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Design of a single-feed 60 GHz planar metallic Fabry-Perot cavity antenna with 20 dB gain

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ABSTRACT:
In this paper a Fabry-Perot cavity (FPC) has been used to design a 60 GHz single feed directive antenna. The FPC antenna is made by a ground plane covered by a frequency selective surface (FSS). We have provided simple design guidelines based on a transmission line model. Numerical simulations confirm the design guidelines and antenna performances.

INTRODUCTION

Nowadays, the unavoidable requests on applications requiring high frequency bandwidth force the industries to look for free bands at higher frequencies. One of those free bands, according to FCC regulation, is from 59 GHz to 67 GHz. Efficient antenna design at higher frequencies, e.g., 60 GHz, is one of the challenging problems in this area. Because at higher frequencies the environment acts so lossy, e.g., ≈10-15dB/Km, then the maximum possible gain for this kind of antenna is desirable. To achieve a high gain design, the effective radiation area of the antenna must be increased. Typical methods lead us to use the array concept at 60 GHz but the larger the gain of the antenna, the larger the array size and hence the larger and the more complex the feeding network which is the main source of losses and design complications at high frequencies. To overcome this problem, the Fabry-Perot cavity (FPC) concept has been employed, which is a leaky-wave antenna [1-2] that can be excited by a single feed. The leaky wave is a fast wave in the transverse plane and leaks power from the entire structure. Von Trentini [3] introduced and used the concept of frequency selective surface (FSS) that acts as a partially reflective surface (PRS) to form a FPC to improve the radiation characteristics of waveguide apertures. Later on significant work has been accomplished by numerous papers by D. R. Jackson and coworkers (for brevity, here we just report [4] and [5] where the transmission line concept and a slot PRS has been considered). The more reflective the PRS, the higher the quality factor of the cavity and hence the higher the gain of the antenna. In [6], an optimized PRS is placed in front of a waveguide aperture to enhance the total gain of the structure. Also some other configurations had been used to increase the gain of the antenna, for example in [7] photonic bandgap materials are used to reflect the electromagnetic waves, which is the same concept implemented by a PRS. The FPC is one of the easiest ways to enhance the gain of an antenna which has been used previously at lower frequencies than the one considered here. The simple TL model in [4] and [5] that applies to thin FSS is no longer valid since at 60GHz even a small thickness can be electrically large. That is why we have here generalized the work in [4], [5] and [8] to FPCs that use thicker FSS structures modeled as a two port network and characterized by HFSS results. To limit losses, the FPC is made only of air and metallic parts whose losses have been considered in the numerical simulations. We also provide simple design guidelines, generalizing the TL concept developed in [4], [5] and [8], that can be followed for designing similar very directive antennas at very high frequency.

ANTENNA DESIGN

The goal is to design a 20dB-gain antenna at 60 GHz with a single feed. The chosen design is based on using a FPC consisting in a ground plane covered by a metallic FSS as shown in Fig. 1. As mentioned before, to limit the losses we avoid using any dielectric layer inside the cavity. A critical aspect of the design is to choose a proper FSS that leads to the specified gain. Indeed the higher is the reflectivity of the FSS, the higher is the quality factor of the cavity and the higher is the gain. In the following we use an FSS made of brass with rectangular apertures ($W \times L$) and thickness T = 1mm to guarantee a mechanical stability. The period of the FSS is chosen to be $A = B = 2.4$mm, and thus less than $\lambda/2$ at 60 GHz to avoid grating lobes. The FPC is fed by an aperture in the ground plane, and for designing purposes we assume that it is represented by a magnetic current lying on top of the ground plane. The design of the FPC antenna is made in a few steps that are outlined below.

