Technique for wireless reading of passive microfluidic sensors

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The remote reading of high-resolution microfluidic and passive (i.e. batteryless and chipless) temperature sensors is focused. These sensors are remotely interrogated from a 24 GHz frequency-modulated continuous-wave radar performing a mechanical beam scanning for locating the sensors and measuring the variation of sensors electromagnetic echo level due to temperature fluctuation. From radar measurement data, an estimator is proposed here for determining the meniscus position of the fluid inside the sensors microchannel and for deriving the temperature at the sensors location. It is shown that the estimator presents a convenient linear dependence with the meniscus position at the sensor location. The smallest measurable variation of the meniscus position is of 40 μm.

Introduction: Nowadays, the wireless reading of passive sensors is still a very challenging issue to overcome. To render such sensors competitiveness compared with the active sensors, two main technical improvements must be performed: (i) increasing the reading range to reach significantly more than few metres and (ii) achieving higher measurement resolution. As a matter of fact, the typical interrogation range achievable by sensors integrated in RFID tags does not exceed few metres and the typical long-range qualification for batteryless RFID tags is around 12 metres [1, 2]. Moreover, passive sensors using an electromagnetic transduction (see, e.g. [3–5]) allow higher reading range (up to some decametres [6]) but suffer from poor measurement resolution of the physical or chemical quantity of interest compared with their active counterpart.

In this Letter, we report for the first time a wireless reading technique for improving the measurement resolution of wireless, batteryless and chipless sensors. The technique is applied here for the remote interrogation of the passive microfluidic temperature sensors reported in [7]. This novel technique consists of performing the mechanical scanning of the monostatic frequency-modulated continuous-wave (FM-CW) radar antenna main lobe in order to locate the sensor in the 3D illuminated scene and to compute an estimator for remotely deriving the temperature at the sensor location. Unlike previously reported approaches (see, e.g. [6]), this estimator is not only computed from the beat frequency spectrum obtained in the sensor direction but, from the appropriate combination of numerous spectra measured in many directions around the sensor direction.

After a very brief reminder of the microfluidic sensor design reported in [7], the Letter describes the proposed radar beam-scanning technique for the sensor detection and wireless reading. The last section focuses on the remote estimation of the meniscus position of the fluid (water) inside the sensors microchannel by the original combination of multiple beat frequency spectra. The temperature resolution of the microfluidic sensor is finally estimated.

Principle of the wireless reading of passive sensors: Recently, some of us have reported the design of a passive sensor using a fluidic microchannel within a gap of an impedance matched microstrip transmission line [7]. Owing to the dilatation coefficient of the liquid (water), the meniscus position of the fluid inside the microchannel is modified as the temperature changes at the gap location. The temperature-dependent gap capacitance is designed on a 525 μm B33 glass wafer metalised both sides with 0.5 μm aluminium. A top view of the microchannel is shown in Fig. 1. The fluidic microchannel is located in the gap of the microstrip transmission line of length 1.4 cm, which propagates only the fundamental mode at 24 GHz. This line is impedance matched (50 Ω) at one port and is connected to a horn antenna via a delay line (effective length of 1.8 m) at its other port. A pressure monitoring system controls the meniscus position of the water inside the sensor microchannel.

The position of the fluid meniscus inside the microchannel may be wirelessly derived from pointing the main lobe of a monostatic radar antenna in the direction of the sensor and measuring the echo level, as reported in [7]. However, the resulting measurement sensitivity is significantly degraded when the main lobe direction is slightly changed. To overcome this critical issue, the mechanical scanning of the monostatic FM-CW radar antenna main lobe is proposed here in order to obtain a 3D radar image. In many directions around the sensor position, the radar transmits a chirp at a carrier frequency of 23.8 GHz with a triangular frequency modulation band of 2 GHz (sweep rate of 400 MHz/ms). This bandwidth provides a theoretical depth resolution of 7.5 cm. At the front-end of the radar are connected a parabolic antenna [transmitter (Tx)-antenna] and a 1 × 4 patch array antenna [receiver (Rx)-antenna]. The Tx-antenna has a narrow beamwidth of 2° and a high gain of 33.5 dBi. The Rx-antenna has a beamwidth of 60° in azimuth and 25° in elevation. Antennas and FM-CW radar are mounted on a rotating platform in order to point the Tx-antenna main lobe in controlled directions. The azimuth and elevation sweeps of ±10° of the Tx-antenna main lobe with an angular resolution of 1° are applied here. The sensor antenna is located at 2.5 m in front of the radar while the effective length between the radar and the fluidic microchannel (including the delay line) is of 4.3 m. Unwanted echoes (clutters) may hide the electromagnetic backscattering from the sensor. To avoid this undesirable effect, the length of the delay line is adjusted in order to locate the desired sensing backscattering mode in a region without clutters.

