ADAPTIVE BEAM STEERING BASE STATION ANTENNA: PERFORMANCES OPTIMIZATION OF THE RECONFIGURABLE EBG MATERIAL

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ABSTRACT

The aim of this paper is to present a new principle of beam steering using a controllable Electromagnetic Band Gap (EBG) based on the commutation between two complementary states of the metamaterial thank to PIN diodes along metallic wires for a wide frequency band including GSM, DCS and UMTS in place of classical feeding network including phase shifter, amplifier, ...
After a short presentation of the beam steering principle and the antenna design, we will present the measurements of the electromagnetic characteristics of the antenna in several configurations (single or multibeam). These measurements will show the capabilities of this antenna to manage the radiation and some problems to steer the beam on all the working bands. Additionnal simulations, including lumped elements, will be presented in order to understand the radiation control problems, to "improve" the performances of the EBG material and find the best RF characteristics of the PIN diodes to be able to manage the radiation on all frequency bands.

INTRODUCTION

The needs for mobility lead to the use of increasingly complex base stations. To address the need of multi-band and multi-beams antenna capacities (GSM, DCS and UMTS), we have tried to replace the complex classical feeders systems (RF components, Butler matrix, …) by the association of an EBG material. The main advantage of this new kind of antenna is to simplify the beam steering by the biasing of PIN diodes inserted along the metallic wires that composed the EBG material. The diodes control the size of the composite wire: long metallic wire when the diodes are ON and the EBG material is reflector, discontinuous wires when the diodes are OFF and the EBG material is transparent. So the azimuth angle, the beamwidth and the number of beams are managed by the two states of the EBG material in the different angular sectors of a “simple DC voltage”[1].

1. BASE STATION ANTENNA DESIGN

1.1. Controllable EBG

The radiation control, over 360° in the azimuth plane, is obtain by a cylindrical reconfigurable EBG, composed of a lattice of metallic wire along wich PIN diodes are inserted. The diodes control the lengh of the wires: long metallic wires when the diodes are ON and discontinuous wires when the diodes are OFF. This two wire states correspond to two complementary states of the EBG material: reflector when the wires are long and transparents when the diodes are OFF [2].

1.2. Beam Steering

If we place an omni-directionnal probe at the center of the EBG material, it’s possible to manage the coverage of the base station antenna: azimuth and width of the beam(s), single or multibeam coverage only with the biasing of the diodes (fig. 1).

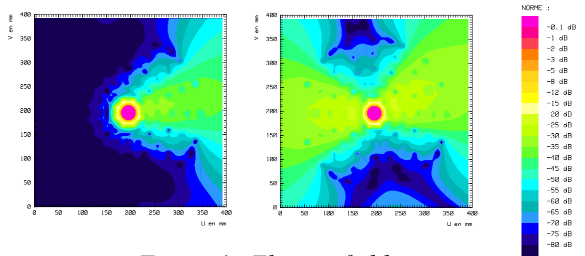

Figure 1. Electric field maps

1.3. Antenna Design

In a first time, all the designs have been made with "perfect" diodes equivalent to:

- short circuit when diode is ON: wires are equivalent to long ones,
- open circuit when diode is OFF: wires are equivalent to discontinuous ones.

Several omni-directionnal probe have been tested and the final choice has been made for a biconical structure including the cylindrical EBG material between the two cones. A shape "optimisation" have been made with our software SR3D [3] in order to reject resonnance along the "equivalent long wires" outside the frequency bands. This geometrical configuration allows to maintain the maximum of radiation the $\theta = 90°$ direction for all working frequency bands. The reconfigurable EBG material design gives us a four cylindrical layers including 216 wires with 5 diodes per wires [4]. The final design is presented fig. 2.

Before the manufacturing of the adaptive antenna, we have manufactured a "passive" version to validate the principle of the beam steering and the simulations.

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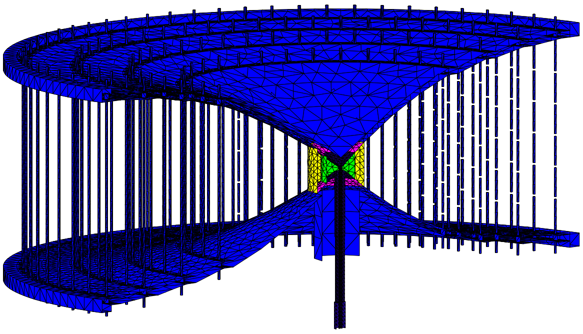

Figure 2. Geometry of the biconical antenna with EBG

All the simulations and the measurements of this "passive" antenna have showed the capabilities to manage the coverage thanks to the apperture in the reconfigurable EBG material in single or multibeams configuration and to match the input impedance of the antenna with small modifications in the ON/OFF wires distribution [1].

