Wireless Controllable Reflectarray Antenna

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***Abstract*—The demand for high gain and high aperture satellite antennas has been evolving tremendously recently and will carry on during the next years. They may be required to not only provide a good RF performance yet versatile operation but also to keep an easy integration mechanism with the platform for applications that require beam steering. One such application for large aperture antennas is Synthetic Aperture Radar (SAR). This paper presents a novel concept of a wirelessly controllable electronic modular beam steerable and beam shaping X-Band reflectarray concept. The reflectarray is composed of a two-dimensional array of identical tiles, where each one is composed of several similar unit cells. Each unit cell has an active low-power device to control its reflection phase, allowing beam manipulation. Simple radio control signals, based on amplitude modulation, are sent by a separated feed providing the command for specific antenna pattern configurations. This command is interpreted and decoded by a specific low-footprint circuit embedded in the back of each tile that actuates on the phase control elements of each unit phase cell. The only external connection required for such reflectarray is a DC low-power bus, thus reducing the complexity of integration into a satellite.**

***Index Terms*—reflectarray, wireless, digital beam steering, satellite antenna, SAR.**

I. Introduction and Motivation

A reflectarray is an antenna consisting of a flat reflecting surface and a feed ideally located at its focal point, where the reflecting surface can use various radiating elements. These elements are designed to reradiate and reflect the incident field with the desired electrical phases to form a planar phase front in the far-field. One radio-frequency (RF) challenge in space relates to equipment size and mass optimization for the desired performance. Regarding reflectarrays, stowage volume is driven by the panel thickness and hinge stack height which determines the total depth of the folded panel assembly. A recent work performed by Jet Propulsion Laboratory, JPL, for a deployable high-gain antenna for Mars Cube One (MarCO) CubeSat mission to Mars [1] addresses this topic and proposes an innovative design where the performance of the antenna is maintained. A reflectarray antenna is, therefore, a promising choice to maximize the ratio between antenna effective deployed area and stowed volume [2]. There is also a recent increasing interest in electronically reconfigurable reflectarray antennas. Equipping satellites with such capabilities potentially exhibits exceptional performance in scanning/tracking velocity, tolerance to coplanarity mechanical imperfections associated with deployment, beam orientation and shaping modification. Space and terrestrial communications, remote sensing and Synthetic Aperture Radar (SAR) systems are examples of where such antennas can be used [3].

One of the most challenging aspects of reconfigurable reflectarrays is their control. First, there is a need to individually and precisely control each cell reflection phase, which can add up to more than a thousand for the aimed application. Second, the current systems require complex wiring to convey power supply and digital control information from the platform to the antenna. This paper proposes a new concept for the design of a modular X-Band reflectarray, where its beam is wirelessly controllable. The proposed configuration allows for finer beam steering tuning since the reflectarray is divided into similar parts (modularity). By following a modular approach, it is possible to use this concept on different satellite platforms. In addition, the total wiring and integration complexity will drastically decrease by wirelessly controlling the beam. This solution allows using such a modular approach in smaller satellite platforms, where there is a small stowed volume available for antenna panels and the harnessing. Also, it is versatile enough to employ this system in bigger satellites requiring higher performance either for SAR, communications, etc.

Sections II and III of this paper present the reflectarray and wireless beam steerable control proposed architecture, respectively. Section IV presents the reflectarray antenna budgets, and in section V, simulation results are shown. Section VI contains a conclusion on the potential of using the proposed approach.

II. Reflectarray Architecture

The proposed reflectarray architecture is composed of a two-dimensional array of identical tiles equipped with wireless control of individual cells. In this way, by just adding the desired number of tiles it is possible to obtain the desired size and format for the entire reflectarray. Figure 1 presents the concept for the proposed reflectarray antenna.

Furthermore, each tile is composed of an array of unit cells, as shown in figure 2. Typically, reflectarray elements can be individual patch antennas or dielectric resonators such as Printed Circuit Boards (PCB) or volumetric types, respectively [4]. In this work, each unit cell consists of a PCB element and an embedded active device capable of changing the reflection coefficient phase of the unit cell. The authors of this work consider that 25 unit cells per tile is a reasonable number to control. Having one single device controlling individually

