Title

Design of patch antennas and thinned array of patches in a Fabry-Perot Cavity covered by a partially reflective surface

ISBN
9789290929376

Authors

Gardelli, R
Donzelli, G
Albani, M
et al.

Publication Date
2006-11-01

DOI
10.1109/eucap.2006.4584837

DESIGN OF PATCH ANTENNAS AND THINNED ARRAY OF PATCHES IN A FABRY-PEROT CAVITY COVERED BY A PARTIALLY REFLECTIVE SURFACE

R. Gardelli [(1)], G. Donzelli [(2)], M. Albani [(2)], F. Capolino [(2)]

[(1)] *Dipartimento di Fisica della Materia e Tecnologie Fisiche Avanzate, Università di Messina, Messina, Italy,*
rgardelli@unime.it:
[(2)] *Dipartimento Ingegneria dell'Informazione, Università di Siena, Siena, Italy,*
matteo.albani@dii.unisi.it, capolino@dii.unisi.it

ABSTRACT

Antennas with large gain are obtained here with one or few radiators. The main idea consists of inserting simple radiating elements, as patches, inside a Fabry-Perot Cavity (FPC) resonator. This consists of a ground plane covered by a partially reflecting surface (PRS). We provide here some simple rules for the design of such systems, paying attention to a) the required bandwidth and gain, and b) the equivalent model of the periodic surface that forms the PRS, with the goal of designing large antenna gain by using arrays with thinned number of elements. In the present investigation we obtain 19 dB gain with a 2x2 array with a bandwidth of 3.6%.

1. INTRODUCTION

The Fabry-Perot Cavity (FPC) antenna consists of a source between two parallel plates, i.e., a totally reflecting ground and a partially reflecting surface (PRS) which acts as a radiating aperture. A first prototype was made by Von Trentini with a PRS surface [1] in 1956. Then, all the pioneering studies carried out in the 80' and early 90', [2]-[4], used a PRS formed by alternating high-density and low-density quarter wavelength dielectric layers. More recently Frequency Selective Surface (FSS) or more complicated metasurfaces (i.e., printed or etched periodic metallic structures) are employed to achieve more compact, low profile and low cost PRS [5]. A resonance in the FPC occurs when the distance between ground plane and PRS (the cavity height) is approximately half wavelength; such condition results in a noticeable enhancement of the directivity of the source.

The directivity enhancement can be described in terms of the excitation of a leaky wave, which is based on the excitation by a single radiator of a leaky wave along the antenna geometry. When the slowly attenuating leaky wave has also a small propagation constant the antenna radiates a narrow beam at broadside [3],[4], [6]-[8] and a trade-off exists between the gain enhancement and the operating bandwidth.

Besides PRS surfaces made by a FSS over a cavity, studies on Electromagnetic Band Gap (EBG) structures led to the idea that a resonant defects in an EBG material could be used to produce high directivity outside the crystal [9]-[15]. In practice, in these studies the reflective superstrate was replaced by a single or multiple layers of EBG material, still over a resonating cavity.

Since in the FPC arrangement, the directivity enhancement is obtain to the detriment of gain bandwidth, the design of sparse arrays inside the FPC is proposed to achieve high directivity still preserving the needed operating bandwidth. The thinning of the array results in a simpler structure with fewer elements, a simpler feeding network and a lower coupling between elements. Furthermore, the empty space available between sparse elements can be utilized to accommodate active RF circuitry or to interleave two different antennas, as in a dual feed arrangement or for dual polarization [16].

