2.45 GHZ SAW-BASED PASSIVE BINARY TRANSPONDER FOR WIRELESS INTERFACES OF INTEGRATED SENSORS

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ABSTRACT

This paper describes the development of a MEMS tunable surface acoustic wave (SAW) device that allows an integrated sensor to be interrogated wirelessly in a range of several meters. The component itself requires no power for the wireless communication, as the principle is based on evaluating the reflected signal similar to a radar echo. The structure is similar to a one port reflective SAW delay line device. A MEMS switch is used to modulate the SAW according to the binary sensor output. The encoding solely requires an electrostatic tuning voltage of as low as 3 V for the MEMS switch. We successfully demonstrated that the device assembled on a microstrip antenna wirelessly transmitted ASCII characters over a distance of up to 2 m.

1. INTRODUCTION

Wireless sensor technology possesses a large potential concerning measurement flexibility, monitoring of moving objects, and measurement in hazardous environments. Remote monitoring and sensing is a key technology for an emerging ubiquitous computing society, in which tiny wireless sensors will be embedded in virtually all items around us. Integrated sensor solutions based on MEMS technology have been commercially successful in particular for acceleration, angular rate, and pressure sensing applications. These devices are assembled with additional discrete components to form a complete sensor module. Wireless operation of the sensor can be realized using commercially available wireless modules, e.g. based on ZigBee™ [1]. These solutions in general turn out to be larger in size than the actual sensor and require a considerable amount of power during operation.

Following the rapid development of wireless RF ID technology, future generations of integrated sensors are expected to feature wireless operation. However, the technological platforms used for the fabrication of integrated sensors today are not suitable for the integration of an RF front-end into the existing mixed IC and MEMS solution. Therefore a hybrid solution containing discrete components seems inevitable. Furthermore, the demands concerning a low power operation, large operating range (> 1 m), small size, fast sampling rate, low error rate and parallel operation of sensors are challenging.

In this work we have investigated the use of a tunable SAW delay line as a hybrid wireless interface solution for existing integrated sensors. The developed solution is a passive interface, and has the advantage that no additional power is required for the communication itself. The parallel operation of several sensors is possible using a TDMA (time division multiple access) scheme similar to the system developed in [5].

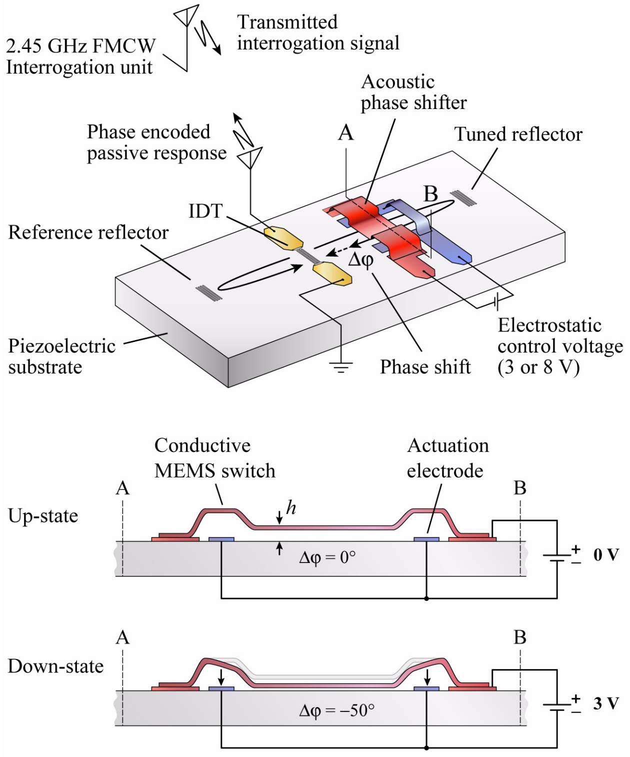

Figure 1: Illustration of the electrostatic controlled wireless communication interface and cross section of the switch used for the phase encoding.

2. OPERATING PRINCIPLE

We have recently shown that the phase shift of a SAW can be tuned by controlling the gap between a conductive MEMS switch and the substrate surface [2]. For a gap height h between the substrate surface and the switch using the device illustrated in Figure 1, the phase velocity of the SAW is given by

$$v(h) = v_0 - \Delta v \cdot \frac{1 - tanh(hk)}{1 + \varepsilon_\infty tanh(hk)}, \tag{1}$$

where v_0 corresponds to the Rayleigh velocity for a free surface, $\Delta v = v_0 - v_m$ to the difference of free and metallized Rayleigh velocity, ε_∞ to the static relative permittivity of the substrate, and k to the propagation constant of the Rayleigh wave, respectively. The material constants for 128°YX $LiNbO_3$ used as the piezoelectric substrate material in this study, are $v_0 = 3979.3$ m/s, $v_m = 3870.7$ m/s, and $\varepsilon_\infty = 54.03$, enabling velocity tuning of $\Delta v/v$ of up to 2.7 %.