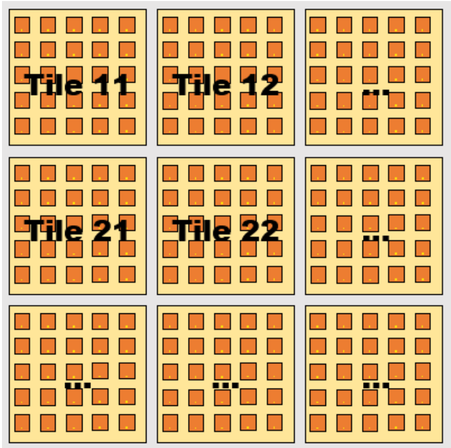

Fig. 1. Reflectarray architecture.

every cell of the full antenna would be challenging both in terms of signal routing and control device fanout - dividing the antenna into tiles, distributing control, solves this problem and brings the advantage of modularity. For an X-Band application, each unit cell has $25 \times 25\ mm$ and each tile, consequently, $125 \times 125\ mm$. There are several examples of such printed cells in the literature, and depending on the chosen format, it is possible to obtain a variety of characteristics for the reflectarray, such as frequency band, bandwidth and polarization.

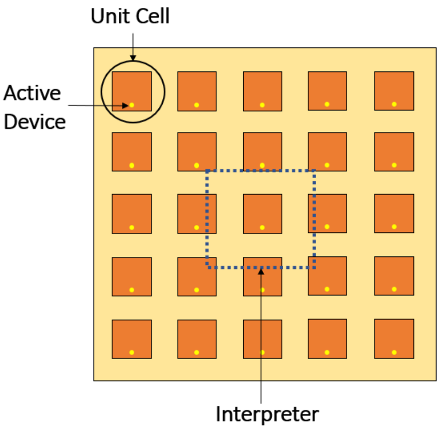

Fig. 2. Tile architecture.

As previously mentioned, there are several possible devices to be used to adjust the phase of this reflectarray concept taking RF and DC performance into account (PIN Diodes, Varactor Diodes, RF MEMS). PIN diodes are an impracticable solution for the proposed design since they are mainly used for a binary control; the proposed reflectarray requires to be controlled with a finer granularity of the reflected phase between $0°$ and $360°$. An even more relevant aspect is that they have a high power consumption (given the large total number of unit cells on the reflectarray). Although varactor diodes have higher losses when compared with MEMS, they allow for a continuous phase variation control within a lower voltage range. Regarding MEMS, even having a lower power consumption and insertion loss, presenting high linearity and isolation [5], they still are in technology maturation phase; they lack robustness, stability and availability. Liquid crystals and similar solutions require special facilities to be used when manufacturing and testing the reflectarray, which makes such solutions impracticable until further technological improvements of such technology. Also, they are significantly sensitive to temperature variations [6], which makes them difficult to use in space applications. The currently best suitable devices to use are, therefore, varactor diodes.

The varactor diode provides variable capacitance by applying a controlled reverse bias voltage (low current), providing the means to control the reflectarray unit cells reflected phase by changing its capacitance. One design detail considered in this work is that all the active components are powered using the same low DC voltage power line. This approach simplifies the overall system design once no voltage conversions are necessary and only one single power bus is required to be distributed along the entire antenna, minimizing electrical interconnection between antenna tiles. The varactor diode capacitance range needs then to be attainable within the voltage values of the system.

In [7], the authors described a method for implementing the variable phase surface required for reflectarray scanning operation based on a C-shaped patch printed on a substrate and loaded with one varactor diode. In this method, a variable voltage-controlled varactor diode provides the required phase shift at each cell on the reflectarray surface, enabling beam steering capabilities at the 13 GHz Ku frequency band. In [8], a similar approach is presented. The authors demonstrated the effect of the diode position and patch size on the reflection phase response of a patch antenna loaded with a shunt-connected varactor diode. They showed that such design achieves full phase control, thus enabling the design of varactor-loaded reflectarrays with full-beam steering at C-Band.

As previously mentioned, the authors propose a wireless control mechanism by using an independent feed on the platform exclusively to send specific configuration signals. These radio control signals will be interpreted and decoded by a specific low footprint circuit, designated as *interpreter*, embedded on the back of each tile, that will actuate on the varactor diodes by regulating their individual reverse bias voltage. In the following section, the interpreter circuit architecture is further analysed.

III. Wireless Beam Steerable Control

The wireless control is composed by the interpreter circuit and the radio signals. The following subsections describe details on each one of them.

A. Interpreter Architecture

Regarding the interpreter, it will use a dedicated carrier, possibly using a lower frequency. The radio signal reception at each tile can be based on an antenna that connects to a simple power detector that drives a comparator connected to an FPGA input pin. The FPGA demodulates the information from this simple amplitude 1-bit sampler. After computing the phase of each device, the FPGA generates PWM signals in its outputs to control the varactors of the respective tile. Figure 3 represents a block diagram for this possible interpreter implementation. Although this paper does not explore the radio control signal antenna, the following section shows that it can have a simple design since the link budget is easily closed.