The first step consists in designing the FSS that has been characterized by its S parameters (transmission and reflection coefficients), function of L and W, found with numerical simulations carried out with Ansoft HFSS assuming an FSS structure with infinite extent and periodic boundary conditions. Once the S parameters have been determined for a certain choice of L and W, we determine the Z (impedance)- parameters associated to the FSS and use them in the TL

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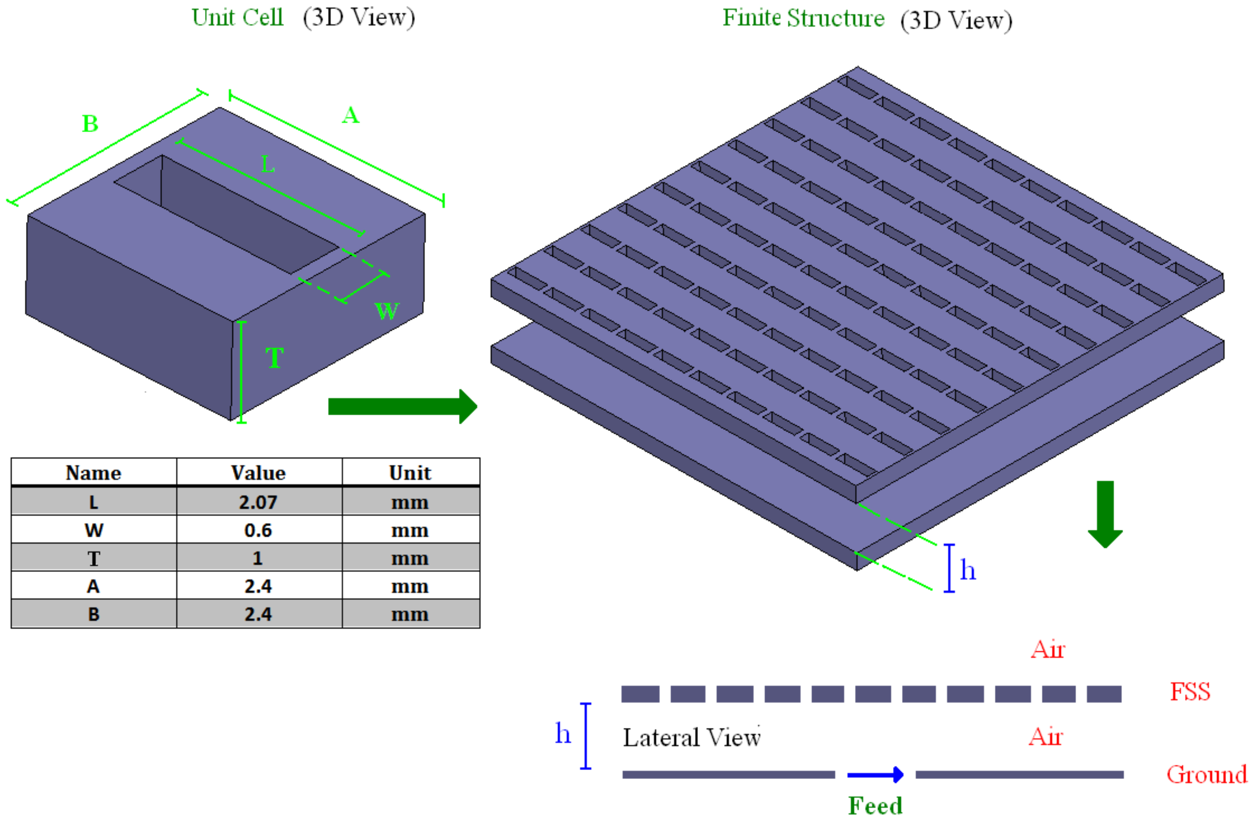
model shown in Fig. 2, where the space above and inside the FPC is modeled by a TL with characteristic admittance Y_0. To have a resonance at 60GHz we impose that the transverse resonance condition shown in Fig. 2 is satisfied and we determine the FPC height h.



Name	Value	Unit
L	2.07	mm
W	0.6	mm
T	1	mm
A	2.4	mm
B	2.4	mm

Fig. 1 The FSS unit cell and a FPC antenna (of finite size) made by a ground plane covered by an FSS.

