Phase-Control-Integrated LTCC-Printed Radiating Elements for Mobile Satellite Communications

Alfonso T. Muriel Barrado, Fernando Estévez Llavería, José Manuel Fernández González, Manuel Sierra Pérez.
E-mail: {atmuriel, festevez, jmfdez, m.sierra.perez}@gr.ssr.upm.es
Dpto. de Señales, Sistemas y Radiocomunicaciones.
Universidad Politécnica de Madrid. E.T.S.I. de Telecomunicación. Av. Complutense 30. 28040 Madrid

***Abstract* - This paper presents several design possibilities for full integration of phase control with a LTCC-printed radiating element. The target is to define a high-efficient, low-profile, low-priced radiating element with phase control for using in T/R active phased-array antennas for satellite communications in the K/Ka-band (18-20GHz/28-30GHz). Mobile satellite communications and internet links, mainly for commercial aircrafts, are the applications for these elements to be used. The phase control is done by varactor diodes, though some different options have been considered. All the design proposals implement a three-bit phase control in order to change not only phase, but circular polarization as well. The feeding network consists of a microstrip transmission line, suitable for soldering phase-shift components. The radiating element is a double-stacked circular printed patch in LTCC substrate to reduce losses.**

***Index Terms* — LTCC, Phased-Array Antennas, K/Ka-Band, Varactor Diodes, Microstrip, Circular Polarization.**

1. Introduction

Satellite mobile communication for commercial flights and other means of transport is a recent area of research and development due to the challenge of performing electronic and automatic control over the embedded antenna. Moreover, satellite communication frequency bands (K/Ka) are high enough to present more difficulties in the development of an accurate and low-loss phase control. The specifications [1], [2] and [3] for K/Ka band satellite communication antenna systems lead to important restrictions in the antenna design for mobile terminals in terms of losses, size, profile or price.

Since a high gain in the antenna is required, a large antenna size is needed, and thus a considerable number of radiating elements. In addition, the main beam control must be fine enough and forces to include phase shifters into each element of the array [4]. Phase control elements generally add losses in the structure. In order to preserve G/T, either antenna size has to be increased or the antenna radiating element has to be passive phased-subarrays with an amplifier at the input [5]. Therefore, an economical, low-loss phase control system is needed in order to implement a cost-effective antenna. This has to do not only with the number of phase shifters per radiating element or its price, but also with their power consumption, which can reach very high values.

In some applications like mobile satellite communications for airplanes, antenna profile is another important aspect to consider. Low-profile planar antennas suits perfectly since they don't interfere with the airplane aerodynamics.

Many papers have been published about the design and manufacture of K and Ka band antennas for mobile satellite communications [6], [7] and [8], though few commercial antennas have been developed with full phase control in the radiating elements of planar arrays. Some of these commercial antennas are claimed to be successful in the manufacturing process, though any information about the way or the electronics used to implement it is offered [9], [10] and [11].

This paper presents the design flow of a low-loss, low-profile and low-price radiating element fully integrated with a phase control system suitable for mobile satellite communications. The radiating element consists of a double-stacked circular patch printed in LTCC technology. This element is included in a passive 4x4 planar subarray fed by a LTCC-printed microstrip corporate distribution network. The final subarray could be connected to an amplifier in order to get a larger active array antenna, as seen in Figure 1, with enough gain for satellite applications and low-cost phase control circuits [5]. This minimizes the fabrication costs of the antenna. LTCC substrate provides low losses and low profile to the array and varactor diodes perform an affordable phase-shifting element in terms of price and power consumption. Alternative phase-shifting elements such as PIN diodes, MEMs or MMICs are discussed.

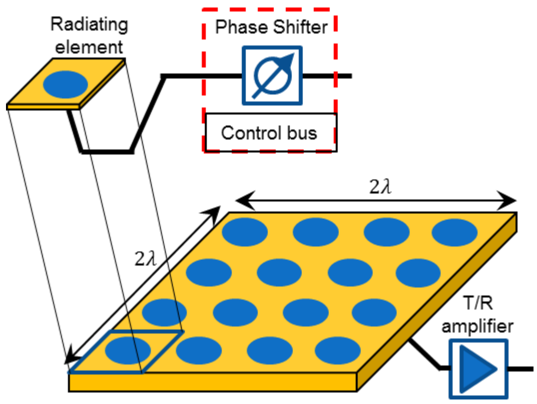


Fig. 1: Full active phased-subarray antenna scheme.