The reflectarray control can be separated from the reflectarray itself by not sharing the same carrier frequency, making the interpreter circuit easier to implement. Although it might require an external antenna to receive the radio control signals, this approach avoids the possible need to add directional couplers or even LNAs to the reception chain. By separating the control carrier frequency and its receiving antenna from the reflectarray operating frequency, there is also an interference reduction and risk mitigation during implementation.

Given the nature of the signals to be decoded, both interpreter architectures do not require the FPGA to operate at high clock frequencies. This detail enables for low power consumption at the FPGA level.

IV. Budgets

In order to evaluate this work feasibility, power and data budgets were elaborated. Also, to study the ability of the reflectarray and corresponding active devices to withstand a high RF power transmitted through the antenna feed was evaluated.

A. Power Budget

There were some considerations to estimate the reflectarray power budget. This analysis is based on the reflectarray architecture present in fig. 3:

- Each varactor diode has leakage currents in the order of magnitude of $100\ nA$, operating at $5\ V$. This results in $0.5\ \mu W$ for each unit cell. As previously mentioned, each tile will have 25 controllable unit cells and, therefore, the total average power for the varactors is $12.5\ \mu W$;
- As mentioned before, the FPGA will operate using a low frequency clock, allowing lower power devices to be selected. There are suitable FPGAs for the required operation consuming about $0.2W$.

Each tile will consume around $0.22\ W$ for beam shaping and steering applications. Since each tile will have $0.125 \times 0.125\ m$, a $3\ m^2$ antenna will consume less than $45\ W$. This value will also multiply by the duty cycle factor of the reflectarray usage.

B. Reflectarray Power Handling

This subsection assesses if the RF power transmitted to the reflectarray can damage the active devices. Again, as a reference, a SAR X-Band mission is considered. Assuming then that:

- The RF peak power is $1000\ W$ ($60\ dBm$);
- The reflectarray antenna feed gain is $6\ dBi$;
- The minimum distance between the feed and the closes tile of the reflectarray is 2 meters, resulting in a $58.1\ dB$ of free space losses at a $9.6\ GHz$ transmission frequency.

The total power received by each reflectarray unit cell is then $60 + 6 - 58.1 = 7.9\ dBm$.

Using a patch antenna as the printed element of the unit cell with an efficiency lower than expected given the existence of a tunable varactor diode, the expected gain compared to an isotropic antenna will be around $4\ dBi$.

The total power reaching the varactor diode is $7.9 + 4 = 11.9\ dBm$, which corresponds to approximately $15.4\ mW$.

From (1) is possible to compute the voltage increment, V, at the varactor diode terminals during the transmission of an RF Power, P, of $1000\ W$ at the reflectarray feed antenna:

$$P = \frac{V^2}{R} \Leftrightarrow V = \sqrt{P \times R}\ , \quad (1)$$

where R corresponds to the unit cell impedance, 50Ω, assuming that the antenna is matched. The average voltage increment is then $0.88\ V$. By multiplying the obtained voltage value by $\sqrt{2}$, it is possible to get the peak voltage value, $1.25\ V$ ($2.5\ V$ peak-to-peak voltage). A varactor diode can cope with such value without disruption and using a control voltage between 0 and $5\ V$.

C. Radio Control Signals Link Budget

There are several suitable modulation schemes to send the control signals. However, due to its implementation simplicity, On-Off Keying (OOK) is selected as the primary option. Also, due to the signal nature, it is possible to use simple electronics to receive the signal and send its information to an FPGA. Considering 0 dBm EIRP for the radio control signal transmission, 4 meters distance between the transmitter and the furthest reflectarray tile and a receiver antenna gain of $-10\ dBi$, a receiver noise figure of approximately $36\ dB$ is enough to close the link budget for a bit error probability of 10^{-4} and 20 kbps data rate. This result shows that the receiver can be simple with no tight requirements.

The 20 kbps data rate also considers Forward Error Correction (FEC) and Cyclic Redundancy Check (CRC) to achieve robust detection while avoiding picking false messages. With FEC, the objective is to obtain bit error probabilities of 10^{-7}, while CRC allows the detection of accidental changes due to noise or SAR/communications transmissions.

