Electronically Re-Configurable, Non-Volatile, Nano-Ionics-Based RF-Switch on Paper Substrate for Chipless RFID Applications

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Article

Electronically Re-Configurable Non-Volatile Nano-Ionics based RF-Switch on Paper Substrate for Chipless RFID Applications

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Abstract: This article reports the first results of a Nafion® based solid state Non-Volatile electronically reconfigurable RF-Switch integrated to a Co-Planar Waveguide transmission line (CPW) in shunt mode, on flexible paper substrate. The switch is based on a Metal-Insulator-Metal structure formed respectively using Silver-Nafion-Aluminum switching layers. The presented device is fully passive and shows good performance till 3GHz, with an insertion loss less than 3dB in the RF-On state and isolation greater than 15dB in the RF-Off state. Low power DC pulses in the range 10V/0.5mA and -20V/0.15A are used to operate the switch. The device is fabricated in an ambient laboratory condition, without the use of any clean room facilities. A brief discussion on the results and a potential application of this concept in a re-configurable chipless RFID tag is also given in this article. This study is a proof of concept, of fabrication of electronically Re-Configurable and disposable RF electronic switches on low cost and flexible substrates, using a process feasible for mass production.

Keywords: CBRAM, MIM Switch, Chipless RFID, RF-Switch, Reconfigurable Switch

1. Introduction

Low-power, Passive and Non-Volatile RF-switches are an area of keen interest among the scientists and industry in the current decade. Non-volatile switches would benefit every field of RF-engineering by drastically cutting down the power budget. With the current threshold of development in disposable printed RF electronics, the requirement for passive and low power switches has been intensified.

One of the available solution for Passive non-volatile switches are the Memristive devices such as the Conductive Bridging Random Access Memory (CBRAM) switches [1], Phase Change Memory (PCM) switches [2,3] etc. These techniques utilize electrochemical properties and molecular arrangement properties of materials respectively to achieve the switching action. The CBRAM switch is also referred to as a Metal-Insulator-Metal (MIM) switch owing to its switching layers construction. Working principle and details of this technology is explained in this article. In case of the PCM switches, the change from amorphous to crystalline state and back, of certain materials like Germanium Telluride upon application of controlled heating pulses are utilized for switching. A handful of articles have reported fine non-volatile switches based on the above mentioned principles[1,2,4–6]. However, in majority cases, the fabrication technique is very much complicated and often requires a 'clean room' facility for the same. And in most cases the devices are fragile in nature and require dedicated conformal protection schemes to protect it from the ambient atmosphere and thus adds to the total cost budget.

In this article for the first time we present the design, development and application of a simple and robust CBRAM based MIM RF-switch on flexible paper substrate. In this experiment, the entire device fabrication was carried out in ambient laboratory conditions, without the use of any clean room facilities. In this study, we aim to prove the feasibility of integrating a MIM switch in electronically reconfigurable RF devices on flexible and low cost substrates like paper, which are seen around in our daily life as packaging materials for goods, transport tickets and visiting cards.

An RF-Identification tag using the RF-Encoding particle proposed in this paper could be easily fabricated as a sticker, on a paper substrate with adhesive background and could be attached to an object, like a barcode sticker, with far more advanced functionalities in comparison to the optical barcodes, like identification out of the optical-line-of-sight, electronic reconfigurability etc.

2. Motivation and Background

The basic building block of the presented RF-Switch is a nano-ionic MIM switching cell. Fig. 1 shows the basic layer structure and working principle of the proposed switching technique. The MIM cell is comparable to a parallel plate capacitor in which the electrolyte is replaced by an ion-conductor, which is an electrically insulating material, such as PMMA[7] or doped Chalcogenide glass [4], or Nafion [8], etc. One electrode of the cell is an ion-donor metal like silver or copper, generally called the active electrode and the other is a relatively inert metal like aluminum or gold. On the application of an electric field from active to inert electrode, ions from active electrode under the influence of this field grow a filament to inert electrode, through the ion-conductor layer. This closes the switch, to form the Set state, with a low resistance across the cell. Similarly, a field of opposite direction is used to dissolve the filament and open the switch to form the Reset state, with a high resistance across the cell. The switch once commuted to a stable state does not require any maintaining power supply to retain its state, making it a non-volatile passive device. Power is applied to the switch only to change its state. Electrical equivalent model of the MIM switch could be approximated to a parallel plate capacitor in parallel to the filament resistance as shown in Fig. 1, where C_{MIM} is equivalent capacitance due to geometry of electrodes and R_{MIM} is equivalent filament resistance across the cell.

