Chipless RFID Radiation Detector for high-dose monitoring- The ATTRACT project CHEDDAR.

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ABSTRACT

The development of low-cost, efficient, printable RFID sensors is a fundamental research domain for the future high-technology era of the Internet of Things. The CHEDDAR project aims at using the powerful and extremely low-cost chipless RFID technology to realize sensors of ionizing radiation. The sensors have no electronics in the tag, are extremely cheap, and are suitable for use in wireless networks or remote detection also in harsh environments. The first prototypes have been demonstrated and tested. Applications are foreseen mainly in the field of high-dose radiation monitoring.

Keywords: RFID; radiation detection; chipless sensors; high-dose radiation.

1. INTRODUCTION

- In this project, we exploit chipless RFID technology for high-dose ionizing radiation sensing. This sector needs urgently a relatively simple, cheap, and easy-to-use sensor in order to reliably measure high-dose levels inside new or existing nuclear reactors, or the post-process storage of nuclear wastes or contaminated sites. Low-cost wireless ubiquitous tagging and sensing will make the systems more efficient, reducing waste of money and resources, enabling a faster response to emergencies and lowering the probability of accidents.
- Radio-frequency identification (RFID) sensors are one of the fundamental components of the Internet of Things (IoT) future scenario, that aims at connecting every physical object to the cloud database for the exchange of information and activities. RFIDs are a powerful wireless technology for automatic identification and tracking, access control, security, and surveillance and electronic toll payments. The development of low-cost, efficient, printable RFID sensors is fundamental for this technology to fully exploit its technological potential. The combination of RFIDs and radiation sensors offers, therefore, new, more efficient and pervasive possibilities to monitor radiation levels in indoor and outdoor environments.
- Chipless RFIDs are a breakthrough technology because they remove the cost associated with the chip, overcoming the main economic limitation. Moreover, they are also printable, passive, low-power, and suitable for harsh environments, because they do not contain electronics in the tag.
- During this project, we have demonstrated the feasibility of the proposed solution for monitoring high-dose radiation. The realization of a chipless RFID sensor prototype has been the main goal of this project and its application in the field of high-dose radiation detection seems highly promising. More in detail the sensor has been tested with x-ray radiation up to 7 kGy, showing no sign of damage. Further testing has been so far limited by the availability of high-dose radiation sources. Moreover, the possibility of remote detection was also demonstrated. The precise sensitivity assessment, the high-dose limits, the specificity for different types of radiation, and the optimization of remote detection still need to be further addressed in the future.

2. STATE OF THE ART

Monitoring of radiation level and dosage is the primary factor in radiological protection, as well as in the estimation of material endurance and degradation. Electronic dosimeters based on solid-state MOS sensors are very precise and widespread for in situ monitoring of low and medium doses. However, at high radiation doses, these dosimeters fail because their electronic circuits cannot survive the radiation damage. High doses of radiation can only be estimated retroactively employing passive thermic, colour and photoluminescence indicators or hydrogen pressure dosimeters [1,2]. There is, therefore, a real need for continuous, in situ monitoring of radiation for ranges above 10 kGy.

In this project, we address this issue proposing a completely novel and low-cost concept of high-dose radiation detector that can overcome the current limitations for high dose monitoring. There is currently no comparable approach reported in the literature for this specific application. Recently, similar approaches have been reported for sensing a variety of different parameters [3,4], including movement, proximity, velocity, and position, as well as sensing of physical and chemical factors and monitoring of structural health or package integrity.

In order to be successful, this new concept of radiation detector faces two main challenges. The first one is common to all chipless RFID sensors and is the remote detection of the sensing signal, including limitations in terms of frequency sensitivity and normative limits. The second one is at the core of this specific project and includes the design and selection of the best material and resonating structure in order to optimize the detector sensitivity and radiation resistance at the same time.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

For remote monitoring of ionizing radiation, the current technologies, based on solid-state detectors or scintillators, are expensive and need complicate signal transmission methods, prone to environmental interferences. On the other hand, flexible reliable detectors for ionizing radiation are still to come. Our approach meets these two requirements, realizing a product which is at the same time extremely cheap and easy to fabricate and suitable for wireless remote sensing. As anticipated in the previous section, there is currently no similar approach reported in the literature for high dose monitoring. In this sense, the project is certainly proposing a completely new technology.

