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The Application of Reconfigurable Filtennas in Mobile Satellite Terminals

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ABSTRACT Reconfigurable antennas play an important role in wireless communication systems as the physical and electrical properties of their structures can be modified, allowing them to be used in different applications. In this paper two reconfigurable filtennas are presented to integrate mobile devices that communicate (uplink and downlink) with satellites in low-orbit constellations. A microstrip patch antenna in uplink mode (29 GHz), is surrounded by copper structure that, once connected via a PIN diode, takes the antenna to resonate in a lower frequency band (20 GHz). To deal with both bands, two filters were integrated into the radiating structure: edge-coupled and hairpin filters. The antennas were characterized and compared through simulation and measurements, in terms of impedance adaptation, radiation pattern and isolation between operating bands, validating their operability. Their small size and low cost allow these antennas to be integrated into mobile terminals that communicate with satellites or 5G systems.

INDEX TERMS Filters, satellites constellations, microstrip antennas, PIN diode, reconfigurable architectures.

I. INTRODUCTION

With today's technological developments in the field of wireless communication, society is increasingly surrounded by communication systems that comprise different technologies and with a multitude of applications, as illustrated in Fig. 1. Global technological priorities for the next few years or decades include connecting everyone, the entire planet, and using technology to make their daily life easier, providing more services and amenities. Science and business are converging in this direction, developing infrastructures to enable a continuous communication and effective, keeping everything synchronized through a global network.

The fifth generation of wireless communications (5G) will be available soon, increasing the capacity of networks, allowing for much more connected devices and sensors. Data rates will be enhanced, reaching much higher speeds in the transmission of information. These features will promote the implementation of Internet of Things (IoT) concept, integrated with 5G networks.

Despite significant progress in the area of telecommunications, the size of the planet is a huge challenge to be overcome, as well as glaring inequalities among countries and continents. Due to this problem, many people still do not have access to the internet. It is almost impossible to provide wired internet to the entire world due to the quantity and cost of required infrastructures [1]. Satellite systems are being developed as a solution to create a global broadband internet network. Some large companies are investing in new projects, developing satellites constellations positioned in low orbits to provide high-speed internet at low cost, reducing latency and delay, as well as providing mobile broadband worldwide [1].

These constellations operate at high frequencies (Ka band), using different bands for signal uplink (29.5-31 GHz) and downlink (19.7-21.2 GHz). Mobile devices must adapt their characteristics to these operating requirements, working in frequency bands that are far apart, maintaining current requirements in terms of simplicity, low cost, compactness and efficiency.

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Their integrated antennas are a crucial component and need to be developed in order to adjust their properties, as the terminal or sensor is transmitting or receiving, thus preventing the need to double the number of antennas.

Reconfigurable antennas can modify one or more of their properties, such as resonant frequency, radiation pattern, or polarization. This procedure can lead to a modification in the physical structure of the antenna, changing the current distribution, allowing the antenna to adjust its characteristics according to the particular needs. This concept is essential in the wireless communications world because with a single element it is possible to meet different requirements, for different applications, as would be achieved using multiple antennas. This reconfiguration is possible using various techniques, including the use of PIN diodes, RF-MEMS (Micro-Electro-Mechanical Systems) and varactors, which can act as ON/OFF switches, modifying the physical structure, allowing the change of their properties.

In [2] a slot with a PIN diode was inserted into a microstrip patch antenna. Working as an isolator (OFF state), the antenna operates at the frequencies of 3.31, 3.55, 4.09, 4.77 and 5 GHz. In contrast, when the diode is conducting (ON state) the structure resonates at 0.42, 1.407, 3.31, 3.96, 4.76 and 4.99 GHz. The radiation pattern and gain are also modified, ranging from 3.19 dBi to 7.3 dBi. Another technique is proposed in [3] where a patch antenna with a slot is presented. This is fed by a coaxial cable and has integrated a PIN diode in its center, responsible for controlling the operating state of the antenna. The diode switches between ON/OFF depending on the bias voltage applied to it. It can operate on two different frequencies (4.2 and 4.55 GHz) and modify its polarization, which can be right or left circular polarization. Authors of [4] describe a reconfigurable antenna in frequency and polarization working at 2.48 GHz and 2.56 GHz with linear polarization. By changing the antenna's structure, it is possible to achieve right and left polarization.

In [5] a reconfigurable polarization antenna is presented, with the ability to select between linear polarization and two circular polarization states. Through the connection of two PIN diodes, four patches integrated above the substrate can be connected, changing the antenna's polarization and allowing slight deviations in the resonant frequency, reaching a bandwidth of 5.07 GHz to 5.95 GHz.

A square microstrip antenna with spiral shape is shown in [6], where RF-MEMS are used as ON/OFF switches. It operates at 6.85 GHz and can modify its radiation pattern, depending on the state of the RF-MEMS.

There are applications of switching elements in antennas working at higher frequencies. In [7] an antenna array to operate in 5G systems is shown. It is composed of some slots with a "T" shape in the ground plane, and the capacity to operate at two frequencies: 28 GHz and 38 GHz. The reconfigurability is achieved through two pin diodes placed in the two arms of each slot. Depending on the switches state, the length of the slot can be changed allowing to have two different operating frequencies. Four models of microstrip patch antennas operating at 60 GHz are presented in [8]. Although they were designed on the same substrate, patches and ground plane are different. Besides that, the slots that characterize the different patches have different shapes with variable resistors inside. Changing the value of the resistors, it was possible to modify some of antenna's characteristics. With a variation of 20 Ω in the resistance, changes of 280 MHz in the operating frequency can be achieved in the different four models.

