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Novel technique for the wireless reading of passive microfluidic sensors.

D. Henry, H. Aubert, P. Pons, J. Lorenzo, A. Lázaro and D. Girbau

Introduction: Nowadays the wireless reading of passive sensors is still a very challenging issue to overcome. In order to render such sensors competitive compared to the active sensors, two main technical improvements must be performed: (1) increasing the reading range to reach significantly more than few meters and, (2) achieving higher measurement resolution. As a matter of fact the typical interrogation reach significantly more than few meters and, (2) achieving higher improvements must be performed: (1) increasing the reading range to very challenging issue to overcome. In order to render such sensors passive microfluidic sensors.

Novel technique for the wireless reading of passive microfluidic sensors. 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. In order 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 23.8GHz with a triangular frequency modulation band of 2GHz (sweep rate of 400MHz/ns). This bandwidth provides a theoretical depth resolution of 7.5cm. At the front-end of the radar are connected a parabolic antenna (Tx-antenna) and a 1x4 patch array antenna (Rx-antenna). The Tx-antenna has a narrow beamwidth of 2° and a high gain of 33.5dBi. 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 2.5m in front of the radar while the effective length between the radar and the fluidic microchannel (including the delay line) is of 4.3m. Unwanted echoes (clutters) may hide the electromagnetic backscattering from the sensor. In order 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.

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]. Due 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 523 μm B33 glass wafer metalized both sides with 0.5 μm aluminum. A top view of the microchannel is shown on Fig. 1. The fluidic microchannel is located in the gap of the microstrip transmission line of length of 1.4 cm which propagates only the fundamental mode at 24 GHz. This line is impedance matched (50 Ω) at one port and connected to a horn antenna via a delay line (effective length of 1.8 cm) at its other port. A pressure monitoring system controls the meniscus position of the water inside the sensor microchannel.

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 33624 voxels of 11.4 cm³. 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 150pF and is higher than the series capacitance (100F) of the empty microchannel. More microwave power is then transmitted through the gap and more power is dissipated in the 50Ω 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 minimizing 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 6dB/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 0.12dB/pF, that is, a value significantly higher than the sensitivity (0.03dB/pF) obtained from the wireless interrogation technique reported in [7] based on radar echoes obtained only in the sensor direction.

The precision of the estimator, that is, the smallest measurable variation $\Delta l$ 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 $\Delta T$ is then derived as follows:

$$\Delta T = \frac{\alpha V_{tank}}{a V_{Frink}} \Delta l, \quad (1)$$

where $\alpha$ designates the dilatation coefficient of the water, $V_{tank} (=3mm^3)$ denotes a cylindrical tank volume and $S_c (=0.015\mu m^2)$ is the cross-section area of the microfluidic channel. The dilatation coefficient $\alpha$ of water ranges from 247ppm/°C to 385ppm/°C between 24.0°C and 40.0°C but, for the sake of simplification, this variation is not considered here and the dilatation coefficient $\alpha$ is taken at the initial ambient temperature of 24°C. Consequently, from (1) one derives $\Delta T=0.8^\circ C$. 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 24GHz Frequency-Modulated Continuous-Wave 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 -6dB per mm. The smallest measurable variation of the meniscus position is found to be of 40µm.

Preliminary measurement results (not yet published) indicate that the proposed radar beam scanning technique allows reading passive sensors up to 60 meters. 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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