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The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating 2017: 5.03
TPI 2017; 6(4): 80-86

www.thepharmajournal.com
Received: 14-02-2017
Accepted: 15-03-2017

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Radio frequency based sensor: An innovative detection tool for food spoilage

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Abstract
Market demands for new sensors for food quality and safety stimulate the development of new sensing technologies that can provide an unobtrusive sensor form, battery-free operation, and minimal sensor cost. Intelligent labelling of food products to indicate and report their freshness and other conditions is one important possible application of such new sensors. RFID systems have been used in numerous applications like asset tracking, toll collection and libraries and capability to an adverse environment. The frequency of RFRD system can vary from the lower ranges of the spectrum 135 kHZ to SHF rang at 5.875 GHZ inductive coupling and back scatter modulation are use at lower frequencies as opposite to system operating at 2.45 GHZ RF system comprises of tag, reader and host interface. This system forms LCR circuit which is described by inductance, capacitance and resistance. Milk spoilage is a result of the growth of micro-organisms that modifies the composition of the medium with the metabolic products, changing the ionic content and conductivity of milk hence, determination of milk quality is critical to maintaining food safety and human health. RFID sensors should have the ability for self-calibration and self-correction for variable ambient conditions.

Keywords: RFID, Passive tags, Sensor, Food Safety, Antennas

1. Introduction

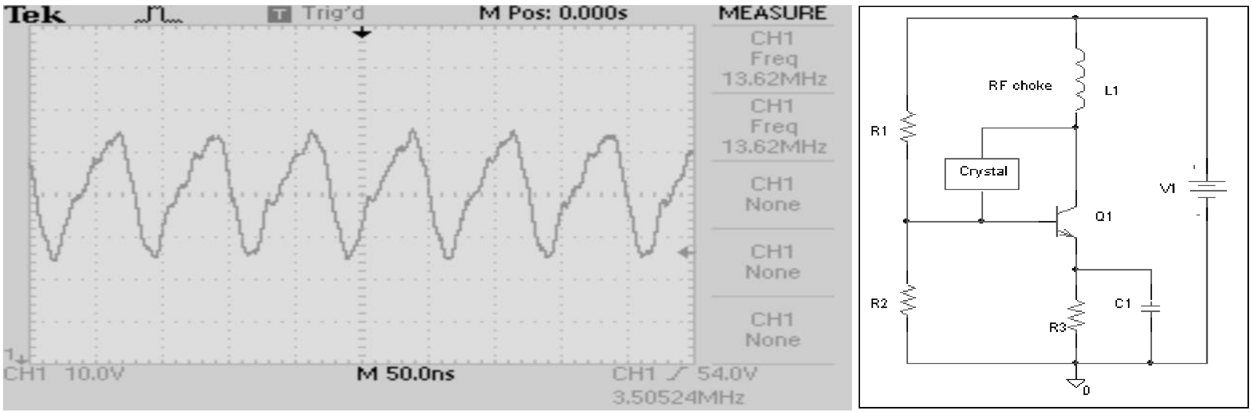
Food freshness is a key factor for public safety. Management and monitoring of food quality are important in food storage and transition. Food safety issue is a vital concern as shown in the Hazard and Critical Control Point (HACCP) by the U.S. Food and Drug Administration (FDA). The waste of food due to spoilage is also a major concern for not only business owners but also many countries [1]. Three different modalities for food spoilage monitoring have been utilized in research and commercial fields, besides direct tasting by experts. A common food freshness monitoring method is to use gas sensors which often are made of metal oxide semiconductors (MOS), conducting organic polymers, or piezoelectric crystals. These sensors rely on the changes of conductivity in the sensing films induced by the adsorption of gases and subsequent surface reactions that are produced by food during spoilage processes [2], [3]. For the MOS sensors, the required operating temperature is between 200 C and 650 C as the organic volatiles transferred to the sensing surface need to be oxidized which causes the changes of electrical resistance [2]. The selectivity and sensitivity of MOS sensors are easily influenced by the operating temperature and microstructures of metal oxide films since the sensing depends on the physical characteristics of MOS. Conducting organic polymer sensors, on the contrary, require a low operating temperature and usually are very sensitive to moisture which may not be suitable for robust applications [3]. For piezoelectric crystal sensors, a good quality of coating process is required during the fabrication to maintain a consistent sensitivity which may not be a cost-effective option [3]. In general, gas sensors are easily affected by environmental conditions such as moisture and temperature due to the sensing principles. The other two modalities to monitor food freshness are based on the detection of enzymes and storage temperature changes [4-8].

