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Design and Characterization of Effective Antennas for K-band Rectennas

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Abstract—This paper addresses the design and the characterization of an innovative antenna so-called *crossed dipoles array antenna* which is integrated into a broadband compact rectenna operating in the K-band. A dedicated methodology design is presented in order to take into account the impact of the rectifier part of the rectenna on the antenna performances. Simulation and experimental results as well as design considerations relative to such antenna are presented with a focus on the trade-off between frequency bandwidth, antenna gain and the beamwidth.

Index Terms—antenna, rectenna, planar dipole, energy harvesting.

I. INTRODUCTION

Recently, energy harvesting by using rectennas was identified as a promising solution to power autonomous wireless sensors for satellite health monitoring [1]-[3]. Antennas are key elements in order to design any effective rectenna. This paper addresses the design and the characterization of an innovative antenna to be integrated in a broadband compact rectenna operating in the K band [3]. The incident waves illuminating satellite panels come from various directions and have various polarizations (depending on satellite antennas types and their mounting position). Thus the antenna has to be engineered to meet technical specifications (operating frequency, polarization and radiation pattern shape/tilt angle, gain) in order to maximize the amount of the RF power injected at the input of the (rectenna) rectifier. The proposed antenna is called here the *crossed dipoles array antenna* (CDAA) and should exhibit in the targeted frequency band a gain as high as possible, a large bandwidth and an input impedance matched with the complex input impedance of the rectifier.

II. RECTENNA TOPOLOGY

The proposed topology [3] is based on the use of a high gain planar antenna directly connected with a high frequency rectifier using (only) one Schottky diode. Fig. 1 shows the top view of the rectenna while its bottom view is represented in Fig. 2. The antenna consists of an array of two planar crossed dipoles. The rectifier consists of (i) a Schottky diode mounted on the top side of the planar circuit board (PCB) and (ii) a lumped filtering capacitor of 1.5 pF and a load (see Fig.2).

Thus, the low-pass filtering function is achieved by the coplanar strip supported structure mounted on the bottom side of the rectenna. The connection between the diode and the low-pass filter is performed by using two via holes. The matching between antenna and rectifier input impedances is achieved by properly controlling the mounting position of the Schottky diode.

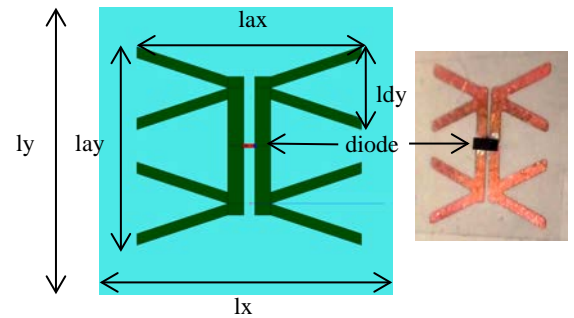


Fig. 1. Top view (left, not to scale) of the simulation model (FEKO) and a photo (top side) of the manufactured rectenna (right).

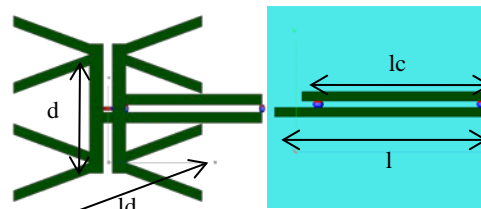


Fig. 2. Top view (left, not to scale) of the simulation model (PCB substrate is not represented) and bottom view (right, not to scale) of the rectenna.

III. ANTENNA DESIGN

The antenna located on the top side can be viewed as an array composed by four printed half-wavelength dipoles. The maximum theoretical gain (G_{max} in dBi) of such an array antenna can be computed using the following formula:

$$G_{max}=10 \cdot \log(4) + G_d = 6 + 2.15 = 8.15 \text{ dBi} \quad (1)$$

where $G_d = 2.15 \text{ dBi}$ is the gain of a lossless half-wavelength dipole. This gain is 3 dB higher when a metallic reflector is properly positioned below the antenna surface.