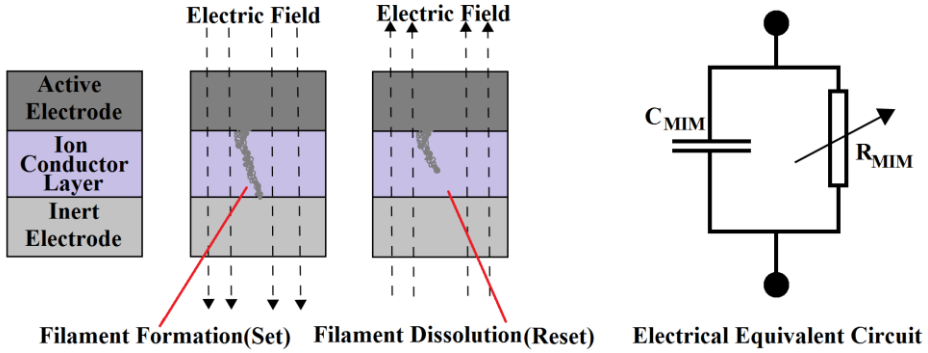


Fig. 1 Layer architecture of MIM cell showing the filament formation and dissolution, along with the electrical equivalent circuit.

The Fig. 2 shows 100 switching cycles for a typical MIM cell with Nafion as ion-conductor v/s filament resistance. We have not yet done a full-fledged study to find out the maximum number of functional cycles or the switching time of the MIM cell, to preserve the devices for detailed RF-characteristics analysis. This would be carried out in near future.

3. Design and Construction

The presented design is a modified version of the predecessor reported in [8]. The reported version in this article [8] is a 50Ω CPW switch in shunt mode on FR-4 substrate, similar to the one shown in Fig. 3. This device is fully fabricated in an ambient environment without the use of any clean room facilities. The device shows good performance features at least up to 3GHz in

comparison with existing switching technologies available. The CPW shunt mode design is chosen over the simple Microstrip design to avoid the fabrication difficulties in ambient laboratory conditions. With the Microstrip design, there are size limitations on the dimensions of the switching area in order to limit very high capacitance at higher frequencies. This requires having very small dimensions than what is used in this study. The photograph of this realization is depicted in Fig 4 (a) and the inset shows the close-up microphotograph of the MIM switch area.

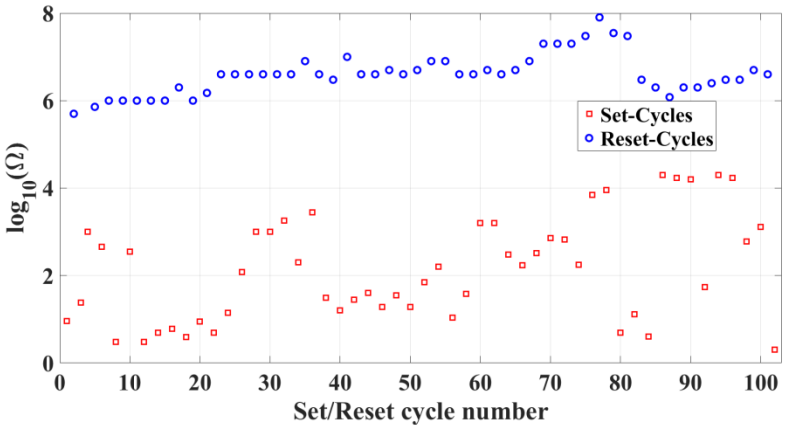


Fig. 2 100 switching cycles of a typical MIM cell with Nafion as the ion-conductor.