Enzyme sensors are used to monitor different types of foods on the basis of was require different specific enzymes. Detection of total volatile basic nitrogen (TVB-N) and histamin enzymes are widely used for detection of total volatile is sensing nitrogen (TVB-N) and seafood [4-7]. However, Gram reported that spoilage mechanisms vary for different races of fishes [9]. Glutamate dehydrogenase and glucose oxidase detection is widely used for freshness sensing of fruits, vegetables, and related food products such as juice or wine [10]. The detection of enzymes often needs to be carried out manually in selected samples as it is impossible to conduct the tests on every product.

It is also difficult to integrate specific enzyme sensors in a food package that allows wireless interrogation. The enzyme sensors often utilize enzyme oxidases in the sensing electrodes which may not be appropriate or even safe to be used directly in a food package. Furthermore, the enzyme sensors usually require complicated fabrication processes such as the polymer treatment, temperature control, and chemical compound mixing to achieve the required sensing performance [4]. The expensive chemical agents, specific surface treatment, and complicated fabrication process will increase the costs which in return is difficult for large-scale applications. To manage produce quality by monitoring ambient temperatures during transit and storage is an indirect but common means to “estimate” the food quality; often it is not accurate or specific enough. Therefore, a direct, simple, accurate method that can be integrated with low-cost electronics and wireless capability to monitor food quality is needed.

During the food spoilage processes, the growth of yeasts and microbes plays a notable and major role inside the food. The original chemical compounds such as glucose, lactic acid, and certain amino acids are catabolized by microbes or micro flora in food [11]. As the food condition changes, the pH level also changes with the metabolism actions of the bacteria and microbes [7, 11, 12]. Therefore, monitoring pH profiles in food provides a means for food quality measurement. Sensors development for detecting foodborne pathogens has been motivated by need to produce safe foods and to provide better healthcare [13, 14]. Improve food and safety and security depends on the ability to detect, identify, trace food and water pathogens. As milk is a compulsory part of our daily diet and being nutritious food for human beings, also serve as a good medium for growth of many microorganisms which cause spoilage of milk and milk products earlier for detection pathogen conventional methods were use, and are considered a gold-standard for foodborne pathogens detecting which rely on specific media to enumerate and isolate to viable bacteria cell in food. These methods are very sensitive, inexpensive and can give both qualitative and quantitative information and involve the basic step: pre-enrichment, selective enrichment and selective plating, biochemical screening and serological confirmation. Hence, a complete series of tests is often require before any identification can be confirmed although methods are powerful, error-proof and dependable but are lengthy, cumbersome and are often ineffective because they are not compatible with the speed at which the product are manufacture and the short shelf life of products [15]. To overcome these challenge criteria of time and sensitivity rapid method rapid method which include nucleic acid, fluorescent antibody or immune based technique have been developed which give instant real time results but required additional expansive device and equipment [16].