2. RADIATING ELEMENT STRUCTURE

A circular printed patch fed by metallized vias has been selected as the radiating element. In order to broaden the bandwidth response of the structure, a parasite patch is stacked on top of the active patch at a certain height. Both active and parasitic patches as well as the feeding structure are designed in LTCC substrate to achieve low-loss and low-profile requirements. A metallic cavity between patches is included to reduce mutual coupling between elements.

Figure 2 shows the layer structure of the proposed radiating element. It is fed through metalized vias that connect the active patch with the microstrip feeding circuit, where the integrated phase control is placed. Although Figure 2 shows the radiating element fed by only one via, four vias are needed to provide the required phase control, as it is explained in the following section.

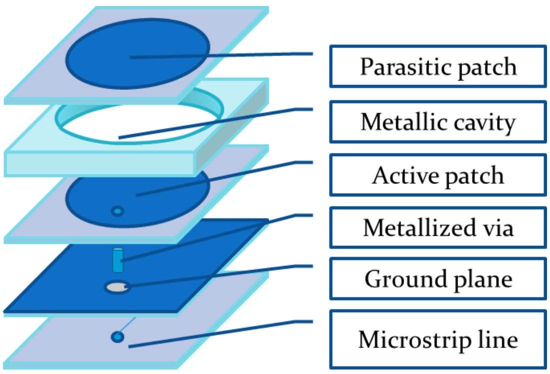


Fig. 2: Circular LTCC-printed double-stacked patch fed by microstrip line.

Dupont D-9K7V LTCC ceramic substrate is selected to design the radiating structure. Its dielectric constant is ε_r=7.1 with measured loss tangent tanδ=0.0009. It is available in 0.11 and 0.22 mm thickness sheets. The metallization process involves using conductive painting. The proposed multilayer structure has a lot of metalized vias and cavities. In general, LTCC is more expensive than other substrates and only a few European laboratories can manufacture accurately these circuits. On the other hand, metalized vias and multi-layer attachment is much easier.

3. PHASE-CONTROL-INTEGRATED FEEDING STRUCTURE.

The phase-control-integrated feeding network scheme is depicted in Figure 3a. It consists of a symmetrical switchable network under the active patch, with a common input/output point placed in the middle of the radiating element. The input/output point is linked to four feeding probes by means of microstrip straight lines with a phase-shift element per line (grey arrows). In the same way, the feeding probes are connected between them two-by-two through microstrip circular lines with the same phase-shift element. The feeding probes are located at the same distance from the center of the patch and rotated 90º one from each other. The electrical length of these microstrip circular lines is λ/4. The feeding probes are directly connected to the active patch of the radiating element.

According to previous studies [5], a two-bit phase control combined with a random phase term is enough to accomplish SLL satellite communications requirements. The presented network performs a three-bit phase control, with 8 phase shifters per radiating element. Thus, the network uses 2 bits to change the radiated phase in 90º jumps, and the other bit switches between left-handed and right-handed circular polarization.

Figure 3b shows one of the eight possible states that the feeding network is able to achieve. Shift-control elements placed on the straight lines select the radiated phase, while elements placed on the circular lines sets the polarization sense. For each switch combination the patch is fed into two orthogonal points with signals in quadrature, leading to a circular polarization. In this switching scheme it is important to point out that the non-selected lines are open-circuited, and may add some parasite effects to the structure behaviour that must be taken into account.

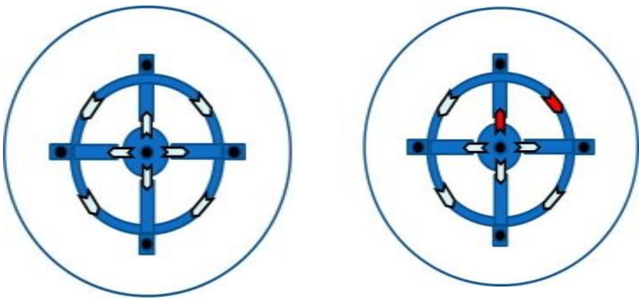

(a) (b)

Fig. 3: Phase shifter network scheme.

The proposed feeding network is designed in LTCC Dupont D-9K7V substrate used, and it is independent of which element is used for phase-shifting control. The election of this element is discussed in the section below.

4. COMPARISON OF PHASE CONTROL ALTERNATIVES.

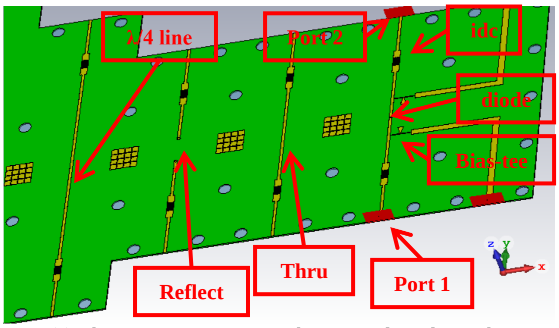
At K/Ka-Band frequencies radiating elements are small enough to consider phase control elements size in the integration process. Besides, price and power consumption are also important properties.

