Extracting Dielectric Permittivity with a Cross-Like Stripline

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Abstract — Parametric retrieval of electromagnetic properties is important for both new materials characterization and an accurate design of devices. While quite a few techniques have been developed over the years, precise mapping of high-permittivity samples remain challenging. Here we advance a so-called micro-strip technique, where transmission coefficients of a waveguide system with an analyte on top are used to extract electromagnetic parameters of the later. Our cross-like strip line configuration has a split ring resonator on one edge and an open circuit termination on another. This design allows performing a simultaneous test of cylindrical and rectangular samples. Our new post-processing scheme was tested on a water-filled container and showed 96.3% accuracy, assessed by comparing our results with tabulated data.

1. INTRODUCTION

Material science keeps developing and provide novel composites with remarkable electromagnetic properties. Apart from the celebrated topic of metamaterials, where, in principle, electromagnetic constants can be tailored on demand [1],[2], there are other promising directions, based on conventional approaches. For example, high-quality ceramic materials, obtained by sintering of powder in a preform, become extremely important in a range of modern applications [3]. Since free space wavelength shrinks with the refractive index of an embedding medium, high index materials allow performing an efficient miniaturization of electromagnetic devices. This capability is especially important for MHz and low GHz applications, where antenna devices are relatively bulky in respect to integrated circuits, powering them. However, this promising size reduction approach comes at a price—the design become increasingly sensitive to refractive index fluctuations. In particular, a small inaccuracy in estimating the permittivity can lead to appearance of parasitic resonances, which can completely govern the performance. Consequently, a capability of an accurate parametric retrieval of high-index composites is a new challenging and highly important task.

Existing approaches to material parameters extraction include anomalous dispersion analysis method on low-GHz range[4],[5], sensor response analysis for ε-μ-extraction[6],[7], and stretchable resonators techniques [8]. In many occasions waveguide [9] and strip line [4],[5],[7] geometries are in use owing to the ease of their practical implementation.

Here we utilize the transmission line technique for special purposes of high-permittivity samples retrieval. We also develop a new algorithm for data post processing. Our approach has several key advantages, which allow an accurate assessment of both real and imaginary parts of permittivity. Typically, a real (ε') and an imaginary (ε'') parts of a response function, being linked to each other by Kramers–Kronig relations, affect each other in a measurement, making their retrieval less accurate. In our method, however, ε' is predominately responsible for a frequency shift, while ε'' influences the resonance quality factor. While this behaviors is quite obvious from basic physical consideration, the measurement is done by assessing both amplitude and phase information, making the data extraction significantly more accurate. The main drawbacks of our method is a demand to perform an accurate pre-calibration, though similar steps are done in waveguide-based techniques. Another issue, inherently directly linked to the high-permittivity samples retrieval is an extreme sensitivity to noise. In order to reduce the noise sensitivity we apply Savitsky-Golay signal filter[10], which increase the method robustness without a significant loss of accuracy.

2. RESULTS

The circuit, presented in the Fig. 1 (a, b), consists of a strip line, connected to feeding ports. The geometry crossed with another strip line, which has one open circuit edge, while another is functionalized with a circular split ring resonator. The geometry is placed above a ground plane and the spacer is FR-4 dielectric. The design of the scheme is an improved T-like design[4] is conditioned by the aim to gain high-quality peaks that are relatively uniformly split between 1 GHz and 20 GHz to achieve the permittivity on these frequencies. On the stripline there can be a sample, which can be either rectangular parallelepiped or a cylinder those are put on the simple
stripline or above the SRR-unit correspondingly with their shape-factor. It is noticeable that the position of the probe brings the impact into the final result, so it is recommended to cover the SRR (or a free-end) uniformly or even leave outbounds to avoid possible discrepancies between the numerical experiment and the real one.

![Fig.1. (a) Geometry of the circuit. (b) Picture from CST Studio Suite.](image)

This model is put into the numerical experiment using CST Studio Suite. Its parameters are given below in the Tab. 1. below.

| Tab.1. Parameters of the circuit |
|---------------------------------|
| Parameter name                  | Value      |
| PCB length                      | 94 mm      |
| PCB width                       | 20 mm      |
| Transmission line length        | 20 mm      |
| Transmission line width         | 3 mm       |
| Stripline length                | 30 mm      |
| Stripline width                 | 2 mm       |
| SRR outer radius                | 2 mm       |
| SRR inner radius                | 1.5 mm     |
| Copper foil layer height        | 0.07 mm    |
| FR-4 layer height               | 1 mm       |