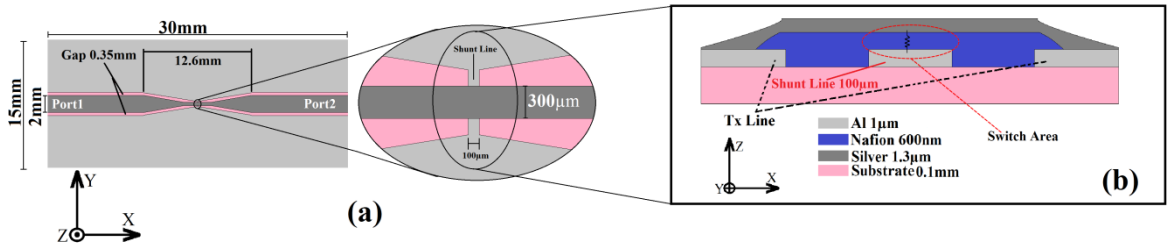


Fig. 3 Geometry (a), and layer architecture (b) used in the CPW shunt mode RF-Switch

In this article we try the same technology on flexible paper substrate. The topology and dimensions of the switch are given in Fig. 3. Process used for the fabrication is detailed in the following paragraphs.

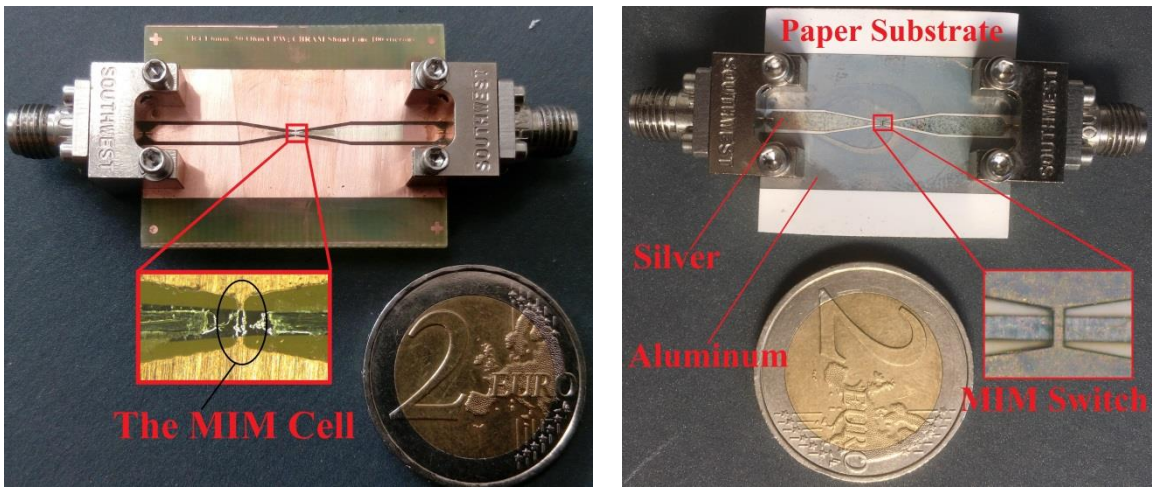
The substrate used for the fabrication of the device is 80 grams per sq. meter (GSM) special quality RF-paper developed at the IES lab. This paper is flexible and specially treated to reduce the losses at radiofrequencies and also has an improved surface for better adhesion of metal layers. Metal layers are formed on the substrate by thermal vapor deposition of Silver (Active electrode) and Aluminum (Inert electrode). Thermal vapor deposition is done with the help of dedicated Nickel masks which carry an engraved aperture of the presented topology in Fig. 3. After formation of the active electrode, the electrolyte layer is formed by spin coating the Nafion solution (supplied by Sigma Aldrich) at a rate of 500RPM for 30 seconds. The formed layer is then air dried on a hot plate at 100°C for 2 min. Then the inert electrode is formed using thermal vapor deposition. Detachable SMA connectors are then attached to the device to feed RF power.

It is now apparent that the proposed switch could be integrated into most RF- Designs using a three step process. 1. Deposition of active electrode. 2. Deposition of electrolyte/ion-conductor. 3. Inert electrode deposition. These steps could be easily carried out in an industrial environment by techniques like flexography[9]. The use of silver metal in the tags could be limited to the switch area only, by adjusting the nickel mask design, so as to reduce further the cost of realization.

Photograph of the fabricated CPW shunt mode switch is shown in Fig. 4 (b) and the inset shows the microphotograph of MIM switch area revealing the sandwich structure. The thickness of Silver and Aluminum deposit is measured to be 1.3µm and 1µm respectively and that of Nafion deposit is 600nm. The measurement is carried out with the help of Dektak-150 mechanical Profilometer.

