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Increasing the bandwidth of coaxial aperture arrays in radar frequencies

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Abstract Arrays of coaxial cavities in a silver slab are an angle-independent frequency-selective structure in the optical wavelengths. We show that understanding major resonant effects can achieve a similar structure in the radar frequencies. We use a biperiodic boundary integral method to explain the resonances. We suggest a geometrical evolution of the coaxial cavities that presents an enhanced bandwidth under oblique incidence in TM polarization.

1 Introduction

A possible use for metamaterials and frequency-selective surfaces (FSS) is the conception of radomes (cf. [1]). We are interested in radomes that show specific properties in the X band: similar behavior for both TE and TM polarizations, independence to the angle of incidence and wideband. Obtaining such properties with structures that are light and not too expensive is a challenge.

In the optical frequencies, a structure that meets these requirements well is presented in Ref. [2]: an array of square coaxial cavities made in a silver slab. The properties are stable with the angle of incidence and relatively similar for both polarizations. The transposition to radar frequencies is not straightforward. By using our own developed numerical code, based on a boundary element method and described in Refs. [3] and [4], we study how the different resonances relate to the bandwidth.

In Sect. 2, we summarize the different resonant phenomena that influence the bandwidth. In Sect. 3, we show that simple physical laws can be derived and explained with the help of the developed numerical code to describe the behavior of the array of coaxial cavities. Finally, in Sect. 4, we suggest an evolutive profile of the coaxial cavities that creates an interesting transmitting behavior: nearly 100% on a 7% bandwidth in TM polarization under oblique incidence.

2 Identifying the resonances

In Ref. [2], an array of square coaxial cavities in a slab of silver is presented. At optical wavelengths, silver is not a perfectly conducting metal: the skin depth is not negligible and virtually enlarges the cavity (cf. Ref. [5]). This results in a wide transmission band, but the transmission is not total. The transposition to the radar frequencies is not straightforward as perfect metals (Perfect Electrical Conductors, PEC) modify the resonant phenomena that create the band pass behavior: the transmission coefficient reaches 100% but the transmission band is much narrower (cf. [3], Chap. 7), due to the absence of losses. The resonances must be correctly understood in order to choose the best geometrical parameters. In this paper, we study cylindrical coaxial cavities instead of square ones, as shown on Fig. 1.

In Ref. [6], the coaxial waveguide modes are used to describe the fields in the cavities, in a mode-matching method of moments. But the cavities are of finite height and the

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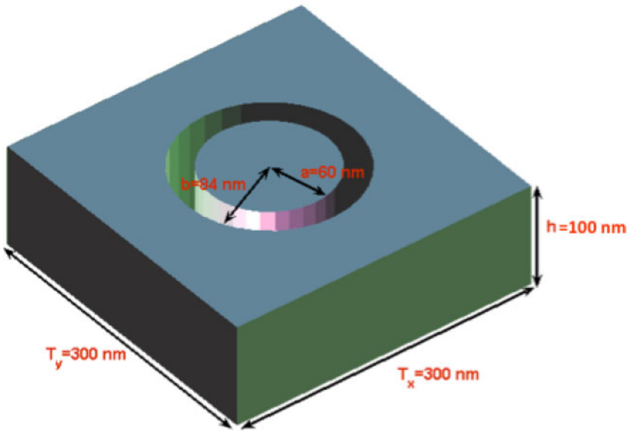

Fig. 1 Unit cell of the array of cylindrical coaxial cavities for the optical wavelengths

coaxial waveguide modes (see e.g. [7]) can not very accurately describe the fields in the cavities. Nevertheless, the different involved resonances that explain the transmission peaks (cf. Refs. [2] and [5]) are the Fabry-Pérot-like resonances due to coaxial waveguide modes. They can be identified by plotting the fields in the cavities or the (equivalent) currents on the interfaces of the model. Two of these resonances are of primary interest, as they appear at the lowest frequencies:

- Fabry-Pérot-like resonance of order 1, due to the TEM mode.
- Fabry-Pérot-like resonance of order 0, due to the TE11 mode, at the cutoff of the TE11 mode.

The grating resonances (Wood's anomalies) are usually to be avoided as we do not want high-order Floquet modes.

3 Influences of geometrical parameters

The coaxial waveguide modes that are involved in the resonances are affected by the finite height of the structure. Thus the analytical formulas for the cutoff frequencies and morphology of the modes are not accurate anymore. Here, we focus on the influence of the height of the structure. We set all the parameters as follows:

- Lattice constants: $T_x = T_y = 8$ mm
- Inner and outer radii: $R_{\text{int}} = 2.13$ mm and $R_{\text{ext}} = 2.7$ mm
- Cavities filled with PTFE with refraction index $n = 1.58$ without losses
- Oblique incidence at 44° ($k_x = 0.7$) and 64° ($k_x = 0.9$) for frequencies from 8 GHz to 24 GHz, under TE (H) and TM (V) polarizations.

