Investigation of Filtering and Sensing Properties of Complementary Metamaterial Resonant Cells by Computer Simulation

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Abstract. In this paper we propose a resonant structure based on complementary metamaterial that can be used to control and monitor parameters of a material under test. We used CST Studio Suite to create a computer model of the proposed device and simulate it performance. The performance of the sensor is characterized by its scattering parameters that can be calculated by simulation. The results obtained are then analyzed and used to derive the relation between the sensor’s resonant frequency and the characteristics of the analyte. The proposed resonant structure and method can be used for nondestructive evaluation of dielectric substances, defect control, monitoring and measurement applications.

1. Introduction

Recently microwave sensors and sensitive elements has become one of the most promising way to solve many problems in chemistry [1], biology and medicine [2]. These industries are experiencing an increasing need for low-cost, but effective means of monitoring of substances’ parameters. Moreover, often, especially in medicine, an invasive control/monitoring is required. Microwave sensors built on resonant elements of microwave lines can meet these requirements. The operational principle of microwave sensors is based on interaction between the sensor’s field and analyte, that leads to shift of resonant frequency.

Microwave sensing hugely benefited from introduction of metamaterials. Metamaterial is an artificially made composite periodically arranged media. Its properties are dependent on its structure rather than its composition. As the unit cells of MTMs are always smaller than a wavelength, the incidental wave interacts with the metastructure as a whole. Theoretical research on what was later named metamaterials was firstly carried out by V Veselago in 1967 [3], while the real metamaterial was introduced by Pendry et al. in 1999 [4]. They used conducting wires and split ring resonators (SRR) as unit cells for their metamaterial. Since then many new types of unit cells were introduced. The high popularity of metamaterials in microwave electronics is advocated by huge advantages they can offer. MTM-based structures can provide a strong localization and enhancement of fields as well as exotic features not available in “classic” electrodynamic systems and natural materials. These properties sparked a remarkable interest in MTMs and led to a significant number of proposed applications for MTM-based structures and devices. Nowadays they are used as antenna elements, phase shifters, parts of filters and attenuators etc [5-7].
This letter presents a research of filtering and sensing properties of complementary "Jerusalem cross"-shaped metamaterial resonant cells. The proposed structures were simulated in CST Studio Suite software and their S-parameters were calculated.

2. Resonant cells design and modelling
The resonant cells presented in this letter are complementary variants of classic Jerusalem cross MTM unit cell described in [10-13]. Usually complementary unit cells are etched in the ground layer of a microstrip of another transmission line that excite them. Three types of resonant cells have been studied: a simple complementary Jerusalem cross (CJC) cell, a complementary contour Jerusalem cross (CCJC) cell and a complementary mushroom Jerusalem cross (CMJC) cell. All three types of cells are presented in the figure 1.

![Figure 1. Unit cells (from left to right): CJC, CCJC, CMJC.](image)

The CMJC unit cell also has a “leg” – a conductive element that connects its central cross with the microstrip. Basically, CMJC is very similar to classic mushroom MTM that are often used as elements of frequency-selective surfaces (FSSs).

Each type of the cells acts like a distributed oscillator circuit. The electric field is concentrated inside the etched area of the ground layer, so the equivalent capacity of the unit cell can be regulated by varying the size of etched area. That, in addition to varying the general size of the unit cell provide opportunity to determine the resonant frequency of the cell. In order to keep it relatively low, the dimensions of the unit cells are set as: $a = 9$ mm, $b = 4.5$ mm, $c = 1$ mm, $d = 8.5$ mm, $e = 4$ mm, $f = 0.5$ mm. The materials used in the simulation are copper for all metallization and FR-4 for substrate.

The properties of the resonant cells can be enhanced by placing several of them in a row along the microstrip line. This way equal unit cells act as 1D transmission line and keep the properties of a single cell while also enhancing them. It manifests itself as increasing of resonant notches depth while the resonant frequency remains the same for a single cell and a series of equal unit cells of the same type.

The resonant properties of the cells were studied by computer simulation in CST Studio Suite software. The frequency range was from 0 to 10 GHz and the boundary conditions were set as open space. Initially, a single unit cell of each type was simulated separately and its S-parameter were calculated. Then the simulation was repeated for series of five consecutive unit cells. The results of those simulations are presented and described in the following section.