PIN diodes are common phase control circuits. Despite its low price, they present an intrinsic resistance when it is forward-biased. This means high power consumption in larger arrays only for phase control. MEMs offer an accurate phase control, but they are more expensive than diodes and they are still big for an integration process at these frequency bands. MMICs microwave integrated circuits suits perfectly the requirements. However, they are too expensive for now.

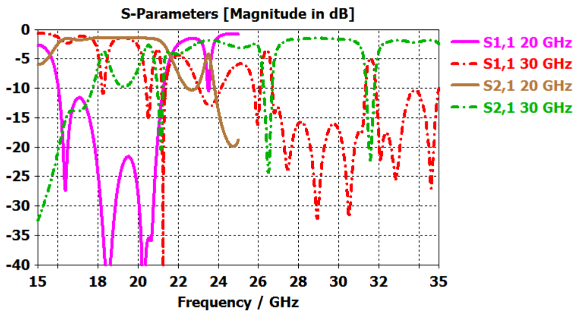
Varactor diodes are small, low-priced and they work reverse-biased so their power consumption is insignificant. The bias voltage allows a gradual control over the capacity of the semiconductor junction. For these diodes there is a maximum and a minimum bias voltage (V_{max} and V_{min}) that leads to a minimum and a maximum capacity (C_{min} and C_{max}). A C_{max}/C_{min} ratio high enough allows performing the required phase shift in the network. Therefore, an integrated phase control radiating structure based on varactor diodes is selected as the most feasible solution for the application under research. It is important to clarify that these diodes does not behave as switches, but rather unbalance the feeding structure towards one of the eight available radiating modes.

5. VARACTOR DIODES CHARACTERIZATION.

Once the phase-shift element is selected, it is necessary to characterize its behavior in order to integrate them properly in the feeding scheme presented above. A bias-tee circuit and an interdigital capacitor (idc) are designed for both T/R frequency bands. This way the diode is biased and the RF and DC ports are isolated between them. Finally, several measurements at a certain voltage step are taken to integrate them in a future design step. Figure 4 shows the circuit designed and its frequency response at T/R bands. Beside the line with the diode, a TRL calibration kit is designed to de-embed from the measurements undesired effects.



(a) Characterization circuit: bias-tee, idc and TRL kit

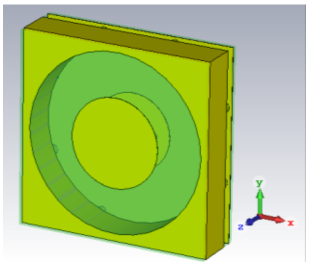


(b) Frequency response at T/R bands

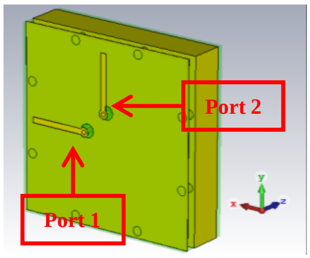
Fig. 4: Varactor diodes characterization circuit

6. DESIGN FLOW OF THE INTEGRATED-PHASE-CONTROL RADIATING ELEMENT.

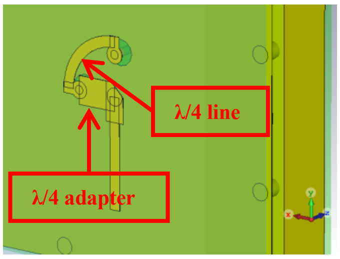
First steps performed in the radiating element design are displayed in Figure 5. They are tests about the radiating element viability in terms of adaptation or axial ratio. The first design (Figure 5b) has independent ports in quadrature, which are combined via software (a phase difference of 90º is applied afterwards in a post processing step) to get the theoretical behavior of the patch circularly polarized. The second design (Figure 5c) uses a λ/4 line and a λ/4 adapter to achieve circular polarization. The third design is based on the second one, and adds parasites to the feeding scheme, in order to see if it is possible to adapt the structure. All these structures have been designed for the reception band (18 to 20 GHz).



