EFFECT OF THE METAL SHEET THICKNESS ON THE FREQUENCY BLUESHIFT IN SINGLE LAYER COMPOSITE MATERIALS AT KA MICROWAVE FREQUENCY

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Abstract—The frequency shift of the transfer function of single layer composite materials has been analyzed and tested. The effects are studied by means of planar pseudo-elliptical filters in Ka waveguide. The filters, consisting of a frequency selective surface placed perpendicularly to the waveguide axis, have been realized by a high resolution photolithographic technique. Deviations of the experimental transfer functions from the simulation are analyzed with particular emphasis to the effect of metal thickness. The finite thickness of the metal constituting the frequency selective surface causes a shift of the transfer function towards high frequencies (blueshift), attributed to dipole-dipole interaction in the metal layer. Such an effect is only partially predicted by full wave analysis based on finite element method. The increase of the thickness determines a reduction of the attenuation for thickness values between 10 and 100 skin depths.

1. INTRODUCTION

The dependence of the response of frequency selective surfaces on the metal thickness is studied in the 26–40 GHz microwave domain towards reliable design of metamaterials for microwave, infrared and visible applications [1]. We characterized the effect of the metal thickness on the transfer function by means of a waveguide loaded by composite material layers specifically designed to behave as a pass-band filter [2–4]. Such a composite material is realized by using a

process typical of the fabrication of metamaterials for infrared and visible frequency, where blueshift and redshift between the simulated and experimental transfer functions have been previously reported due to coupling between the cells [5, 6]. In order to avoid the effects due to coupling among multiple cells, we consider samples with only two identical cell repeated along the long side of the waveguide in the transverse direction. We characterized the frequency shift of the transfer function in Ka band, where the micrometric size allows a deterministic control of the thickness, and the frequency is sufficiently high to observe a deviation from the predicted frequency poles. The comparison with numerical simulations provides useful indications to determine its origin.

Several metamaterials [1] developed for infrared and visible applications exploit the dielectric properties of semiconductors [7], glass [8] and ceramic based materials, patterned with a gold [7], NiSi, aluminum and copper metal sheet. Above the X band, the transfer function of such metamaterials is frequently affected by a rigid blueshift from the model calculated by means of MoM code and the commercial software HFSS. Here, we determine the origin of the discrepancy among experiments and the theoretical models and we suggest how to minimize such an effect when projecting metamaterials and frequency selective surfaces in the high frequency domain.

One of the most investigated planar waveguide composite materials is E plane filters. These structures are designed by means of classical microwave circuit techniques [9], and they are accommodated along the waveguide direction. Despite the fact that they are a well established technique for realizing mass-producible microwave configurations, E-plane filters suffer from bulky size and stop-band performance that may often be too low and too narrow for many applications [6, 10]. Moreover, standard manufacturing techniques for these filters involve machining the waveguide. The tight tolerances bring either to high cost or to imprecise frequency response. The main problem with this type of mass production is the frequency shift in the final response [11], if tolerances are slightly relaxed.

In this paper we discuss a waveguide filter based on one or more frequency selective surfaces placed perpendicularly to the waveguide axis. Such a composite material can be accommodated in the waveguide by simply screwing them on the flange. The design method was previously introduced in [12, 13].

An attractive application of the investigated structure is for instance the emerging standard IEEE 802.16 Wireless MANs (Metropolitan Area Networks). Aim of this standard is to extend the wireless broadband access up to kilometers to facilitate the

long-range "last-mile" solution. The original standard specifies the Wireless MAN-SC air interface, a single-carrier (SC) modulation scheme designed to operate in the 10–66 GHz spectrum. That spectrum supports continuously varying traffic levels at many licensed frequencies (including 10.5, 25, 26, 31, 38 and 39 GHz) for two-way communications. One hurdle with moving to higher frequencies for these systems is the cost of the high frequency devices. An off-the-shelf waveguide filter for the LMDS bands currently sells for $200 US or more.

The dependence of the transfer function of the pass-band filter on the metal sheet thickness is reported. It is shown that the in-band experimental transmitted power presents a strong dependence on the metal thickness even when the metal is 100 times thicker than the skin depth.