Chipless RFID technology is considered itself a breakthrough approach in the field of RFIDs because the RFID tag does not contain any silicon chip, making it not only extremely cheap but also suited for environments where electronics cannot survive. Being the sensing tag electronics-free, flexible and extremely low-cost, it is very appealing for applications in harsh and inaccessible areas or drone-assisted monitoring.

The outcome of this project can provide a completely new way to track and measure environmental radiation intensity and pollution in all those areas where the risk is considerably high, as contamination levels inside new or existing nuclear reactors, or the post-process storage of nuclear wastes or contaminated sites. This can be made more effective through a network of distributed sensors that could benefit from all the techniques of wireless monitoring recently developed in the framework of the Internet of Things. Low-cost wireless ubiquitous tagging and sensing will make the whole monitoring process more efficient and cheaper, reducing waste of money and resources, enabling a faster response to emergencies and lowering the probability of accidents.

4. PROJECT RESULTS

The sensor concept is relatively simple. The sensing tag is made of a sensitive layer applied on top of a thin metallic structure resonating in the microwave range. The resonating frequency of the tag depends on the dielectric properties of the layer, which is sensitive to ionizing radiation.

In case of wireless measurements, the signal can be detected directly (as shown in Fig. 1(a)) or coupled with receiving and transmitting antennas. However, in this project, we focalized our efforts mainly on ELC microstripped resonators, (depicted in Fig. 1 (b)) covered with a smart material for the sensing measurements, while performing the remote measurement activities only on the bare ELC resonating structure. This allowed us to work separately on the two main challenges of our work, which are the demonstration of the sensing capabilities of our resonator and the validation of the remote sensing approach.

We used a specific sensing material, namely Nafion 117. This material was selected among the other alternatives because of its peculiar characteristics. Nafion (sulfonated perfluorocarbon) is an ionomer and is composed of both electrically neutral repeating units and ionized units covalently bonded to the polymer backbone. The backbone is chemically equivalent to polytetra-fluorethylene, which is easily damaged by irradiation. The ionized units are made of sulphonic groups, responsible for both the high dielectric constant and ionic conductivity.

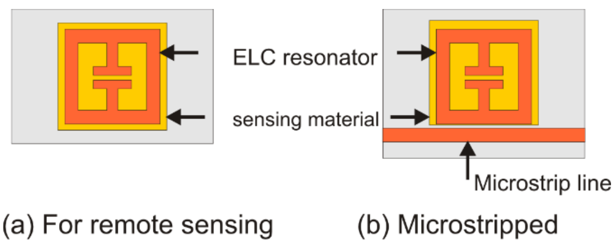

Fig. 1. Scheme of the ELC resonators used in this project.

This polymer is expected to show both damages to the fluorocarbon chains and loss of sulphur when sufficiently irradiated. This, in turn, means that its conductivity and dielectric properties should significantly change upon irradiation, making it a good candidate material for a chipless RFID radiation sensor.

Irradiation experiments

Six identical Nafion 117 samples of 1.2 cm x 1.2 cm area were irradiated with X-rays at room temperature at different doses. A structure like that in Fig. 2 was present below the irradiated Nafion in order to verify the possible substrate damage. The source was a tungsten tube, operating under 40kV.

No cracks and no apparent change in colour, roughness or texture of the samples or resonators were detected upon irradiation.

Nafion 117 x-ray absorption coefficient has been calculated using the data reported in the NIST Database. At the energy of 40 KeV, which is the central energy value of the radiation source employed, the ratio between the absorbed and total energy is 1.1%.

Before and after irradiation the resonating frequencies of the irradiated samples were measured by means of two ELC resonators of different dimensions corresponding to two frequency ranges (around 2.1 and 0.22 GHz). Nafion conductivity is strongly frequency dependent. If the conduction channels are affected by irradiation, the quantitative effect should be different at different frequencies. Data are reported in Fig. 3 where the relative frequency shift is reported as a function of the total dose. While the maximum relative shift is of the order of 0.5% at 2.1 GHz, the corresponding value increases up to 3% in the case of 0.22 GHz. It should be noted that the limit of 7 kGy is given by the availability of the irradiation source and not by the sensor itself, that did not show any sign of damage.