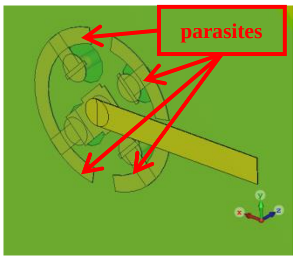
(a) Front view



(b) First design: independent ports



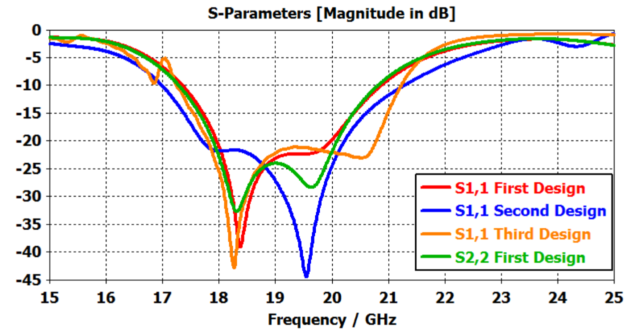
(c) Second design: λ/4 line + adapter



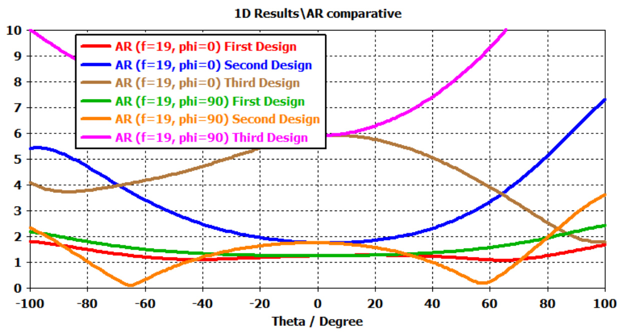
(d) Third design: second design with parasites

Fig. 5: Radiating element design steps

Figure 6 shows the results of these three structures in adaptation and axial ratio after an optimization process. Re-adapting the radiating element is feasible, and the axial ratio is only affected in the parasites case, where it is sensitively reduced. This is a problem to take into account when the final radiating element design is tackled.



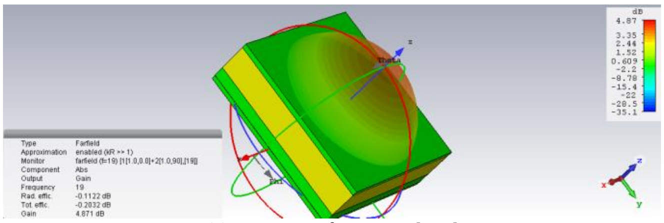
(a) Magnitude of reflection coefficient in dB



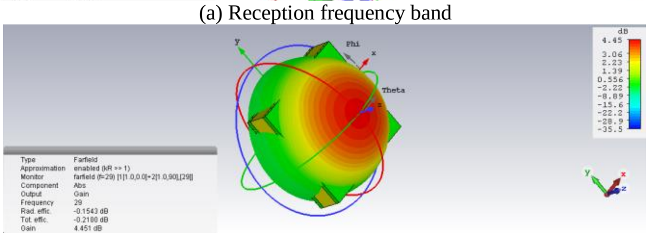
(b) Axial ratio of the antenna at central frequency RX. band

Fig. 6: Design tests results

After these prior tests, both reception and transmission radiating elements have been designed and optimized with independent 2 port feeding scheme (like in Figure 5b). This process considered periodic conditions in the structure, as if it were surrounded by the same radiating elements. This way, mutual coupling between elements is reduced as much as possible. Figure 7 shows both optimized T/R elements.



(a) Reception frequency band

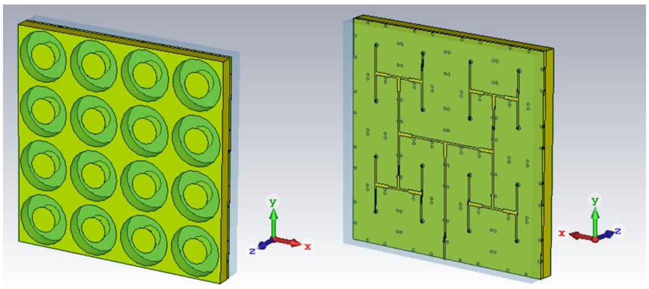


(b) Transmission frequency band

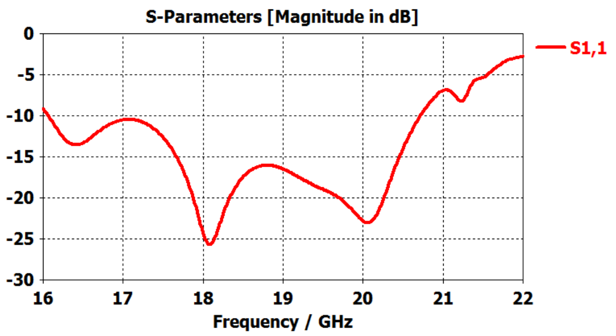
Fig. 7: Designed radiating elements with 2 independent port feeding.