Nafion [8] is chosen as the ion-conductor in this realization due to some specific advantages inherent to this polymer in contemplation to materials used classically [4]. Nafion is a sulfonated tetrafluoroethylene based fluoropolymer-copolymer, well known for its fast ion conducting properties and use in proton-exchange-membrane fuel cells, and is stable upto 190°C [10]. Nafion layer could be easily formed by spin coating and could be air-dried at temperatures around 100°C. From our experience in realization, this material is stable in the ambient air and do not require an additional conformal coating for protection. The maximum temperature observed on the sample during the thermal vapor deposition in around 120°C.

Working of the presented CPW shunt mode switch could be explained with reference to Fig. 3. MIM switch structure is formed in this device between the 100µm wide shunt line and 300µm wide transmission line sandwiching 600nm layer of Nafion. Shunt line connects the two ground planes on either side of the CPW line. When the MIM switch is Set as shown in Fig. 1, at the switch area labeled in Fig. 3 (b), RF power from Port 1 is short circuited to ground, thus disconnecting it from Port 2. This is the RF-Off state of the switch. When the MIM switch is Reset as shown in Fig. 1, the short is removed and Port 1 is connected to Port 2, forming the RF-On state.



(a) (b)

Fig. 4 Photographs of the fabricated RF-Switch on classic FR-4 substrate (a), and on paper substrate (b). Inset of both photographs shows the microphotograph of the MIM switch area.

DC pulses used for operating the switch are given in Fig. 5. In order to ensure smooth and stable operation of the switch, a positive growing current limited triangular wave form of peak voltage 10V/0.5mA is used for the Set and a flat -20V/0.15A square wave is used for the Reset as shown in the plot. These wave forms are optimized by various trial and error experiments. In the case given in Fig. 5, switch is Set at 7.5V and Reset at -20V, power consumed for the Set and Reset are calculated as 0.76mW and 9.6mW respectively. These power values are calculated from the instantaneous value of Set/Reset voltage and current pulses. An abrupt fall in the measured voltage across the switch and rise in current during the Set pulse indicates a Set state by the formation of a low resistance filament from active to inert electrode in the MIM Cell (see Fig. 5). Similarly an abrupt rise in voltage and fall in current during the Reset pulse indicates dissolution of filament and establishment of high resistance Reset state across the MIM cell. The Set/Reset pulses where applied to the switch with the help of custom made metallic probes attached to metallic parts of the switch.

4 Results

RF response of the switch is given in Fig. 6. Measurements of the device is done using Agilent ENA E5061B (3GHz) Network Analyzer, using Short-Open-Load-Thru calibration scheme. Power level used for the test is -15dBm. The RF-switch shows acceptable performance up to 3GHz with an insertion loss less than 3dB in RF-On condition and isolation greater than 15dB in the entire band, in

RF-Off condition. Filament resistance values for the respective Set and Reset are given in brackets of the respective legends for each cycle of operation. We were able to achieve filament resistance values of 4Ω and 60kΩ respectively for Set and Reset states.

In this experiment the maximum Set resistance value is 10Ω and the minimum Reset resistance value is 40kΩ. This is a good R_{Reset}/R_{Set} value. RF response of realization of the CPW shunt mode switch on classical FR-4 substrate [8] is given in Fig. 7 for comparison. This device shows an insertion loss less than 1dB in RF-On state and greater than 16dB in the RF OFF state. From this response it is clear that the realization on paper substrate has acceptable performance. Minor degradation in the On-state insertion loss could be justified by the losses inherent to paper substrate.

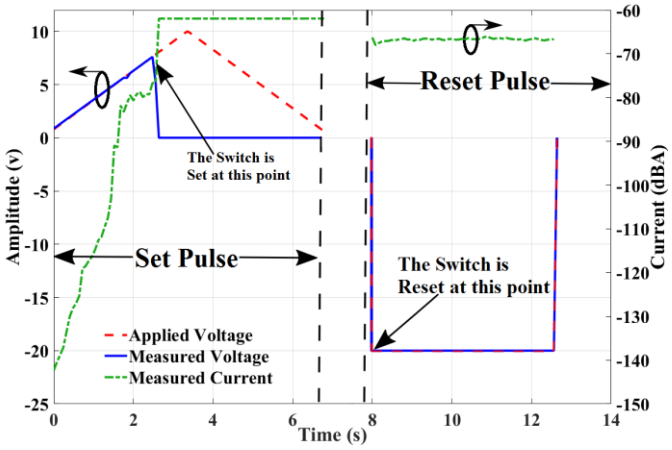


Fig. 5 DC pulses used to operate the switch.