Regarding to techniques that combine filters with antennas, in [9] is proposed a microstrip patch containing a hairpin filter in its structure, allowing the operation between 4.06 GHz and 4.26 GHz. In [10] a wide bandwidth antenna capable of radiating from 3.1 GHz until 10.6 GHz is exhibited. Since the frequencies out of this band can generate interference with others communication systems, it is essential to remove them. For this purpose, a bandpass filter was inserted in the antenna's feed line, allowing that the frequencies outside the antenna's operating band were filtered. In [11], a broadband antenna is presented. A band pass hairpin filter is integrated in the structure, filtering between 2.03 GHz and 2.3 GHz. It allows the antenna to radiate only at frequencies in the filter's band. In [12], an antenna capable of working from 20 GHz until 32 GHz is reported. It has two ports: one for reception and another for transmitting signals in two different bands. Two filters for both modes were built with radial stubs. A PIN diode was inserted in the filter to select the operation band.

Authors in [13] present a novel resonator that can switch and create three important behaviors within the same antenna using miniaturized capacitors. The resonator was integrated into a conventional ultra-wide-band antenna to achieve UWB and single/dual continuously tunable-notch behaviors, by changing the value of the capacitors.

A filtenna composed of a fan beam array antenna and a miniaturized wideband bandpass filter is shown in [14]. The bandwidth of the filter is 5 GHz, allowing the overall structure to have a bandwidth of 3 GHz and the ability to radiate in a large range of angles (50 ° to 125 °).

A vast set of antennas, filters, and reconfigurable structures were presented, however, none of them is capable of efficiently switch between frequencies used in satellite communications, for Tx and Rx, in the Ka band.

In this paper, two compact reconfigurable microstrip patch filtennas are presented, which can be integrated into mobile terminals to communicate with low-orbit satellites. Each antenna is capable of operating in transmitting and receiving bands, centered at 20 GHz and 29 GHz respectively. A PIN diode is used to change the resonance frequency of the patch antenna. Different microstrip printed filters are inserted in the antenna structure in order to suppress the unwanted frequencies, isolating the receiver from the transmitter, working as a DC blocker and improving the antenna matching.

This paper is divided into five sections, starting with an introduction to the topic, stating the reconfigurable antennas technology state of the art. Section II describes the antenna structure, explaining the need to use the PIN diode and filters, and in section III the proposed antennas are designed. The main results are reported in section IV and, finally, the most important conclusions are drawn in section V.

II. RECONFIGURABILITY AND STRUCTURE

Microstrip structures were used in the design of the antenna as they make it possible to obtain efficient, simple, and compact antennas, with low manufacturing cost. They are composed of a dielectric substrate covered in both sides with a conductive material, one side working as a ground plane while in the other face the radiating elements and transmission lines are placed. Through the modification of its physical structure, different characteristics can be achieved [15].

Regarding the switching element, there are different possibilities that can be considered and weighted during the design stage. RF-MEMS require very high bias voltages and involve greater overall cost [6][16]. Varactors are highly nonlinear, which led to the choice of PIN diodes [17]. They require a low bias voltage, present fast switching speed and are easy to find on the market at a low cost [17].

Considering the high working frequencies, it was decided to filter the RF signal before reaching the antenna to avoid any impact in the performance of the radiating element or affecting the nonlinear behavior of the switching elements used. Since it is necessary to apply a DC voltage to control the PIN diode state, it is also necessary to isolate the DC and the RF paths.

Filters based on coupled lines, with no DC path, and capable of transferring RF energy have been designed to employ them in the feeding structure.

Several filters have been analyzed, such as end-coupled, edge-coupled, hairpin filter, interdigital filter, comb line filter or a pseudo comb line filter. These structures are constructed with $\lambda/4$ or $\lambda/2$ length lines, differing only in their layout and in some of their characteristics [18]. Edge-coupled and hairpin present higher bandwidths and are those that best suits our application.

III. ANTENNA DESIGN

The project of the frequency reconfigurable microstrip antenna starts with the design of the radiating element, regarding the highest resonance frequency. A rectangular microstrip patch structure was chosen due to its simple structure, and the straightforward techniques to feed this type of antennas.

To feed the patch antenna there are several different methods, however, one of the simplest to feed in the antenna plane is the inset feed technique. This method creates a reentrance on the patch face, with a length that allows to find an input impedance close to the characteristic impedance of the feed line [15].

A rectangular microstrip antenna operating at 29 GHz was initially designed, with dimensions of 2.41 × 3.25 mm^2, using the referred feed technique, matched to a 90 Ω input impedance (patch 1 in Fig. 2). After designed the patch at 29 GHz, an outer strip was added to increase the size of the structure, both in length and width, as shown in Fig. 2, and thus make it resonant at 20 GHz, the central frequency of the reception band (patch 2 in Fig. 2). The dimensions of this patch resonating at 20 GHz are 3.32 × 4.33 mm^2.

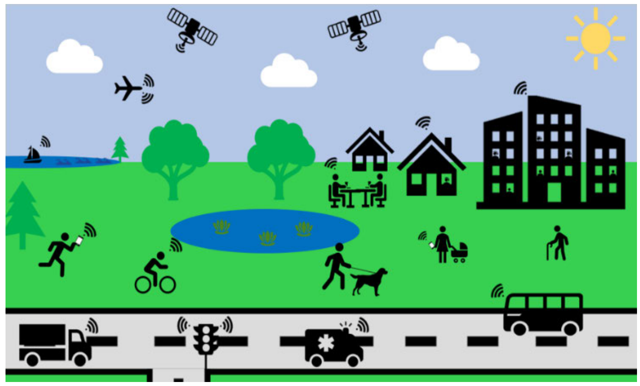

FIGURE 1. IoT scenario and satellite communications.