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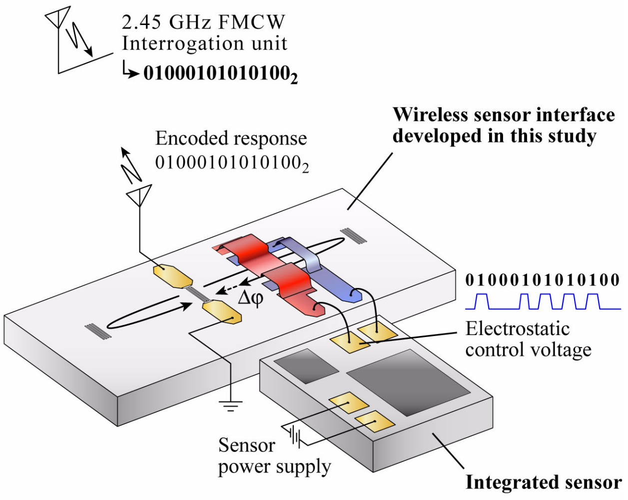

Figure 2: Application of the developed interface for the wireless operation of existing integrated sensors without RF front-end.

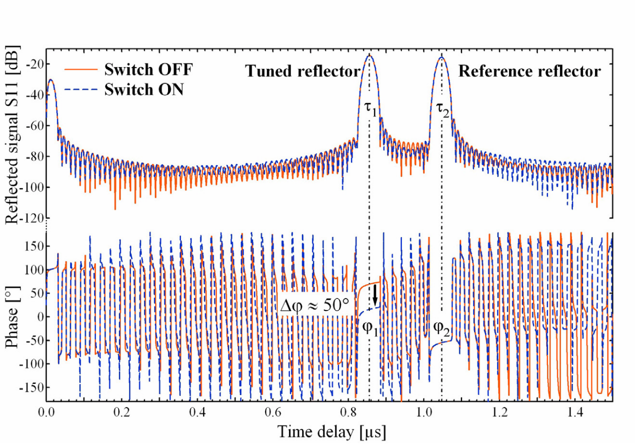

Figure 3: Simulated time response and phase of the wireless sensor interface. The phase of the reference reflector is not affected by a tuning voltage applied to the switch.

For a switch with width w the resulting phase shift for a given gap height is obtained as

$$\Delta\varphi = 2\pi f\left(\frac{w}{v(h)} - \frac{w}{v_0}\right), \qquad (2)$$

where f corresponds to the operating frequency of the device [2]. The structure of the device is similar to a one-port reflective SAW delay line, which has found wide application for passive wireless sensing [3, 4, 5]. The passive operating principle of evaluating the reflected signal of the sensor has been applied in this work to the development of a passive RF front-end for integrated sensors. As illustrated in Figure 1, the device consists of an interdigital transducer (IDT), two reflectors and a MEMS switch used for the electrostatic control. The reference reflector to the left is not affected by the tuning.

An RF signal transmitted by the interrogation unit is received by the antenna connected to the IDT of the wireless interface shown in Figure 1. The IDT converts this electrical signal into SAWs. The waves propagating to the left are reflected at the reference reflector and return to the IDT, where the SAW is converted to an electrical signal again and transmitted back to the interrogation unit. At the same time, the SAWs emitted towards the right of the transducer encounter the second reflector and pass twice beneath the MEMS switch, before returning to the IDT. Depending on whether the switch is in the up or down state, the SAW is not affected or slowed down. From the received signals, i.e. the phase difference of both reflectors, the state of the switch is evaluated.

The operation of the wireless interface with an integrated sensor is illustrated in Figure 2. The idea is to use the sensor output voltage signal, which could be a digital signal or a duty-cycle-coded signal, to actuate the switch. This sensor output connected to the MEMS switch of the wireless interface leads to a phase encoding of the interrogation signal according to the measured sensor value. The sensor data is finally extracted from the phase difference of the reflected time response.

The simulated time response and phase of the wireless sensor interface are shown in Figure 3. The time response shows the reflected signals of the two reflectors at τ_1 and τ_2. Inspecting the phase of these two reflector responses (φ_1 and φ_2), we see that φ_1 is reduced by a voltage applied to the switch, i.e. the switch being in the down state. As expected, the phase of the reference reflector φ_2 is not affected by the state of the switch. The actual phase change obtained by the MEMS switch, in this case 50°, depends on the switch design and residual gap height beneath the switch [2]. As seen later, larger phase shift values, i.e. 180°, are desirable to improve the transfer error rate.