Radio Frequency Identification (RFID) systems have found favour over other identification and inventory techniques chiefly due to their non-line-of-sight operation and capability to function in adverse environments. The frequency of RFID systems can vary from the lower ranges of the spectrum around 135 kHz to the SHF range at 5.875 GHz. The most commonly used frequency which has a whole range of applications associated with it is the 13.56 MHz ISM (Industrial Scientific Medical) band. Inductive coupling and backscatter modulation are used at lower frequencies as opposed to systems operating at 2.45 GHz and higher bands, where true RF communication links are used [2]. There are three components in a RFID system, a remote device called the tag, a reader and a host interface. The reader, or scanner, transmits a constant amplitude high frequency sine wave. The reader acts as a transceiver, not only transmitting radiation to the tag, but also receiving backscattered radiation from the tag [3]. In inductive coupling mode, the reader detects variations in the voltage or current levels when a tag comes in its vicinity. If an on-board battery powers the tag, it is termed an active tag. Passive tags draw power from radiation emitted by the reader and are less expensive and generally preferred over active ones. Their only drawback is a much-reduced reading range compared to an active tag. This disadvantage is offset by the very long lifetimes and durability of passive tags compared to active ones. The host interface is normally an application program that is running on a computer system. The program communicates with the reader and makes sense of the data that is obtained from the tag. Tags can be read-only or read-writable. If the tags can also be written to, then the application sends out the required data to the reader through, for instance an RS232C serial port of the computer [3]. The reader then writes this data to the tag in the field. Our ultimate goal is to interface a biosensor with a passive tag, which can be interrogated by the reader. The objective is to relay the sensory information over a wireless medium to the tag. As a stepping-stone to this goal, our present research is focused on developing an RFID temperature tag.



(a) **(b)**

Fig 1: (a): Crystal-controlled oscillator circuit (b): Output wave form of the oscillator.

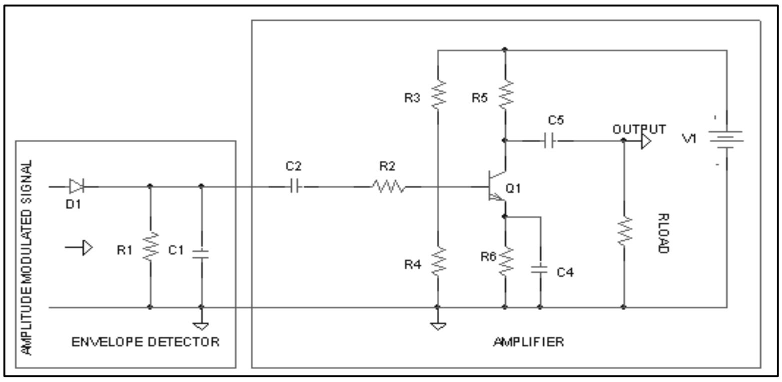


Fig 2: Detector followed by an amplifier.

