Design and Evaluation of a High Bandwidth Patch Antenna Array for X Band Space Applications

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***Abstract*—The use of high frequency data transmission in space applications, e.g. in the X band, offers a variety of advantages compared to the frequently used S band transmission. Not only the antenna size and weight is dramatically reduced, which is a very crucial point in space applications, but also the possible bandwidth is increased. This paper describes the theoretical properties and the design process for a stacked patch array antenna in the frequency range between 7 and 8.5 GHz. Another advantage of a broadband antenna is that it can be used "off-the-shelf" for a variety of different applications, even for those with smaller needs regarding bandwidth.**

***Keywords—* patch antenna; stacked patch; circular polarization; space; design; evaluation**

I. Introduction

Conventional patch antennas are able to cover bandwidths of only a few percent. To increase the total bandwidth, stacked architectures like described in [1] can be used. These stacked arrangements show significant higher bandwidths compared to conventional single layer patch antennas. A stacked arrangement combines the advantages of the high bandwidth potential of a thick substrate and the low-loss-capabilities of a thin substrate for the feeding network.

The antenna described in this paper should be circularly polarized. This is especially important for certain space applications, as e.g. LEO satellites spin around their own axis, so that the direction of a linearly polarized wave cannot be guaranteed.

Another requirement for the use in space environment is temperature stability regarding the electric properties and the service life. Also of high importance is the mechanical stability to guarantee the survival of the mandatory qualification tests.

II. Antenna Theory and Design

The bandwidth of a conventional patch antenna increases with increasing the substrate thickness and reducing the dielectric constant of the substrate material which leads to a reduced quality factor and therefore enhances the radiated power. On the other hand there exist certain limits for substrate thickness regarding losses of the feed network and due to surface waves. Also the feed structure becomes more inductive which complicates impedance matching of the antenna.

To handle this conflict of interests, stacked patch architectures like shown in Fig. 1 were invented. In this case, the lower substrate should be thin compared to the upper substrate and should feature a higher dielectric constant to concentrate the electric field in the substrate and minimize radiation losses of the feed network [2]. As bottom substrate Rogers TMM3 with a thickness of 1.27 mm was used. The top substrate was provided by a Rogers 5880 LZ with 3.7 mm strength. To guarantee the needed physical stability, a very thick upper substrate was used. It was found that the loss due to surface waves compared to a 1.9 mm thick substrate can be neglected. These substrates were chosen in order to ensure the thermal stability needed for LEO satellite use. Both materials are qualified as "low-outgassing" [3].

For the final antenna, an air gap d_L was introduced to further reduce the dielectric constant "seen" by the upper patch.

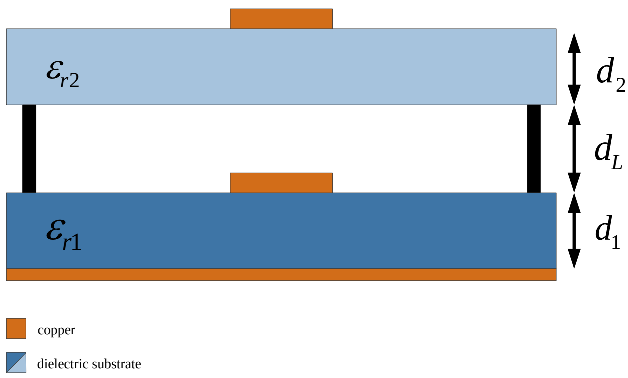

Figure 1. Schematic representation of stacked patch structure

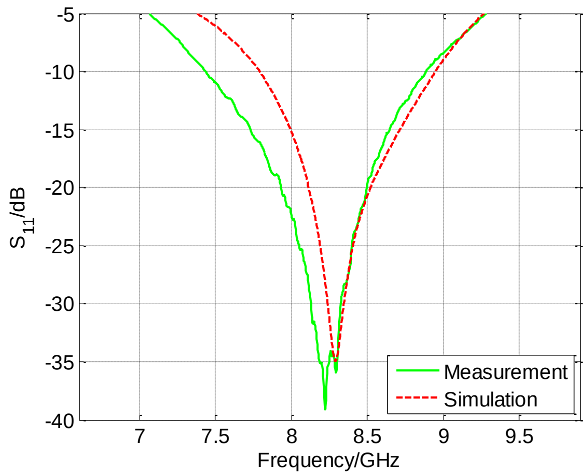

Figure 2. Input reflection coefficient S_{11} of the single element

The generation of circular polarization was realized using the well-known principle of truncated corners. This single-feed approach offers the advantage of simplified design and reduced crosstalk between the array elements compared to multi-feed solutions. In contrast, the possible AR bandwidth is much lower compared to multi-feed patch antennas. To face this problem, some techniques regarding the array arrangement were developed, which are discussed in section III.

