Paper

A lightweight planar antenna element with optimized feed for use onboard spacecraft

Krzysztof Wincza and Paweł Kabacik

Abstract—This paper is a report on low gain antennas (LGAs) manufactured with bonded lightweight materials. These antennas can sustain large temperature variations and are capable of functioning in modern miniature spacecraft, mainly in the telemetry, command and ranging (TC&R) links. When made of cheaper materials, the proposed circularly polarized antenna can be widely used in the base stations of short-range wireless systems. The recommended operating frequencies are between 1 and 8 GHz. One major technical consideration is obtaining the required high quality of circular polarization with as low space demands as possible. A lightweight 90° polarizer, printed on a dielectric membrane and operating over a broad bandwidth, is proposed for the antenna feed. Owing to the bandwidth advantage of the polarizer and the use of carefully designed aperture coupled feed, the electrical characteristics maintain good properties over a wide frequency range (15%).

Keywords— microstrip antennas, spaceborne antennas, circularly polarized antennas.

1. Introduction

The presented lightweight patch antenna is intended to operate in two main applications: the telemetry, command and ranging (TC&R) links of small spacecraft and radio interfaces of short range wireless systems. Regardless of the spacecraft, an ideal TC&R antenna should feature radiation properties which do not give rise to more than a tolerable risk of problems with TC&R signals, irrespective of problems with the orbital position of the given minisatellite [1]. Antennas with a deployment mechanism are regarded as too troublesome in minisatellites, as they add an unacceptable complexity. As minisatellites are characterized by low volume and dense packing of components, TC&R low gain antennas (LGAs) should be planar antennas suitable for mounting on a wall. They should be manufactured from various derivatives of microstrip technology, and be preferably mounted directly onto the walls of minisatellites [2]. In wireless systems, among the several properties key for market success are broadband operation, low weight and polarization properties capable of improving the link budget.

2. Lightweight broadband patch elements

The patch shape and the feed are responsible for broadband operation. The beamwidth is similar, at least in the case of the most popular patch shapes. However, in order to achieve broadband impedance match and high quality circular polarization, patch shape requires special attention. It is very important that the patch should retain the symmetry which is one of the primary conditions for achieving a good axial ratio in circularly polarized antennas. Patch feed is a key technical issue [3]. Generally, the use of feed via through-slot coupled lines is unavoidable, and fortunately, such a feed ensures a low profile for the radiating part of the LGA. When optimizing aperture through-slot coupling, the use of differently shaped slots may result in high isolation, which is required to achieve excellent circular polarization. An important advantage is that aperture-coupled antennas offer a great flexibility in terms of modeling their electrical parameters.

The various parts of the lower S-band are the primary target for the described antenna design. To provide the necessary bandwidth for all operational conditions in the uplink or in the downlink at the S-band, the height of the patch should approach 10 mm when a substrate with a dielectric constant close to one is used. A conceptual sketch of an LGA displaying the desired merits is depicted in Fig. 1. The antenna is fed with slot-coupled microstrip lines. We found that the stripline feed is possible to match to 50 Ω with the extra slots in the enclosing ground of the stripline.

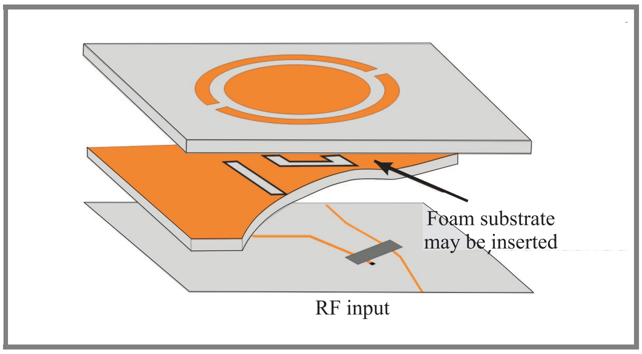

Fig. 1. The circular patch investigated in the course of our studies. It features a high quality of circular polarization as field is favorably modified by parasitic semicircular strips.

An advantage of lightweight LGAs is that their parts combine electromagnetic and structural functions. Tiny elements generate weak loads which can be borne by a simple structure. Two basic structural designs for the patch were studied. In one concept, the patch substrate was a honeycomb composite, and in the other, it was foam [4].

The honeycomb composite has a dielectric constant close to 1.1, while the foam has a broader range of dielectric constant values, usually up to 1.8 (Rohacell foam has $\varepsilon_r \approx 1.05-1.1$). In our view, honeycomb composite has become of great value in larger antennas which should have high structural strength. In honeycomb panels, the electrical properties of the bonding layers become difficult to control after curing. That is the main reason why in our opinion, the honeycomb structure is far less suitable for small microstrip LGAs than foam. It is worth mentioning that our investigation into the thermal behavior of patch antennas showed that some types of foam display excellent thermal properties. One such type of foam is quartz fiber composite, which shows a high resistance to temperature variation [5]. The bonding system applied is essential for achieving adequate mechanical strength and good electrical properties.