The voltage necessary to electrostatically control the state of the MEMS switch is as low as 3 V. The low operating voltage originates from the initial gap height of the switch being as small as 300 nm for devices operating at 2.45 GHz on 128°YX $LiNbO_3$. As opposed to RF MEMS switches with the difficulty of ensuring sufficient isolation, this device supports very small gaps, because the sensitivity of the SAW velocity is highest for gaps around e.g. ~5 nm at 2.45 GHz [2]. This enables us to design a very small initial gap, which in turn leads to a very low operating voltage of the switch. As the electrostatic control requires virtually zero current to charge the MEMS switch, the power consumed by the wireless interface for modulating the interrogation signal is negligible compared to the power consumed by the integrated sensor itself.

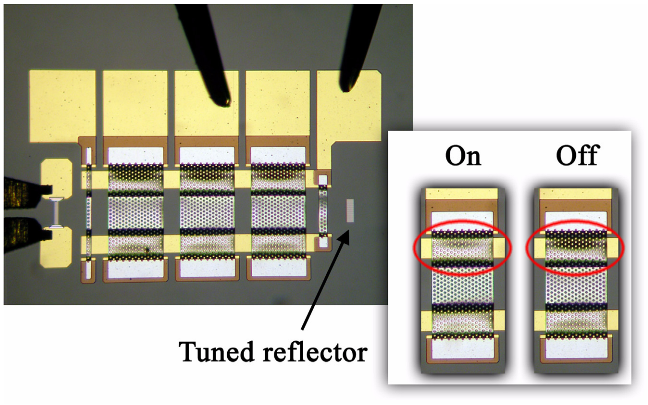

Figure 4: Microscope image of the wireless interface during wafer-level testing. The inset shows the two states of the switch contacted with probes for voltage application.

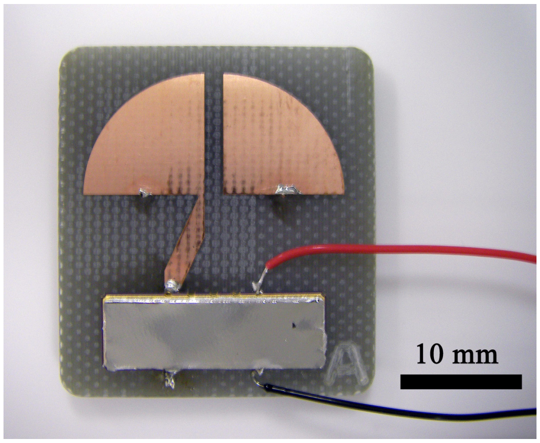

Figure 5: Picture of the wireless interface after packaging and assembly on a microstrip antenna. The voltage applied to the transponder is remotely evaluated.

Taking the phase difference of both reflectors makes the interface independent of the operating range, since the free space propagation between the interrogation antenna and device antenna causes a shift of the absolute phase values. At the same time, temperature effects are reduced due to the reference reflector and can be prevented entirely by using an edge-based evaluation of the phase output.

3. FABRICATION

The device fabrication is similar to a standard SAW device with an additional low temperature surface micromachining process identical to the one used in [2]. First, alignment marks, IDT bondpads and switch electrodes are formed by the lift-off of 50 nm thick Cr and 400 nm thick Au. Next, the SAW device is fabricated using direct electron beam lithography and lift-off of 50 nm thick Al. In order to define a small initial gap height of the switch above the acoustic track, photoresist is used as the sacrificial layer. Furthermore, to prevent the pull-in and shorting in the region of the actuation electrodes, another thicker sacrificial photoresist layer is patterned on top to form a larger initial gap. The combination of the gap above the acoustic track and above the actuation electrodes was 0.5 µm/3.5 µm and 1 µm/5 µm, resulting in switching voltages of 2.6 V and 7 V, respectively.

The switch is fabricated on this double layer of photoresist by sputtering 1 µm thick Al and patterning the Al by wet etching. The switch is finally released by an oxygen plasma process. A completed device during wafer level testing is shown in Figure 4. The image does not show the reference reflector to the left, which is hidden beneath the RF probe. The device after dicing has the dimensions of 4.3 × 1.6 × 0.5 mm, where the length is determined by the desired time delay.

The device was packaged in a ceramic SMD SAW package and mounted on a miniature microstrip antenna, identical to the one used in [5]. The completed binary transponder is shown in Figure 5. By applying a voltage to the transponder the state of the switch can be controlled, which in turn is remotely measured by evaluating the reflected interrogation signal.