2. "ACTIVE ANTENNA"

2.1. Manufacturing

So we have assembled the complete base station antenna including 1080 diodes (Philips BAP64-03) on 216 metallic printed strips between the two cones (fig. 3).

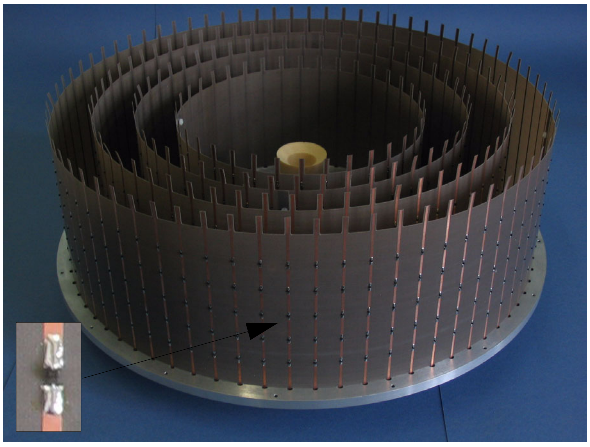

Figure 3. 4 layers EBG between the two cones

We use the coaxial waveguide feeding to put the DC voltage on the top of the biconic antenna where we have placed the bias feeding network of the reconfigurable EBG material including switches, inductances, resistances and LED to visualize the wires states (fig. 4).

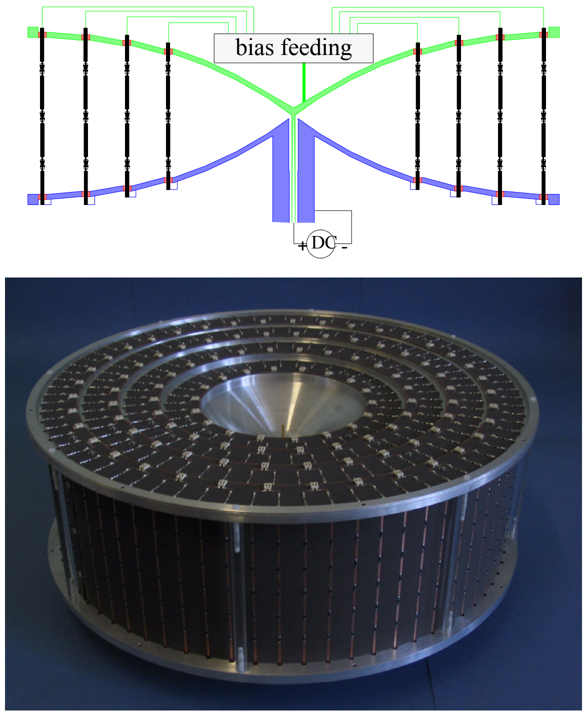

Figure 4. active base station antenna

2.2. Experiments

Before the EM characteristics measurements, we have tested the antenna in two complementary configurations of the EBG material: all the diodes are ON and all the diodes OFF. The input impedances, presented fig. 5, show that up to 1.7 GHz:

- the polarized wires act as short circuits and the reconfigurable EBG is reflector, all the energy is reflected and the input impedance is high,
- when all the diodes are OFF, the EBG material is transparent and the antenna is matched.

But beyond 1.7 GHz, the two complementary states gives an identical input impedance. The decrease of the input impedance when the diodes are ON is due to cylindrical step of the EBG material that increase with the freqeuncy and gives a less reflector material.