In this paper, a design procedure for the optimization of the patch antenna inside the FPC is presented. In particular the patch design and the FPC size optimization will be presented by resorting to an approximate model of the PRS consisting in a high permittivity thin superstrate layer, that allows the use of commercial planar antenna simulation and design tools, such as Ansoft Designer. Note than in this case the layer is not a quarter-wavelength thick, as usual for these kind of FPC antennas. In a second step the PRS is designed resorting to well assessed FSS design criterions and software tools, which assume an infinite periodic structure and provide the same reflection and transmission characteristics of the thin homogeneous dense layer. By using an appropriate aperture size estimation rule, the actual truncated (periodic) PRS is finally inserted into the full wave model. Since this last step requires a considerable numerical effort, the previous intermediate steps are very important to speed up the design process by providing a nearly optimized antenna structure which only needs a fine refinement.

The same approach can be used to provide guidelines for the design of thinned arrays of patches under a FSS. Here the numerical effort of the entire array antenna is challenging and the possibility of developing the design with the intermediate simpler steps becomes crucial.

A design example will be presented showing a FPC antenna made by a thinned array of patches.

In summary, the suggested design outline comprises the design of the FPC (determination of allowed gain enhancement for a given bandwidth, cavity height

Proc. 'EuCAP 2006', Nice, France
6–10 November 2006 (ESA SP-626, October 2006)

tuning, synthesis of the PRS with FSS technology) and the design of the 2x2 array of patches, whose design is accelerated resorting to an effective homogenized single dielectric layer for the PRS. The full wave simulation with the PRS and the 2x2 array is then performed with the geometry suggested by the approximate model.

2. FPC GREEN'S FUNCTION

Before using any full wave simulation, a preliminary analysis of the FPC antenna is conducted resorting to the Green's function of the structure. As a first approximation the FPC is modeled as an infinite (in the transverse *x,y*-plane) structure stratified in the *z* direction. The PRS is effectively modeled as a concentrated subsceptance (positive or negative for capacitive or inductive screens). Such a model is well assessed and is found to be very accurate at low frequencies, i.e. when the FSS periodicity is small compared to the wavelength. The presence of the dielectric substrate over the ground plane supporting the patches inside the cavity has to be accounted to correctly predict the cavity resonances (see [16]).

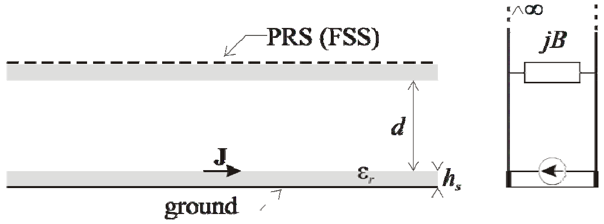

Fig. 1. (right) Dipole in the FPC and (left) associated z-transmission line for the Greens' function calculation.

The Green's function of this structure is calculated as a plane wave spectral integral involving modal voltage and current in the associated *z*-transmission line (see Fig.1), which are explicitly calculated using standard network analysis and ABCD transmission matrices. Important parameters as radiated power, far field radiation pattern are thus simply calculated from the Green's function knowledge, thus allowing a semi-analytic characterization of the FPC. Hence, on the basis of this simple model some antenna features are explicitly calculated. We analyze here the gain enhancement, defined as the ratio between the broadside gain of the dipole source with and without the covering PRS, as it would be a characteristic of the structure regardless of the specific source is inserted inside the cavity, at least for broadside wide-beam sources like patches or slots. Therefore a parametric analysis of the gain enhancement was conducted, varying the effective subsceptance B of the FSS, the cavity height *d* and the frequency *f*. We present here the case of a source over a substrate with $\varepsilon_r = 2.5$ and $h_s = 30\,\text{mil} = 0.762\,\text{mm}$. In Fig.2 the broadside FPC gain enhancement is presented as a function of the cavity height *d*, for various effective FSS subsceptance B, within a range from $B*Z_0=0$ (flat curve) to $B*Z_0=3.77$ (curve with the highest maximum) at the operating frequency f_0=14GHz. It is noticed that for each B an optimum height exists that maximizes the gain enhancement. This establishes a design criterion for the cavity height *d* [6]. In Fig. 3 the maximum gain enhancement for optimally sized FPC is plotted vs. the FSS effective subsceptance B (normalized with respect to free-space impedance Z_0), revealing that the gain enhancement can be arbitrarily increased by increasing B, i.e., the PRS reflectivity, as already noticed in [3],[4],[6]-[8] in the case without the inner substrate.