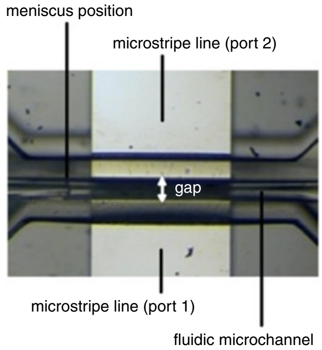

Fig. 1 *Top view of fabricated microfluidic temperature sensor (detail)*

Measurement results and discussion: Fig. 2 shows the obtained 3D radar image resulting from the FM-CW radar beam-scanning technique when the microchannel is empty and when the water completely fills the gap (Fig. 2 does not include the electromagnetic echo from the sensor antenna). This image, obtained from the pointing of the Tx-antenna main lobe in 441 directions, is composed of 33,624 voxels of 11.4 cm^3. It can be conveniently analysed by computing the so-called *isosurfaces* [8], that is, sets of superimposed 3D contours sharing the same echo level. When the microchannel is empty, the number of voxels for which the echo level is higher than a given threshold (here of −20 dB) is found to be larger than the number of voxels obtained when the water completely fills the gap. This was expected because the fluidic microchannel in the gap behaves mainly as a series capacitance: when the gap is completely filled with water, the measured series capacitance is of 150 fF and is higher than the series capacitance (100 fF) of the empty microchannel. More microwave power is then transmitted through the gap and more power is dissipated in the 50 Ω loading impedance. As a consequence, less power is available for the sensor electromagnetic backscattering. This is the reason why the number of voxels when the gap is empty is larger than the number of voxels obtained when the water completely fills the gap. Note that the threshold value (−20 dB) was chosen here to facilitate the analysis of 3D radar images obtained for various meniscus positions. The number of voxels for which the echo level is higher than the threshold is a function of the quantity of fluid inside the microchannel or, in other words, is dependent on the position of the fluid meniscus in the microchannel. From this number of voxels, a convenient parameter or estimator is now defined for deriving the fluid meniscus position from the radar measurement data.

The proposed beam-scanning technique allows selecting the voxel for which the echo level is maximal in the 3D radar image of the microfluidic sensor. This echo is used here as an estimator of the temperature-dependent position of the fluid meniscus in the microchannel. In Fig. 3, the echo is displayed as a function of the position of the fluid (water) meniscus in the microchannel. From minimising the squared distance between the echo and a regression line (ordinary least-square regression technique), a convenient linear model is derived with a coefficient of determination R^2 of 0.932. The slope of the regression line – or equivalently, the sensibility of the estimator to meniscus position – is of

6 dB/mm. The maximal echo level may also be displayed as a function of the microfluidic gap capacitance. The resulting linear model yields to a sensitivity of 0.12 dB/pF, that is, a value significantly higher than the sensitivity (0.03 dB/pF) obtained from the wireless interrogation technique reported in [7] based on radar echoes obtained only in the sensor direction.

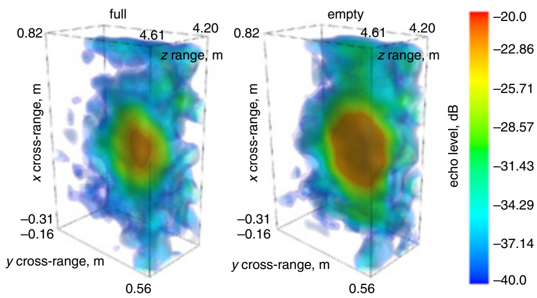

Fig. 2 *3D representation of microfluidic sensor echo when gap is completely filled with water (left) or empty (right). Electromagnetic echo from sensor antenna is not present in 3D region considered in figure*

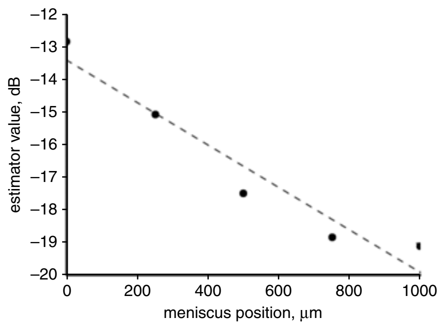

Fig. 3 *Estimator of temperature-dependent position of fluid (water) meniscus in microchannel as function of meniscus position (0 μm: gap is empty; 1000 μm: water completely fills gap). This estimator is highest echo level value detected in 3D radar image of microfluidic sensor. Linear model built from five meniscus positions has slope of −6 dB/ mm with coefficient of determination $R^2 = 0.932$ and standard error of 0.3 dB*

The precision of the estimator, that is, the smallest measurable variation ΔL of the meniscus position, is found to be of 40 µm when applying the proposed beam-scanning technique (it is of 60 µm when applying the wireless technique reported in [7]). The resulting smallest measurable temperature variation ΔT is then derived as follows:

$$\Delta T = \frac{S_c}{\alpha \, V_{\text{tank}}} \Delta L \qquad (1)$$

where α designates the dilatation coefficient of the water, V_{tank} (=3 mm^3) denotes a cylindrical tank volume and S_c (=0.015 µm^2) is the cross-section area of the microfluidic channel. The dilatation coefficient α of water ranges from 247 to 385 ppm/°C between 24.0 and 40.0°C but, for the sake of simplification, this variation is not considered here and the dilatation coefficient α is taken at the initial ambient temperature of 24°C. Consequently, from (1) one derives $\Delta T = 0.8$°C. The microchannel is completely filled at a temperature of 37.6°C. The full-scale temperature range is then of 13.6°C and the temperature measurement resolution is of 6% of the full-scale measurement range. This is a significant improvement compared with our previous work [7] in which the temperature resolution was of 14% of full-scale range.

Conclusion: The radar beam-scanning technique applied to the remote detection and reading of passive microfluidic sensor allows the estimation of the temperature at the sensors location with a temperature measurement resolution of 6% of the full-scale range. The sensor is remotely interrogated from a 24 GHz FM-CW radar. By defining an appropriate estimator, a linear model for deriving the variation of the meniscus position of the fluid in the microchannel is reported, with a sensitivity of −6 dB/mm. The smallest measurable variation of the meniscus position is found to be of 40 µm. Preliminary measurement results (not yet published) indicate that the proposed radar beam-scanning technique allows reading passive sensors up to 60 metres. Next step consists of exploring the practical and theoretical limitations of the proposed radar beam-scanning approach in terms of measurement resolution, precision and reading range.

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One or more of the Figures in this Letter are available in colour online.

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