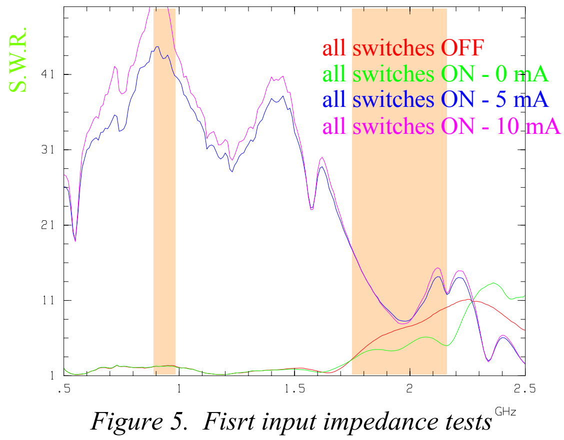

Figure 5. Fisrt input impedance tests

After all, several configurations of the antenna have been tested. We present fig. 6 the input impedance for a single 60° aperture in the EBG material and two bias levels. We can see that small modification of the ON/OFF wires allow to match the antenna in all the working frequency bands. The input impedance is independent of the bias level.

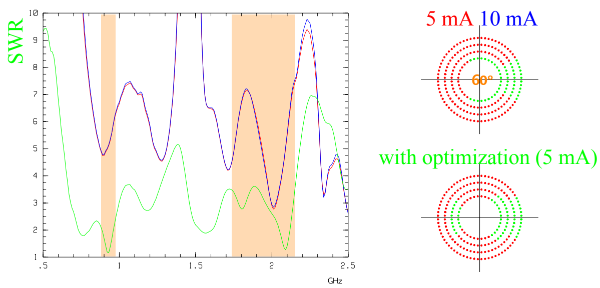

Figure 6. Input Impedances for a 60° EBG aperture

The radiation patterns, in E^{θ} polarisation at different frequencies, the directivity and the gain are presented fig. 7 for the 60° aperture, fig. 8 for two 90° apertures and fig. 9 for three 60° apertures in the EBG material. The radiation patterns are plotted in a 2D polar representation where the axis corresponds to the $\theta = 0°$ direction and the exterior circle to $\theta = 180°$.
For the single beam configuration, like for input impedance, two levels of baising have been tested: 5 mA and 10 mA in each wire.
We can see that for all configurations, the apertures in the EBG material manage the radiation up to 1.7 GHz. Beyond this frequency, the antenna don't steer the beam(s) in the $\theta = 90°$ direction and the azimuth(s) of the aperture(s) but near the $\theta \sim 0°$ direction over the superior cone. This phenomena is visible on the directivity and gain curves. The discontinuity of the directivity appears at this frequency and the losses are important beyond 1.7 GHz.
Like for the input impedance, it is possible to minimize the side lobes that appear at certain frequencies by changing the profil of the aperture(s) in the EBG material. The configuration of 3 beams, we can see high side lobes at 0.9 GHz because the 60° separations between the apertures are small in wavelenght to have a good isolation between the lobes.

The measurements of the adaptive antenna breadboard showed the capabilities to manage the beam(s) in the required direction(s) with the adequate beamwidth(s) thanks to the reconfigurable EBG material including PIN diodes. The level of losses and the electromagnetic characteristics are independent of the biasing level as soon as the diodes are "enough" polarized.

Additionnaly tests have been made and demonstrated that this problem is partly related to the reverse capacitance of the diodes that is not too small to simulate an open circuit when the diodes are OFF. Up to 1.7 GHz, these diodes have "good" performances and we can steer the beam(s) in the azimuth plane with control of the aperture(s) of the EBG material and match the antenna by small modification in the ON/OFF wire distribution. But beyond 1.7 GHz, we can no longer monitor the radiation.