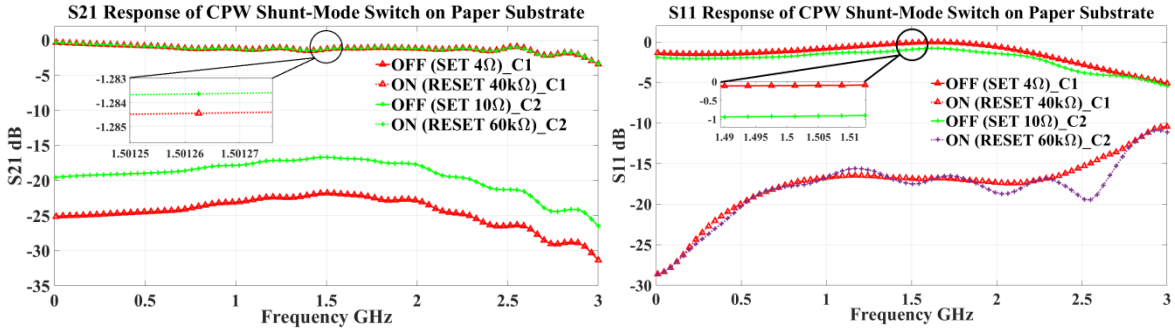


Fig. 6 RF-Response of the CPW shunt mode switch, on paper substrate.

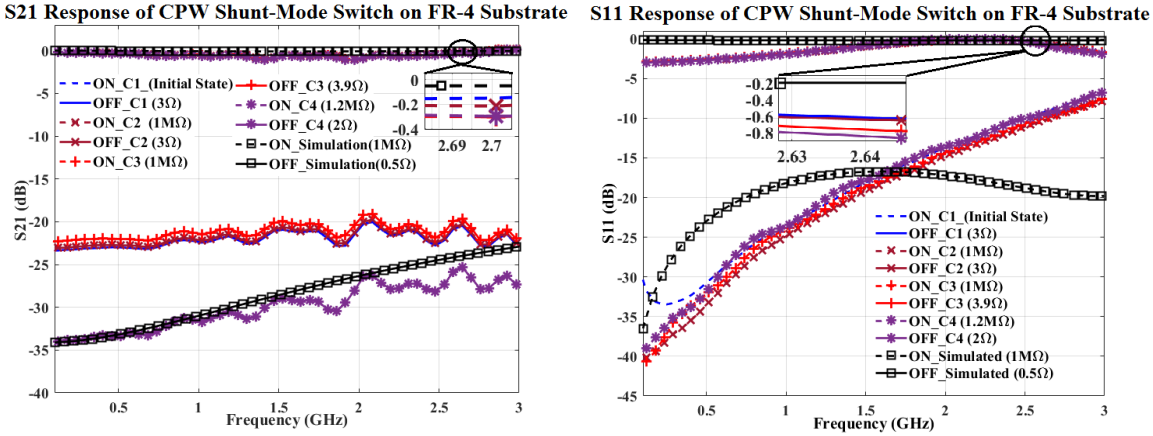


Fig. 7 RF-Response of the CPW shunt mode switch, on FR-4 substrate.

Table 1. is a comparison of the features of proposed RF-Switch on paper substrate with the state of the art and design on classic FR-4 substrate.

Table1. Comparison of proposed device to state of the art.