The height of the structure is successively taken to be 1 mm, 2.5 mm, 5 mm and 10 mm. We calculate the bandwidth as a function of the height h. The variations can be explained by invoking the quality factor, Q, which is the inverse of the bandwidth, and it can also be defined as the ratio of the energy stored w_{cav} in the cavity by the losses P_{rad}/ω (cf. [8]):

$$Q = \frac{f_{\text{res}}}{\Delta f} = \frac{w_{\text{cav}}}{P_{\text{cav}}/\omega} \tag{1}$$

Under the assumption that the electromagnetic energy per unit of volume $\mathcal{E}$ is uniform in the cavity of volume V, then we have $w_{\text{cav}} = \mathcal{E}V$. Likewise, as the only possible losses are radiative losses on the apertures of the cavities, it is reasonable to expect that P_{cav}/ω is proportional to the surface of the apertures: $P_{\text{cav}}/\omega = \mathcal{P}\mathcal{S}$. Thus, the quality factor is directly proportional to the height of the structure:

$$Q = \frac{\mathcal{E}}{\mathcal{P}} h \tag{2}$$

Figure 2 shows how the approximation is relevant for both polarizations and all the angles of incidence. The value of $\frac{\mathcal{E}}{\mathcal{P}}$ is different for each case. It is possible to adopt the same point of view to explain the modification of the resonance frequency, appearing at the cutoff of the TE11 mode (cf. [3]). The accuracy of the law becomes bad when the height tends to 0, when the waveguide vanishes.

Other simple physical laws can be derived for different parameters and help choose the best parameters that achieve the desired bandwidth. The main drawback of this approach is that enlarging the bandwidth also increases the transmission efficiency of the filter out of the passing band, which should be near 0. A modification of the shape of the structure can then be explored to improve the transmission response.

4 Suggestion of an evolutive profile of the cavities

From the last paragraph, we can deduce that arrays of cavities with a large aperture ($R_{\text{ext}} - R_{\text{int}} \to T_x/2$) are less selective than arrays of cavities with a small aperture ($R_{\text{ext}} - R_{\text{int}} \to 0$). We wondered if the analogy could be made with stacks of FSS, where it is advised to place the most selective ones in the center of the stack and the least selective ones on each side of the stack. The array of coaxial cavities can then be considered as a continuous version of a stack of FSS: increasing its selectivity in the center would mean reducing the aperture ($R_{\text{ext}} - R_{\text{int}}$) in the center of the cavity, as shown on Fig. 3, where the geometrical parameters are given. The evolutive profile consists in arcs of circle in any vertical planes of symmetry of the cavity, which is filled with PTFE ($n = 1.58$). The calculations are done in a extended X band, from 8 GHz to 15 GHz, under normal and oblique incidences (44° and 64°), for both TE and TM polarizations.

