Complementary frequency selective surfaces in a waveguide simulator

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Abstract—This paper presents an application of complementary frequency selective surface (CFSS) structures in a waveguide, for permittivity characterization of dielectrics. Parametric studies using electromagnetic (EM) simulations of different structures have been carried out and the results presented.

Index Terms—complementary FSS; permittivity characterisation; waveguides

I. INTRODUCTION

Dielectric materials form a crucial part of various microwave systems which has led to the need for robust techniques for the characterization of these properties. Different simulation and measurement techniques exist for measuring the complex permittivity of homogenous and heterogeneous materials. These methods include the use of microstrip and ring resonators [1–4], plane wave techniques [5–7] and waveguides [8–11] including their different variations.

The method presented in this paper applies the operation of a dipole resonator and that of the complementary frequency selective surface structure (CFSS) [12] which potentially could lead to a new method of dielectric measurements. This paper examines how these structures can eliminate the instability of other resonators to produce a more accurate result. The CFSS is based on having very closely coupled FSS printed on either side of a dielectric material in order to create narrow passbands. Some of the advantages of using this technique are the low insertion loss, the stability and high Q-factor of the passband which occur at frequencies lower than that of the individual array. This passband is highly stable with angle/frequency. From Fig. 1, the unit cell sizes of each element for each array are equal but the spacing between the elements in the conductor array is different from that of the aperture array. The length of the conductor and aperture are the same.

II. OUTLINE OF METHOD

A suitable CFSS structure is placed within an X-band waveguide and simulated using the FDTD simulation tool, Empire XCell®. The structure of the CFSS is as shown in Fig. 1. The CFSS is made up of two arrays that complement each other—an array of conductors and apertures. The length of the conductors and apertures are represented by l, while the unit cell size is $s_1 \times s_2$ in Fig. 1. Individually, these arrays resonate when an EM plane wave impinges on them as shown in Fig. 2. Note, in Fig. 2. the parameters used are as follows: the conductors and apertures were 3.5mm long; the unit cell size $S_1 \times S_2$ were 5.715 × 4.572mm. The dielectric in-between the two layers was 50microns thick with a relative permittivity of 3. By making sure that the dimensions of these elements of these arrays are identical and bringing them in very close proximity, the “transmission responses produced by the two layers interact” [12], creating a narrow passband at lower frequencies than that of the individual array. This passband is highly stable with angle/frequency. From Fig. 1, the unit cell sizes of each element for each array are equal but the spacing between the elements in the conductor array is different from that of the aperture array. The length of the conductor and aperture are the same.

The aperture acts as the Babinet complement of the conductor. Thus, this method is loosely based on the Babinet’s principle which states that: “when the field behind a screen with an opening is added to the field of a complementary structure, the sum is equal to the field when there is no screen” [15]. The presence of a thin dielectric between the conductor and aperture array does not exactly follow the principle, but the general concept still applies.

Once the dimensions of the elements have been selected such that the CFSS structure resonates at the desired frequency, the unknown dielectric material is placed behind it. The resonant frequency now decreases as the structure has more dielectric loading. Thus by using the thickness of the material and these resonant frequencies, the permittivity of the material can be determined. More details in including the required equations can be found in [16].
III. INITIAL PARAMETRIC STUDIES

In order to fully understand this method, parametric studies on some of the parameters affecting the response of the CFSS were carried out. Studied here are the thickness of the dielectric material between the arrays and the length of the conductors and apertures. Common data used here: waveguide dimensions $= 22.86 \text{ mm} \times 11.43 \text{ mm}$, in-between dielectric permittivity, $\varepsilon_r = 3$, $\tan \delta = 0.001$, unit cell size, $s_1 \times s_2 = 5.715 \text{ mm} \times 4.572 \text{ mm}$. Note: the values of the permittivity used here are the absolute relative values.

A. Thickness of in-between dielectric, $d$

Fig. 3 shows the effect of the thickness of the dielectric between the arrays on the resonant frequency of the CFSS. Data used: $d = 50 \mu m$, $l_c = 3.50-4.61 \text{ mm}$, $l_a = 3.50-4.57 \text{ mm}$. In both cases, as the lengths increase resonant frequency reduces, but the insertion loss remains very low – between 0.5 and 1 dB. The green continuous (stand-alone) lines in both figures represent the case where the dipoles or apertures touch forming a continuous line/slot. In these cases, the frequency shift is higher. For that of continuous slots, the frequency response does not have a clear resonance compared to when the apertures are separate (see Fig. 4 (b)).

B. Length of conductors, $l_c$ and apertures, $l_a$

Fig. 4 shows the effect of the conductor and aperture lengths on the resonant frequency of the CFSS. Data used: $d = 50 \mu m$, $l_c = 3.50-4.61 \text{ mm}$, $l_a = 3.50-4.57 \text{ mm}$. In both cases, as the lengths increase resonant frequency reduces, but the insertion loss remains very low – between 0.5 and 1 dB. The green continuous (stand-alone) lines in both figures represent the case where the dipoles or apertures touch forming a continuous line/slot. In these cases, the frequency shift is higher. For that of continuous slots, the frequency response does not have a clear resonance compared to when the apertures are separate (see Fig. 4 (b)).
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Figure 4: Variation of $S_{21}$ with frequency for increasing (a) conductor and (b) aperture lengths

IV. CONCLUSIONS

The results from initial parametric studies of the different parameters affecting the performance of a CFSS in a waveguide have been presented in this paper. Future work will include extending the method to measure the effective permittivity of heterogeneous materials. This can be calculated by placing the substrate behind the CFSS and noting the change in the passband frequency. Similarly, the resonance frequencies and the Q factor can be used to find the tan delta values.

REFERENCES