**Computational algorithm**

The key is in sweeping two parameters inside the digital experiment: tangent delta, which is responsible for loss in the material, and real part of relative dielectric permittivity. First, we set the tangent to a relatively small value and do a sweep with $\varepsilon'_r$. Then we put the achieved spectra into our program that continues analyzing data. For every $\varepsilon'_r$ spectra the algorithm converts it into module/phase view and then finds every inflection point on the phase curve and memorizes its frequency. The trend of the inflection is the same for all spectra (Fig. 2a), but their special frequencies differ. The algorithm takes first derivative of the phase curve (Fig. 2b) and finds all significant peaks in it. These peaks corresponds to inflection points in original signal. These points will be further used for finding the frequency shift. After all the inflection points for all spectra are found, one of the spectra ($\varepsilon'_r = 2$ in the Fig. 2) becomes a reference one and the program calculates for other their frequency shifts relatively to the reference one. Then the algorithm predicts sample $\varepsilon'_r$ basing on the calibration values fitting curve. This means $\varepsilon'_r$ is responsible for the relatively small (up to several hundreds of megahertz) frequency shifts of resonant peaks on the phase derivative plot. For our numerical experiment we set a task to predict water’s dielectric permittivity. We made an experiment with water sample on the stripline and put its spectrum into algorithm.

![Fig.2. (a) Phases of signals and (b) Derivatives of these phases for $\varepsilon'_r = 2$, $\varepsilon'_r \approx 15.5$, $\varepsilon'_r \approx 120$ for the same $\tan \delta$ and $\varepsilon'_r$ water which is studied. (c) Calibration plot (yellow) and water position (blue) on the frequency axis.](image)
As we analyzed frequency shifts for $\varepsilon'$, for the imaginary part of dielectric permittivity ($\varepsilon''$) we analyze the half-width of the corresponding resonant peaks as far as with increasing losses in material the peak diffuses.

![Fig.3. (a) Phases of signals and (b) Derivatives of these phases for $\tan\delta = 0.1$, $\tan\delta \approx 0.41$, $\tan\delta \approx 1.70$ for the same $\varepsilon'$ and $\tan\delta_{\text{water}}$ which is studied. (c) Calibration plot (blue) and water position (yellow) on the frequency axis.](image)

**Iterative nature of the experiment**

After we gain the approximately value of $\varepsilon'_{\text{sample}}$ for our sample from the first attempt, there is a sense to make the second part of experiment for tangent delta using that exact value of $\varepsilon'_{\text{sample}}$. Thus we can get closer to the real value of $\varepsilon_{\text{sample}}$, using better calibration curve. Then we take this value of tangent delta and re-make the first part of experiment, gaining new $\varepsilon'_{\text{sample}} = \varepsilon'_{(2)}$ from the second attempt and new calibration curve for the real part of dielectric permittivity. Repeating these iterations we are able to get the precise value of $\varepsilon_{\text{sample}}$. In our experiment after the first iteration we obtained $\varepsilon'_{(1)} = 80.83 + 25.87i$ on the 1.11 GHz frequency, whether the exact value for this frequency is about $78.00 + 25.59i$. That makes a total error of 3.7% after the first iteration.

**Real experiment**

To bring this experiment to life we built an appropriate PCB-plate with a cross-like stripline on the surface (Fig. 4a and 4b). After that we connect the circuit to a Network Analyzer, gain its phase spectrum (Fig. 4c) and implicited it into our algorithm. The in-between result is a smoothed curve for the derivative of the sample phase spectrum (Fig. 4d).

![Fig.4. (a) and (b) Cross-like stripline structure with a parallelepiped PLA sample or cylindric resin sample. (c) Typical sample signal phase specter. (d) Phase derivative (blue) and peaks determined (other colors).](image)

The last but not the least step is to put these spectra into the algorithm to proceed the experiment and gain the final value of dielectric permittivity. It is significantly important to notice that we can gain only values on the frequencies for inflection points on the phase curve. Changing the geometry of our stripline, we can measure epsilon in every particular position of inflection.
3. CONCLUSION

At the conference we are going to present the complete high-accuracy method for enumeration \( \varepsilon_r \), using stripline circuit and our computational algorithms. There will also be discussed the impact of form-factor on the determination the exact value and the results for different humidity, densities and materials e.g. water, PLA, resin and some others in range 1 GHz to 20 GHz.

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