Thus the expected maximum gain is 11.15 dBi. The main geometrical parameters for optimizing CDAA performances are: the length of the crossed dipole arms (l_d), the angle between crossed dipoles (α), the array step (d), the strip width (w) and the gap between the strips of the coplanar stripline (g). The length of the crossed dipole arms (l_d) and the array step must be close to the half-wavelength. A special design methodology was adopted for optimizing the overall rectenna conversion efficiency. The proposed design methodology combines full-wave electromagnetic simulation (for CDAA) and non-linear circuit simulation (for rectifier part) and is described in [3]. Concerning antenna design, the main goal was to simultaneously achieve a high gain for the CDAA with an acceptable matching in a large frequency bandwidth between CDAA and the rectifier for various load impedance and incident RF power. Additionally, the 3D beamwidth must to be quite large in order to match the incoming direction of the incident electromagnetic waveform. We target also a compact design. At such high frequencies and for such a compact structure the overall PCB layout can impact the radiation pattern of antenna. Thus the CDAA was first designed, simulated and optimized using FEKO software for operation in the desired frequency band. The diode was replaced by a voltage port while the capacitance (e.g. 1.5 pF) and the load (e.g. 300 Ω) were modeled as port loads. The antenna radiation pattern and the distribution of the electric currents on the metallic strips were simulated in order to insure the proper radiation mechanism and to maximize the gain in the Oz-axis direction (that is, in the direction perpendicular to the rectenna/antenna surface). By adopting this design methodology we assured that (i) the impact of the overall PCB including the load and the capacitance) was taken into account and (ii) the radiation pattern and the radiation mechanism of the designed CDAA were not strongly perturbed by the rectifier part of the rectenna. Fig. 3 shows the simulated gain along Oz axis for the optimized CDAA loaded by the rectifier (PCB traces located on the bottom of the rectenna, the capacitance and resistance modeled as port loads). A metallic plate acting as reflector is positioned at a distance of 2.4 mm below the antenna. Fig. 4 represents the simulated gain of the optimized CDAA (loaded by the rectifier) in two vertical planes (xOz-plane: $\phi=0^\circ$ and yOz-plane: $\phi=90^\circ$) at 17.7 GHz. A MoM-SEP (Method-of-Moments Surface Equivalence Principle) [4] simulation approach with a medium mesh size was selected in Feko as a good trade-off between accuracy and simulation time. We note that (i) the gain of the CDAA is higher than 8.5 dBi in the targeted frequency band and (ii) the 3dB beam-width is in the range of the 60° .

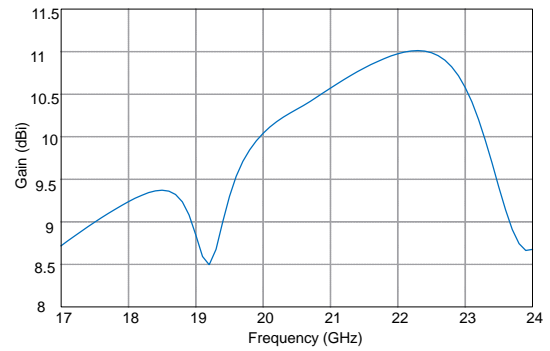


Fig. 3. Simulated gain (FEKO) along Oz-axis versus frequency.

CDAA is excited by a coplanar strip line (CPS) and their performance was checked by using only full-wave electromagnetic simulations. In order to measure the radiation pattern of the optimized CDAA a test structure (represented in Fig. 5) was designed, fabricated on Rogers 6002 substrate (relative permittivity: 2.94, loss tangent: 0.0012, thickness: 508 μm) and characterized in an anechoic chamber. The same substrate was used for the rectenna/CDAA design and simulation. A dedicated T-junction CPS-to-microstrip line transition [4]-[5] inserted between the CDAA and the end-launch K (coaxial) connector was designed and then optimized by using intensive electromagnetic simulations. This transition consists of (i) a T-junction for matching the field distribution between the CPS section and the microstrip lines and (ii) three section of microstrip line (Fig. 5) acting as quarter wavelength impedance transformer. The design of this transition is not addressed here but it will be presented at conference.

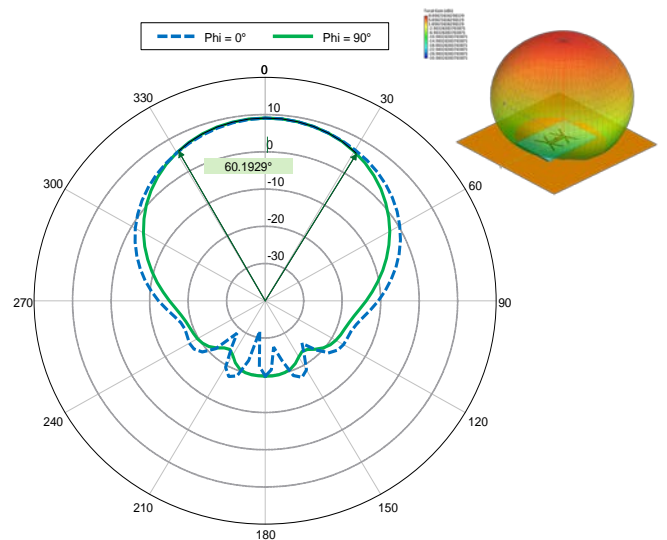


Fig. 4. Simulated (FEKO) gain of the CDAA (xoz-plane: $\phi=0^\circ$ and yoz-plane: $\phi=90^\circ$) at the frequency $f=17.7$ GHz. The inset shows the 3D (gain) radiation pattern.