The antenna was designed and optimized in CST Microwave Studio 2012. In a first step, a single element antenna was built. The simulation results as well as the measurement results of the input reflection coefficient S_{11} are shown in Fig. 2. The center design frequency was defined to be 8.25 GHz. However, due to tolerances of the dielectric constant, a deviation of the resonance frequency between the measurement and the simulation could be observed. This was compensated by slightly increasing the design frequency in the simulation towards higher values.

III. Array Design

To achieve the desired gain, the previously designed single element was arranged in a 2x2 array. The optimum distance regarding gain and side lobe level was found to be 0.63λ.

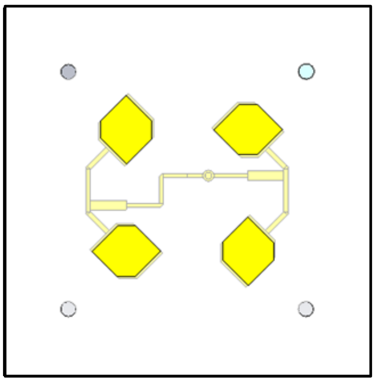

Figure 2. Schematic top view of patch array. The structure on the lower layer is shown in light yellow

To broaden the impedance- and AR-bandwidth, the principle of "sequential rotation" as presented in [4] and [5] was used for the arrangement of the elements. In this constellation, the unavoidable elliptic polarization patterns of the single elements superimpose in that way, that the resulting polarization pattern becomes circularly polarized in theory. To compensate the physical rotation of the elements, these shifts have to be undone by shifting the electrical phase of the feed of each element. Furthermore, this method also promises a broadening of the impedance bandwidth due to cancellations of the reflections in the feed lines. For the reflected wave V_r at the input of the port holds:

$$V_r = V_0 \Gamma \sum_{n=1}^{N} e^{j2\varphi_n}$$

with

V_0 = Magnitude of the incoming wave

Γ = Reflection coefficient

N = Number of elements

φ_n = phase of the n-th element

For a four element array with a 90° phase shift for each element it holds, that the reflections of the single elements cancel out and therefore V_r equals zero:

$$V_r = V_0 \Gamma [2e^{j0^\circ} + 2e^{j180^\circ}] = 0$$

In Fig. 2, the final array design including the phase shifting network is shown. The different lengths of the microstrip lines were optimized in AWR Microwave Office. The Figures 3 and 4 show the milled prototype of the antenna array.