We observe that, under such hypothesis, the value of the AC surface resistance, ordinarily assumed to predict the losses in frequency selective surfaces, should depend only on the skin depth, and it should be independent of the metal thickness.

All the filter prototypes present a shift of the transfer function towards higher frequencies with respect to MoM simulations where the metal thickness is considered infinitesimally thin. Full wave simulations by means a FEM (Finite Elements Method) code reveals an opposite shift of the transfer function while increasing the metal thickness. Predictions obtained by the commercial software CST Microwave Studio qualitatively agrees with the experimental findings but less effective.

The composite structure consists in a single layer and multiple layer FSS planar transverse filters designed for Ka waveguide (26.5 GHz–40 GHz).

The paper is organized as follows: in Section 2, the design methodology is briefly described; in Section 3 the experimental finding is presented, with particular emphasis on the realization of the samples, the characterization of the effect of the metal sheet thickness on the blueshift of the transfer function and the in-band attenuation, the effect of the overetching, and the comparison with the simulations. The results are summarized in the Conclusions (Section 4).

2. DESIGN OF WAVEGUIDE COMPOSITE MATERIALS BASED ON GENETIC ALGORITHMS

The design of the cells for composite materials placed transversally in a waveguide at microwave frequency can be robustly worked out by employing a genetic algorithm (GA) in conjunction with an

efficient periodic MoM solver. Such an approach allows a quick and sufficiently approximated analysis of the device. For our research we adopted frequency selective surfaces in order to magnify the frequency discrepancy among the experimental measurements and the theoretical predictions referred to samples with ideal characteristics. Consequently, the use of the GA [12, 13] with the MOM solver makes possible to consider a large number of arrangements for the conductive regions of the frequency selective surface. To this end transversally arranged FSSs can be analyzed by resorting to a free-space periodic MoM counterpart. The full wave analysis and the optimization was conducted on infinite extent FSS filters by considering a different incident angle for each frequency sample. The fundamental mode of a rectangular waveguide can be interpreted as a pair of plane waves bouncing at oblique incidence between the waveguide lateral walls. In particular, the propagation angle of the plane wave with respect to the waveguide longitudinal z direction corresponds to the incidence angle on the FSS plane; at each frequency point, the correct incident angle must be taken into account as derived from

$$\theta_{inc,\,degrees} = \frac{180}{\pi} \cos^{-1}\left(\frac{\sqrt{(2\pi f/c)^2 - (\pi/a)^2}}{(2\pi f/c)}\right) \tag{1}$$

where c is the speed of light in free-space, a the widest dimension of the rectangular waveguide, and f the operating frequency. A detailed description of the design procedure can be found in [12], and it is out of the scope of the present paper. The size of the cell is determined by the minor side of the waveguide and an integer sub-multiple of this length is allowed. The determination of the proper FSS is performed by using a genetic algorithm [13]. All design parameters have been coded in a binary string to form a chromosome, representing a solution for the filter. In particular, the basic periodicity cell is subdivided into elementary pixels coded as 1 or 0, depending on whether they are covered by a printed metal element or not; the choice between symmetric and asymmetric shapes is also allowed. In the simulations the metallic sheet is replaced by a perfect electric conductor boundary condition, i.e., an infinite conductive layer with negligible thickness. Such a hypothesis does not take into account the non-zero thickness of the metal layers obtained during a fabrication process and losses. As a consequence of this approximation some circumstances are not taken into account, like parasitic capacitances due and the imperfect reflection due to limited conductance. Triples of filters were designed to obtain a multipole summations in order to design a narrow pass-band waveguide filter operating within the band of WR28 waveguide [2, 13].

In order to include the non negligible thickness of the metal sheet, we employed a full-wave 3D solver such the FDTD (Finite Difference Time Domain) commercial code CST Microwave Studio. The full wave simulations by CST which include the variation of the copper thickness present small attenuations. The non negligible metal sheet thickness of the composite material was analyzed by considering several mesh lines within the metal slab.