3. Broadband generation of circular polarization in patch elements

We focused on two separated slots responsible for orthogonal modes in the LGA feeding (Fig. 2). For the needs of circular polarization generation, the two slots must be fed with in-quadrature signals of equal power. Various pairs of slot shapes were investigated: rectangular, and C-, X- and H-shaped. Another considered shape of coupling aperture was a single cross slot. A cross slot requires a balanced feed of two orthogonal slot branches [6]. The application of cross slots has little demand on space [7]. However, the width of the feed lines varies continuously over the coupling section. It is important that such a method results in good radiation properties when patches are clustered into modules, as the concept fails to produce good circular polarization with a single element.

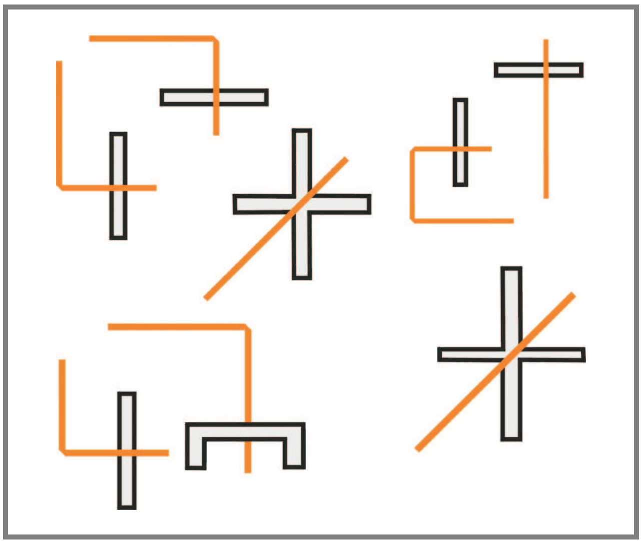

Fig. 2. A variety of slot shapes enabling the generation of circular polarization (a line shows the arrangement of the microstrip feed line).

As shown in the course of our studies, the optimum energy transmission is when the rectangular slots extrude outside the patch outline (an optimum displacement is of 12% of a slot length). The widths of slots ensuring efficient excitation of the patch account for roughly 10% of the patch resonant length [8]. A slight displacement of the transmission line off the slot center gives another noticeable improvement. In order to keep the pair of slots entirely under the patch, other shapes must be used (e.g., C-shaped slot).

We found that two rectangular slots feature low isolation between ports and that this shortcoming is difficult to overcome unless the displacement between the ends of the feed lines resembles a “T”. Further improvement can be obtained via a combination of a rectangular and a C-type slot [9]. In our simulations, the improvement in isolation was by 12 dB. In order to have a good line coupling to the patch, the width of the C-slot must be relatively large; however, this complicates its application with thick substrates.

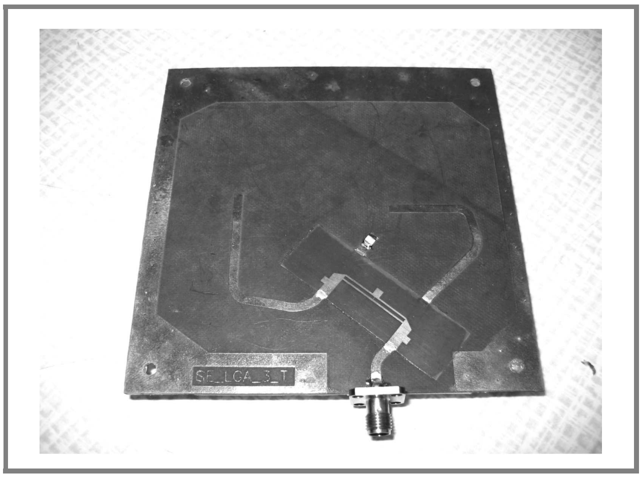

Fig. 3. A three-strip line directional coupler made on a thin dielectric membrane (125 μm) bonded to a 31 mil thick microwave laminate.

A minute area occupied by the polarizer is a prerequisite of LGA miniaturization. In our LGA, we used a three-strip coupler (Fig. 3). The coupler was thoroughly investigated by Sachse and Sawicki [10]. The compensation of phase velocity is achieved with conductive bridges in the middle of the coupling structure; thus, no troublesome superlayer dielectric bars are required. Usually, the core part of a coupling circuit is made on a 1 to 5 mil-thick laminate, and this circuit is bonded to a typical microwave laminate. By consequence, there is virtually no extra volume required for such a polarizer, apart from the unavoidable spacing around the coupler diminishing undesired external couplings. Such thin dielectric laminates are flexible. Polyimide films are good for such applications. A three-strip coupler is a quarter wavelength long, and has a total width which is approximately that of two 50 Ω microstrip lines. Thus, the three-strip directional coupler has 8-times smaller area requirements than a branch or Gysel coupler for the same center frequency. A further decrease in coupler dimensions requires the application of non-uniform coupling circuits. Roughly, the total volume of the RF part of the described LGAs operating at 2 GHz ranges between 100 cm^3 and 200 cm^3 (Fig. 4).