Features	**Proposed design on paper substrate**	**Design on FR4** [8]	**State of the Art (Nano-Ionic Switch)** [4]
Min. Fabrication size Requirement	100μm	100μm	10μm
Frequency Range	DC - 3GHz	DC - 3GHz	DC - 6GHz
Isolation (avg.) (Off state)	-23dB	-16dB to -34dB	-35dB
Insertion Loss(avg.) (On state)	1.2dB	0.5dB	0.5dB
Actuation Voltage	~10V/-20V*	~10V/-20V*	~1V
Power Consumption	μW/mW*	μW/mW*	μW
Energy Consumption to Maintain State	0	0	0
'Set' - Resistance (avg.)	7Ω	2–5Ω	10Ω
Switching Speed	#	#	1 - 10μs
Alignment Accuracy required for fabrication	Low	Low	Very High
Number of Fabrication Steps	3	6	6 (Clean Room Procedures)
Fabrication Environment	Ambient room	Ambient room	Clean room
Fabrication Cost (Laboratory Perspective)	Low	Low	High
Fabrication Cost (Industrial Perspective)	Low	Low	Moderate

* For Set/Reset respectively. # At present, we do not have enough information for calculating the switching time of the presented device.

5. Potential Applications

This idea of fabrication of RF-switches is seen to be functional and feasible in several applications in the field of disposable RF-Electronics, in devices such as reconfigurable RFID Tags [11,12], reconfigurable filters and reconfigurable antennas.

Radio Frequency Identification or RFID is a multi-dimensional ingenious concept that has evolved in the past couple of decades and still advancing at a very high speed. RFID finds application in an all-round domain from identification, sensing, energy harvesting etc. [12–14]

Amongst this, the chipless-RFID technology is an innovative identification technique often referred to as the 'Barcode of the future' due to its various versatile functionalities like large read range without optical contact, sensor integration functionality [11,14,15] etc., which cannot be implemented in the current scenario, with the optical barcode technology. Still a limiting factor to widespread use of this technology is the cost per unit tag in comparison to optical barcodes. However, recent developments in the field of disposable printed RF-electronics would lift this technique, to the technology main stream in near future. Thanks to CBRAM switches for adding revolutionary reconfigurability functionality to the chipless RFID tags, which would help in reducing cost per unit tag and increase the versatility of this technique.

An example of potential advantage of using the proposed switch technology could be explained as follows. Fig. 8 shows the method of frequency shift coding of RF-Encoding Particles (REP) in a chipless RFID tag [10,14]. In this example a shorted dipole resonator is used as the REP. Classically,

this is achieved by modifying the dimensions of each REP on the tag as shown in Fig. 8, for this, a unique geometry has to be designed for each REP. But instead, if we introduce the proposed MIM switch technique to this REP as shown in Fig. 8, the same performance could be achieved with a general REP of fixed dimension, by electronically switching the MIM cell.

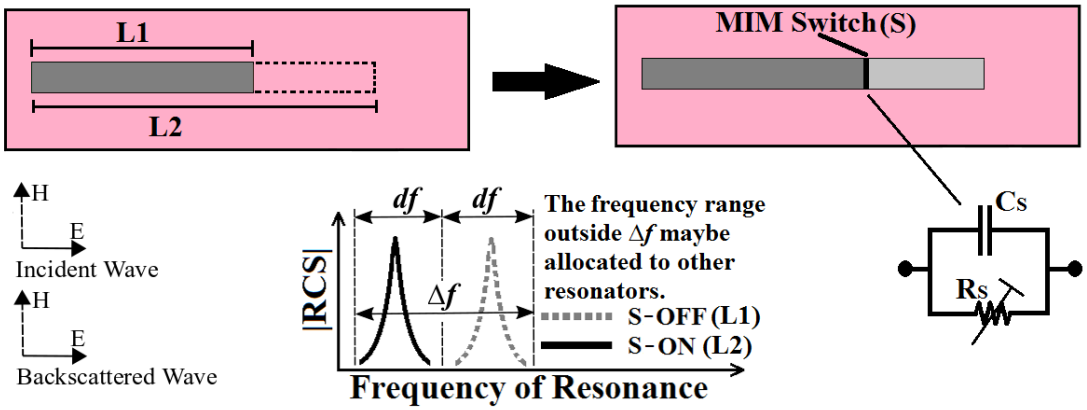


Fig. 8 Concept of application of MIM switches in an REP for chipless RFID tag.

If we integrate such REPs depending on how much bit density is required, on a credit card size tag, with contact pad and Set/Reset lines, it forms a general reconfigurable chipless RFID Card. This could be programmed by a dedicated logic device similar to a credit card reader to encode information. And then could be used for identification in wireless mode similar to a conventional chipless RFID tag. An illustration of this idea is depicted in Fig. 9.