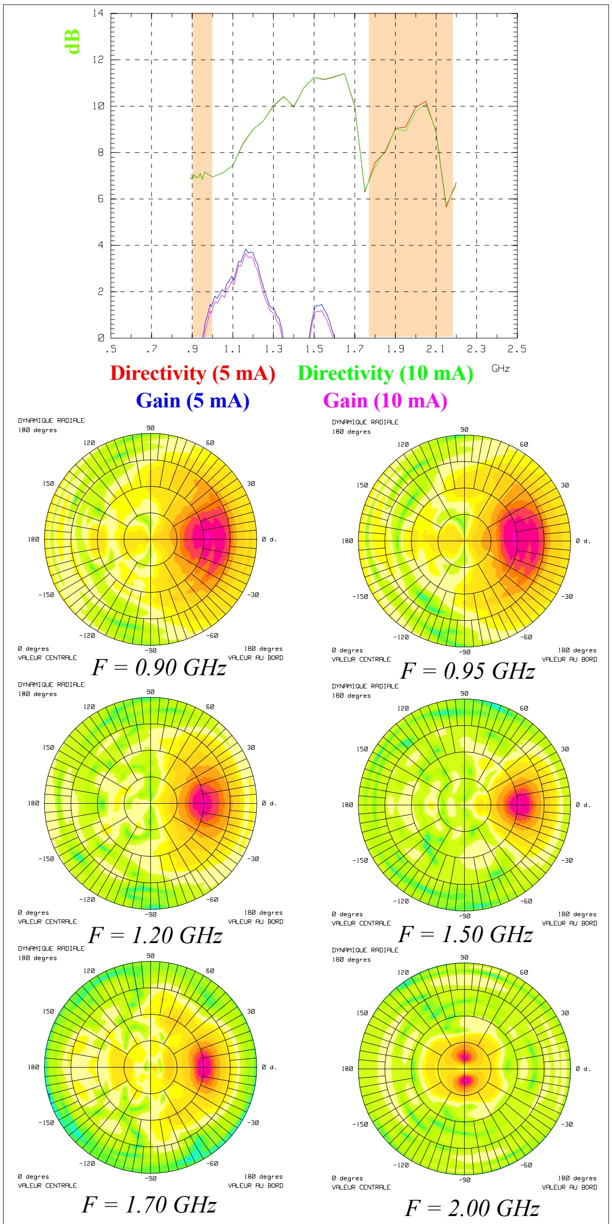

Figure 7. radiation patterns - 1x60° aperture in EBG

3. PERFORMANCES "OPTIMIZATION"

The design of the antenna has been made without taking into account the parasitic elements of the PIN diodes in its two states (see 1.3). So in order to avoid this problem in next designs and studies of reconfigurable material, we have introduce in our code SR3D [3] the capabilities to taking into account the equivalent RF circuits of the diodes thanks to RLC lumped components.

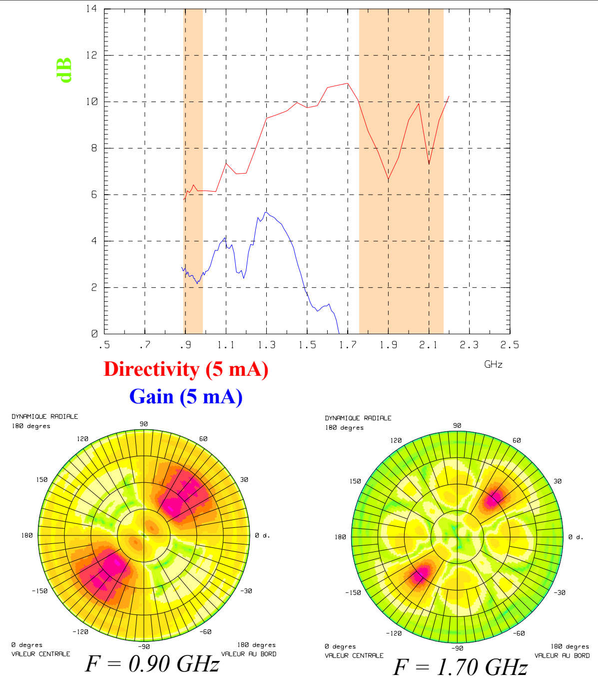

Figure 8. radiation patterns - 2x90° apertures in EBG

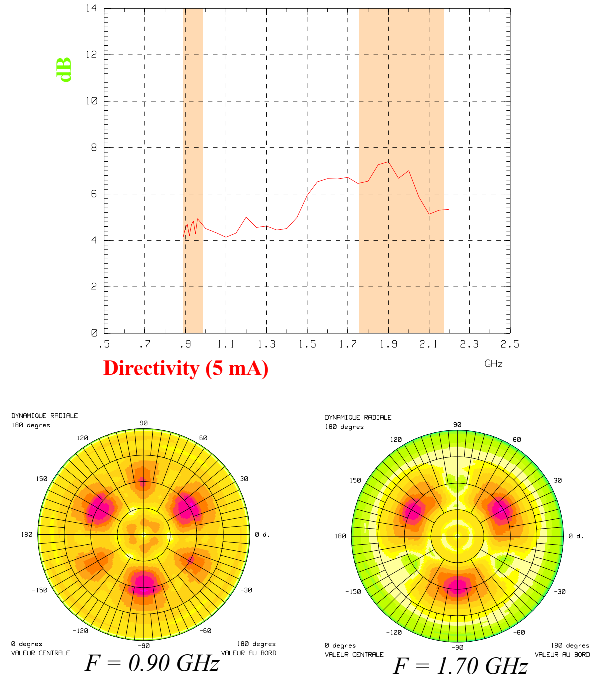

Figure 9. radiation patterns - 3x60° apertures in EBG

This implementation will reduce the dubiousness of the simulations due to the integration of "simple" electronic components and their parasitic elements that modify the behavior and the performances of the radiating structures.