They show good matching impedance, below -20 dB in the whole frequency bands. Mutual coupling between feeding probes is near to -15 dB. The radiation diagram shows good behavior with a maximum directivity of 4.87 dBi/4.45 dBi for T/R respectively, with a total efficiency of 98 %. Axial ratio response at central frequency of T/R bands is below 2 dB for ±30º.

After this point, the plan is to design a pair of 4x4 arrays with the second feeding scheme (Figure 5c) to validate their properties and the LTCC fabrication process. Figure 8 shows a preliminary linearly polarized array and its frequency response.



(a) Array configuration (front and rear views)



(b) Array frequency response

Fig. 8: Linearly polarized 4x4 planar array.

From here, an accurate characterization of the varactor diodes with the circuits presented above is required. The measurements will be introduced in next design steps. Finally, the specific values of the eight diodes capacities have to be found to perform the three-bit integrated phase control. All simulations have been performed with CST Design Studio.

7. Conclusions and Further Research.

A phase-control-integrated radiating element for satellite mobile communications is presented. It makes viable the design of a high gain phased-array antenna with a large number of elements. It also provides a low-loss, low-profile choice for embarked applications as commercial flights satellite communications. First design steps and their results are introduced in this paper, as it is showed the short-term work lines that will be carried out. Simulations presented here and future design steps will lead to some prototypes that are expected to be shown in the conference, such as the diodes characterization circuit, the measurements of the diodes, the integration process or the 4x4 designed arrays. Future research lines cover the design of high-gain active antennas with these elements attached in passive subarray modules, or the use of different phase-shift elements.

Acknowledgment

This study has been made under the project Jetstream, supported by the call “Retos Colaboración” from the Spain “Ministerio de Economía” (RTC-2015-3495-7) and with the collaboration of the company Telnet. We also acknowledge the contribution from the project Enabling 5G supported by the Spanish “Plan Nacional de Investigación” (TEC2014-55735-C3-1-R) and the project Spacer Debris Radar (Project number S2013/ICE-3000 SPADERADAR-CM) that supported most of the simulation software.

References

[1] ITU-R SA.364-5 *Preferred Frequencies and Bandwidths for manned and unmanned near-earth research satellites*.

[2] UIT-R S.580-6 *Radiation diagrams for use as design objectives for antennas of earth stations operating with geostationary satellites*.

[3] ITU-R S.524-9 *Maximum permissible levels of off-axis e.i.r.p. density from earth stations in geostationary-satellite orbit networks operating in the -fixed-satellite service transmitting in the 6 GHz, 13 GHz, 14 GHz and 30 GHz frequency bands*.

[4] Manuel Sierra Pérez “*Antenas en array activas para comunicaciones y sistemas de localización*” XXX Symposium Nacional de URSI. Pamplona 2-4 de septiembre de 2015. España.

[5] M. Sierra-Castañer, J.M. Fernández-González, M. Sierra-Pérez, A. Tamayo-Domínguez, A. Muriel-Barrado. *“Ka band active array antenna for mobile satellite communications”.* International Symposium on Antennas and Propagation ISAP 2016.

[6] R. Baggen, S. Holzwarth, M. Böttcher, B. Sanadgol *Phased Array Technology for Mobile User Terminals*. Eucap 2011.

[7] S. Vaccaro, D. Llorens del Río, M. C. Viganó *Phased arrays with reduced number of phase shifter bits for polarization and pointing control*. IEEE APS 2013

[8] Nathan Kundtz, Redmond, Wash. “*Next Generation Communications for Next Generation Satellites*” Microwave Journal. Augost 2014.

[9] Mikala C. Johnson, Steven L. Brunton, Nathan B. Kundtz, and J. Nathan Kutz “*Sidelobe Canceling for Reconfigurable Holographic Metamaterial Antenna*” IEEE TAP VOL. 63, NO. 4, APRIL 2015.

[10] *Introduction to Reconfigurable Holographic Metamaterial Antenna (RHMA).* In Q-Tel Article. 2014

[11] Bahram Sanadgol, Sybille Holzwarth, Alberto Milano, Rafi Popovich “*60 GHz Substrate Integrated Waveguide Fed Steerable LTCC Antenna Array*” EuCAP 2010.