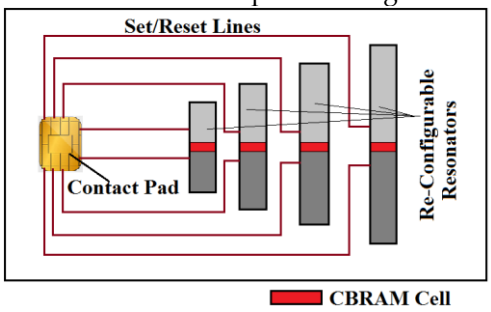


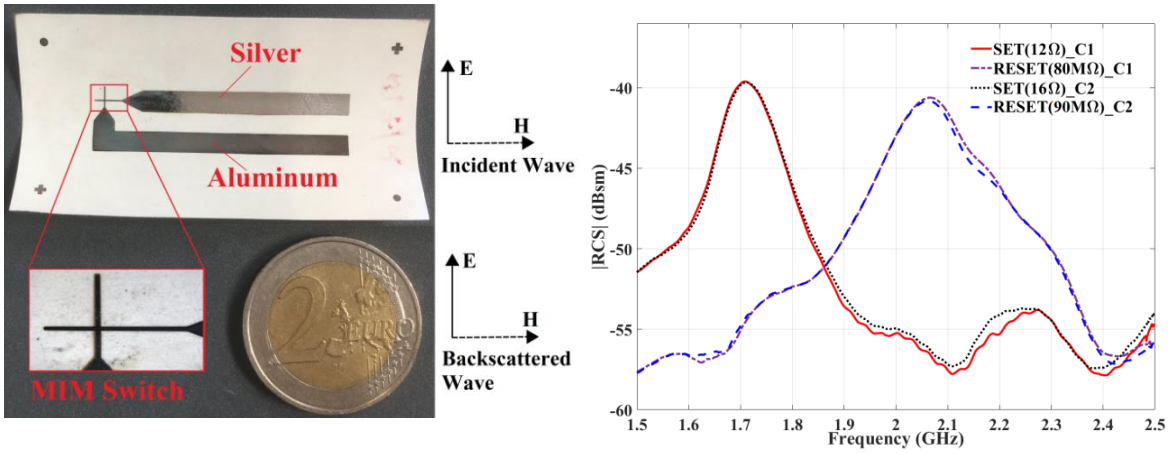
Fig. 9 Conceptual illustration of an electronically reconfigurable chipless RFID tag.

The proof of concept of this technique is reported in [10], and Fig. 10 (a) and (b) shows respectively the photograph and response of a similar design on flexible paper substrate. Fabrication of this tag is carried out in similar way like the RF switch on paper, by thermal vapor deposition of Silver (active) and Aluminum (inert) electrodes, and spin coating of Nafion. The proposed design is inspired from the 'C' resonator reported in [16]. Here we use a MIM switch, as shown in Fig.10 (a) with Silver-Nafion-Aluminum layers, to reconfigure the resonator by tuning its electrical equivalent circuit depending on the filament resistance (of the nano-ionic filament in the MIM cell). Equivalent circuit analysis and simulation studies of this concept are reported in [10]. Fig. 11 shows the experimental Bistatic Radar setup using Agilent N5222A PNA and two wide band horn antennas in co-polarization in an anechoic chamber [16]. This setup is used to record the RCS response of the tag shown in Fig.10. It is apparent from these results that we are able to switch the tag at two different resonant frequencies separated by 400MHz, with Set/Reset position of the MIM switch.

Discussion on the application of this concept for a commercial mass production and use, and the expected convenience is explained in the following paragraphs.

[17] Reports a 20-bit chipless RFID tag. Let's suppose to use this particular tag for labeling application in which the tag is encoded by using two different dimensions for each resonator. Thus by using the well-known frequency shift coding technique [14] expression (1) could be used to compute the possible number of combinations (refer Fig. 8 for illustration of the concept of bandwidth allocation for each resonator).

$$N = \left\lceil \frac{\Delta f}{df} \right\rceil^{k} \tag{1}$$



(a) (b)

Fig. 10 Photograph (a) and measured |RCS| response (b) of the reconfigurable RF-tag on paper substrate.