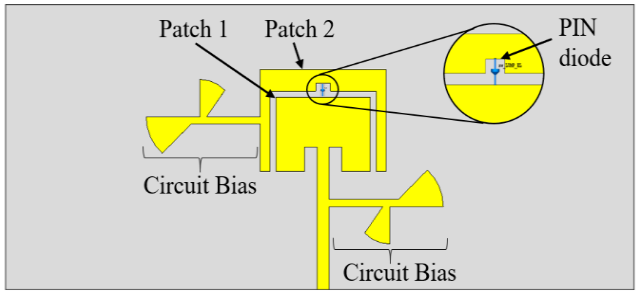

FIGURE 2. Dual frequency patch antenna structure.

The dielectric substrate used is the RO4350B, with dielectric constant ε_r of 3.48, thickness of 0.762 mm and loss tangent of 0.0037 (@10 GHz).

The frequency reconfiguration, that is, the interchange in the operating frequency is carried out by connecting (or disconnecting) the outer structure, through an RF switch, which in this work is a PIN diode.

The PIN diode chosen is the MA4PBL027 [19], which is a silicon beam diode from MACOM's. This diode exhibits a low series resistance, an ultra-low capacitance, and an extremely fast switching speed. It is highly recommended for use in microwave and millimeter wave switch designs, where low insertion loss and high isolation are required.

Fig. 3 presents the model of the PIN diode that was used in the electromagnetic simulator [19]. For the ON state (forward biased), the intrinsic values of its model correspond to a series inductance Ls of 0.15 nH, a maximum series resistance Rs of 4.0 Ω, and a total capacitance Ct = Cj + Cp, which is the sum of the junction capacitance of 0.04 pF and the parasitic capacitance of 8.0 fF. When the diode is switched OFF (reverse biased), the model has an Ls of 0.15 nH, a Ct of 40 fF, and a Rs, which in this work for the OFF state, is equal of 70 kΩ.

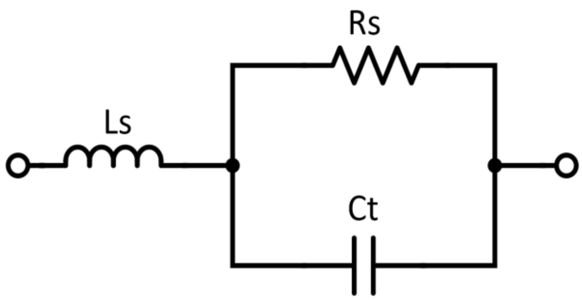

FIGURE 3. PIN diode equivalent model.

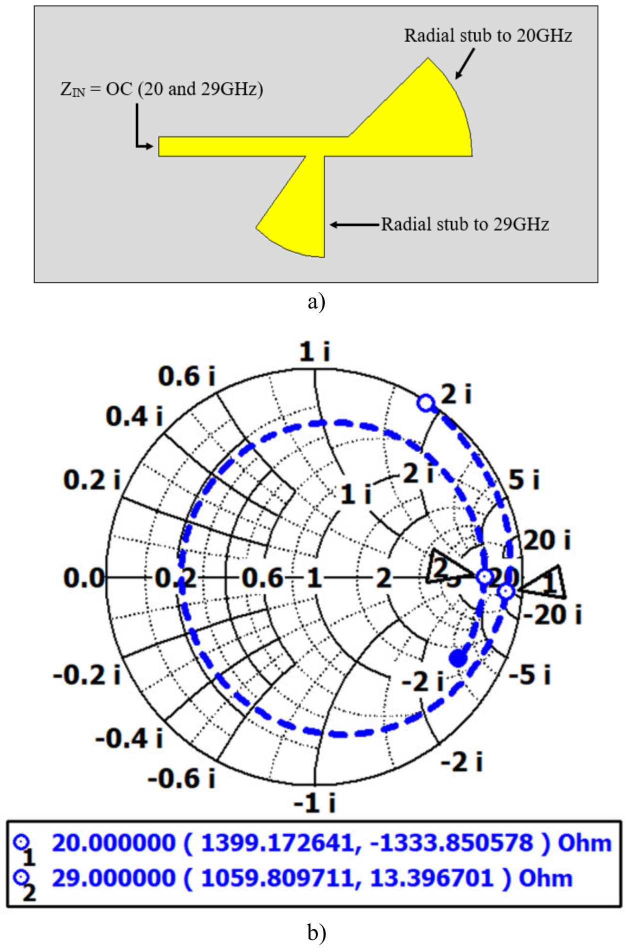

FIGURE 4. Bias circuit to the PIN diodes: a) Structure a) Smith chart of input impedance simulation.

To provide DC voltage to the PIN, a bias circuit working as a RF blocker, preventing the RF signal to escape to the DC path, was developed and exhibited in Fig. 4 a). Since the antenna operates at two different frequencies, it is mandatory to ensure for both frequencies that the bias circuit works properly and does not affect the antenna performance. This circuit is a structure based on $\lambda/4$ lines and radial stubs to ensure that its input impedance corresponds to an open circuit (OC) for both frequencies (20 GHz and 29 GHz). The

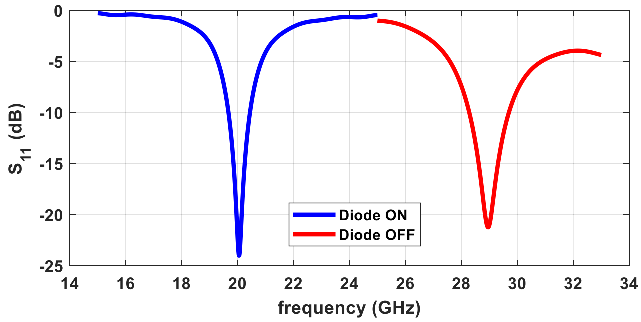

FIGURE 5. Simulated reflection coefficient of the single patch for the two operation modes (Diode OFF – Patch 1 and ON – Patch 2).