3. EXPERIMENTAL CHARACTERIZATION

3.1. Realization of Samples

We produced two batches of single layer composite materials (indicated by A and B) acting as waveguide filters. The filters of the batch A were realized from metal copper sheets of different thickness, keeping the remaining construction parameters constant. The samples of batch A have respectively thickness of 35 µm, 17 µm, 9 µm, 7 µm, and 4 µm. For this set of filters we designed and realized three different design (sample 1, 2 and 3), characterized by three different FSSs, in order to discriminate the features independent from the FSS. The unit cells of the designed FSS filters are shown in Figure 1.
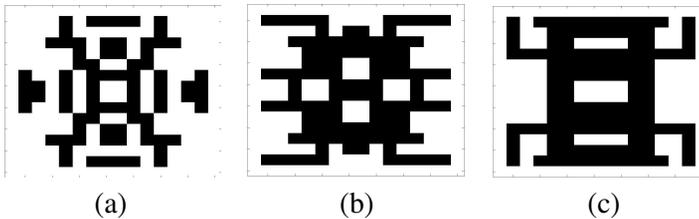

(a)   (b)   (c)

Figure 1. Unit cells of the three analyzed FSS filters. The FSS filter consists of two unit cells with periodicity of 3.556 mm. (a) filter 1, (b) filter 2, (c) filter 3.

The batch B of composite materials consisted of a series of filters identical to those of batch A at a fixed metal sheet thickness $t = 17$ µm with an over-etching ranging between 20 µm and 60 µm. The filters of the batch B have different over-etching while all the other features are the same, in particular the metal sheet thickness.

The realization was carried out by means of a photolithographic process typical of integrated circuit fabrication. All the filters are printed on a Teflon based substrate with a dielectric permittivity of $2.2 - j0.002$ and a thickness of 0.5 mm. A typical FSS sample placed within the WR28 waveguide is shown in Figure 2.
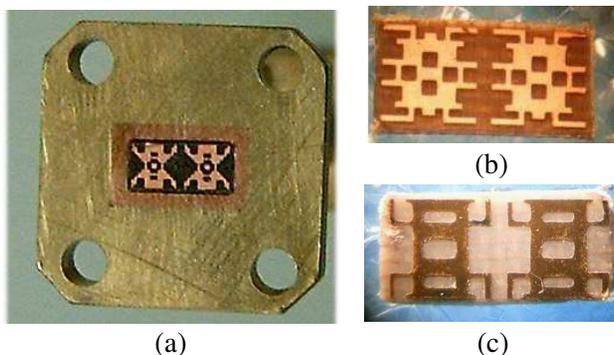
Figure 2. The composite material consists of two square cells with a side of 3.556 mm placed along the transverse direction of the Ka waveguide. (a) Picture of a sample accommodated in the waveguide. (b) Realized sample of the filter 2, and (c) filter 3.

The waveguide filters designed are composed of two square cells with a side of 3.556 mm. The frequency selective surfaces are printed on the surface of a dielectric slab, which is considered part of the filter. The composite structures behave as a pass-band transfer function centered around 32.5 GHz. The overetching of the metal deposition of each cell is caused by the finite thickness of the metal sheet. Overetching is obtained by dipping the sample into the etching solution, as the solution removes the metal anisotropically. Consequently, the conductive regions of the FSS are narrower than in the design. The lateral size reduction is comparable with the metal sheet thickness. A sketch of the overetching effect is depicted in Figure 3.
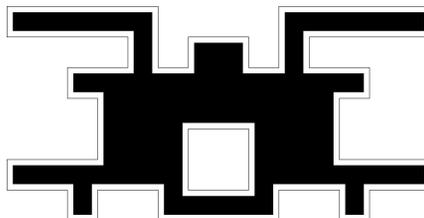