For implementation simplification purposes, the messages to all tiles will be the same (broadcast). Although broadcast, there are two possibilities for each tile control: each tile knows its reflectarray position and automatically computes the required phase variation, or the signal sends a tile ID followed by the respective message. There are then two types of suitable signal architectures that can be used:

- To send the exact phase configuration for each active phase cell device at any given instant of time;
- To send the coefficients of a 2-D phase function (e.g., polynomial) with the correct phase configuration for the initial time and a trend for the following samples.

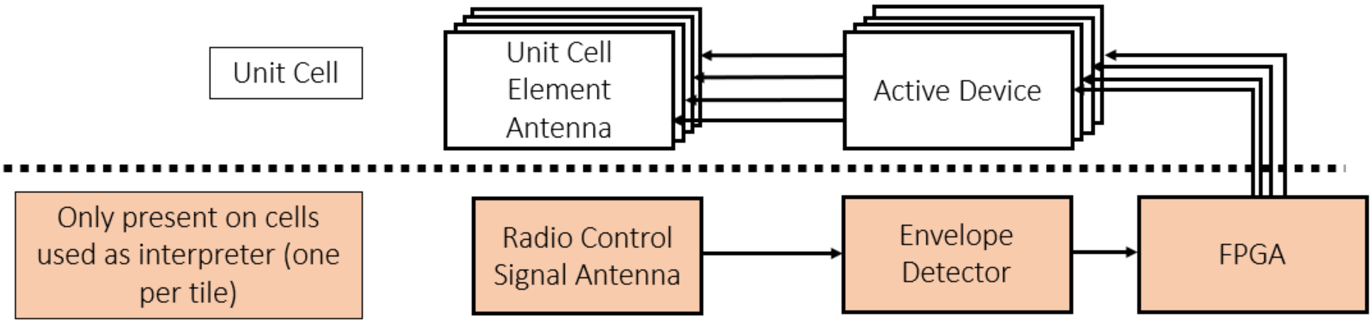

Fig. 3. Possible Interpreter Architecture

The first approach allows for sending shorter signals more often, while the second option leads to longer signals sent less frequently. The chosen method can depend on the data budget constraints for the radio control messages - higher clock frequency *vs* higher message bandwidth.

D. Reflectarray Wireless Control Data Budget

A spotlight SAR mission is used as a reference to predict the required beam steering rate. A maximum of 1 degree per second rate is considered a good estimation for the satellite beam steering rate. Calibration messages can be sent at a lower rate to verify that the beam points in the correct direction.

At this stage, the update rate of 20 Hz is enough to satisfy the requirement for the beam steering capability for one antenna of more than 1.75 meter diameter. Assuming that the protocol allows for each tile to adapt its own phase delay, using messages up to 100 bytes and FEC / CRC overhead of 1:2, is compatible with a 19200 baud rate, which fits 20 kHz bandwidth, which is suitable to easily close the link budget, as previously shown.

V. Simulations

In this section, the authors present results from simulations of a linear polarization unit cell performance considering the equivalent model of the varactor diode. It is planned to show the actual measurements of the unit cell using a waveguide at the conference. The objective of this section is to present the feasibility of the idea. It shows that it is possible to have a full range of control of a unit cell that will serve as a baseline of a wireless reconfigurable reflectarray.

A. Unit Cell simulation

The unit cell will consist of a rectangular patch antenna with a varactor diode as presented in Figure 4. A patch antenna was the chosen unit cell to keep the design simple for this work since wireless control is the main focus.

It consists of a rectangular patch of width, *patch_W*, of 12.27 mm, length, *patch_L*, of 7.86 mm, and uniform inter-element spacing, *substrate_LW*, of 25 mm. The array is printed onto a 0.812 mm thickness Rogers RO4003C. The bias line is where the DC power is applied. By inserting it in the middle of the patch of the non-radiating edge, where the