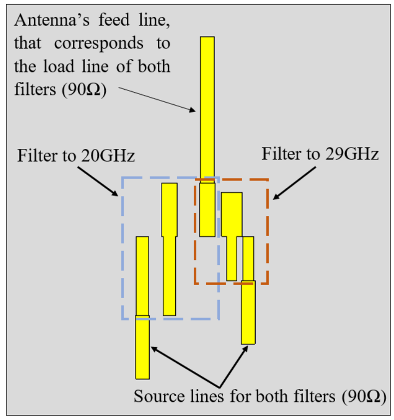

FIGURE 6. Edge-coupled filter to 20 and 29 GHz, with a common centerline.

simulated Smith chart of the input impedance bias circuit is shown in Fig 4 b), in which is possible to verify the markers at the two frequencies near the OC zone.

A detailed study was carried out to find where the circuits allowed the antenna to have a better performance. Fig. 5 shows the simulated reflection coefficient of the designed reconfigurable microstrip patch antenna (of Fig. 2), for the two states of the PIN diode used. It is possible to observe the resonance frequency in the central frequency of the two bands, 20 GHz and 29 GHz.

To isolate antenna operation in the two different frequency bands, minimizing the impact that received/transmitted signals from one frequency may negatively influence the adjacent RF frontend on the other frequency, RF filters were introduced in the path to the antenna. As aforementioned, two different planar microstrip filters, with edge-coupled and hairpin topologies, were implemented and integrated in the feeding structure of the antenna, to compare the two performances. The antennas differ from each other on the filters used.

A. RECONFIGURABLE ANTENNA WITH EDGE-COUPLED FILTERS

The microstrip edge-coupled filter is a popular filter topology at microwave and millimeter-wave frequencies and consists

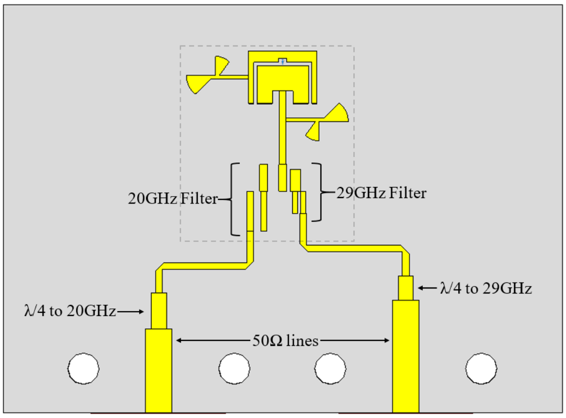

FIGURE 7. Reconfigurable antenna with edge-coupled filters.

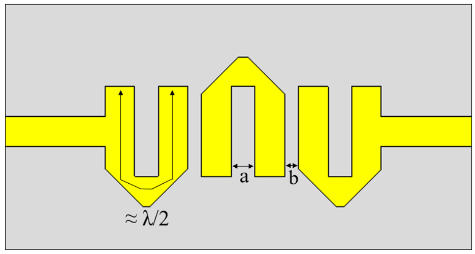

FIGURE 8. Structure of a hairpin filter.

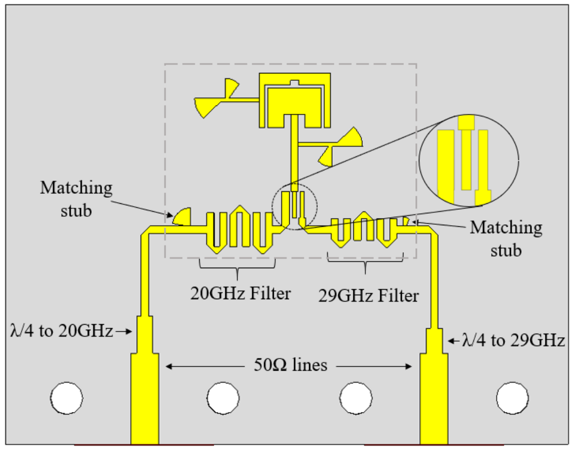

FIGURE 9. Reconfigurable antenna with hairpin filters.

of half wavelength parallel coupled strip lines which are placed close to each other and opened at both ends. Each strip is coupled to its near ones over a quarter wavelength [18]. There is different combinations of strip widths and gaps for a given filter design.

To integrate the filter into the antenna feed path, for better antenna simplicity and matching, as well as to obtain proper and functional line sizes, the edge coupled filter was designed using characteristic impedance of 90 Ω in the input and output port. The challenge is, since the antenna operates in two distinct frequency bands, to design and integrate two independent edge-coupled filters, with the antenna, maintaining its functionality, and sharing a single antenna 90 Ω feed line.