General Principles of Design and Operation of RFID Food Sensors

It is critical to understand the general principles of their design and operation to assess the broad applicability of sensor for food safety applications (Fig. 1a). The equivalent circuit of the sensors forms an LCR circuit and is described by the inductance LA, capacitance CA, and resistance RA of the sensing antenna coil, capacitance CS and resistance RS of the sensing region, and capacitance CC and resistance RC of the integrated circuit (IC) chip (Fig.1b). Reading and writing of digital information into the RFID sensor and measurement of impedance of the RFID sensor antenna are performed via mutual inductance coupling between the RFID sensor antenna and the pickup coil of a digital/analog sensor reader. Impedance spectra Ž (f) of the sensor are measured using a laboratory or a portable network analyser component, and digital data from an IC chip are measured with the digital RFID reader component of our custom sensor reader [24]. Digital data include sensor calibrations, food manufacturing data, end-user data, etc. The network analysers are used to scan the frequencies over the range of interest (typically centred at 13 MHz with a scan range of 10 MHz). The electric field generated in the RFID sensor antenna extends from the plane of the RFID sensor (Fig. 1b) and is affected by the ambient environment providing the opportunity for sensing. This environment may be in the form of a food sample within the electric field of the sensing region or a sensing film deposited onto the sensor antenna. In both cases, the impedance of the antenna circuit Ž (f) is modulated through changes in capacitance CS and resistance RS of the sensing region. This sensing region can be in the form of a full antenna or a complementary region in contact with the antenna [25]. Numerous types of sensing materials applicable for the food quality sensing were recently analysed [26]. The measure of real Zre (f) and imaginary Zim (f) parts of the impedance spectra Ž (f) and calculation several spectral parameters are required to achieve. A schematic representation of the real Zre (f) and imaginary Zim (f) parts of the impedance spectrum Ž (f) of the sensor without possible effects from a pick-up coil is illustrated in Figure 1. Several calculated spectral parameters include the frequency position Fp and magnitude Zp of Zre (f) and the resonant F1 and antiresonant F2 frequencies of Zim (f). Additional parameters can also be calculated (impedance magnitudes Z1 and Z2 at F1 and F2 frequencies, respectively, zero-reactance frequency, quality factor, etc). From the measured parameters, resistance, capacitance, and other parameters of the resonant antenna can be also determined. Fig. 2 shows examples of RFID sensors applied in our studies for food quality and safety. Uncontrolled temperature fluctuations produce independent effects on the different components of the equivalent circuit. These independent effects are correlated with the spectral features of the resonance impedance spectra and are resolved by the multivariable response of the sensor [27-28]. For scenarios when the food is irradiated by ionizing radiation as a food safety measure to destroy bacteria, pathogens, and pests conventional RFID IC memory chips do not survive the applied radiation dose, which can be up to 30 k Gy [29-30]. We have developed a technical solution was developed to solve this problem wherein an IC chip is based on the Ferroelectric Random Access Memory (FRAM) technology and provides reliable γ-resistant RFID tags and sensors [31]. The FRAM memory chips have 2000 bytes of user memory (MB89R118A, Fujitsu Microelectronics Ltd., Japan) and are made using a standard RF signal modulation circuitry fabricated using a 0.35 μm complementary metal oxide semiconductor (CMOS) process and a non-volatile FRAM memory [32-33]. A photo of this IC chip is shown in Figure 3A, whereas one of our RFID sensors with such an IC chip is shown in Figure 1b.

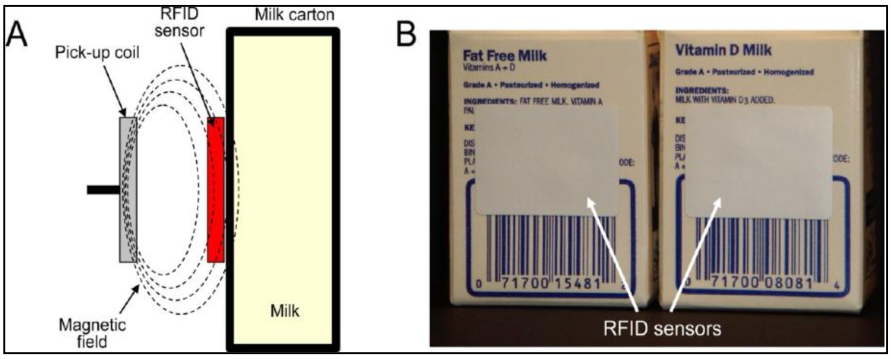


Fig 3: RFID sensor layout for demonstration of determination of milk freshness: (A) schematic of sensor positioning onto milk carton and sensor-response readout with a pick-up coil; (B) photograph of milk cartons with attached RFID sensors.

Reader

The reader is a series RLC circuit, where the inductance is a loop antenna, designed to resonate at 13.56 MHz. When a carrier wave is fed to the reader circuit, a magnetic field emanates along the plane containing the loop according to Amperes' law. The strength of the magnetic field depends on various factors like the driving current, the number of turns in the loop, the radius of the loop and the distance of the tag from the center of the loop. This magnetic field induces a voltage across the antenna terminals. The tag then rectifies this signal to generate a DC voltage, which it uses to power the electronics and send a signal back to the reader [34]. A very basic reader (Fig. 1) is built to detect the presence of a tag up to 10 cm away. The carrier signal is generated with a crystal-controlled transistor oscillator circuit in the reader circuit. The output waveform of this oscillator is shown in Fig.1b. Fig.2 shows detector followed by an amplifier. The reader does not include any complex demodulation or decoding circuitry but does have a circuit that can detect the backscatter by filtering out the high frequency carrier through an envelope detector and low-pass filter. The schematic of our detector circuit followed by the amplifier is shown in Fig. 2. The amplitude-modulated signal received from the tag is demodulated in the AM detector of the reader using peak (or envelope) detection. The simple peak detector circuit on the left side of Fig. 2 consists of a diode, a resistor and a capacitor. This circuit extracts the envelope of the amplitude modulated signal, which is then boosted by an amplifier circuit.