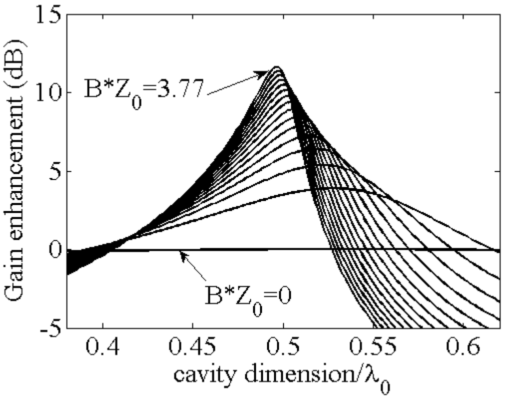

Fig. 2. FPC gain enhancement vs. cavity height d, for varying FSS subsceptance B at fixed operating frequency $f = f_0$. For each B, an optimum height exists which maximizes the gain enhancement at f_0.

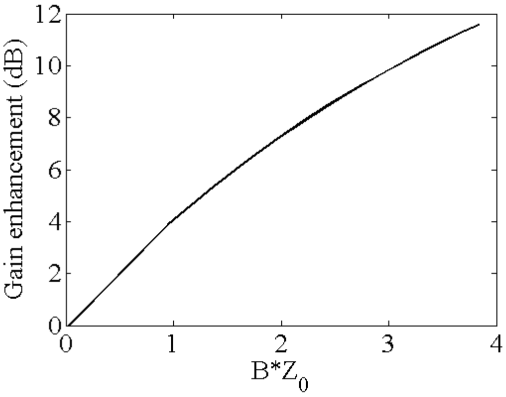

Fig. 3. FPC gain enhancement vs. PRS (FSS) effective subsceptance B, at f_0 for optimal dimensioned cavities. The gain enhancement increases with B.

Then, a frequency analysis is performed. The frequency dependence is mainly given by the length of the *z*-transmission line sections. We have observed numerically that the FSS subsceptance frequency dependence $B = \omega C$ or $B = -(\omega L)^{-1}$ does not significantly affect the curves, especially for large *B* and gain enhancement. In Fig. 4, the optimally sized FPC gain enhancement is plotted vs. frequency, for various

B. It is seen how the optimum cavity size criterion allows to chose *d* for tuning the cavity resonance to the operating frequency. It is also noted that increasing *B*, the gain enhancement is increased to the detriment of the bandwidth. Such a feature is highlighted in Fig. 5, where the maximum gain enhancement is plotted vs. the resulting 3dB bandwidth. Such behavior was already discussed in [4],[6]-[8], for the case without the inner dielectric substrate.

3. FPC DESIGN

Based on the above FPC parametric analysis, we can define the following FPC design outline: 1) the needed 3dB gain bandwidth (determined by the required operating bandwidth) dictates the maximum obtainable gain enhancement which still preserves such a bandwidth (Fig. 5). 2) The chosen gain enhancement is obtained by choosing the corresponding FSS effective subsceptance *B* (Fig. 3) and the respective optimum height *d*. 3) From the value of the effective subsceptance *B* the FSS geometry is determined using standard FSS design procedures. In our case the desired bandwidth of permits a gain enhancement for the *single* patch of 7.2dB, it is the same value obtained in [16], which in turns requires the subsceptance $B = 0.005$ mho.

In case the required bandwidth does not allow the required gain, further gain is achieved by using the thinned array, made of a few elements. The distance of the elements need to be determined based on the gain, i.e., larger gain allows larger inter-element distances.