Using the TL model and the gain expressions in [8], we can find the maximum gain of the FPC antenna, and we decide if the dimensions of the FSS unit cell are acceptable or not. If the gain is not the specified one, the same process is repeated with a different choice of L and W. In general, the farther the passband resonance frequency of the FSS is from the working frequency, the higher the reflectivity of FSS and thus the higher is the gain. We have found that the dimensions in Fig. 1, which leads to the S parameters in Fig. 3a, leads to the desired 20dB gain in Fig. 3b. Note that the passband resonance of the FSS is significantly higher than 60GHz so that the S parameters are pretty smooth around the operational frequency.

For thin FSSs one can use the design rules in [4] and [5] which are based on modeling the FSS by a simple TL shunt susceptance. In this case the electric thickness of the material at 60GHz cannot be neglected and in most of the cases we cannot use a simple susceptance to model the FSS that is here characterized by a two-port network. Despite this difference, the used TL model is similar to that in [4], [5] and [8]. At 60 GHz, the exact values of the S and Z parameters that lead to 20dB gain are given in Fig. 2. Following the expressions in [8], a plot of the gain versus frequency is given in Fig. 3b, and one can observe that the 3dB pattern bandwidth is 400MHz. We report here only the pattern bandwidth because for these kind of high gain FPC antennas that is the critical parameter, and usually the input bandwidth is limited by the pattern bandwidth.

If a larger bandwidth is desired more complicated FSS should be used (including multi-layers) or one should design a FPC for a lower gain and use the concept of sparse arrays in [8]. For this class of FPC antennas the bandwidth is inversely proportional to the directivity. A figure of merit F = (directivity) × (3dB bandwidth) was given in [9] for the case of thin FSS represented by a shunt admittance (in the present case the FSS is modeled by a 2-ports network because of the thickness). For that class of antennas it was found that F =2.48 (a typo is present in [9]) is an upper limit, unless more complicated FSS are considered. More or less the same number limits also our design possibilities.

Once the TL has been used for an initial design tool, we numerically simulate the whole FPC antenna with finite transverse extent of the FSS and ground plane, with lateral walls left open. In our case we have considered and FSS made of 10 × 10 unit cells (24 ×24 mm^2), and an exciting dipole located in the middle of the cavity where the electric field is maximum. We need to mention that for high gain FPC antennas, the excitation does not significantly affect the directivity (it may affect the efficiency though) since the directive pattern is mainly due to the excitation of a leaky wave. The simulation confirms that the gain is 20.4dB.

The far-field HFSS-simulated E and H radiation patterns for the finite structure are shown in Fig.4.