Tag

The tag is an LC circuit with component values chosen for a resonant frequency of 13.56 MHz. When the tag comes in the near field of the reader, a voltage is induced in the antenna, which forms the inductance part of the tank circuit. The communication between the reader and tag is similar to a weakly coupled transformer. The AC voltage that is generated in the tank circuit is rectified in further stages to provide a DC voltage to the rest of the tag. A transistor, termed the modulation transistor, is connected to the tapped antenna coil of the tag in such a way that when it turns on, it effectively lowers the inductance of the coil. When it is in the off condition, the tag sees an inductance and capacitance in parallel tuned to 13.56 MHz. When a control signal is applied to the transistor input, the tank circuit is tuned and detuned continuously at a rate equal to the frequency of the controlling signal. This control signal is detected in the reader circuit as the amplitude-modulated form of the carrier. The detector circuit is used in the reader to demodulate this signal and extract the information that is being sent by the tag. Quality factors of the reader and tag resonant circuits are very important parameters for system performance [26]. Antennas for the reader and the tag are being modelled using NEC (Numeric Electromagnetic Code) Windows Professional software. Realistic models of loop antennas can be obtained using NEC. We have designed a multi turn rectangular loop antenna for a resonant frequency of 13.56 MHz. Matching networks have to be used to achieve a low VSWR. Read range is another key factor in the design.

A conceptual Setup

The reader was realized as a series combination of resistor, capacitor and antenna. The tag was implemented as a parallel capacitor and a tapped antenna circuit. In Fig. 2, L1 and L2 represent the reader and tag antennae, respectively. L2 and C2 together form the tank circuit in the tag and are tuned to resonate at 13.56 MHz. A gating signal that can be generated using a microcontroller is applied to the base of the transistor so that the base-emitter voltage goes above and below its turn-on voltage. When the transistor is switched on, the output at the collector terminal is near ground potential. The voltage then rises to the bias voltage when the transistor turns off.

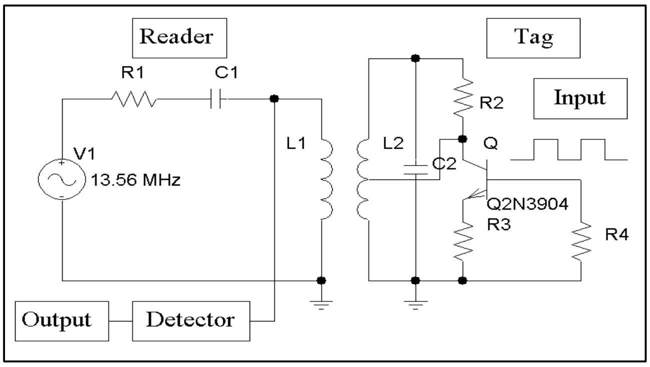


Fig 4: Schematic of the reader and tag circuits.