The major problem of the entire structure is that the filters to 20 GHz and 29 GHz have different dimensions, and to connect both load lines of each filter, the last coupled line of each filter would overlap, as it is possible to see in Fig. 6. The solution was to find a central line common to both filters, that is, a line for both filters with the same dimensions. To solve this problem, the theoretical calculations were made for the 20 GHz filter, until the ideal characteristics for a bandpass filter were found. After that, parametric analyzes were performed on the simulator until find the dimensions of the lines that originated a 29 GHz bandpass filter were obtained. In the end, there were two bandpass filters for 20 GHz and 29 GHz, with a common center line. So, it was possible to place the 90 Ω load line and connect it to the antenna. The final structure of the filters is shown in Fig. 6.

The final step was to connect two λ/4 transformers (characteristic impedance of 67 Ω) to each of the filter source lines to convert the 90 Ω of the filter line to the standard 50 Ω characteristic impedance. The reconfigurable antenna combined with the filter, the filtenna, was designed in the electromagnetic simulator, optimized, and its structure is shown in Fig. 7.

The global size is 35.31×25.79 mm^2. Notice that the structure to be integrated in the mobile devices is the one surrounded by the gray dashed zone, with the dimensions of 11.4×12.7 mm^2.

As seen in Fig. 7, the antenna is composed of a main rectangular patch, that operates in the uplink band, which is surrounded by a second metallic structure. When these two cooper's pieces are connected through the PIN diode, they behave like a single patch operating in the downlink band. So, if the diode is reversed-biased the two patches are then disconnected. The structure would then operate at 29 GHz. If the diode is forward-biased the current will be redistributed to both patches increasing the radiating element's area, and consequently, decreasing the resonating frequency to 20 GHz.

B. RECONFIGURABLE ANTENNA WITH HAIRPIN FILTERS

The hairpin filter is a structure using folded λ/2 parallel-coupled lines, which the name provides from its "U" shape. Hairpin has a relatively smaller size in comparison with other topologies. However, folding the lines, it is necessary to consider the reduction of the coupled area, which reduces the coupling [20]. The selection of element order in hairpin method affects the dimensions and frequency response, so a compromise between the selectivity and size must be considered.

Two third-order hairpin filters, whose structure is presented in Fig. 8, were designed one for the 20 GHz band and the other for the 29 GHz band.

The filters were designed and optimized in the electromagnetic simulator, which allowed to find the ideal dimensions and gaps ('a' and 'b'), achieving a filter with good charac-

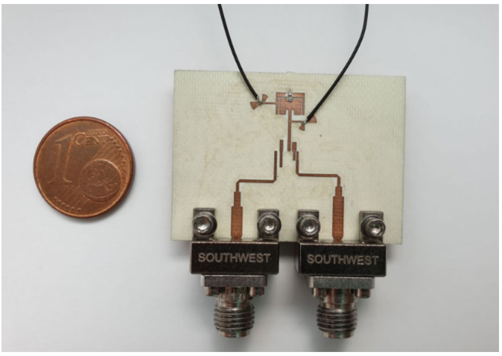

FIGURE 10. Fabricated filtenna prototype - filttenna with edge-coupled filters.

teristics and preserving a good reflection coefficient of the overall structure.

The energy is transferred from the filter to the antenna by coupling. At the end of each filter, two microstrip lines were created, and a center line connected to the antenna's feed line. Their dimensions were optimized (width, length, and separation) until the point of good energy transfer was found, that is, the point where there was low attenuation of the signal. So, after the RF signal is filtered, it is transferred to the antenna's feed line and then is radiated.

Finally, two radial stubs were designed and placed after the filters, to improve the antenna's matching. One is close to the 29 GHz filter, do adapt the antenna to the uplink band, and the other was inserted close to the 20 GHz filter to improve the matching to the downlink band.

In the path between each filter and the connector, two λ/4 transformers with 67 Ω of characteristic impedance were designed (one to 20 GHz and other to 29 GHz), to transform the 90 Ω (characteristic impedance of the filter's lines) to the standard 50 Ω lines.

All the elements were combined and the designed reconfigurable filtenna is shown in Fig. 9. The dimensions of the global structure are 34.24 × 26.58 mm^2. Once again, the part of the structure that is going to be integrated in the mobile terminals is the one in the gray dashed zone, with the dimensions of 15.2 × 11.6 mm^2.

IV. RESULTS AND DISCUSSION

Both designed filtennas were manufactured. In this section, they will be characterized comparing some simulated and measured results regarding their most important properties, such as impedance matching, efficiency and radiation pattern, in the two operating bands, 20 GHz and 29 GHz. The port 1 was used for downlink (20 GHz band) while the port 2 for the uplink (29 GHz band).

The prototype of the reconfigurable filtenna with two edge-coupled filters is presented in Fig. 10.

In Fig. 11, the simulated and measured S_{22} parameters are shown for this filtenna, with red and blue solid lines respectively, for the upper band of operation (around 29 GHz). In this situation, the PIN diode is reverse-biased (OFF state), so only the inner part of the antenna structure is working.

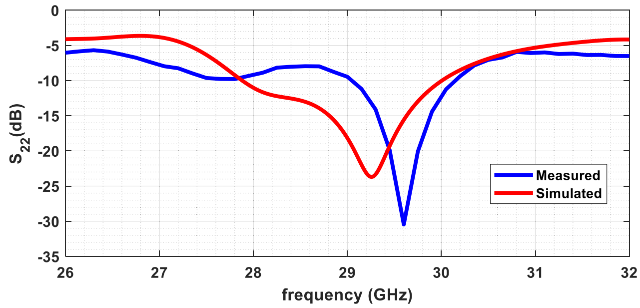

FIGURE 11. Simulated and measured reflection coefficient in the 29 GHz band – filtenna with edge-coupled filters.