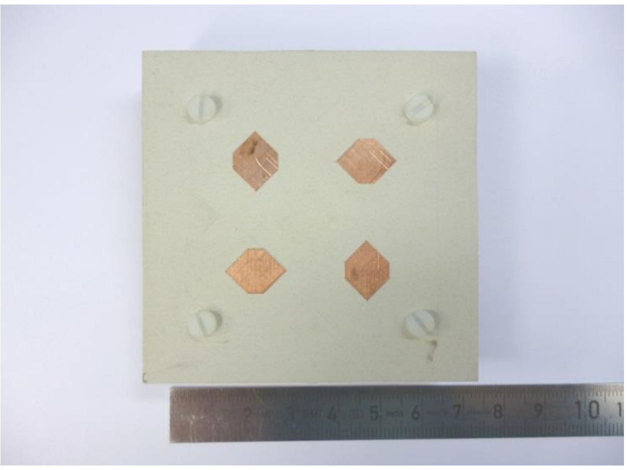

Figure 3. Top view of milled patch array, only the upper layer is visible

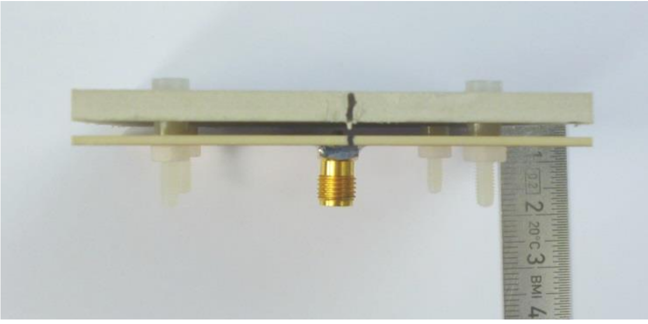

Figure 4. Side view of milled patch array

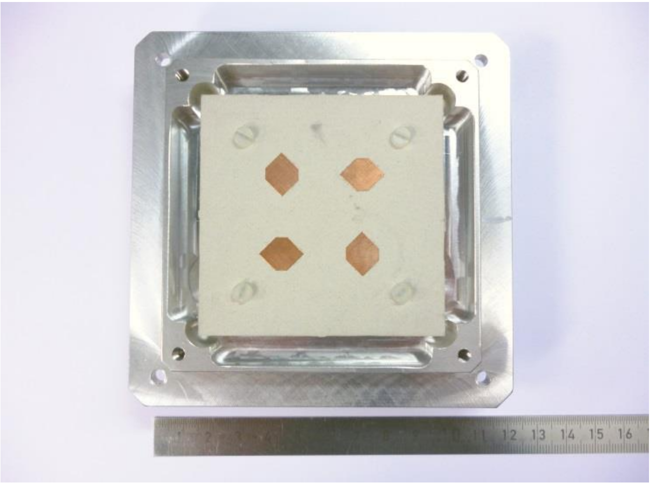

Figure 5. Patch antenna array with mounted housing

IV. INFLUENCE OF HOUSING AND RESULTS

In the last step, a protective housing made of aluminum has been designed to mount the antenna on the test equipment. Main goals for the design were a minimum influence regarding the alteration of the radiation characteristics of the antenna and the possibility to mount a protective random. The RF input is realized through a coaxial feed and an SMA connector on the back of the antenna. The complete arrangement of the patch antenna array and the housing is shown in Fig. 5. It turns out, that the housing has a minor effect on the input reflection coefficient S_{11}, which is shown in Fig. 6 for the simulated as well as measured structure. Nevertheless, a certain alteration of the antenna diagram can be observed (see Fig. 7). With housing, the main lobe becomes broader and is reduced in its maximum value. The axial ratio of the antenna did not undergo significant changes due to the introduction of the aluminum housing (see Fig. 8).

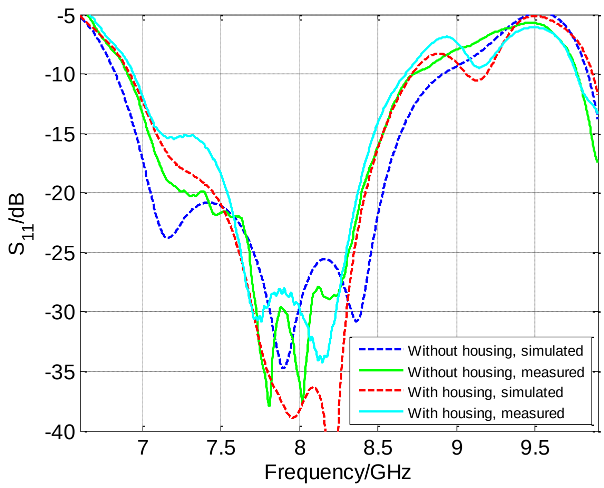

Figure 6. Input reflection coefficient S_{11} of the 2x2 array

V. THERMAL BEHAVIOR

As already mentioned in Sections I and II, importance was attached to good temperature stability in the range between -30 °C and +95 °C. This was accomplished using materials with low thermal coefficients regarding the mechanical dimensions as well as the dielectric constant. In Fig. 9 the thermal behavior of the input reflection coefficient is shown for different temperatures. It can be seen, that there is literally no change regarding the input reflection coefficient $S_{11.}$ The ripple and different shape of Fig. 9 compared to Fig. 6 is the result of unwanted reflections inside the climate chamber which was made out of metal.