The tap in the antenna coil of the tag is applied between the collector and the ground. Hence the switching of the transistor shorts the coil and effectively reduces its inductance. This tunes and detunes the coil from the resonance condition [26]. When the carrier from the reader is on, the repeated switching from the resonance condition is observed in the form of an amplitude-modulated carrier at the output of the detector circuit. This is clearly seen in Fig. 4 where the lower waveform shows the control signal applied to the transistor and the upper waveform is the amplitude modulated signal obtained at the reader. A one-to-one correspondence between control signal and detected signal is thus obtained. After detection, the input square waveform, which was used to switch the transistor, can be recovered. So if a variable binary waveform corresponding to some code in the form of high and low voltage levels is given as input to the tag, it can be recovered at the reader. As per the recent researchers, It is required that powered saucer-sized device without rectified power. External clock to the tag for the switching circuit. The signal for the switching circuit is supplied by an external microcontroller programmed to output a specific binary or hex code. For the next generation of this tag circuit, the microcontroller will be on board. This tag would be a proof-of-concept device that will serve as a precursor to eventual miniaturization of circuit components. The passive tag will be designed to go into sleep mode until it is scanned by a reader. On receiving energy from the reader, the tag will wake up and start transmitting a unique identity code for a specific time period. During this period, a microcontroller in the reader will decode the identity of the tag. After the specified time, the tag will then send out the information bits. A temperature tag is implemented to, a sensor which will indicate to the microcontroller if a set temperature value is exceeded. The controller will process this information and send a code appropriate for the state of the system. A microwave frequency tag is also being developed at 5.8 GHz with a reduced antenna size and longer read range. A simple block diagram illustrating the architecture of such a tag is shown in Fig. 5.

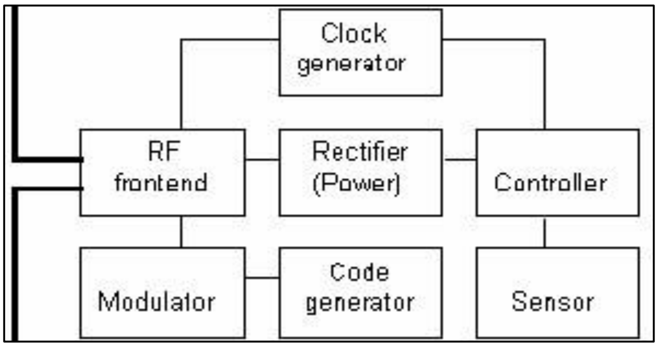


Fig 5: Architecture of the 5.8 GHz tag circuit.

Applications

Monitoring of Milk Freshness. Milk is a major component of diverse diets across the world and has been the supply source, especially in the developing world, of a wide range of nutrients [17]. Milk spoilage is a result of the growth of micro-organisms that modifies the composition of the medium with the metabolic products, changing the ionic content and conductivity of milk [18] hence, determination of milk quality is critical to maintaining food safety and human health. Measured dielectric and viscosity parameters of milk have been successfully related to milk freshness and milk adulteration [17, 19, 21]. Non-invasive and noncontact determination of milk quality attracts significant research and commercial interest [19, 22, 20]. Our RFID sensors for monitoring the freshness of milk were constructed using 23 × 38 mm RFID tags from Texas Instruments (Plano, TX, USA). Changes in the dielectric properties of milk were sensed with these RFID sensors that had an adhesive backing attached to the side wall of the milk cartons. Fig. 4. A illustrates a schematic of the sensor positioning on milk carton and sensor-response readout with a pick-up coil. Two types of milk were used for evaluation, fat-free milk and whole milk. Before the RFID sensing experiment, reference measurements of the dielectric properties of fresh and spoiled milk were performed. To determine the milk spoilage rate, which is related to the changes in the dielectric properties of milk during storage, non-invasive determinations with RFID sensors were done directly through the walls of the original milk cartons. Fig. 2. Is a photograph of milk cartons with attached RFID sensors and demonstrates the simplicity of this sensing technology. A control experiment was performed with an RFID sensor attached to a carton filled with water that was identical to that filled with milk. Sensors monitored the change in solution dielectric constant as a function of storage time by taking advantage of the electromagnetic field penetration depth out of plane relative to the sensors and performing analysis directly through the original thin wall of the milk cartons. Results of real-time non-invasive monitoring of the condition of the two types of milk in cartons and the control water sample at room temperature are presented in Fig. 3. The data illustrate different rates of spoilage of whole and fat-free milk and no signal change for the control RFID sensor. The change in Fp signal of the RFID sensor due to changes in the dielectric property of milk was indicative of milk spoilage and was correlated with results obtained from the reference measurements, before and after milk spoilage. We also observed a small drop in the sensor response during an initial stage of milk monitoring. This behaviour was observed in the past with impedance probes inserted in milk [18] [23] and was attributed to being the result of several competing mechanisms of milk spoilage.