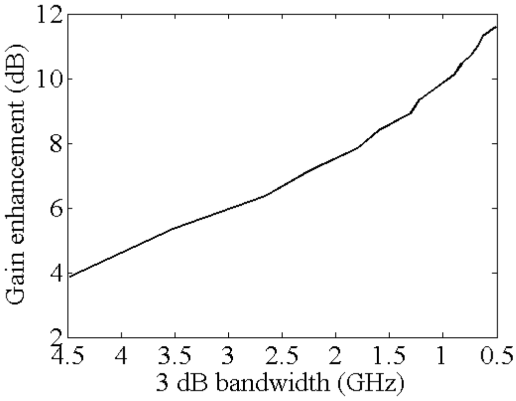

Fig. 1. FPC gain enhancement vs. 3dB gain bandwidth for an operating frequency of 14 GHz.

4. ANTENNA DESIGN

The design of the antenna to be inserted inside the FPC can be efficiently conducted using standard patch design tools (in our case Ansoft Designer), assuming an effective homogenized layer representative of the FSS. We assume the PRS made by a dielectric layer with thickness $t \ll \lambda_d$ (the wavelength inside the dielectric) and permettivity $\varepsilon = B/t$. Such a layer inserts a shunt *B* subsceptance in the *z*-transmission line (Fig. 1) corresponding to the FSS. The use of this effective layer allows to reduce the computational effort (number of unknowns) in the antenna model to the same as for the case without the PRS, because in a method of moment analysis the thin dielectric slab is accounted for by the layered Green's function. When the antenna design and optimization is complete, the full wave analysis of the entire structure (including the FSS) can be performed to check the behavior of the antenna also accounting for FSS truncation effects and for final tuning. When there are no space constraints, the PRS can be truncated when the leaky wave excited by the source is attenuated, as described in [16]. An approximation of the leaky wave attenuation constant can be obtained by simple formula provided by D. Jackson and co-authors (see [4], [6]-[8] for example) as a function of the subsceptance B.

In the following the design aims at obtaining a 19 dB gain with a 2x2 thinned array. The size of the cavity are first guessed with the criteria in the previous Sections. Once the subsceptance $B = 0.005$ mho is found (Sec. 3), then the full wave model is used with the PRS replaced by the thin homogenous substrate with $\varepsilon_r = 37.6$ and $t = \lambda_d / 20 \simeq 0.17\text{mm}$. Then the 2x2 array is simulated with this simplified assumption. The data is then verified by using the heavier simulation with the 2x2 array under the actual periodic and truncated FSS as in Fig. 6-9. The FSS is made by a layer of metallic crosses with length *L*=6.3mm and width *w*=1.7mm for each arm, arranged on a square lattice of period equal to 8 mm, and printed on a dielectric layer with thickness equal to 0.762mm and relative permittivity of 2.5. In this design the interelement distance is $1.6\lambda = 34\text{mm}$, where λ is the free space wavelength. As alredy shown in [16] and confirmed here for this new geometry, the mutual coupling between elements is negligible despite the elements are inside a resonant chamber, and operating at the resonant frequency, because of the larger-than-usual element distances. In Fig. 8 we show the gain of a single patch without FSS, under the FSS, and the gain of the 2x2 array under the FSS, versus frequency. The radiation pattern on the E and H plane is shown in Fig. 9. Note that the beam aperture is the same in the two planes as expected for these high gain structures.

5. CONCLUSIONS

Simple rules for the design of a thinned array inside a Fabry-Perot Cavity (FPC) are given here. The cavity is designed according to the steps in Sec. 3. The full wave simulation takes advantage of the use of an effective thin, dense, dielectric layer that replaces the FSS in the design procedure, therefore not requiring the mesh of the actual FSS. Full wave simulation of the FSS is considered only in the final tuning. When the desired bandwidth is not compatible with the desired gain (Fig. 5) the use of these thinned arrays is suggested. Thinning of the array elements is possible because the large gain of each element when inserted in the FPC permits larger-than-usual interelement distances without the occurrence of grating lobes.