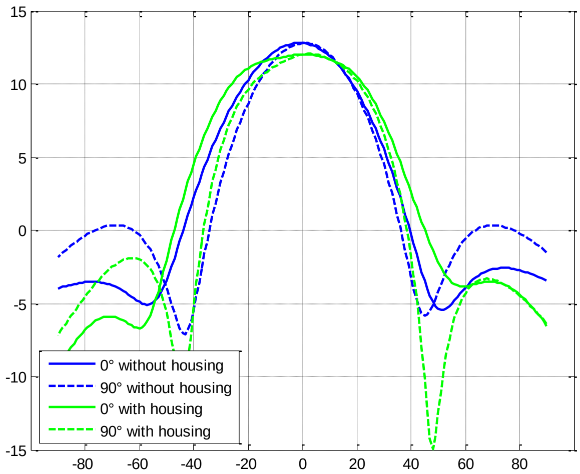

Figure 7. Simulated radiation pattern for 8.25 GHz

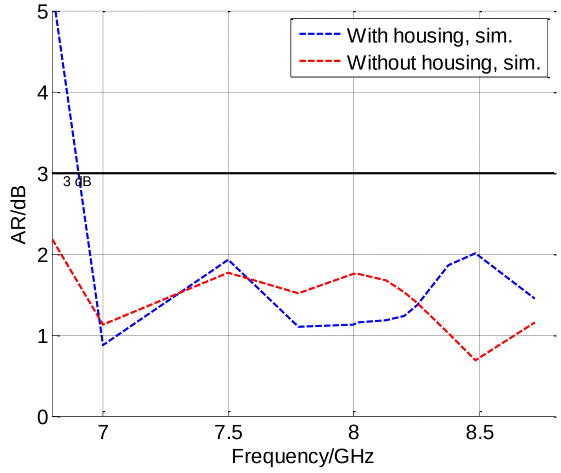

Figure 8. Simulated axial ratio of the antenna array

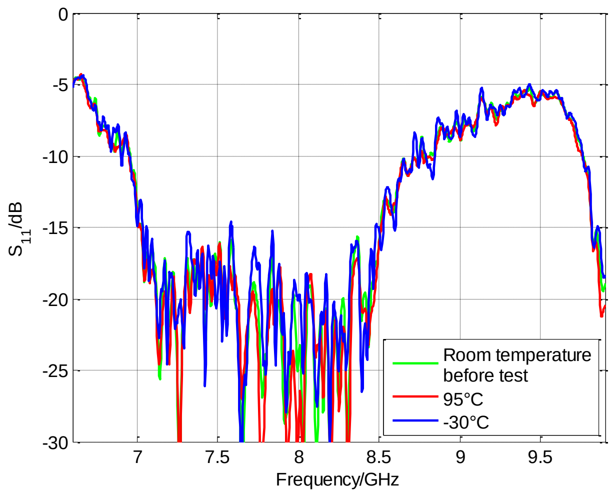

Figure 9. Input reflection coefficient S_{11} of the antenna array under different temperature conditions

VI. Conclusion and Outlook

A compact and lightweight circular polarized array antenna with a high impedance bandwidth compared to traditional single layer patch antennas has been designed and built. The total impedance bandwidth is 28%. The radiation characteristics meet the expected values for a 2x2 array. Due to the use of the principle of "sequential rotation" a very low axial-ratio over a large bandwidth is achieved, despite the use of single-fed patch elements. The whole downlink frequency range for space applications in X Band designated by the ITU is covered with this antenna.

Regarding the space qualification tests, the thermal test was already passed successfully with very good results. Due to the attached importance to a sturdy structure in combination with the housing, no bigger issues are expected regarding the following mechanical stress tests.

References

[1] Rod B. Waterhouse, "*Stacked Patches Using High and Low Dielectric Constant Material Combinations*", IEEE Transactions on Antennas and Propagation, Vol. 47, No 12, 1999

[2] Constantine A. Balanis, *Antenna Theory*, New York: Wiley, 2005

[3] Rogers Corp., *"Low Outgassing Characteristics of Rogers Lamonates Approved for Spacecraft Applications",* Chandler, AZ, USA, 2002

[4] Daniel H. Schaubert, David M Pozar, *Microstrip Antennas*, IEEE Press, 1995

[5] Kai Fong Lee, Kwai Man Luk, *Microstrip Patch Antennas*, Imperial College Press, London, 2010