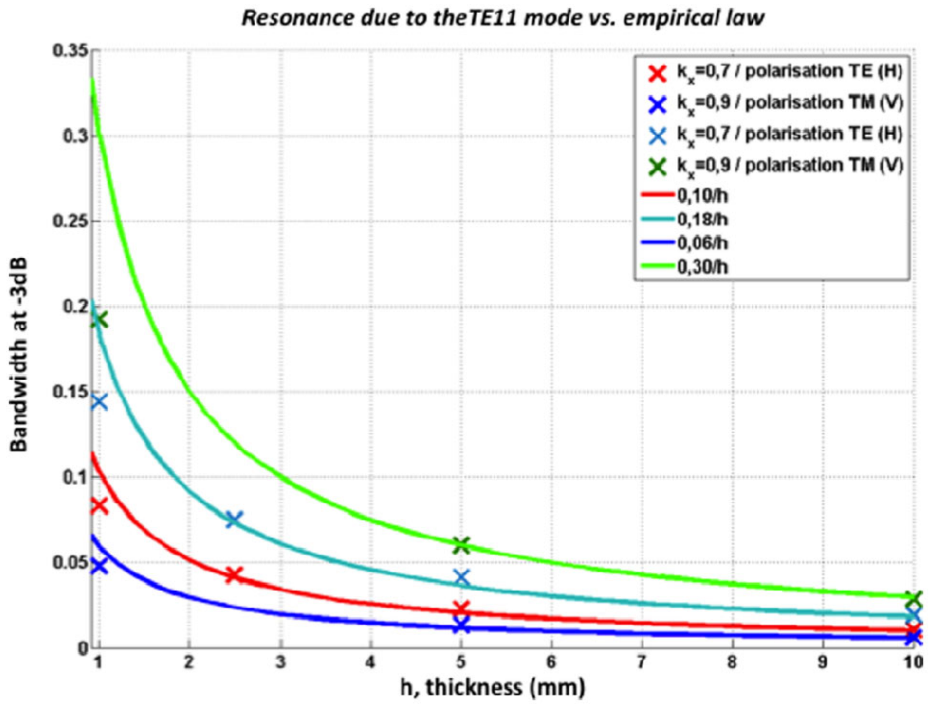

Fig. 2 Influence of the height of the structure on the bandwidth

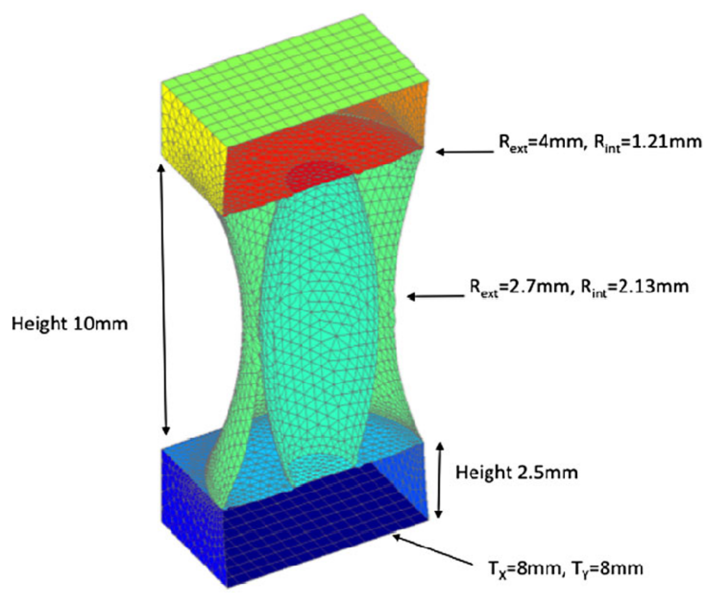

Fig. 3 Geometrical parameters of the coaxial cavity with an evolutive profile

The modification of the structure does not affect much the transmission responses under normal incidence or TE polarization (results not shown here, but in [3] and [4]). The changes are significant and interesting under oblique incidence in the TM polarization, as seen on Fig. 4: there is nearly total transmission for almost 0.6 GHz and very low transmission out of the passing band.

Contrary to what we thought, it does not behave as a continuous variant of a stack of FSS, but the transmission response is due to a coupling between the resonances listed in paragraph 2, due to the modes TEM and TE11.

5 Conclusions

One of the purposes of this work was to show that our numerical code (included in Dassault Aviation's *Spectre* code) could be used to describe and study physical problems.

The array of coaxial cavities with an evolutive profile show a nearly 100% transmission efficiency on an about 7% bandwidth in the TM polarization under oblique incidence (64°). We have shown that the influence of the thickness of the film can be qualitatively explained. The large broadening of the transmission peak has been attributed to the coupling

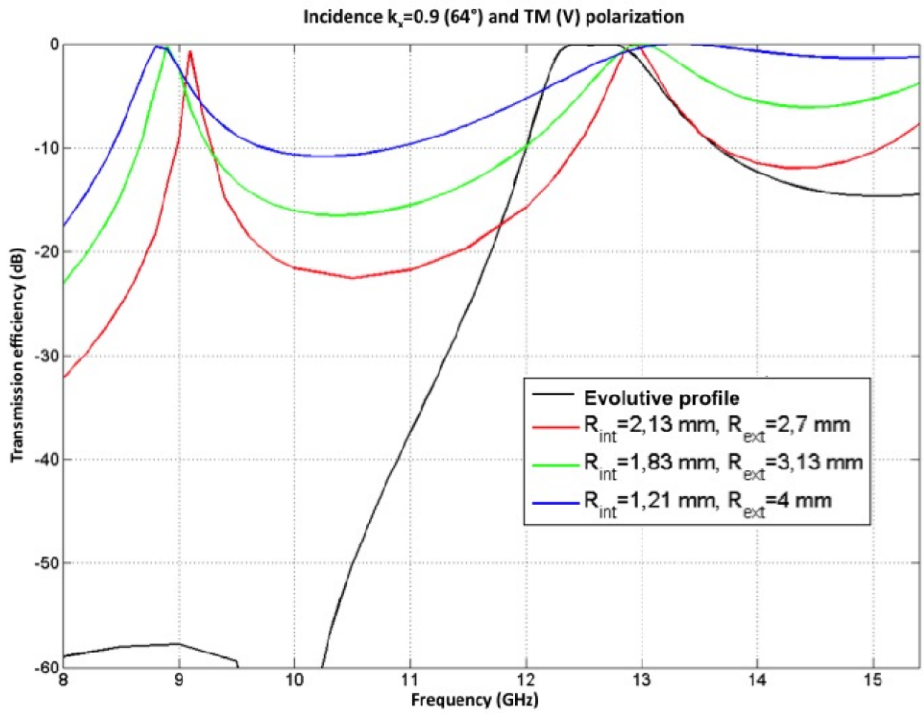

Fig. 4 Transmission response of the array of evolutive coaxial cavities in TM polarization under oblique incidence ($k_x = 0.9$), compared to the responses of arrays of straight coaxial cavities with the narrowest, median and the largest apertures

between two different coaxial cylinder modes. The structure could be improved by using optimization tools to find the best parameters. Moreover, a further study of the coupling between the modes should allow one to clarify if the modes are in a strong coupling regime.

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