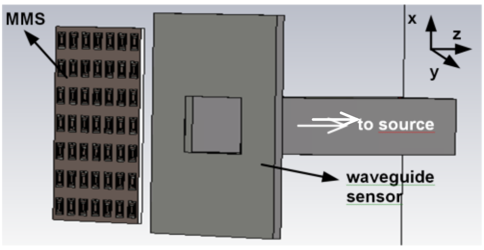

Fig. 1b. Waveguide probe tuned with designed metamaterial structure

Metamaterials are in general anisotropic and dispersive; therefore a various numerical method should determine the permeability tensor at different frequencies. Usually, metamaterial anisotropic magnetic medium can be characterized by the permeability tensor [2, 8]

$$\overline{\overline{\mu}} = \begin{bmatrix} \mu_{xx} & 0 & 0 \\ 0 & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{bmatrix} \tag{1}$$

where $\overline{\overline{\mu}}$ follows the Lorentz model and $\mu_{xx} = 1$, $\mu_{yy} = 1$, $\mu_{zz} = 1 - \dfrac{F\omega^2}{\omega^2 - \omega_{\mathrm{m}}^2 + \mathrm{j}\gamma\omega}$, where ω is the angular frequency, γ is the loss coefficient, ω_{m} is the magnetic plasma angular frequency and F is the fractional volume of SR unit cell Value of parameter F depends on geometrical parameters of designed resonant unit cell which create the metamaterial structure [8].

The thin wire array can be used to simulate the plasma, because their effective permittivity is expressed in the same form [9, 10]

$$\varepsilon_{\mathrm{eff}} = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2}, \tag{2}$$

where ω_{p} is the plasma frequency, ω is the frequency of the incident electromagnetic wave. The effect of negative permittivity in the wire structure is while ω is less han ω_{p}. The material parameters of metamaterial structure - relative permittivity and relative permeability were calculated [9]. The designed metamaterial structure allocates resonant feature and is characterized by negative refraction index.

3 EXPERIMENTAL RESULTS

Measurements of reflected wave signal amplitude from defect in metal sample were realized on the standard microwave measuring set in the basic connection schematically represented in Fig. 2. As a microwave signal source the signal generator HP 8684D with the frequency stabilization was used.

The measurements were realized on the X band frequency with 1 kHz modulation and the measured signal was detected by the selective amplifier. For the sample positioning towards the detector the crossing shift with the micrometrical reading was used.

For the detected signal quality evaluation on the one hand from the point of view of the instrument layout and on the other end from the point of view of the very metamaterial, measurements of more quantities and experiment conditions influencing the detected signal were taken.

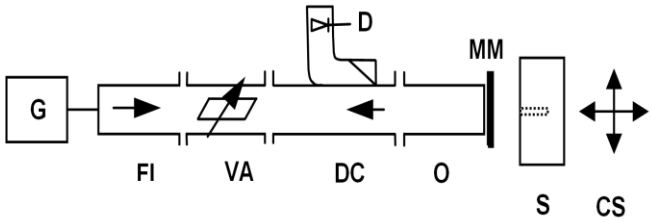

Fig. 2. Experimental setup for microwave method: G – microwave generator, FI – ferrite isolator, VA – variable attenuator, DC – directional coupler, O – open waveguide probe, MM – metamaterial structure, S – sample with defect, crossing shift, D – detection diode, CS – crossing shift

Since the very metamaterial structure has its own frequency characteristic, the measurement interconnected with defect detection was taken in the layout according to Fig. 2 with the sample in front of the probe. As a sample it was used a steel prism with an artificial defect 9 mm deep and 1 mm with. All measurements interconnected with the defect were performed on this sample. During the reflected signal measuring the directional coupler was applied in the indicated orientation. The measurements were taken in the frequency band round 10 GHz.

The measurement layout enabled at the adjusted frequency to measure the reflected signal with the metamaterial structure and immediately afterwards without it. The measuring results are presented graphically in Fig. 3, where the difference by which the signal increased, respectively reduced with the use of metamaterial towards the signal without use the metamaterial, for each frequency is plotted. The processing like this provides with immediate information about the metamaterial influence on the measured signal.

From Fig. 3 it is possible to find the maximum of the signal amplitude reflected from investigated defect, [11]. The frequency of reflected signal maximum corresponds to the resonant character of metamaterial structure incorporated to the waveguide probe. It is needed from the nondestructive testing practical point of view to suggest metamaterial structure which resonant properties will be in agreement with the quarter wave transformer property of investigated defect [9]. If this condition is fulfilled it is possible to achieve the maximum of reflected signal.

