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Development of a radio frequency resonator for monitoring water diffusion in organic coatings

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ABSTRACT

A battery-free wireless sensor dedicated to water diffusion monitoring in dielectric materials is presented. It is applied here to the monitoring of water diffusion in organic coatings. The method is based on the variation of the radiofrequency (RF) wave propagation in an open microstrip structure covered by the coating under consideration when water diffusion occurs. Simulations and experimental characterization of electromagnetic wave propagation in a microstip line and a planar stub resonator are described. The results achieved on the resonator prove unambiguously the feasibility of the method. As a consequence, the proposed sensor should be considered as a promising and reliable tool for civil engineering applications.

1. Introduction

Corrosion and degradation of metallic infrastructures are, most of the time, governed by the presence of water molecules in the surrounding media. Paints or coatings which act as ionic and electronic barriers to the environment [1,2] are thus frequently used to increase the lifetime of the operating infrastructure and thereby to limit the maintenance operations. However, with aging, coating degradation is unavoidable. It is most of the time initiated by the presence of defects in the coating and leads to water absorption and diffusion towards the metal that constitutes the structure. At this stage, the efficiency of the coating against corrosion is rather limited and degradation of the underlying metal occurs. The ability to predict such coating degradation is of first interest because it enables to improve maintenance actions of infrastructures and can lead to significant financial savings in many industrial domains. Within this context, there is a real interest in developing sensors which enable the detection of water absorption in coatings.

Numerous methods exist for monitoring water penetration in polymer or coating such as gravimetric [3], NMR relaxometry [4,5], or spectrometric methods [6]. Among them, electrochemical measurements are well-known to monitor the change of properties of electrical insulating materials such as organic coatings in water or in humid environment. In particular, Electrochemical Impedance Spectroscopy (EIS) is a well-established laboratory technique for such investigations. This method consists in measuring the change of capacitance of the coating during its degradation and can be applied to evaluate the coating performance [7], the presence of coating discontinuities [8], or the diffusion of water through the coating [9,10]. However, despite the success of the EIS method, most of the instruments like potentiostats are expensive, large in size, and require line power to operate. The practical integration of the EIS method in sensors is thus not straightforward. Some authors recently overcome this limitation and proposed some wireless sensors small in size based on the EIS technique [11,12]. Davis et al. [11,12] proposed an innovative wireless coating health monitoring system (CHM) consisting of a series of mini-potentiostat modules. They measure the impedance variation between a tape electrode mounted on top of the paint coating of the structure and the underlying metal. Wireless communication is achieved through the Zigbee protocol. Shi et al. [13] proposed a similar sensor operating from 20 KHz to 80 KHz to investigate the change of the coating impedance between the substrate and a working electrode placed in an electrolyte. A second method of coating degradation monitoring consists in measuring the dielectric permittivity of the coating during its degradation by using capacitive electrodes. Similarly to EIS measurements, an impedance-meter connected to the electrodes is needed [14].

All these methods imply to realize physically some capacitors with at least two conductive electrodes connected to an impedance measurement device. The suppression of external potentiometers, electronic boards or batteries would provide a major improvement

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of the method and authorizes new potential applications. In particular, embedding the sensor between the metallic substrate and the coating should be feasible. The widely developed passive wireless RFID technology in which a very thin flexible tag is interrogated by a reader without the use of any external battery can be considered for the development of such sensors. Numerous examples of sensing capabilities of UHF passive RFID tags exist for water diffusion monitoring in concrete [15,16] and for water presence detection [17,18]. The sensitivity of the sensor is then based on the change of the electromagnetic performance of the tag antenna due to the presence of water in the surrounding environment. Due to the long distance propagation of EM wave, the sensitivity of this method to water diffusion in very thin organic coatings is not guaranteed. To overcome this drawback, we consider here sensitive microstrip planar resonators presenting a more confined EM field with respect to antennas. This technology presents several advantages with respect to other sensitive microwave devices. Indeed, embedding the sensor in the structure is possible since the underlying metal acts as the ground plane and the conductive strip as well as the dielectric substrate can be covered by the organic coating under monitoring. Such microstrip lines present the second advantage of being fully compliant with the chipless RFID technology proposed by Preradovic and Karmakar [19]. In the present work, to support the proposed method, simulations are first performed for electromagnetic wave propagation in coated microstrip lines and resonators for a variation of the coating dielectric permittivity in the range from $\varepsilon = 3$ to $\varepsilon = 60$ and for different coating thicknesses. As it will be shown, the use of a stub resonator provides definitely better results with respect to the single transmission line. The main requirement of the sensor being the ability to detect the early stage of water diffusion in coatings, the study focus afterward on resonators covered by coatings with dielectric permittivity of about 4. These results serve as a guideline to explain the experimental data achieved on water diffusion in an epoxy resin of 0.6 mm thickness. As highlighted, the physical and chemical changes associated with the observed variations are identified though a comparison with the numerous existing investigations performed on this type of coating.

