Ultra-wideband SAW sensors and tags

M. Lamothe, V. Plessky, J.-M. Friedt, T. Ostertag and S. Ballandras

A sensor system using ultra-wideband frequency technology and passive surface acoustic wave (SAW) sensors/tags has been demonstrated experimentally. The system operates with a frequency bandwidth of 500 MHz, which results in compressed RF pulses of about 2 ns duration, including just a few sinusoids with amplitude modulation. A correlation method is developed to measure the delay between two echoes with high resolution, avoiding the phase ambiguity problem. For temperature, deformation or other measurand a simple structure including only two reflectors is sufficient. This method is used in a system which simultaneously remotely measures a few temperature sensors with a resolution of 0.1°C. The operation of the system in a strongly reflecting environment (inside a metal box) is demonstrated.

Introduction: Truly passive surface acoustic wave (SAW) tags and sensors have undeniable advantages, such as the ability to operate at high temperature, long reading distance etc. [1] and now they begin to occupy a corresponding niche market. Usually, such sensors operate in a relatively narrow 80 MHz wide ISM band centred at 2.42 GHz. The used bandwidth determines the minimal pulse duration and imposes a compromise between device size and the volume of codes it can carry. The possibility to use the wider band can significantly advance device performance, which we demonstrate in this Letter. For passive SAW tags and sensors, the ultra-wideband (UWB) frequency range 2.0–2.5 GHz is attractive for many reasons:

- According to the US standard, the maximum power of the emitted radio signal is −41.3 dBm/MHz, which is sufficient for the remote control of the sensors based on the SAW technology.
- The frequency is low enough to allow SAW devices to be mass-produced using optical lithography.
- The band is many times larger than the currently used ISM band, resulting in the decreased size of devices, a larger number of codes and, even a simplified reading algorithm of coded information, as is shown below.

Device geometry: The architecture of the SAW-tag/-sensor is based on the model of a single port reflective delay line including an UWB chirp transducer with linear frequency modulation (LFM) and reflectors in the acoustic channel. A single crystal (YXl)/128° $LiNbO_3$ substrate is patterned with an interdigitated transducer (IDT) Al + 2%Cu electrodes using geometry allowing for LFM chirp signal generation (Fig. 1).

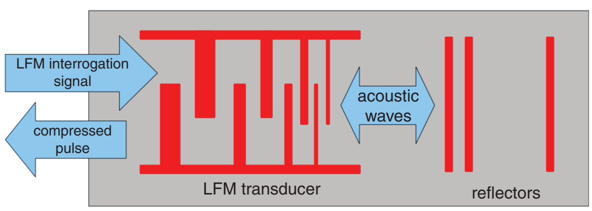

Fig. 1 *SAW tag/sensor device geometry – schematically*

It will be shown below that for sensor applications, e.g. for temperature sensors, two reflectors are sufficient, whereas for SAW tags numerous reflectors are needed. The bandwidth B close to 500 MHz is covered during a dispersive delay $T = 0.1$ µs with a negative rate of the frequency change. The selected interrogation algorithm is based on remote (or wired) measurement of the frequency f dependent reflection coefficient $S_{11}(f)$ in a set of frequency points (continuous wave radar systems, [2]). The spectrum thus obtained can be used for calculation of the response of the sensor on any interrogation signal in the time domain.

Compressed pulses: The impulse response of the fabricated devices contains three echoes, which have the same frequency range as the chirp transducer, beginning with high frequencies, but having two times longer duration. To measure precisely the time positions of these echoes, we first numerically compress the signals in time, as is done in radars using the chirp signals. In the time domain, a chirp echo is selected and returned in time. Then, this time signal is passed into the spectral domain and is used as a numeric filter, which is perfectly matched with the measured signal. The duration of the compressed pulse achieved in this way, (Fig. 2), is close to the theoretical limit: $1/B = 2$ ns with $\boldsymbol{B}$ being the LFM transducer bandwidth, despite the far from ideal LFM signal generated by the IDT.