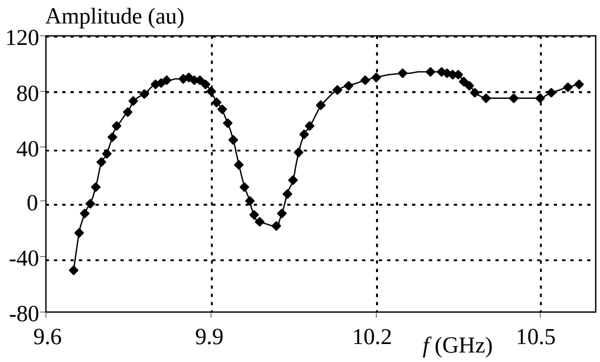

Fig. 3. Frequency dependence of the signal reflected from the defect

The very instrument layout in the experiment, that is a combination of individual elements, represent a connection of parts with different impedances and thereafter resulting reflections. At a constant configuration of the other elements, the resulting signals will also be dependent on the distance probe-defect. The detection of the reflected signal dependence under these circumstances was the object of further assessment of the material characterization at the defect detection, [11]. The experiment arrangement was the same as in the Figure 2, but the distance probe-defect was changing by means of the crossing shift and the frequency was remaining constant. The measurements were in this case performed for the situation with the metamaterial and without it just as at the frequency dependence measurements. The measuring results are in the Fig. 4.

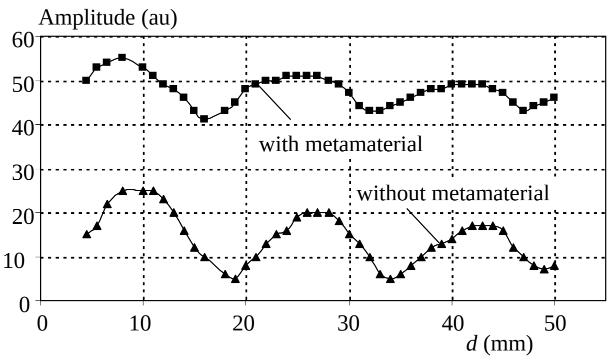

Fig. 4. Dependence of amplitude of signal reflected from defect on the distance probe – defect

The course with metamaterial indicates the signal reflected from the defect by the probe with the metamaterial for different distances of the probe from the defect. The course without metamaterial indicates the analogous dependence with the probe with metamaterial. Both courses as to the shape are identical, but the detected level of the course with metamaterial shows a favorable influence of the metamaterial. Their periodic course documents a well known influence of the phase conditions and they warn about the necessity to take into account the experiment arrangement.

Because the aim of the microwave non-destructive testing - as of the other methods in non-destructive testing – is obtaining information about the existence, geometry of a defect and its characteristic connected with dielectric filling, also experiment of these character were performed. The measuring equipment and the technique at these measurements are essentially identical with some published arrangement [9, 11], but in the presented measurements a probe provided with the metamaterial structure was used. For the sake of comparison of the influence on the measurement, also measurements with the probe without the metamaterial were performed. The measuring results are in Fig.5, 6, and 7.

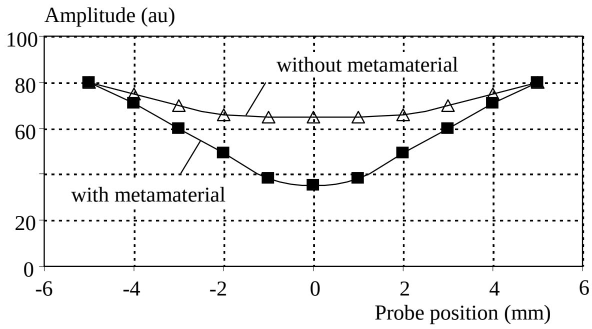

Fig. 5. Dependence of reflected signal amplitude on probe position above defect filled with air

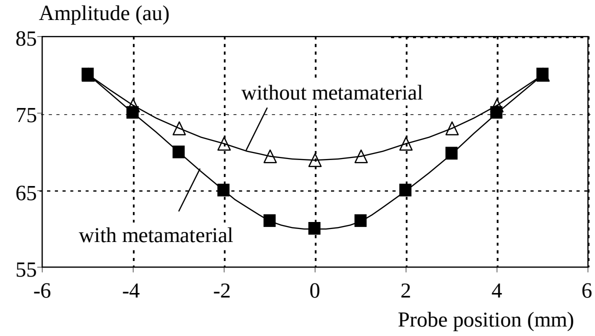

Fig. 6. Dependence of reflected signal amplitude on probe position above defect filled with rust