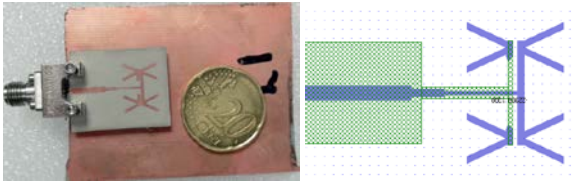


Fig. 5. Manufactured CDAA for radiation pattern measurements (left) and the corresponding layout (right).

A metallic plate was positioned below the rectenna. The ground plane positioned at approximately 3 mm was fixed with the help of the screws of the end lunch connector. The main dimensions of the manufactured rectenna (see Fig. 1 and Fig. 2) are: $l_x=1.4\text{mm}$, $l_y=1.8\text{mm}$, $l_z=10\text{mm}$, $l_{ax}=8.3\text{mm}$, $l_{ad}=4.3\text{mm}$. These geometrical values are a good trade-off as function of the design requirements presented in section III. We note that the layout was accommodated with the manufacturing tolerances available in a university unit equipped for general (low frequency) PCB manufacturing. Fig. 6 and 7 report the measured and the simulated gain in two orthogonal planes (xOz - $\phi=0^\circ$ and yOz - $\phi=90^\circ$) at $f=17.7$ GHz for the manufactured test antenna shown in Fig. 5. The maximum measured gain is approximately 10 dBi and the 3dB beamwidth is 64° in the xOz plane and 52° in the xOz plane. The presented CDAA topology allows an effective design for high-efficiency and compact rectenna design in the microwave spectrum. Measured RF-to-DC conversion efficiency up to 66% was obtained by using rectenna based on CDAA design [7]. The CDAA can be easily scaled in frequency for millimeter wave applications and adapted for circular polarization. Increasing the number of ‘crossed’ dipoles (CDAA is an array formed by two antennas composed by two ‘crossed’ dipoles each) will conduct to a degraded bowtie antenna. Also, the number of crossed dipoles can be increased and more directive and high gain antenna array can be designed at the expense of a narrow beamwidth.

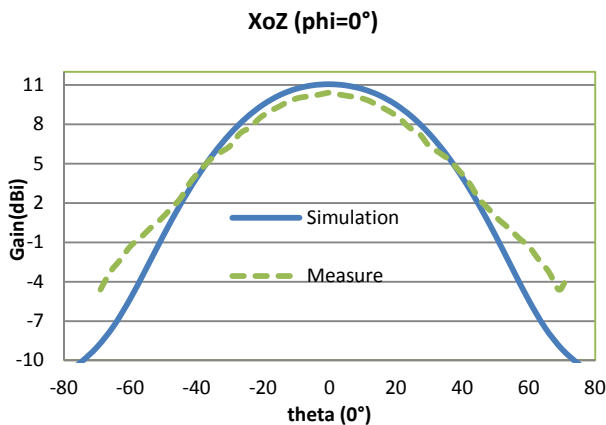


Fig. 6. Measured (green curve) and simulated (blue curve) gain (dBi) of the manufactured CDAA (xoz plane, $\phi=0^\circ$).

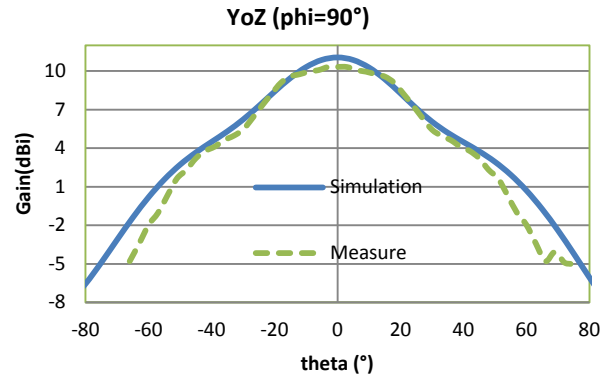


Fig. 7. Measured (green curve) and simulated (blue curve) gain (dBi) of the manufactured CDAA (yoz plane, $\phi=90^\circ$).

IV. CONCLUSION

A compact high-gain and wide beamwidth antenna consisting of an array of crossed printed dipoles was designed for integrating in a K-band rectenna. A dedicated design methodology was adopted in order to take into account the impact of overall PCB of the rectenna (including the coplanar strip lines supported rectifier) on the antenna radiation pattern. Moreover a test antenna was manufactured and characterized proving that the proposed CDAA exhibits a high gain (10 dB) radiation pattern with a quite wide 3dB beamwidth (at least 52°) therefore fulfilling the technical requirements for a high-efficiency K-band rectenna for satellite application.

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