3.1. Lumped elements

We choose in a first time to have simplified equivalent circuits of the two states of the PIN diodes (fig. 10) with the following min and max values (manufacturer datasheets, type of packages (plastic, ceramic)):

- L_p: package inductance: 0.3 nH < L_p < 2.0 nH,
- $C_t = C_{jOFF} + C_p$:
  - C_{jOFF}: OFF jonction capacitance: 0.03 pF < C_{jOFF} < 0.10 pF
  - C_p: package capacitance: 0.06 pF < C_p > 0.35 pF
- R_{jOFF}: OFF junction resistance: ~50 kΩ.
- R_{jON}: ON junction resistance: few Ω.

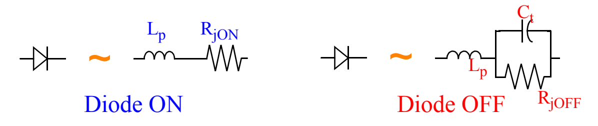

Figure 10. RF equivalent circuits

The C_{jOFF} value could be more smaller if we put an inverse voltage, that is impossible in our case because we can't put a positive and negative voltage on the same cone and 5 diodes are in series on the same strip and we can't put inverse voltage on each diode.

We have remeshed the structure and replaced the metallic wires by metallic strips with lumped elements in place of open or short circuits. The electric currents, presented fig. 11, show that the equivalent circuits give "long strips" for ON diodes with lower currents on the cones and "transparents ones" for the diodes OFF.

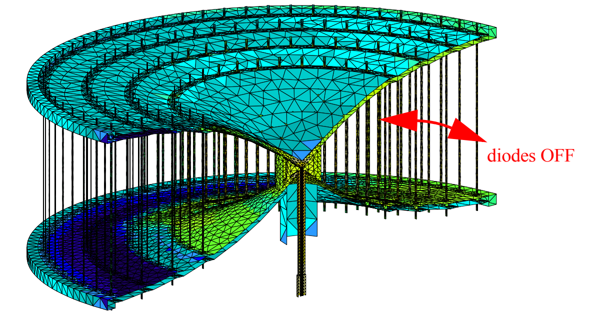

Figure 11. electrical currents

3.2. Simulations

Before the improvement of the radiation characteristics of the antenna, we have tried to find again the measured radiation characterics of a single 60° aperture in the EBG presented fig. 7.

The RLC values for the BAP64-03 diodes, included in the simulations, are:

- L_p = 1.68 nH,
- R_{jOFF} = 50 kΩ,
- R_{jON} = 2 Ω,
- 0.30 pF < C_t < 0.45pF.

We presente fig. 12 and fig. 13 the simulated directivity and gain for respectively C_t = 0.45 pF and C_t = 0.30 pF (the measured directivity and gain are in black dotted lines). The behavior of the simulated directivity for 0.30

pF is similar to the measured one with the step at 1.7 GHz.
The simulated gain is more important for the lower frequencies but variation of the R_{jON} value could align the simulated gain to the measured one. And we must add the parasitic elements due to soldering that are the unknowns in this problems and are a part of this gap with experiments
The radiation patterns for 0.30 pF are presented fig. 13. Like measurements, the "simulated" antenna steer the beam outside the 90° elevation direction beyond 1.7 GHz.

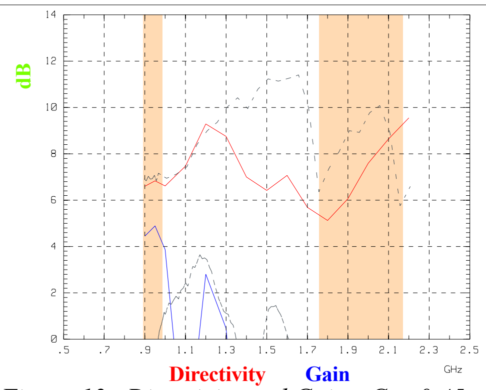

Figure 12. Directivity and Gain - C = 0.45 pF

After that, in order to minimize the capacity of the diodes OFF, we replace the plastic package by a ceramic one with:

- $L_p = 0.40$ nH,
- $R_{jOFF} = 50$ kΩ,
- $R_{jON} = 2$ Ω,
- 0.09 pF $< C_t < 0.20$pF.