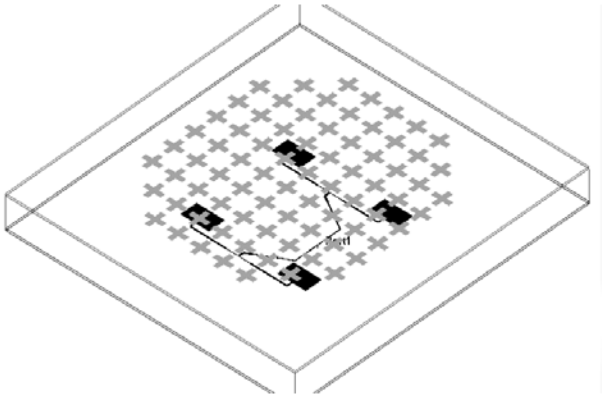

Fig. 5. Array geometry

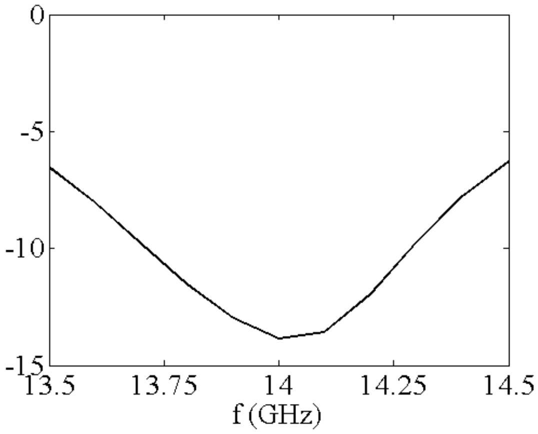

Fig. 6. Return Loss

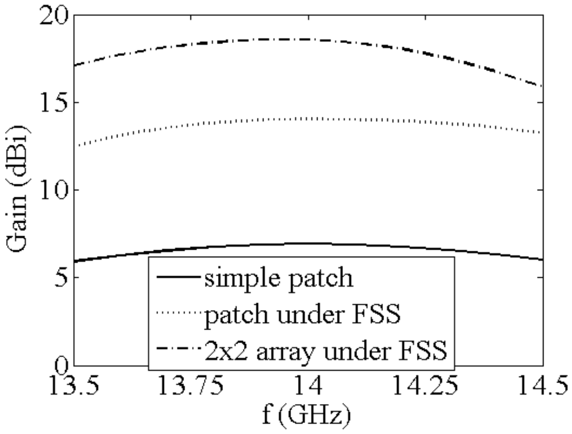

Fig. 7. Gain

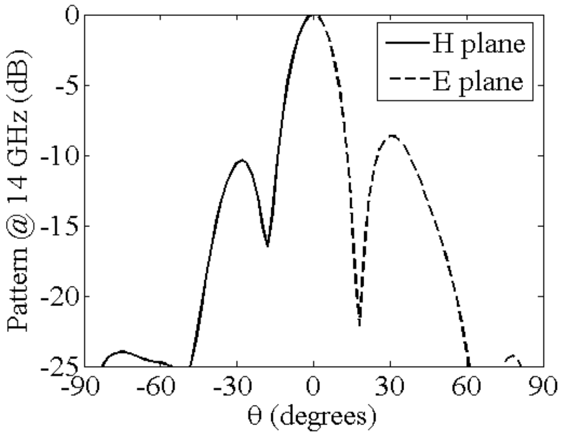

Fig. 2. Normalized radiation pattern for the 2x2 array inside the FPC.

