ELSEVIER

Sensors and Actuators A 93 (2001) 33–43

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Design and application of a wireless, passive, resonant-circuit environmental monitoring sensor

K.G. Ong, C.A. Grimes*, C.L. Robbins, R.S. Singh

Department of Electrical Engineering and Materials Research Institute, 204 Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802, USA

Received 29 September 2000; received in revised form 16 February 2001; accepted 16 February 2001

Abstract

A wireless, passive, remote query sensor platform is presented capable of monitoring the complex permittivity of a surrounding medium, temperature, humidity, and pressure. The sensor is a planar two-dimensional inductor–capacitor circuit, of scaleable-size, that resonates at a characteristic frequency the value of which is dependent upon the parameters of interest. The resonant frequency of the sensor is detected remotely with one or a pair of loop antennas by measuring the impedance or voltage spectrum of the antenna(s), with the environmental parameters of interest then calculated from the measured resonant frequency. The wireless, remote query nature of the platform enables the *LC* sensor to monitor the environmental conditions from within sealed opaque containers. The paper describes the operational principles, design criteria, illustrative applications, and performance limitations of the sensor platform.

Keywords: Sensor; Wireless; Remote query; Bacteria; Complex permittivity; Inductance coupling

1. Introduction

There is an ongoing demand for small and reliable electronic sensors capable of monitoring multiple environmental parameters. For example, in 1995 the world market for industrial process control sensors was approximately US$ 26 billion [1]. Although, many types of electronic sensors offer excellent performance, such as capacitive [2–7], impedance spectroscopy [8,9], and surface acoustic wave (SAW) [10,11] sensors, these platforms require either direct physical connections between the sensor and the data processing electronics, or precise alignment between sensor and detector such as needed with optical telemetry. The requirement of having an electrical connection between the sensor and data processing electronics precludes many in situ applications, for example, the monitoring of the environmental conditions inside a sealed environment such as a food package, medicine container, fermentation chamber, person, etc. Hence there is motivation for development of wireless sensor technologies that enable the monitoring of environmental parameters from within opaque, sealed environments. An additional advantage is gained if the wireless sensors are passive, without an internal power supply such as battery, to avoid sensor life-time issues and to minimize cost. Hence our research is focused on the development of remote query sensors with a low enough unit cost that, should it be desired, could be readily used on a disposable basis [12–15].

This paper describes a wireless, passive, remote query sensor platform the operation of which is based upon the change in the resonant frequency f_0 of a planar, two-dimensional inductor–capacitor (*LC*) circuit; the sensor is designed such that the resonant frequency changes in response to the environmental parameters of interest [16–19]. The sensor is remotely interrogated with one or a pair of loop antennas via mutual inductance coupling between the sensor and antenna(s). The resonant frequency of the sensor is determined by measuring either the impedance or voltage spectrum across the terminals of the antenna(s). Depending upon the sensor design the resonant frequency of the sensor can be correlated to the temperature, pressure, or complex permittivity of the environment surrounding the sensor.

Fig. 1 shows two *LC* sensor designs. Fig. 1a shows a sensor made of a planar inductor and an interdigital capacitor (IDC). Coated with an electrically insulating protective layer this sensor can be used to measure the temperature and complex permittivity of the surrounding medium. In

* Corresponding author. Tel.: +814-865-2262; fax: +814-865-2326.
E-mail address: cgrimes@engr.psu.edu (C.A. Grimes).