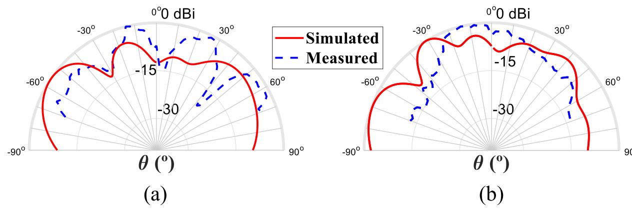

FIGURE 12. Simulated and measured radiation pattern at 29 GHz, (a) Plane $\varphi = 90°$ and (b) Plane $\varphi = 0°$ - filtenna with edge-coupled filters.

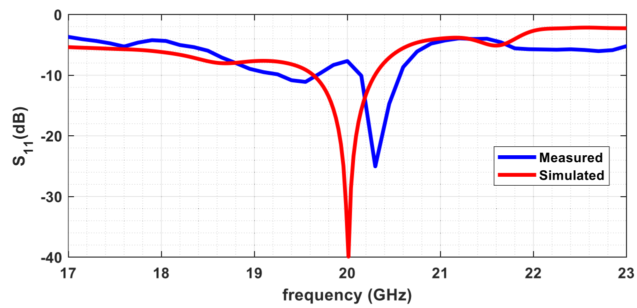

FIGURE 13. Simulated and measured reflection coefficient in the 20 GHz band - filtenna with edge-coupled filters.

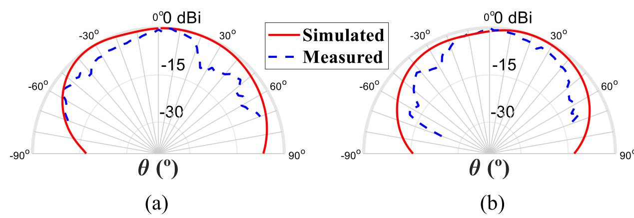

FIGURE 14. Simulated and measured radiation pattern at 20 Hz, (a) Plane $\varphi = 90°$ and (b) Plane $\varphi = 0°$ - filtenna with edge-coupled filters.

Analyzing the Fig. 11, it can be observed that, in terms of the simulation results, the antenna is properly matched at 29 GHz, with −18.18 dB of S_{22} with an impedance bandwidth of 2.12 GHz (27.88-30 GHz). Regarding to the measured values, there is a slight deviation of 350 MHz to the simulation, with −30.46 dB at 29.6 GHz, with a bandwidth of 1.1 GHz (29.05-30.15 GHz). This small variation is mainly due to inaccuracies in the manufacturing process which, given the very small size of the patch, have a direct impact on the resonance frequency.

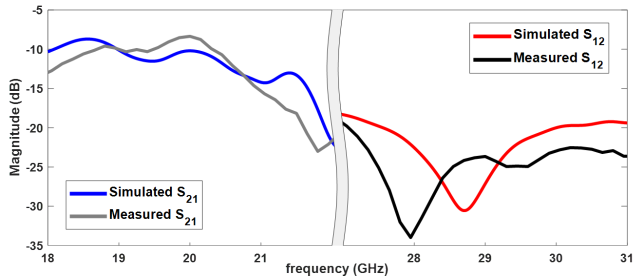

FIGURE 15. Coupling between two ports - filtenna with edge-coupled filters.

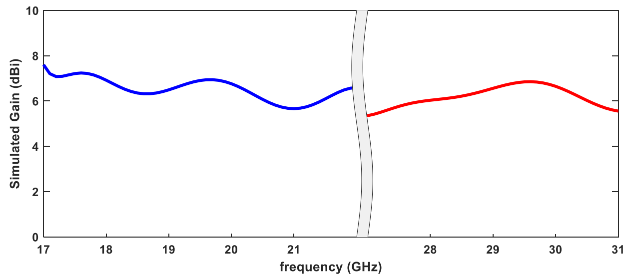

FIGURE 16. Simulated gain of edge-coupled filtenna over the frequency.

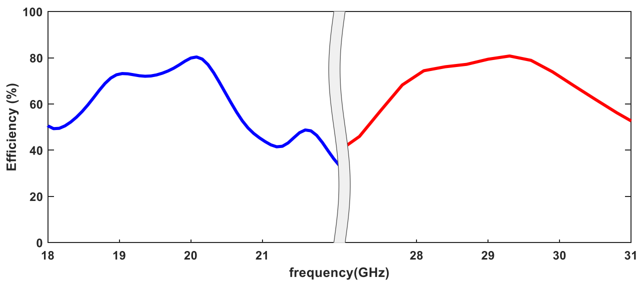

FIGURE 17. Efficiency of the filtenna with edge-coupled filters.

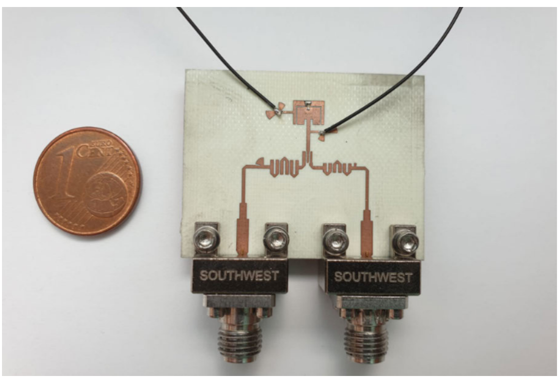

FIGURE 18. Fabricated filtenna prototype - filtenna with hairpin filters.