Irradiation experiments similar to those reported above for x-ray were performed with protons, up to a dose of 1.2×10^{11} protons, corresponding to an absorbed dose of 246.6 Gy. In this case, only three samples were tested and measured with the higher frequency resonator structure.

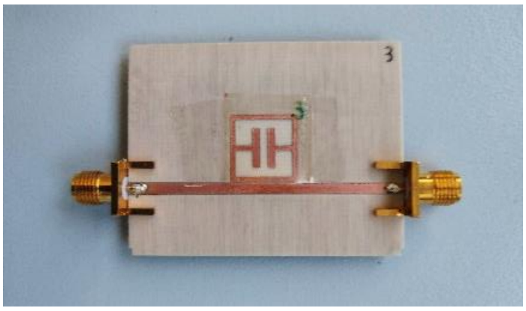

Fig. 2. One of the sensors used in the x-ray irradiation experiment.

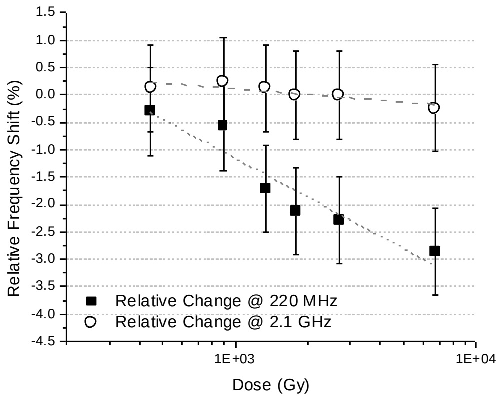

Fig. 3. Relative frequency shift upon irradiation measured with structures resonating at two different frequencies.

The results were similar to those with x-ray, but a definite trend cannot be evidenced due to the limited number of samples and relatively low irradiation dose.

Remote sensing experiments

Radar cross-section of the ELC resonator was first simulated in different measurement configurations in order to maximize the received signal. Remote detection experiments were then performed with an ELC resonator centred around 3 GHz. It was demonstrated that the signal is detectable, but parameters and geometries still need to be optimized.

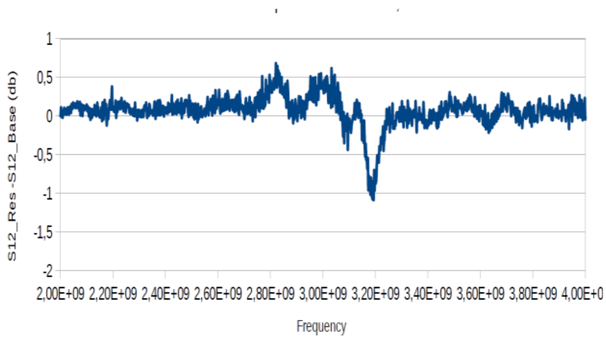

Fig. 4. Measurement of a bare resonator in transmission mode.

5. FUTURE PROJECT VISION

This project was born from a novel and visionary idea that was never proposed before, and consequently, its initial TRL was very low. During the project duration, considerable progress has been made in several directions. As to now, not only the basic technologies and competencies necessary to proceed along the TRL scale are clear, but also the limits and the challenges to be overcome in order to realize a functioning and competitive product.

5.1. Technology Scaling

The project at the time of the deadline will have an estimated TRL of 2-3. In order to reach higher TRLs, the most important goal is to demonstrate the sensing capability at much higher doses, which was our initial goal and is very likely to be reached from our preliminary measurements. So, the first important step is to interact with appropriate Research Infrastructures that can make available suitable radiation sources.

However, other essential steps need to be defined or implemented to make relevant progress:

- Define the sensitivity limits to different types of sources and energies.
- Optimize the remote detection and increase the reading range, with a dedicated design of the tag antennas coupled to the ELC (e.g. Van Atta arrays).
- Implementing non-sensing resonators that can be used to track the sensor ID on the sensing tag.
- Chemically modify the sensing material in order to tailor its properties to enhance its performances (optional).
- Work on a low-cost portable detector for on-field testing.