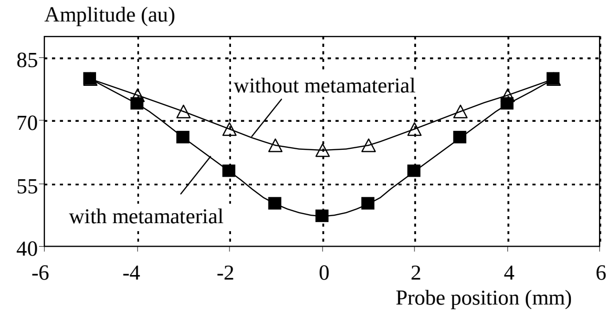

Fig. 7. Dependence of reflected signal amplitude on probe position above defect filled with transformer oil

In each figure there are two courses of the signal reflected from the empty defect and belonging to these two probe characters. The defect was picked up with the open waveguide and its wider side was parallel with the defect. The coordinate "position" gives the waveguide shift from the position close in front of the defect up to the position close behind the defect (that is the defect passes through the complete probe width). It is visible from Figs. 5, 6, and 7 that the reflected signal with the metamaterial on the probe is more noticeable.

In this context also the comparison of differences between reflected signal from the empty defect and the defect with dielectric filling with metamaterials can give some information about defect conditions. We have calculated the differential signal between empty defect and defect filled with rust and transformer oil. Such differences are plotted in Fig. 8a) and Fig. 8b).

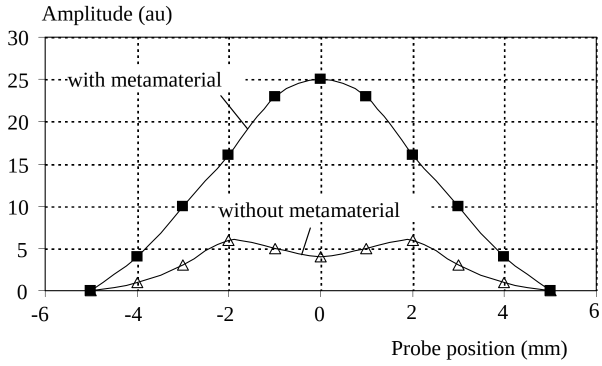

Fig. 8a. Differential reflected signal amplitude for defect filled with rust

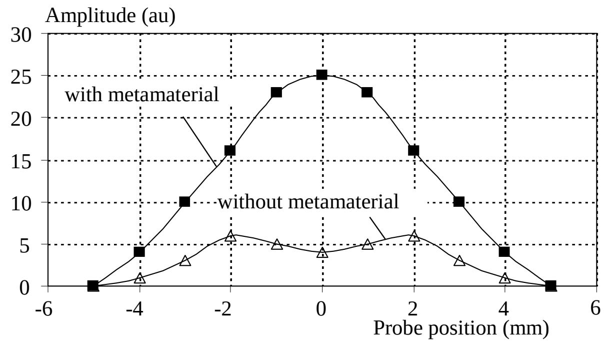

Fig. 8b. Differential reflected signal amplitude for defect filled with transformer oil

From Fig. 8a) and Fig. 8b) it is obvious that the probe with metamaterial structure markedly enhances the detected signal. As the metamaterial structure has also focusing properties, the signal shape can be evaluated more simply.

5 CONCLUSIONS

The experimental results confirm a favorable metamaterial influence on the signal reflected from the defect, but simultaneously warn about circumstances which are necessary to be taken into account at a particular application of waveguide probe furnished with the metamaterial. Apart from universal influences caused by frequency dependences and mutual individual elements arrangement inclusive of the probe distance, it turned out that attention should be paid to the metamaterial structure at a specific application. Further interesting preferential treatment of such detection with the metamaterial can give a focusing of the metamaterial structure, indications of what it was possible to notice at our measurements, [11].

By using numerical simulation it is possible to design the metamaterial structure with properties needed for materials homogenity investigation. Metamaterial structure has to be designed also for desired frequency used at nondestructive testing of metal or dielectric materials.

Analogous tentative experiments carried out on dielectric samples, [11] showed a similar perspective of use such technique also in this area where it was possible to detect a metal object under the dielectric surface. We expect more detailed experiments will bring in this respect results about further abilities of metamaterial structure application in non-destructive testing.

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