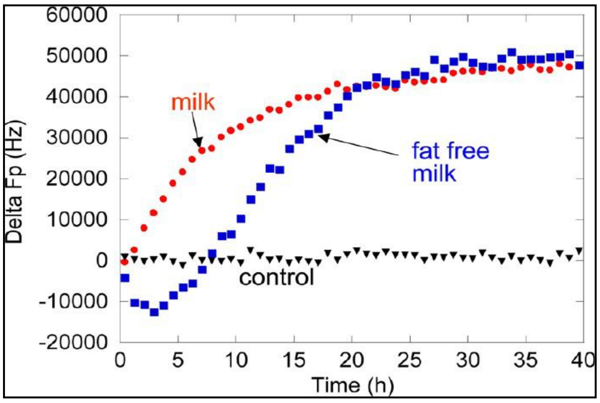


Fig 6: Non-invasive monitoring of whole and fat-free milk using disposable RFID sensors: response of RFID sensors to spoilage of two types of milk and to a control (water) sample [24]

Automatic determinations of milk freshness were further performed. For these measurements, 47 × 47 mm RFID tags from Texas Instruments were employed. Measurements of the resonant properties of the sensors were initially performed manually at different sensor positions relative to the pick-up coil. Further, a program, written in Lab VIEW, automatically determined the resonant properties of the sensors without the positioning effects of sensors relative to the pick-up coil and discriminated between cartons with fresh and spoiled milk.

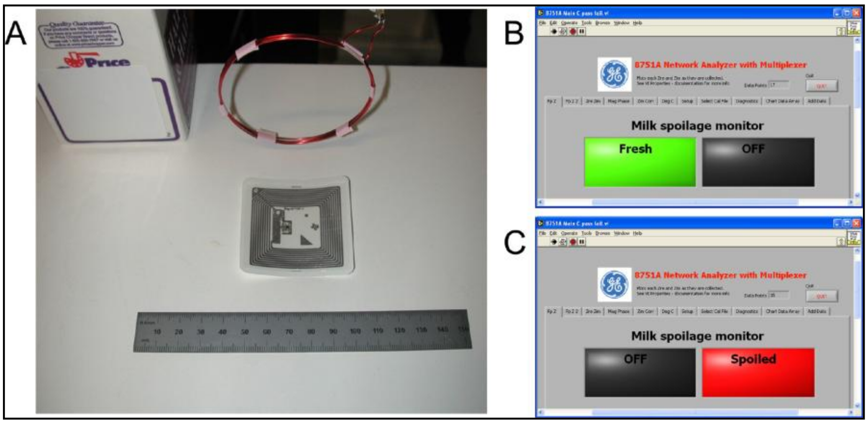


Fig 7: Automatic non-invasive determination of milk freshness: (A) photograph of a milk carton with an attached RFID sensor, pick-up coil, and a second RFID sensor; (B, C) front panel of written program for automatic determination of the resonant properties of the sensors without the positioning effects of sensors relative to the pick-up coil. The program was able to discriminate between cartons with fresh and spoiled milk.

Future Developments

This study demonstrated the applicability of RFID sensors for the monitoring of different aspects of food quality including freshness, aging, and spoilage. In contrast to known wireless sensors, RFID sensors combine several measured parameters from the resonant sensor antenna with multivariate data analysis and deliver a unique capability of sensing with rejection of environmental interferences with a single sensor. Overall, to be accepted for diverse practical application scenarios, RFID sensors should have the ability for self-calibration and self-correction for variable ambient conditions (temperature, repositioning, and others).

Acknowledgments

The authors would like to thank Indian Council of Agricultural Research, New Delhi for financial support.

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