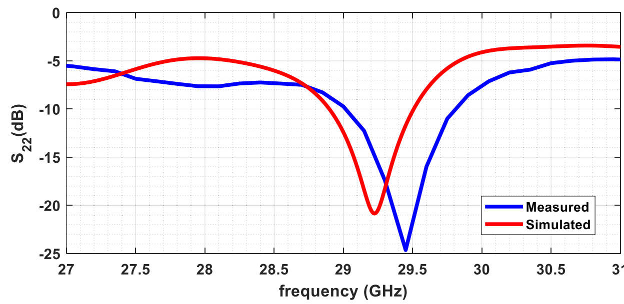

FIGURE 19. Simulated and measured reflection coefficient in the 29 GHz band - filtenna with hairpin filters.

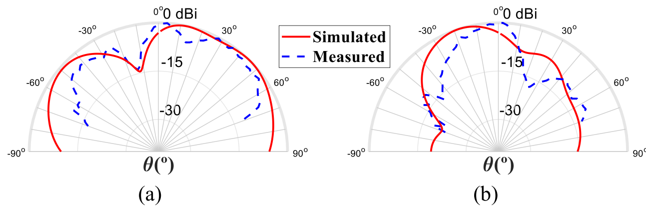

FIGURE 20. Simulated and measured radiation pattern at 29 GHz, (a) Plane $\varphi = 90°$ and (b) Plane $\varphi = 0°$ - filtenna with hairpin filters.

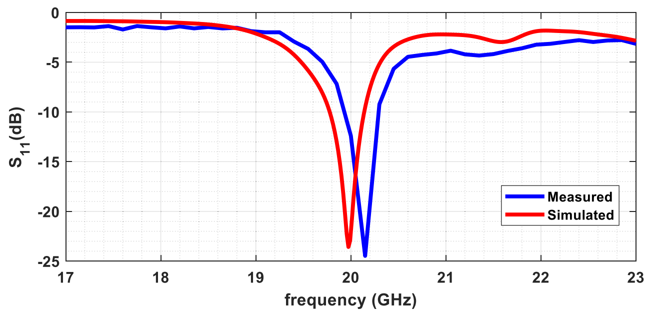

FIGURE 21. Simulated and measured reflection coefficient in the 20 GHz band - filtenna with hairpin filters.

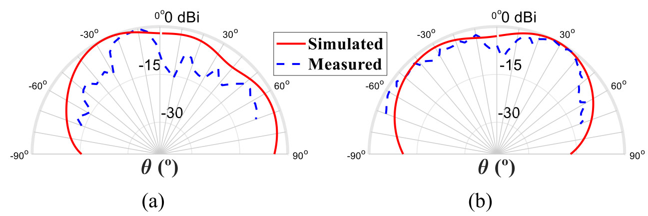

FIGURE 22. Simulated and measured radiation pattern at 20 GHz, (a) Plane $\varphi = 90°$ and (b) Plane $\varphi = 0°$ - filtenna with hairpin filters.

In Fig. 12 the simulated and measured normalized radiation pattern are shown according to the two main radiation planes. It is possible to observe that the antenna radiates, despite some differences between the measured and simulated values. The maximum simulated gain was 6.56 dBi whereas in practice a gain of 7 dBi was measured. These differences could be mainly due to inaccuracies in the manufacturing process that create a greater impact of the outer metal structure surrounding the inner patch.

Then, the PIN diode was forward biased, connecting the external metal structure to the patch antenna, changing its operation to the lower frequency band, 20 GHz, and the RF signal flows through port 1. In this situation the simulated and measured results of S_{11} are shown in Fig. 13.

Analyzing the simulated results, it can be seen a good matching to 20 GHz with −42.48 dB, with a bandwidth of 660 MHz (19.64-20.3 GHz). The measured S_{11} was −25.04 dB at 20.3 GHz with a bandwidth of 440 MHz (20.12-20.56 GHz). There is a negligible deviation of 300 MHz between simulation and measurements, since the values are close to the simulated ones.

Observing the Fig. 14, in both planes, the simulated and measured curves have a similar behavior. The maximum simulated gain at 20 GHz was 6.13 dBi, and the measured gain was equal to 6.34 dBi.

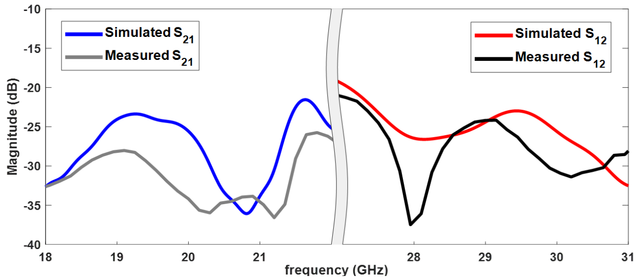

FIGURE 23. Coupling between two ports - filtenna with hairpin filters.

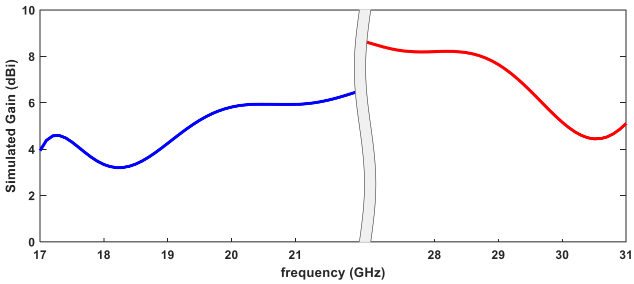

FIGURE 24. Simulated gain of hairpin filtenna over the frequency.