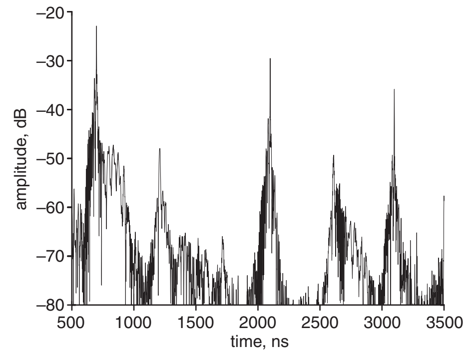

Fig. 2 *Compressed pulses*

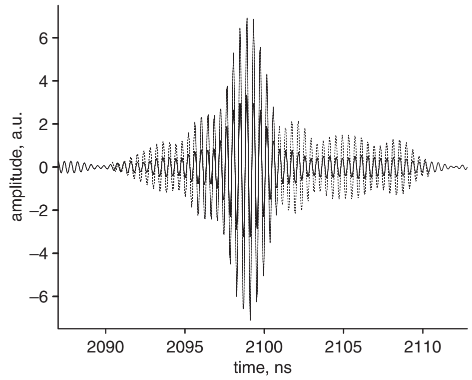

Fig. 3 *First echo (dotted line) superimposed on second echo (solid line)*

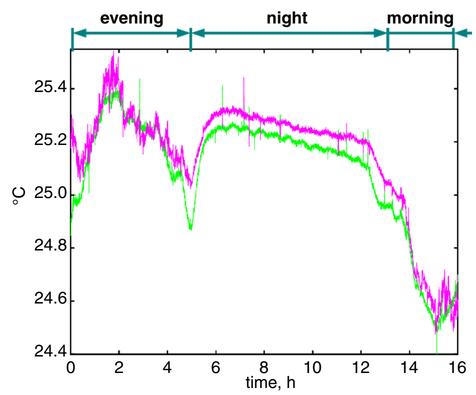

Fig. 4 *Remote reading of two sensors*

The procedure also gives a significant processing gain of about 17 dB for signals reflected by the SAW device compared with the parasitic signals reflected by the environmental objects and with the noise.

Cross-correlation method to measure delay between echoes: Hence, the UWB SAW tags are characterised by the short duration of compressed pulses. As opposed to ISM band SAW tags with $B = 80$ MHz whose interrogation pulse must be at least 30 RF periods long, the compressed pulse under investigation here includes only a few oscillations (Fig. 3) and has a unique shape. Moreover, all the echoes exhibit similar shapes.

These features are used to implement a simple algorithm, which calculates the position of the echoes. An echo (usually the first one) is selected and the entire response signal is analysed by using cross-correlation with this echo. The correlation peaks correspond to perfect superposition of the reflected signals (as in Fig. 3), including correct phases. The obtained accuracy is the same as for the phase measurements, and is much better than the delay time measurements [3].

Remote measurements of UWB sensors: Fig. 4 illustrates the simultaneous wireless measurement of two sensors. These two acoustic tags are used as sensors for monitoring ambient temperature in the laboratory. Simultaneous measurement of many sensors by one reader is possible since all the three echoes 'troikas' can be time shifted.

Operation in strongly reflecting environment: The presence of reflections, typical in industrial applications of SAW tags and sensors, and which are possibly stronger than the SAW device signals, complicates the operation of the system. Furthermore, due to multipath propagation, the sensor antenna receives multiple copies of the interrogation signal with different delays. The SAW sensor, being a linear device, processes all of them and the reflected signals returning by different paths to the reader antenna are further spread in time. As a result, instead of one compressed signal of duration $1/B$, a mixture of reflected peaks of much longer duration is recorded. By using the processing techniques discussed above, simultaneous remote temperature measurement of three sensors located in a closed oven was performed in the 0–40°C range (Fig. 5). For the UWB signals used, the three reflectors give extended but similar responses in time, because the short compressed pulses although multiplicated by multipass propagation have different common delays inside the SAW device. For a narrowband device, the interference would make such measurement impossible.

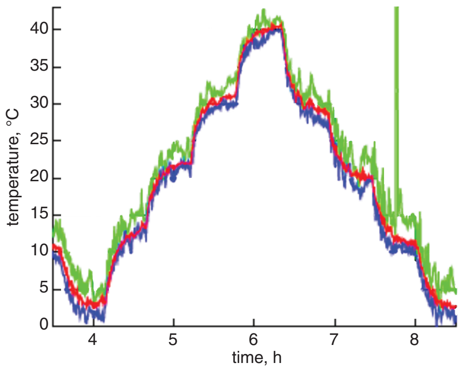

Fig. 5 *Remote measurement of sensors inside metal box (oven)*

Conclusion: The main advantage of using UWB signals for SAW tags/sensors is the available wide frequency band resulting in a possibility to use very short pulses either directly, or, preferably, after the corresponding signal processing procedure. The large information capacity $B \times T > 500$ can be partly used directly in the SAW tag/sensor and the processing gain of the order of 20 dB can be obtained. The time delay between the compressed pulses can be measured by correlation methods, with the same precision as given by the phase measurements, providing a temperature measurement resolution of 0.1°C. The wideband signals allow measuring responses in strongly reflecting environments, such as inside a metal box. The perspectives of using UWB technology in truly passive SAW tag/sensors have been demonstrated, with a proposed solution to the 'collision' problem by time domain multiplexing.

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

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