Project Synergies and Outreach

From the beginning of the project, it became clear that the consortium has to be enlarged in order to advance along the TRL scale because the actual small consortium alone does not have the resources and the infrastructure for doing this. We plan to address preferentially three categories of possible partners:

- Companies with business and experience in the field of radiation detection, that can help us in exploiting the intellectual property and meeting the market requirements and needs.
- Companies (preferably SMEs) and research organizations working in the field of wireless communications and networks.
- Large Research Infrastructure or International Organizations in Field that can provide us with the testing facilities and eventually help us in the field tests.

The authors do not exclude clustering with other ATTRACT projects, but so far, we had no opportunity in this sense, being the topic our project quite unique in whole ATTRACT scenario.

Dissemination activity is and will be one of the main project outcomes of Phase 1. A project presentation video was realized at CERN at the beginning of the project and at least two open access scientific publication related to this project are foreseen in the next future (one is about to be submitted). So far, the main limitation for other dissemination activities has been the lack of resources to dedicate to this purpose. In case the activities are going into Phase 2, a much more comprehensive and widespread dissemination plan will be implemented, including not only scientific publications and participation to conferences and fairs but also communication activities to the general public, set-up of newsletters, press releases and web site and LinkedIn page implementation.

5.2. Technology application and demonstration cases

Demonstration cases in phase 2 will be the direct consequence of the research activities pursued in Phase I. Practically speaking, the demonstrator will be one or more networks of radiation-sensitive detectors connected wirelessly that will be tested at a convenient and appropriate facility.

The impact of the demonstration cases will cover several areas of Scientific Research, Industry and Societal Challenges. Here are the most relevant benefits:

- *Health, demographic change and wellbeing*: the technology under development will help to detect and control radiation contaminated areas, with a clear impact on human health and wellbeing.
- *Secure, clean and efficient energy*: nuclear power plants are one of the end-users for the exploitation of the proposed network of high-dose radiations sensors inside new or existing atomic reactors in order to improve their safety and security.
- *Climate action, environment, resource efficiency and raw materials*: Radiation contamination is one of the most dangerous environmental pollution categories. This demonstrator case will greatly contribute to the reliable control of nuclear wastes or of potential geologically or environmentally induced leakages.

The project progress is only possible through collaboration with European Research Infrastructures operating in the high-dose irradiation domain. We need high radiation sources to test our prototypes and demonstrators, and to do this we plan to apply soon to opportunities and funding schemes offered by H2020 in this field or for access to dedicated JRC Research Infrastructures.

5.3. Technology commercialization

Being the research outcomes still at low TRL, other funding is needed before the product can be considered attractive for the market. In addition to potential ATTRACT Phase 2, the project consortium is currently evaluating how to apply for other funding opportunities in order to increase the TRL of the product under development. Many channels will be explored, such as European and National Calls for applied research related to nuclear safety or Calls for start-ups from public organizations or private companies. Another possibility is contacting the international Atomic Energy Agency (IAEA), given its interest for nuclear safety. That could be a direct or indirect starting point to test the interest in the product and to find connection with the industrial investors.

5.4. Envisioned risks

Lack of funding or human resources (operational): The consortium partners are strongly committed to find adequate funding and to compensate for a temporary lack of dedicated personnel.
Partner poor commitment or withdrawal (operational): the project coordinator will continuously monitor the project progress through internal communication, and will take the necessary actions in agreement with the other project partners with timely adjustments or replacements.
Sufficient sensitivity is not achieved, or the material is too damaged at high doses (technical): More effort will be spent in engineering the material properties and the device design to push this limitation to higher values.
The remote signal is too low (technical): The tag design will include receiving and transmitting antennas. Moreover, the reader will be optimized for the purpose.

5.5. Liaison with Student Teams and Socio-Economic Study

This project did not have the chance to collaborate with MSc. Level student teams during Phase I. However, we are deeply committed to pursuing this activity during Phase II.
One specific person, with good communication skills and deep knowledge of the project topics, will be responsible for this activity. Dedicated dissemination material will be produced with the help of all the partners involved.
The proposers are also open to offer other contributions in the frame of the ATTRACT initiative, offering on-site or virtual visits or preparing demos of the activities. Interviews with the researchers involved and support for technology impact will be also given.

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