The directivity and gain for 0.20 pF are presented fig. 14 and fig. 15 for 0.09 pF. For the lower capacitance, we can see that the gain don't slump beyond 1.8 GHz and the losses stay under 3dB including insertion losses. The radiation patterns are presented fig. 15 for 0.09 pF and we can see that for all frequencies the antenna is able to steer the beam in the azimuth plane, side lobes appear at 2.0 GHz but a modification of the ON/OFF wires around the aperture can minimize its.

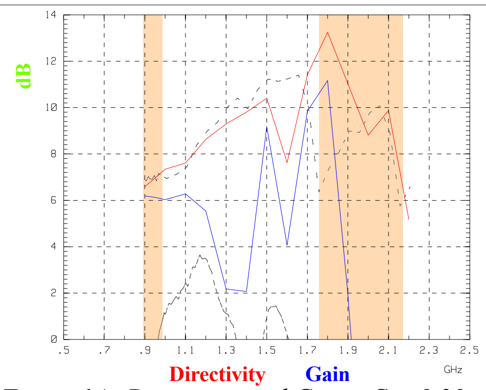

Figure 14. Directivity and Gain - C = 0.20 pF

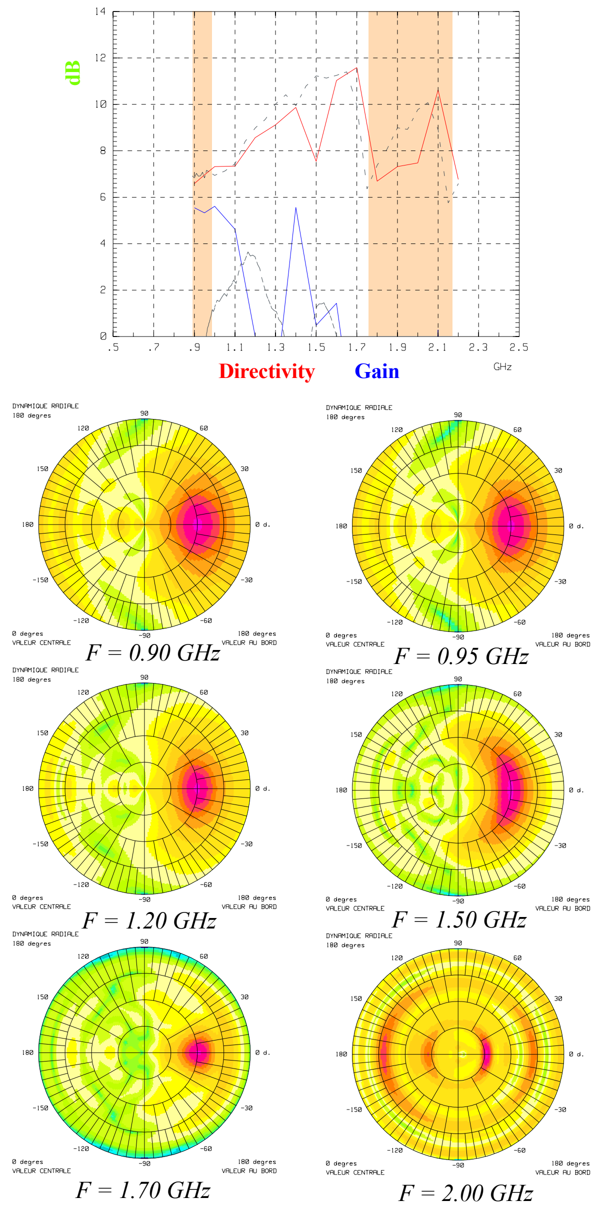

Figure 13. directivity, gain and patterns - C = 0.30 pF

On the fig. 16, we have plotted the total losses in the lumped elements. The reverse capacitance of the diodes is directly "proportional" to the frequency where high losses appear. For the lower capacitance, the losses in the lumped elements stay below 2 dB.