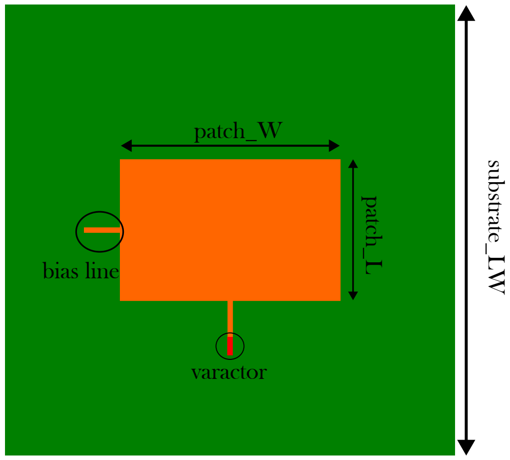

Fig. 4. Unit cell model

patch currents are virtually zero, it is possible to provide isolation between the RF currents on the patch and the bias circuitry [8]. With this approach, there is no need to insert RF chokes, avoiding the use of extra components. The design and analysis of the unit cell elements were conducted using 3D electromagnetic simulations with Ansys HFSS [9]. The varactor will be inserted on the top layer of the unit cell. The preliminary simulation showed that the required capacitance to achieve 360° was too small, making it impossible to use control voltages between 0 V and 5 V. To overcome such a problem, the authors decided to include a parallel capacitor, so it would be possible to fine-tune the unit cell and also increase the required capacitance of the varactor diode. Figure 5 presents the equivalent circuit of the patch antenna with the varactor with a parallel capacitor.

Figure 6 presents the losses and the phase variation for a capacitance variation. As expected, the loss is higher when the phase variation is also higher, less than 3 dB. This loss is due to the intrinsic varactor series resistance. It is also possible to observe that the major phase variance occurs between 1 pF and 3.5 pF. Skyworks SMV1275 varactor diode is one of the suitable devices to use in this design since it allows the required capacitance variation within a voltage range of 0 V and 5 V. This varactor diode does not has the highest Q-factor,

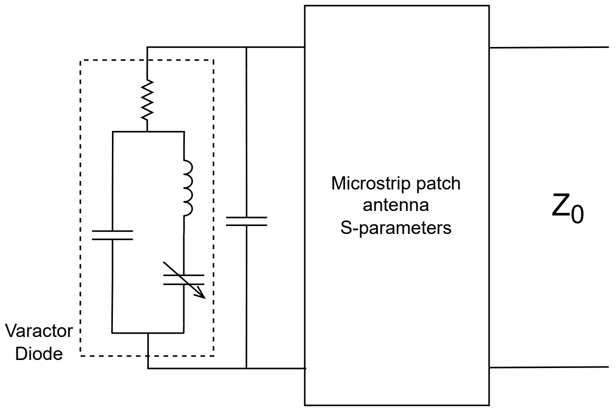

Fig. 5. Unit cell model

but it presents a good trade-off between price and electrical characteristics, allowing for scalability when manufacturing the reflectarray.

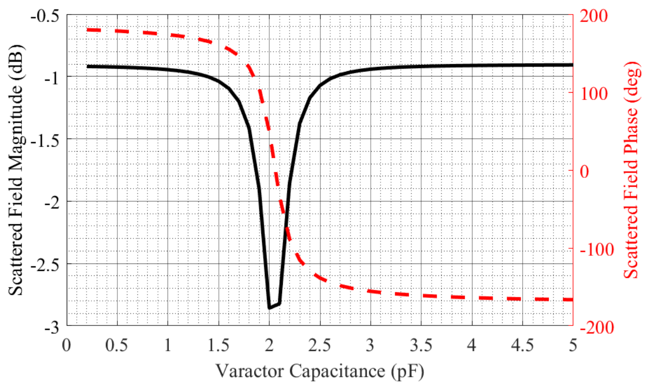

Fig. 6. Simulated reflected magnitude and phase field

B. Tile simulation

A preliminary tile was designed and optimised using the software tool QUPES, a TICRA Tools software framework product [10]. The simulation does not allow the insertion of active devices, but it gives an accurate estimate of the behaviour of the tile. The varactor diode losses can then be discounted on the total obtained gain. Besides the reflectarray gain, such simulations allow the authors to estimate the needed phase for each unit cell configuration, the sensitivity levels in case some of the varactors are not well configured, etc. Further simulation results will also be presented at the conference.

VI. Conclusion

The main challenges that antenna systems currently face are related to the available size for antennas to be used on small platforms, the possibility of pattern reconfiguration - steering capability, sidelobes, beamwidth, etc. - and the complexity of harness enabling control of a high number of cells. This paper proposes a novel digital beam steerable reflectarray design based on modular tiles. Such modular design allows different satellites to use the same tile system in a specific arrangement, creating a dedicated reflectarray antenna for a given application. Also, this work presents a new approach to enable electronic beam steering and shaping based on wireless radio control signals using low-power electronics. This solution reduces the total wiring between the satellite platform from more than a thousand to just a pair of low-power cables, decreasing mechanical and integration complexity. The authors of this work consider that reconfigurable reflectarrays will have an important role in the future of active small satellites Earth Observation and communication satellite constellations due to their versatility and modularity. The wireless control of reflectarray antennas can lead to a friendlier antenna design and a better ratio between an Earth Observation antenna gain and its stowed volume for satellite applications.

VII. Acknowledgments

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