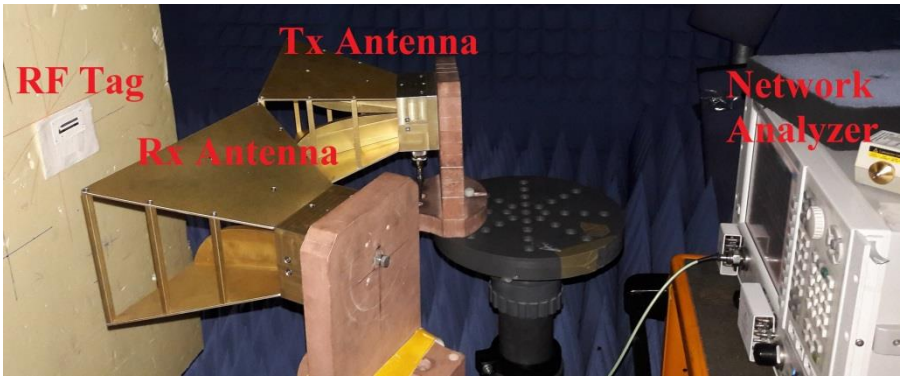


Fig. 11 Bistatic Radar setup used for RCS measurements of the Tag.

In (1) Δf is the allocated bandwidth per resonator, df is the bandwidth of resonance of the resonator, k is the number of resonators on the tag, and N is the total number of possible combinations. In this example let us say the allocated bandwidth per resonator is 200MHz and each resonator resonates with a bandwidth of 100MHz. So each resonator could be reconfigured by modifying physical size to operate in two different frequencies in the allocated bandwidth. Thus using (1) we could see that the total number of possible combinations is 1048576. Now if we try to fabricate the required combinations of tags using classical techniques like screen printing or photolithography, one requires 1048576 numbers of masks for the realization of the entire stretch of tags.

Beauty of the proposed concept could be revealed in the following sentences, taking into consideration the amount of labor and number of masks required for the fabrication. If a MIM switch is introduced to each resonator as in [10], to switch resonators between two different frequencies. It is apparent from the presented work that the switch/tag could be fabricated using just two masks and spin coating of Nafion. Similarly, for this particular RFID tag, the entire stretch of tags could be fabricated as a general tag using just two masks. Then, a dedicated electronic pulse programming circuit with an electrode array could be used to Set/Reset the respective switches and to encode each tag. In essence, the complexity of requirement of 1048576 unique masks for fabrication is solved by

just using two masks and a dedicated programmer circuit. This example clearly indicates the leverage of application of this technology in reconfigurable chipless RFID tags.

6. Conclusion

In this article, we have presented the design, construction and response of CPW shunt mode switch on flexible paper substrate. The speciality of this application is the simplicity in fabrication of the device on a substrate available at a very low cost, without using any clean room facilities. The operation of the switch is tested for at least 50 cycles for several batches, and the results are repeatable and reproducible respectively. We have also explained and proved the concept of integration of CBRAM or MIM switch technology in chipless RFID tags which are fabricated using simple steps on low cost paper substrates. The outcomes of this experiments show a pomising bright future for this technique. Reconfigurable chipless RFID could be the potential labels of tomorrow, backing the idea of Internet-of-Things[11,15]. This switch technique could also be applied in devices like reconfigurable filters and reconfigurable antennas in similar way, which are in development with the authors. With these results and the imparted confidence, the authors of this article are very near to the realization of fully printed electronically reconfigurable RF-Switches and chipless RFID tags on paper, using electrolyte solvents and conductive inks, using an inkjet printer.

Author Contributions: Conceptualization, Jayakrishnan M.P., Arnaud Vena and Etienne Perret; Methodology, Jayakrishnan M.P.; Software, Jayakrishnan M.P., Arnaud Vena and Etienne Perret; Validation, Jayakrishnan M.P., Arnaud Vena, Brice Sorli and Etienne Perret; Writing-Original Draft Preparation, Jayakrishnan M.P.; Writing-Review & Editing, Jayakrishnan M.P., Arnaud Vena and Etienne Perret; Supervision, Arnaud Vena, Brice Sorli and Etienne Perret; Project Administration, Arnaud Vena, Brice Sorli and Etienne Perret; Funding Acquisition, Brice Sorli and Etienne Perret

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Conflicts of Interest: The authors declare no conflict of interest

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