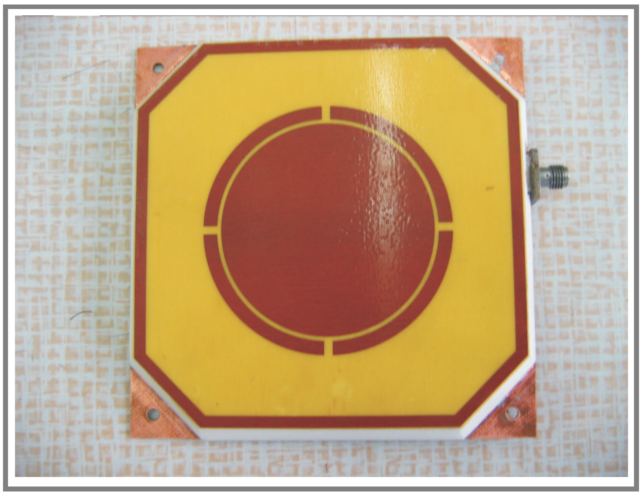

Fig. 4. A model of a lightweight broadband antenna developed in the course of our research.

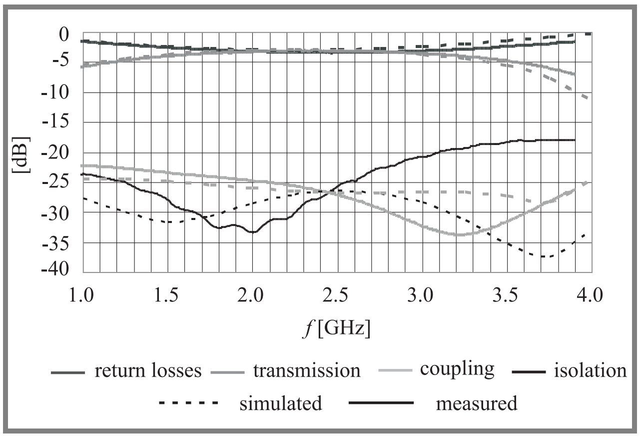

Fig. 5. The calculated and measured characteristics of the three-strip directional coupler shown in Fig. 3.

The electrical properties of the coupler used in one of our LGAs are presented in Fig. 5. The coupler features extremely broadband operation, a typical property of this coupler type. Losses in the antenna feed due to such a coupler are generally not greater than 0.25 dB. This loss can be difficult to obtain at times, particularly when membrane properties are poorly determined. The coupler is capable of handling RF powers much above those which are generated by the few Watt power amplifiers (typically used) onboard minisatellites. The measured impedance characteristics for one of LGA prototypes is plotted in Fig. 6. Our studies showed that to combine a good impedance match with a high quality circular polarization, it is necessary to

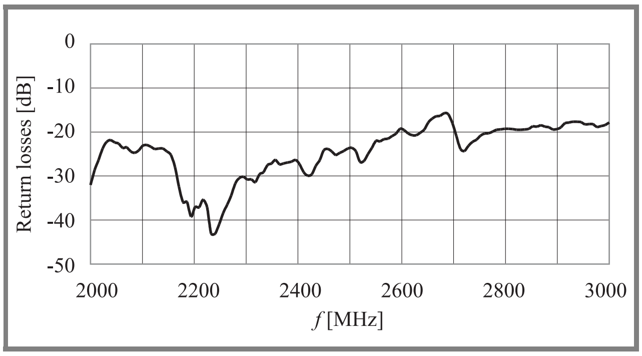

Fig. 6. The measured return loss for the presented circularly polarized antennas. The calculated and measured impedances match each other.

maintain a good balance of the directional coupler and its coupling to the slots. Among the most attractive advantages of the described antennas is their high gain value (8 to 9 dB on average) and good axial ratio. In all the considered antenna designs, the axial ratio was not greater than 1.5 dB over a wide frequency range (broadside direction) and remains good in a wide angular range.

4. Conclusions

Lightweight, circularly polarized antennas manufactured in microstrip technology are attractive for use in small spacecraft and in base stations of short-range wireless systems. A major technical challenge lies in generating circularly polarized waves with a minute feed circuit. Standard approaches are too cumbersome and they do not ensure broadband operation. Some types of directional couplers printed on a piece of thin dielectric, such as a three-strip design, show good electrical properties over a wide band and are recommended for integration into the feed of the circularly polarized LGA. Owing to the advantages of such a polarizer, it is possible to develop a broadband antenna in a lightweight technology. The optimization of the electrical properties requires careful analysis of the aperture through slot coupled feed.

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