2. Material and methods

Experimentally, microstrip lines and stub resonators were produced by standard photolithography techniques on FR4 substrates (woven glass fabric with epoxy resin system). Their adaptation to 50 ohm was guaranteed by elaborating lines of 1.5 mm width (w) on 0.8 mm-thick substrates, and by assuming a dielectric value of 4.4 for the FR4. The length of the stub resonator was set to 3.4 cm, to achieve a resonance at 1.196 GHz in air. To validate the results provided by the electromagnetic simulations, the stub resonator was covered with different dielectrics materials: polycarbonate (Technifilm), polyethylene terephthalate (Technifilm), and FR4 (CIF). These materials were pressed on the planar resonator. Finally, stub resonators were covered by an epoxy coating from Akzo Nobel (Baker E 2000) and subsequently immersed in water for few months. During this period, water absorption/desorption cycles were performed and reflection S_{11} and transmission S_{12} parameter measurements were made using a network analyzer (HP 8720B). Short-Open-Load-Thru (SOLT) calibration method was used. Note that the curing temperature was chosen to be 150 °C, a temperature below the polymerization temperature of the coating (220 °C), to enhance water absorption and thereby to get some experimental evidences of the feasibility of the method within only few months of exposure time. To understand the results obtained experimentally, we used the electromagnetic simulation software: High Frequency Structural Simulator (HFSS 15.0 from ANSYS), utilizing tetrahedral mesh elements to solve the propagation in the microstrip line and the stub resonator.

3. Results and discussion

3.1. Electromagnetic simulations

Microstrip line technology is chosen here because it allows easy connections between devices and antennas. Fundamentally, microstrip line is an open RF structure which leads to a non-negligible spatial extension of the electromagnetic (EM) field outside the dielectric RF substrate. Most of the time, this effect introduces RF losses and unwanted coupling effects and is therefore considered as a nuisance in microelectronics. However, it can be desired for some particular applications. For example, the interaction between electromagnetic field outside the substrate and magnetic materials results to the development of ferromagnetic resonance (FMR) based filters [20,21]. Following this idea, due to the very different values of relative dielectric permittivity of polymers ($\varepsilon \approx 3.5$) and water ($\varepsilon \approx 81$), the main objective of the study is to identify the change of the RF transmission in a microstrip line covered by a coating during the diffusion of water in the coating. During the last few years, a similar approach was considered for development of RF resonators and antennas for water properties monitoring [22–25].

In HFFS simulations, we assume that water absorption leads to a variation of coating dielectric permittivity ε and consequently to the effective dielectric permittivity ε_{eff} of the microstrip line. Simulations of the RF transmission in a copper microstrip line covered by the coating are thus performed for different values of ε. Moreover, to investigate the influence of the coating thickness h on the sensitivity of the method, several values of h are selected. All the dimensions used for the simulations are presented in the supplementary data part (Fig. 1). Fig. 1(a) and (b) display the transmission parameter S_{12} as function of ε for h = 0.1 and h = 1 mm, respectively. As shown in Fig. 1(a), for h = 0.1 mm, almost no change of the RF transmission is associated with the dielectric permittivity variation. The observed slope is explained by the loss in the RF substrate, here the FR4. For h = 1 mm, in Fig. 1(b), a slight increase of the S_{12} loss of about 0.5 dB appears for high permittivity values at high frequency. These results are in agreement with the work of Bahl et al. [26] which showed the appearance of very small RF transmission loss in the range of 0.01–0.1 dB/cm for microstrip lines covered by polymers of high permittivity with respect to microstrip line located in air. As detailed in this previous work, the RF losses could be increased by changing the geometry of the microstrip line, however they remain rather low. Consequently, the proposed method is not sensitive enough to detect the initial stage of water diffusion.

Instead of focusing on the amplitude transmission variation, a second approach consists in producing a resonator sensitive to a change of the coating dielectric permittivity. We consider thus a microstrip stub resonator covered by a coating of thickness h and dielectric permittivity ε. A picture of the resonator is presented in the supplementary information part (Fig. 2). Fig. 2(a) displays the transmission parameter S_{12} in a resonator covered with a coating thickness of 0.1 mm. A shift of the resonant frequency from 1.15 GHz towards 0.95 GHz is clearly observed when the coating dielectric permittivity is increased from 3 to 60. This demonstrates clearly the sensitivity of the method to ε and thus to water diffusion. To further investigate the influence of the coating thickness h on the sensitivity of the method, Fig. 2(b) presents the resonance frequency as function of ε and for different thicknesses h. As observed, a decrease of the resonant frequency is observed for all studied when ε is increased. However, the sensitivity of the method is clearly enhanced for coating thicknesses at the millimeter scale.