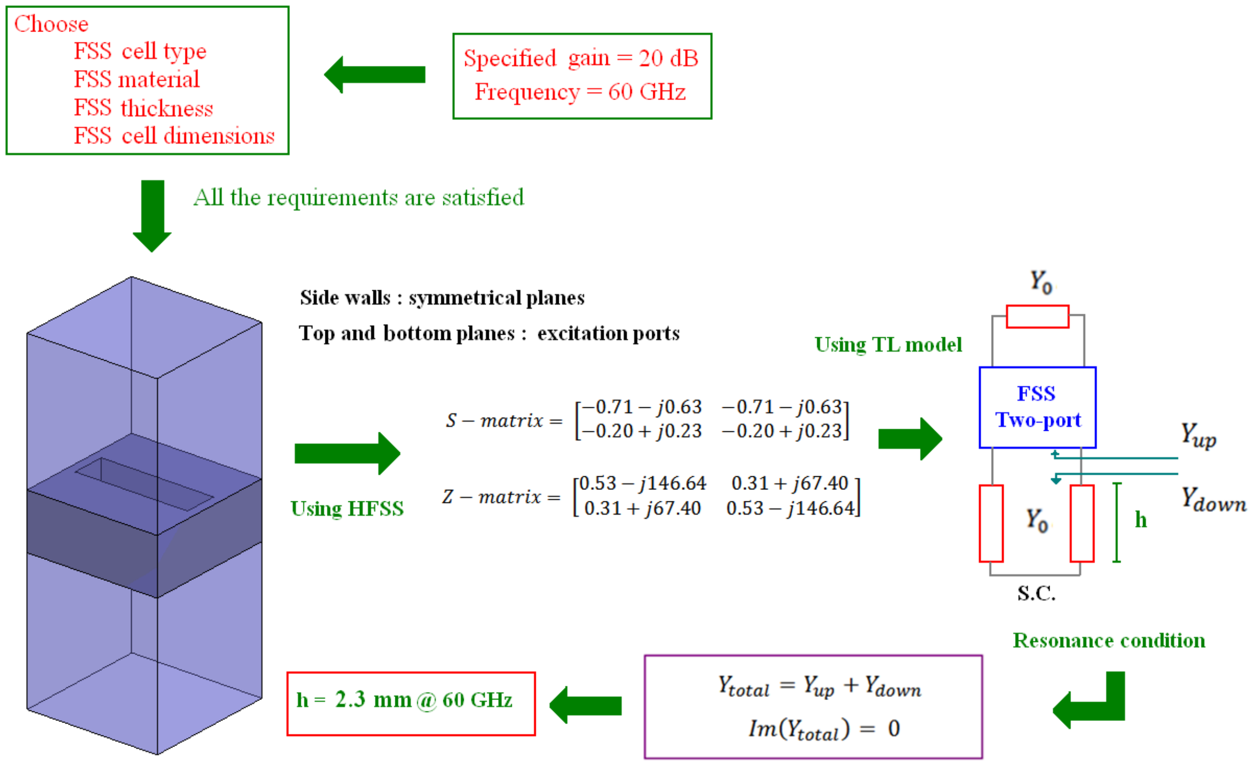


Fig. 2 Design process of a FPC antenna made by a ground plane and an FSS

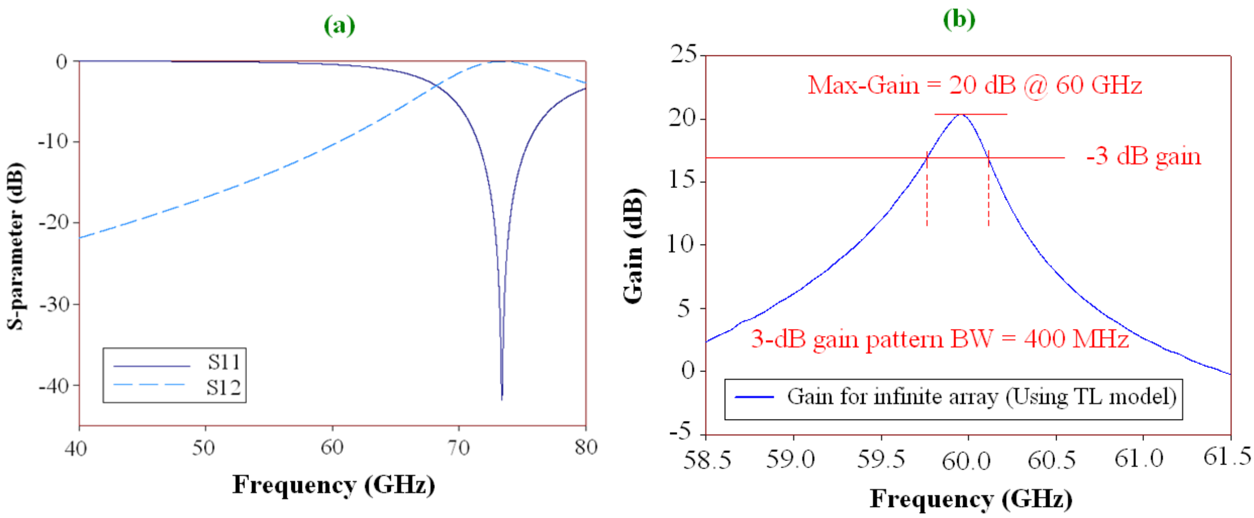


Fig. 3 (a) The S-parameters of the FSS that leads to a FPC with 20dB gain (an infinite structure). (b) The gain of the FPC antenna (infinite FSS) (dB) versus frequency