0924-4247/01/$ – see front matter
PII: S0924-4247(01)00624-0

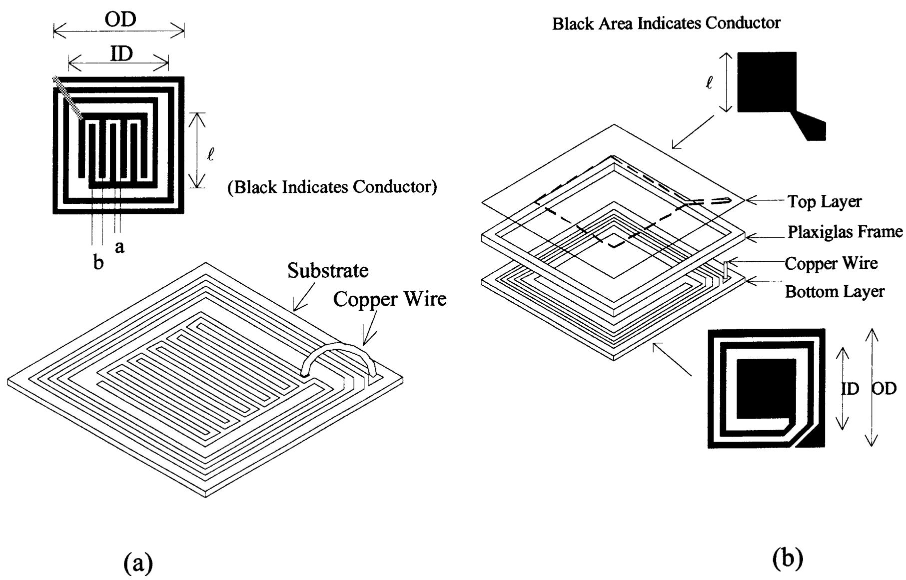

Fig. 1. (a) The *LC* sensor design used for measuring temperature, complex permittivity, and with a TiO_2 coating humidity; (b) the *LC* thick-film pressure sensor made of a parallel plate capacitor; one of the plates is flexible and deflects with ambient pressure variation.

combination with a permittivity-changing, chemically responsive coating the IDC sensor design can be used to monitor chemical analyte concentrations. The sensor design in Fig. 1b contains a parallel plate capacitor and is used for measuring pressure or force.

The *LC* sensor can be remotely monitored using either one or two loop antennas. The one-antenna approach, shown in Fig. 2a, monitors the sensor by measuring the impedance of a loop antenna with an impedance analyzer. Depending upon sensor size, antenna size, and antenna power level this monitoring approach can be used readily for sensors within approximately 15 cm of the antenna. The two-antenna approach, shown in Fig. 2b, monitors the sensor with a pair of transmitting–receiving loop antennas. Instead of measuring the impedance directly, the two-antenna approach measures the induced voltage across the terminals of the receiving antenna. As shown in Fig. 2b, the transmitting antenna is made of two parallel connected loops, while the receiving antenna is made of two loops of opposite winding direction. This specific antenna configuration results in cancellation of the background noise level. Depending upon transmitting antenna power levels, and the size of the sensor and antenna, this technique readily offers a monitoring range of approximately 1.5 m.

The main advantage of the *LC* sensor is its wireless, remote query capability. Sensor information can be obtained without physical connections or rigid alignment criteria such as those associated with optical telemetry. The sensor responds to the interrogation field, hence no internal power supply/battery is needed. Therefore, the *LC* sensor is suitable for long term in situ or in vivo sensing applications, such as monitoring for toxic wastes within a storage facility,

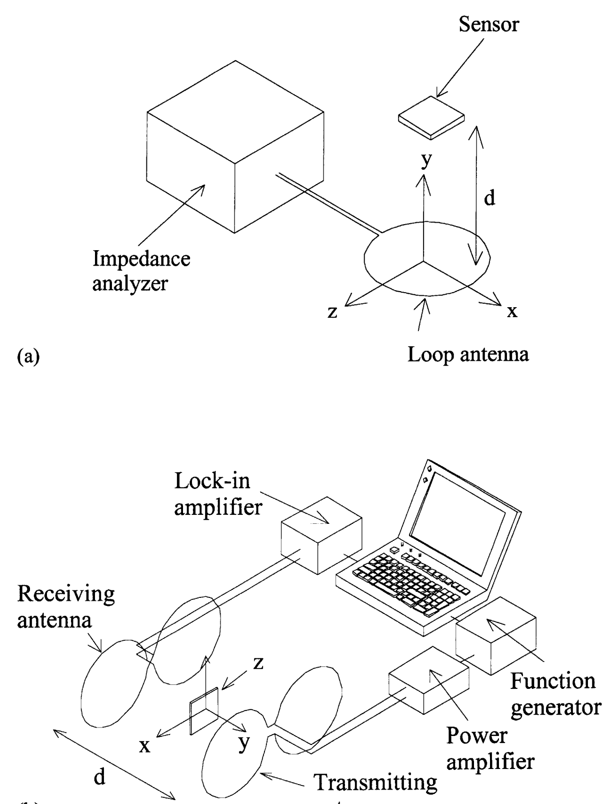

Fig. 2. (a) The set-up of electronic instruments for the one-antenna monitoring approach. A loop antenna is connected to an impedance analyzer, where the impedance of the loop is measured; (b) the set-up of the electronic instruments for the two-antenna monitoring approach. A function generator generates an ac signal which is passed through a power amplifier to the transmitting antenna. The electromagnetic waves are captured by the receiving antenna and recorded by a lock-in amplifier.