3. Simulation of general properties of the proposed resonant unit cells
As it was mentioned before, the resonant frequency of the proposed unit cells is determined mainly by the capacitance of the gap between the central conductive cross and the rest of ground layer. In case of CMJC it is also affected by the presence of conductive “leg” that connects it to the microstrip line directly.
Figure 2. Reflection coefficient $S_{11}$, transmission coefficient $S_{21}$ and VSWR for CJC unit cell.

Figure 3. Reflection coefficient $S_{11}$, transmission coefficient $S_{21}$ and VSWR for CCJC unit cell.

Figure 4. Reflection coefficient $S_{11}$, transmission coefficient $S_{21}$ and VSWR for CMJC unit cell.
The results obtained show that CJC, CCJC and CMJC unit cells perform differently in the provided frequency range. CJC acts as a low-pass filter with a cutoff frequency 4.67 GHz and max attenuation of 24 dB. CCJC structures performs as a multi band-stop filter. The stop-bands are 3.5-5.2 GHz, 5.7-6.8 GHz as well as above 7 GHz. Finally, CMJC provides a stop-band from 4.7 to 8.9 GHz. Additional simulations showed that the sequences of identical unit cells perform the same way as singular unit cells, although the series are able to provide deeper notches i.e. greater attenuation without disturbing the resonant frequencies.

4. Sensing properties simulation

The operational principle of microwave sensors is based on interaction between the sensor and the material under test (MUT). Placing a test sample in the near zone of the sensor leads to general distortion of the field due to additional coupling between the sensor and the MUT. Consequently, it leads to shift of resonance frequency. This shift is associated with the distorted field volume i.e. the difference between initial field configuration and its MUT-affected condition. The shift value is determined either by the volume of the distorted field or by the degree of distortion itself. The volume of the distortion is associated with the volume of the MUT and, therefore, its geometrical parameters. The degree of distortion is dependent on electromagnetic parameters of the MUT like permittivity or permeability.

The shift of resonant frequency can be described using the formula from [14] (approximated for small distortions):

$$\Delta f \over f_r = \int \Delta \varepsilon a |E_0|^2 + \Delta \mu a |H_0|^2 dv \over \int (\varepsilon_0 |E_0|^2 + \mu_0 |H_0|^2) dv$$ (1)

Here $\Delta \varepsilon a = \varepsilon a - \varepsilon_0$; $\Delta \mu a = \mu a - \mu_0$, $E_0$ and $H_0$ are electric and magnetic field respectively. $f_r$ – resonant frequency for the undistorted field (or if MUT is air). $\Delta f = f - f_r$ is the resonance frequency shift, $dv$ is the volume of consideration. The resonant frequency is also dependent on the properties of the matter. In case air is taken as a reference material, this dependence can be formulated as follows:

$$f_{r,MUT} = f_{r,air} \sqrt{\varepsilon_{eff,MUT} \over \varepsilon_{eff,air}}$$ (2)

Paper [15] suggests approximation using a polynomic function:

$$f_{r,MUT}(\varepsilon) = \sum_{i=0}^{N} A_i (\varepsilon - 1)^i$$ (3)

The coefficients $A_i$ are derived using simulation results. It is also supposed that the reference material is air. $\varepsilon$ is the permittivity of the MUT.

We chose CCJC unit cell as a base for the sensor due to its sharp resonance and its relatively low frequency. The curves in figure 5 are associated with resonances that were acquired during the investigation of the sensing properties of the resonant cell. The simulated resonances frequencies are 4.38 GHz, 3.99 GHz, 3.43 GHz, 2.67 GHz for air, Teflon, FR-4 and alumina respectively.
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Figure 5. The simulated transmission coefficient S21 for air (1), Teflon (2), FR-4 (3) and alumina (4).

Figure 6. Calibration curve for the proposed sensor.

The calibration curve depicted in figure 6 was acquired using the second order polynomic function. This curve can be used for evaluating permittivity of unknown MUTs using the proposed sensor.

5. Conclusions
Three types complementary "Jerusalem cross"-shaped metamaterial resonant cells were investigated and simulated numerically. The simulation results show that the proposed structures can be used as a base for a filter and a sensor. The effectiveness of the filtering can be greatly increased by grouping the unit cell in sequences on the ground layer alongside the microstrip line. The structure can also be used as a sensor. The relation between the resonant frequency of the sensor and the parameters of the MUT allow monitoring and control of these parameters through resonant frequency shift detection. The acquired calibration curve can be used for evaluating permittivity of unknown MUTs.

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