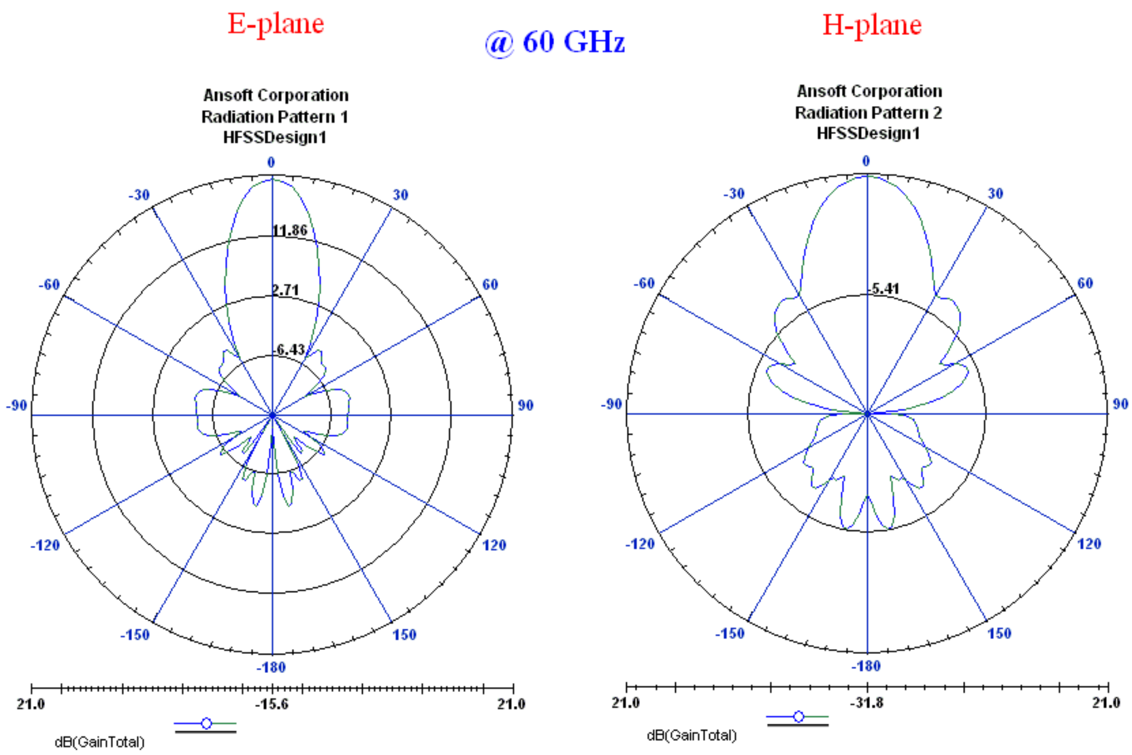


Fig.4 The far-field radiation patterns (E and H planes) for the FPC antenna of finite size shown in Fig. 1

CONCLUSION

In this paper, a leaky wave FPC antenna is used for a novel design of an air-metal 20dB gain antenna at 60 GHz. We have also provided simple design guidelines. The advantage is that a single feed is used and that only air and metallic parts are used to limit losses. The pattern bandwidth is small as usual for these kinds of FPC antennas but techniques exist to increase it (either by choosing a more complicated FSS or by using the sparse array concept in [8]). The impedance bandwidth which is limited by the pattern bandwidth depends also on the type of feed and it will be discussed in future work.

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