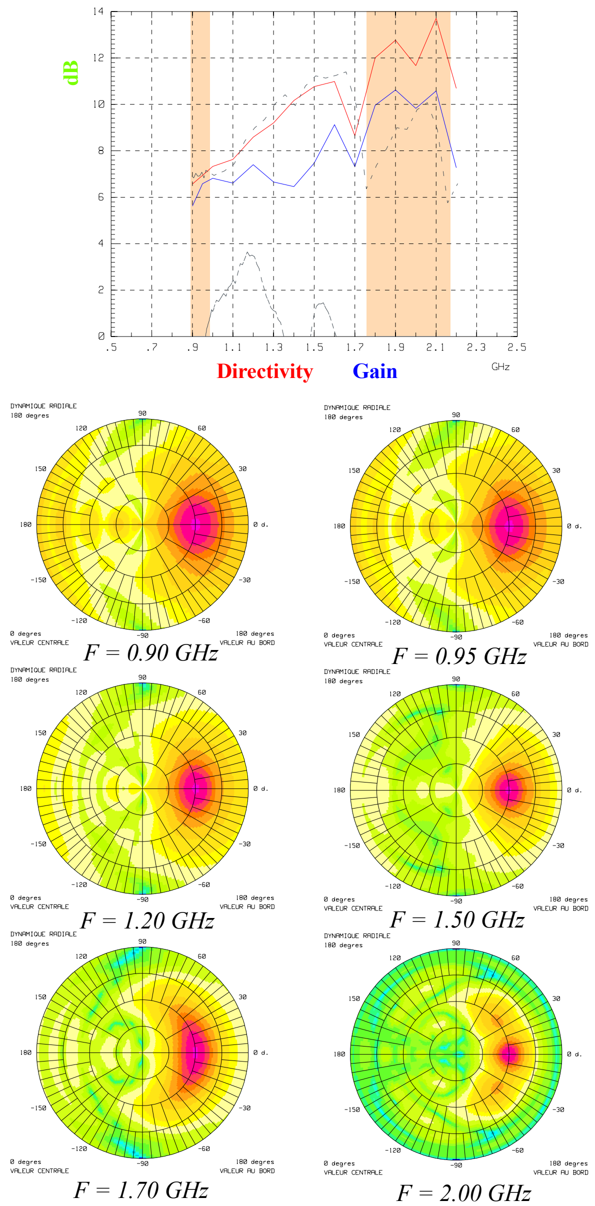

Figure 15. directivity, gain and patterns - C = 0.09 pF

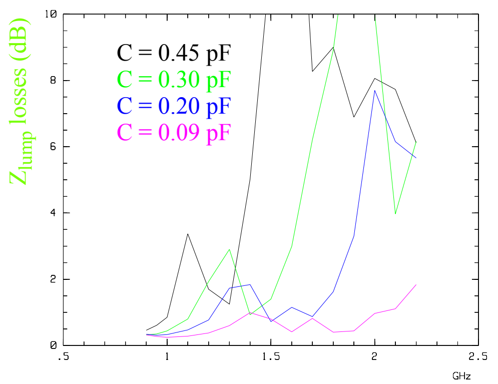

Figure 16. losses in lumped elements

Several reverse capacitances have been tested and compared to the experiments, the inductance, capacitance of the package and resistance of the junction have been taking into account.
These simulations show that a total capacitance below 0.1 pF is the upper limit to manage the radiation and to have losses compatible with the use of the antenna and its adaptive capabilities.

CONCLUSION

The experiments and the simulations demonstrate the beam steering capability offered by a cylindrical EBG material associate to an omni-directional probe. The control device of the EBG material by the application of a continuous voltage on each wire is simplified to the maximum compared to the traditionnal feeding network.
The simulations with RLC lumped elements have shown the important part taking by the reverse capacitance of the diodes in the level of losses and the control of the radiation in all the working frequency bands.
A maximum reverse capacitance has been defined in order to maintain the beam steering capabilities in all the working frequency bands. With the same manufacturing method with printed metallic strip, we must use diodes in ceramic package that allow to obtain small capacitance of the package and take care for the soldering to add negligeable parasitic element, or we must find a new manufacturing method for the controllable EBG with the possibility to assemble the diodes without package.
In all case, measurement of an improved breadboard must be made in order to verify the level of losses and the beam steering given by the simulations. Power and EMC tests must be added to validate the concept of this antenna and its technology for the application to base station antenna.

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