Figure 3. Overetching effect. The line indicates the nominal shape of the cell. The picture reports the unit cell of the filter 2 halved.
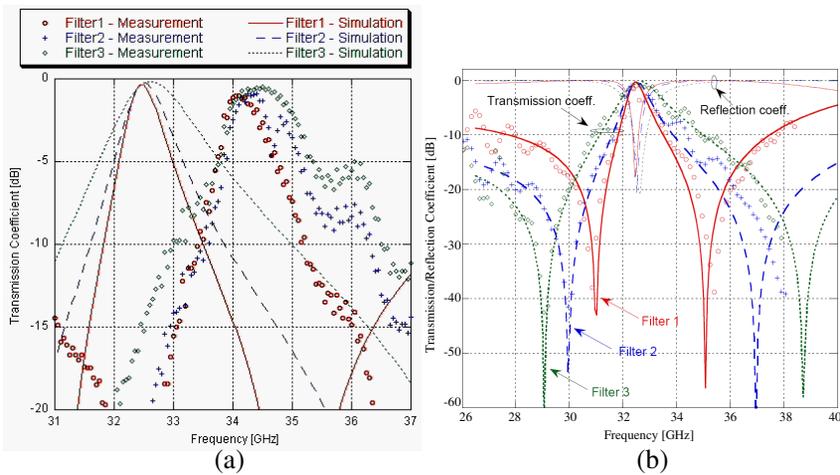
Figure 4. The transmission and reflection coefficient as a function of the frequency for three filter samples (1, 2 and 3) of the Batch A with $t = 17\,\mu m$, compared with the simulations. (a) Comparison between the original experimental (dotted) and simulated (line) TF. (b) Agreement between the measured and the simulated transfer function shape after rigid frequency shift of the former.

3.2. Characterization of the Frequency Shift as a Function of the Metal Thickness

The measured and simulated transfer functions of the three filters of the batch A with $17\,\mu m$ thick metal sheet are plotted in Figure 4. Figure 4(a) reports the row data and the simulations. The measured transfer functions are in good agreement with the prediction, except the center frequency, which shifts towards higher frequencies with respect to the simulations. In Figure 4(b) the agreement between the experimental transfer function shape and the simulations is shown by a rigid shift of the experimental TFs of a suitable quantity. The characterization of the frequency shift between the measured and simulated transfer functions as a function of the metal sheet thickness is plotted in Figure 5 for the whole batch A. An increase of the metal sheet thickness also causes an increasing shift to higher frequencies of the measured transfer functions [14].

The differences between the measured and simulated in-band attenuation as a function of the metal sheet thickness for the filters of the first set are plotted in Figure 6. The attenuation decreases when increasing the thickness of the copper [15]. For the $35\,\mu m$ thick metal sheet a common asymptotic value is achieved. The remaining deviation is ascribed to a tangent loss slightly higher than the value
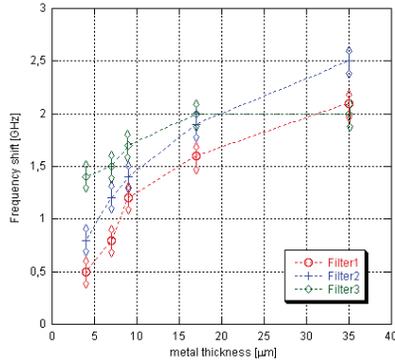
Figure 5. Frequency blueshift of the transfer functions of the filter sample 1, 2 and 3 of the batch A as a function of the metal sheet thickness.

used in the simulations.

The finite thickness of the metal sheet causes two differences from the simulations: a translation of the transfer function at higher frequencies and a higher in-band attenuation. It is also demonstrated that the first one is eliminated by reducing the thickness of the metal sheet whereas the latter is overcome by increasing it. Consequently, a trade-off between the two effects is assessed to design the composite material. In order to distinguish the two contribution, the batch B reported in the next subsection has been characterized.

3.3. Effect of the Overetching on the Frequency Shift and the Attenuation

Samples with an overetching in the range between 20 µm and 60 µm were characterized. The effect of the overetching on the transfer function has been studied by means of the batch B and it is shown in Figure 7. The overetching induces a frequency shift lower than the shift due to the metal sheet thickness in the range considered. The extrapolated frequency shift for the case of a negligible overetching is close to that measured at 20 µm. The attenuation increases as a function of the size of the overetching, as reported in Figure 7.