4. RESULTS

For the evaluation of the developed passive transponder we used a frequency modulated continuous wave (FMCW) Siemens SOFIS II reader unit with a bandwidth of 72 MHz centered in the 2.45 GHz ISM band and a transmission power of +6 dBm (7.8 mW). A measurement software used for wireless SAW sensor systems [5] handled the data readout of the FMCW radar using a RS-232 interface and evaluated the phase of the reflector responses. The evaluation is based on performing a discrete Fourier transform on the output of the Siemens reader unit and extracting the exact time delays of the two reflector positions. The phase of the two reflectors is obtained from evaluating the complex value of the time response at the previously determined peak positions. At the same time the software controlled the voltage applied to the switch through a source meter using a GPIB interface.

For the evaluation of the wireless transponder, voltage patterns corresponding to binary coded ASCII characters were generated and applied to the transponder using the measurement software. The wireless transmission of the six ASCII characters “ESASHI” over a distance of 50 cm was demonstrated as shown in Figure 6. The top channel shows the binary encoded control voltage with an amplitude of 8 V. The bottom channel shows the phase shift extracted from the reader unit. The transmitted data contains no bit errors and allows for a read-out distance of up to 2 m.

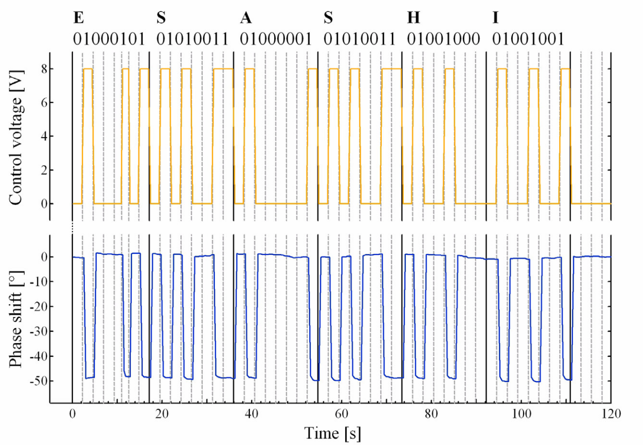

Figure 6: Result of using the developed wireless interface to transmit the six ASCII characters "ESASHI". The characters are encoded with a serial binary voltage train shown in the top channel. The lower channel shows the detected phase difference of the tuned and reference reflector at the reader output.

5. DISCUSSION

Switching voltages as low as 2.7 V were obtained for gaps of 0.5 µm/3.5 µm, but did not work as well in terms of switching speed and repeatability as switches with 1 µm/5 µm gaps requiring a voltage of 7 V. Possibly this originates from charge-up effects of the substrate surface and could be prevented by the use of conductive stoppers.

The sampling rate of the Siemens SOFIS interrogation unit is currently limited to one measurement set per 0.6 s by the data rate of the used serial RS-232 interface. The actual time required by the reader for one measurement is only 1 ms, and could be reduced even further. Due to this limitation of the measurement rate, the maximum data rate could not be evaluated. In principle an operation of the switch in the kHz range seems reasonable.

The uncertainty of the phase measurement σ_φ based on the Cramer Rao Lower Bound (CRLB) and including the effects of using a Blackman-Harris window during the discrete Fourier transform, is given as [6]

$$\sigma_\varphi(\eta) \approx \sqrt{\frac{2}{\eta(N+1)}}, \qquad (3)$$

where η corresponds to the signal to noise ratio and N to the sample length of the radar output, which is 1024 for the Siemens reader unit.

For a phase shift of ~50° the maximum phase error must be below e.g. 20° in both states to ensure a correct bit transfer. In case of using a confidence level of 12σ, and thus an error rate of one bit per 50 MB, a signal to noise ratio of 10 dB is necessary, which is feasible for a wireless sensor. On the other hand, if more than one data point per bit value is available, i.e. by oversampling the sensor output of factor M, the standard error is reduced to $\sigma_\varphi/\sqrt{M}$. For an oversampling factor of 10 the required SNR is reduced by the same factor, i.e. to 0 dB.

6. CONCLUSION

We have developed a passive binary transponder that enables the wireless data transmission of integrated sensors based on the low voltage tuning of a surface acoustic wave device. Wireless operation of the transponder for the transmission of binary code over a distance of up to 2 m was demonstrated. The fabricated device without package measures 4.3 × 1.6 × 0.5 mm and is intended for a hybrid integration with the integrated sensor. Low voltage operation down to 3 V has been achieved.

ACKNOWLEDGEMENTS

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