In Fig. 15 the coupling between the two ports is analyzed. The simulated and measured results are similar for S_{12} and S_{21} parameters. In both cases most of the signal goes to the antenna, as it was expected. When the filtenna operates in the downlink band, the signal from port 1 to port 2 suffers an attenuation approximated of 10 dB, in both simulation and measurements. This is not critical since port 1 is an exclusively receiving port.

When the diode is OFF state, it is essential to ensure a high isolation between ports to guarantee that all the signal is transmitted by the filtenna, and nothing goes to port 1, damaging the receiver frontend. It is possible to see that the signal at 29 GHz suffers a high attenuation (27.18 dB in simulation and 24 dB in measurements) until port 1.

Fig. 16 shows the variation in the maximum simulated gain of the designed filtenna, along the frequency, in the two operating bands. It is possible to verify a gain of approximately 6.76 dBi at 20 GHz, and 6.56 dBi at 29 GHz.

In Fig. 19 the simulated and measured S_{22} of the antenna are shown, when operating in the upper band (PIN diode OFF). It can be observed that the simulated reflection coefficient is −20.85 dB at 29.2 GHz with a bandwidth of 610 MHz (28.89-29.5 GHz). Regarding to measured values, the S_{22} is −24.64 dB at 29.45 GHz, with a bandwidth of 800 MHz (29.02-29.82 GHz). A small deviation of 230 MHz is observed, as in the first prototype, which we believe is due to the issues previously assumed.

Analyzing de polar pattern of Fig. 20, where the comparison between the simulated and measured radiation pattern for the two main planes is shown, it is possible to observe that there is a similarity between the progress of the two curves. The maximum simulated gain was 6.93 dBi, whereas its measured value was 5.46 dBi.

When the PIN diode is ON, the antenna can operate at the downlink frequency. In Fig. 21 the comparison between the simulated and measured reflection coefficient of the antenna at 20 GHz is presented.

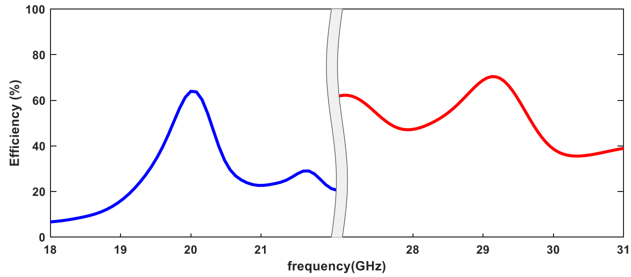

FIGURE 25. Efficiency of the filtenna with hairpin filters.

TABLE 1. Comparison of main characteristics of the designed antennas.

		Gain (dBi)		Bandwidth (MHz)		Efficiency (%)	
		B1	B2	B1	B2	B1	B2
Edge-coupled Antenna	Simulated	6.13	6.56	660	2120	79	81
	Measured	6.34	7.0	440	1100		
Hairpin Antenna	Simulated	5.25	6.93	360	610	64	69
	Measured	6.18	5.46	360	800		

The simulated reflection coefficient is −23.58 dB at 20 GHz with a bandwidth ranging from 19.78 until 20.14 GHz (360 MHz). In this case, the measured and the simulated results are very similar, with a deviation of 150 MHz, since at 20.15 GHz the measured S_{11} is −24.48 dB, and the bandwidth is again 360 MHz (19.93-20.29 GHz).

The radiation pattern is shown in the Fig. 22. Analyzing the measured and simulated results for the two planes, in Fig. 22 (a), it is possible to observe a similar progress in the two curves. Regarding to Fig. 22 (b), the measured values are similar to those simulated. In the simulation, a maximum gain of 5.25 dBi was obtained while maximum gain measured was 6.18 dBi.

Analyzing Fig. 23, when the diode is ON the signal is strongly attenuated to port 2, with 25 dB in simulation and 34 dB in measurements. Observing the S_{12} parameter it is possible to conclude that the uplink band signal hardly reaches the port 1, as it undergoes an attenuation approximated of 25 dB. This is essential, so that almost all of the power is radiated by the antenna.

Fig. 24 exhibits the maximum simulated gain of the designed filtenna with hairpin filter over the frequency, in the two operating bands. It is possible to verify a gain close to 5.8 dBi at 20 GHz, and 8 dBi at 29 GHz.

In Fig. 25 the efficiency of the filtenna for both frequencies is presented. The simulated efficiency to 20 GHz is 64% and to 29 GHz is 69%.

Table 1 presents a comparison between the main characteristics taken from the compilation of the various results presented. It is possible to observe that, in the two developed antennas, the one that generally reveals superior properties is the antenna with edge-couples filter, with higher values of gain, bandwidth and efficiency. However, the antenna with hairpin filters also presents itself as a good solution, functioning in the bands of interest, and with identical dimensions.

V. CONCLUSION

In this paper two reconfigurable filtennas for LEO satellite terminals and IoT sensors were designed, with the ability of operating at two different frequency bands (20 GHz and 29 GHz), that corresponds to the satellite downlink and uplink frequencies. It was shown that by changing the radiating element's area, it is possible to modify the resonating frequency. Two types of filters were used in each structure to achieve better results. The filtenna with two edge-coupled filters presents better bandwidth and efficiency for both frequencies, better gain for 20 GHz and is smaller. On the other side, the filtenna with two hairpin filters has the highest gain for 29 GHz and presents better isolation between ports to 20 GHz. These new structures are easy to manufacture, very cheap and the bias voltage applied to the PIN diode is low. Their small size makes them perfect for integrating with any mobile device.

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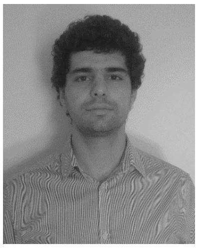

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