3.4. Discussion

A non zero metal sheet thickness causes a considerable attenuation in the transmission band of the filter. Such an effect is not expected since the skin depth for copper, in the Ka frequency band, is below 0.4 µm, while t was between 4 µm and 35 µm. These unexpected variations
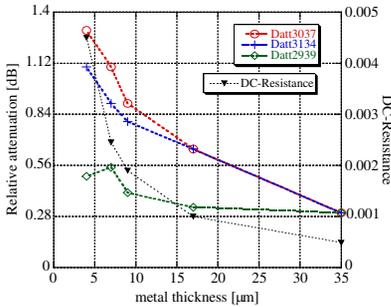
Figure 6. In-band relative attenuation as a function of the metal sheet thickness. Relative attenuation (Datt) is defined as the difference between the measured attenuation and the attenuation calculated by means of the simulation.
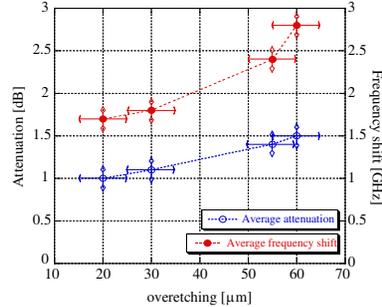
Figure 7. The average frequency shift and the attenuation of the filters 1, 2 and 3 of the batch B. While the attenuation is significantly affected by the size of the overetching, the effect on the frequency is small if compared to that due to the metal sheet thickness in the thickness range reported in Figure 5.

were previously highlighted by other authors for composite materials operating in the Terahertz range [16–19], in agreement with the static surface resistance variation

$$R = \frac{1}{\sigma t} \tag{2}$$

where t and σ are respectively the thickness and the conductivity of the metal. Even if the trend of the attenuation clearly depends on metal thickness (see Figure 6), the introduction of this surface resistance values in the MoM code produces a smaller attenuation with respect to the measured one. In the referred work [16–19], the authors found the same attenuation behaviour but they computed higher static surface resistance values because of a thinner substrates. According to [5, 20], the blueshift is qualitatively associated to a dipole-dipole interaction, which is increasing important in our samples as the thickness allows the circulation of currents in the transverse direction.

In Figure 8 the transmission coefficient of the filter 2 as a function of the metal sheet thickness computed by CST Microwave Studio is shown. In the simulation setup the metal has been discretized by several mesh lines. We notice the presence of a weak blueshift with the increase of the metal sheet thickness. The blueshift is in agreement with the experimental results but the amount of shift is
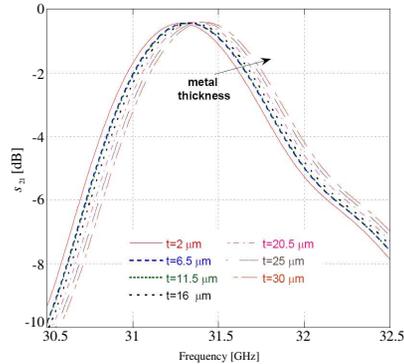
Figure 8. Computed transmission coefficients for different metal sheet thickness obtained by CST microwave studio simulations of the filter 2.

smaller. The impact of errors due to the measurement setup were analyzed in a previous work and estimated to be negligible [21, 22]. Frequency selective surfaces with thick metal are generally analyzed by a MoM approach [22], and it is commonly obtained an opposite trend of the frequency shift as a function of the metal thickness (redshift). However it has to be pointed out that, while usually the first resonance is observed, in the present analysis the pass-band behavior of the capacitive FSS filters analyzed is obtained in correspondence of a high order resonance.

4. CONCLUSIONS

We designed and realized a composite material by adopting the approach typical to realize metamaterials from the microware to the optical domain. We compared the experimental and numerical results of a waveguide planar transverse series of samples behaving as pass-band filter structures operating in Ka microwave band. A systematic study of the dependence of the filters transfer function on the metal sheet thickness showed that the in-band transmitted power presents a strong dependence on the metal thickness. In particular we observed that the increase of the metal thickness causes a decrease of the in-band attenuation. This unexpected effect is remarkable even if the metal thickness is more than 10 times the skin depth. It was shown that the attenuation trend is in accordance to a DC-surface resistance variation. Moreover, the increase of the metal thickness causes a blueshift of the transfer function of the composite filters. We demonstrate that predictions obtained by CST qualitatively agree with the experimental findings but less effective. Such a blueshift effect has to be taken into account when designing composite materials in order to realize metamaterials from the microwave to the optical domains.

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