6. REFERENCES

1. G. Von Trentini, ”Partially reflecting sheet arrays,” *IEEE Trans. Antennas Propagat.* Vol. 4, pp. 666-671, 1956.
2. D. R. Jackson and N. G. Alexópoulos, “Gain enhancement methods for printed circuit antennas” *IEEE Trans. Antennas Propagat.*, Vol. 33, N.9, Sept. 1985.
3. D. R. Jackson and A. A. Oliner, “A leaky-wave analysis of the high-gain printed antenna configuration,” *IEEE Trans. Antennas Propagat.,* Vol. 36, July. 1988.
4. D. R Jackson, A. A. Oliner, and A. Ip, “Leaky-wave propagation and radiation for a narrow-beam multiple-layer dielectric structure,” IEEE Trans. Antennas Propagat. Vol. 41, pp. 344-348, 1993.
5. A. P. Feresidis and J. C. Vardaxoglou, “High gain planar antenna using optimised partially reflective surfaces,” *IEE Proc. Microw. Antennas Propag.*, Vol. 148, pp. 345-350, 2001.
6. T. Zhao, D. R. Jackson, J. T. Williams, H. Y. Yang, and A. A. Oliner, “General Formulas for 2-D Leaky-Wave-Antennas” IEEE Trans. Antennas Propag., vol. 53, no. 11, pp. 3505–3514, Nov. 2005
7. T. Zhao, D. R. Jackson, J. T. Williams, H. Y. Yang, and A. A. Oliner, “Simple CAD model for a dielectric leaky-wave antenna,” IEEE Antennas Wireless Propag. Lett., vol. 3, pp. 243–345, Dec. 2004.
8. G. Lovat, P. Burghignoli, and D. R. Jackson, “Fundamental properties and optimization of broadside radiation from uniform leaky-wave antennas,” *IEEE Trans. Antennas Propagat.,* Volume 54, Issue 5, pp. 1442-1452, May 2006.
9. M. Thévenot, C. Cheype, A. Reineix, and B. Jecko, “Directive photonic bandgap antennas,” *IEEE Trans. Microwave Theory Tech.*, 47, pp. 2115–2122, Nov. 1999.
10. B. Temelkuaran, M. Bayindir, E. Ozbay, R. Biswas, M. M. Sigalas, G. Tuttle, and K. M. Ho, “Photonic crystal-based resonant antenna with a very high directivity,” *J. Appl. Phys.*, 87, 603–605, 2000.
11. R. Biswas, E. Ozbay, B. Temelkuran, M. Bayindir, M. M. Sigalas, d aK.-M. Ho, “Exceptionally directional sources with photonic-bandgap crystals,” *JOSA B*, Vol. 18, N.11, pp.1684, 1689 , Nov. 2001.
12. A. Fehrembach, S. Enoch, and A. Sentenac, “Highly directive light sources using two-dimensional photonic crystal slabs,” *Appl. Phys. Lett.*, 79, 4280–4282, Dec. 2001.
13. C. Cheype, C. Serier, M. Thevenot, T. Monediere, A. Reinex, B. Jecko, "An Electromagnetic Bandgap Resonator Antenna," *IEEE Trans. Antennas Propagat.,* V. 50, N. 9, pp. 1285-1290, Sep. 2002.
14. Y. J. Lee, J. Yeo, R. Mittra, W. S. Park, “Application of electromagnetic bandgap (EBG) superstrates with controllable defects for a class of patch antennas as spatial angular filters,”

IEEE Trans. Antennas Propagat., Vol. 53, N. 1, pp. 224-235, Jan. 2005.

15. A. R. Weily, L. Horvath, K. P. Esselle, B. C. Sanders, T. S. Bird, "A Planar Resonator Antenna Based on a Woodpile EBG Material" *IEEE Trans. Antennas Propagat.*, V. 53, No. 1, pp. 216-223, Jan. 2005.
16. R. Gardelli, M. Albani, and F. Capolino, “Array thinning by using antennas in a Fabry-Perot cavity for gain enhancement,” *IEEE Trans. Antennas Propagat.,* V. 54, N. 7, July 2006.