Note: a dual-chip stroboscopic pulsed RADAR for probing passive sensors

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Stroboscopy provides an energy and computationally efficient means of sampling radiofrequency and microwave signals assumed to be reproducible under external excitation. While well known for impulse mode RADAR receivers, we here investigate its use for interrogating surface acoustic wave (SAW) transducers acting as passive cooperative targets. Amongst the originality of the implementation is the need to keep phase coherence between successive pulse generations which last up to tens of the radiofrequency periods to optimally transfer energy to the transducer. A two-chip receiver architecture is demonstrated, with a trigger signal compatible either with single-period avalanche transistor pulse excitation or frequency-agile Direct Digital Synthesizer source.

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I. INTRODUCTION

Stroboscopy has long been the favored solution for sampling periodic radiofrequency signals. Despite the advent of radiofrequency analog to digital converters (ADC) with sampling rates beyond 3 GHz, the stroboscopic approach in which a returned signal is sampled using a fast track-and-hold followed by a slower ADC remains of interest when high sampling rates (>4 GS/s) and high resolution, or when low power/embedded solutions are searched. On the other hand, the weakening popularity of stroboscopic measurements means that sources of programmable delay lines is running out. Indeed, one of the last high resolution programmable delay lines still commercially available, the 8-bit Dallas DS1023 series, only allows for programming 256 time intervals, and hence requires implementing a composite delay between a slow delay source (in our case generated by a Field Programmable Gate Array – FPGA[1]) and fine tuned with the programmable delay line: the need for an FPGA in such a configuration removes the advantage of the compact and low power solution of the stroboscopic approach, since the FPGA might as well be used to record samples acquired by a radiofrequency grade ADC[2]. Recent developments requiring high timing resolution – including smart grids in which multiple energy sources must synchronize their power sources to add up in phase – provide the opportunity to obtain microcontrollers with timers providing very high resolution. Most significantly, ST-Microelectronics STM32F334C8 and similar series fitted with the HRTIM (High Resolution Timer) peripheral provide 217 ps resolution with 16-bit word length, or an equivalent sampling rate of 4.6 GHz for delays up to 14 μs. Such parameters are ideally suited for short range[3] or ground penetrating[4] RADAR (GPR) receivers.

The core issue when using a stroboscopic measurement method is the assumption of reproducible measuring conditions so that multiple samples acquired at different time offsets with respect to the probe signal accumulate coherently. In the case of pulsed RADAR systems, this assumption is met as a phase condition between the emitted probe signal and the sampling time. When using a single pulse probe signal, generated for example by unloading an avalanche transistor triggered by a reference signal on which the sampling will be defined, the phase condition is met through the rise and fall of the emitted pulse when current flows through the transistor. When probing an acoustic delay line – a transducer designed by patterning interdigitated electrodes on a piezoelectric substrate – a single pulse does not couple efficiently electrical energy to acoustic energy as needed for the sensing mechanism in which the delay of the returned echo is dependent on the acoustic velocity and its variation with a physical quantity under investigation. Indeed, optimal coupling requires that the number of electrode pairs in the interdigitated transducer (IDT) be[5] of the order of the inverse of the piezoelectric electromechanical coupling coefficient K^2. Even in the case of the strongly coupled lithium niobate with $K^2 \sim 5$ %, $N_e = 20$ electrode pairs must be patterned in an interdigitated transducer structure. Optimum energy transfer thus requires that the incoming radiofrequency pulse matches the electrode structure, namely lasts N_e periods: above this value the returned pulse will extend in time but no additional energy is converted to acoustic energy – hence requiring excessive duration between returned echoes inducing additional acoustic losses as the acoustic wave propagates on the piezoelectric substrate – while below N_e only a fraction of the electrodes are actually contributing to the electromechanical coupling and sub-optimal returned pulse power is received by the RADAR. Meeting this optimal number of radiofrequency signal periods in the probe pulse introduces a core difference between the development of a short range RADAR system for probing SAW transducers acting as cooperative targets with respect to the classical requirements of ranging ultra-wideband passive targets.

Hence, rather than using an avalanche process for load-

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ing an antenna at its minimum of the reflection coefficient, we gate a Direct Digital Synthesizer (DDS) configured to generate a radiofrequency signal at the operating frequency of the acoustic delay line acting as a cooperative target. In the following section, we first discuss the internals of the selected DDS source and how the signals for triggering the needed signals are generated from a single timer. We then associate this source with a stroboscopic receiver, and finally experimentally demonstrate how a 100-MHz SAW delay line is probed by such a system, with the ability to finely recover the temperature by a fine analysis of the phase between echoes returned by the transducer, whose geometry is reminded in the next section.

II. SURFACE ACOUSTIC WAVE DELAY LINE AS PASSIVE WIRELESS SENSOR

Surface acoustic wave delay lines are well known transducers for passive cooperative target measurements when remotely investigating physical quantities such as temperature or strain. From a user perspective, the acoustic delay line appears as a broadband electrical dipole with the ability to delay an incoming signal by durations up to several microseconds, despite millimetric dimensions. Such a feat is achieved by converting the electromagnetic signal to an acoustic signal – whose velocity is reduced by a factor 10^5, from 300 m/μs to about 3000 m/s – through inverse and direct piezoelectric effects. Shrinking electrical signal memorizing circuits by converting to acoustic waves has been known since the dawn of computers[6,7], with a renewed interest in a use as passive wireless tags and sensors[8,9]. The delay of the echo is defined by the distance of mirrors patterned on the piezoelectric substrate at the surface of which acoustic waves propagate: IDT patterned on the piezoelectric substrate induce periodic voltage variations as the incoming electromagnetic wave induce a voltage on an antenna connected to the IDT, which translates into a periodic stress in the substrate and hence an acoustic wave. Varying acoustic velocity and hence impedance mismatch induce reflections when this wave meets electrodes or grooves patterned on the piezoelectric substrate: a 1 μs delay is introduced by a 2-mm long path for an acoustic wave propagating at 3900 m/s, as found for the strongly coupled $LiNbO_3$ YXl/128° substrate.

III. DIRECT DIGITAL SYNTHESIZER CONFIGURATION

In a stroboscopic measurement system, a fast track and hold connected to a slow ADC is triggered at varying delays with respect to the probe pulse: the time interval difference between successive triggers yield the inverse of the equivalent sampling frequency, which can reach multiple GHz if the time interval is controlled with subnanosecond accuracy. We will see in our case a time resolution of 217 ps, yielding an equivalent sampling rate of 4.6 GHz.

The phase condition needed for a stroboscopic measurement means that the gate signal on the radiofrequency switch and the carrier generated by the DDS must be synchronized. Such a condition is met when clearing the phase register of the DDS with the same signal than the one used to switch on the emission pulse. However, because the internal registers of the DDS are only updated on the next master clock front, the signal clocking the DDS must itself be phase coherent with the signal triggering the switch, which is generated by the microcontroller timer. One way of achieving the phase consistency between all these signals – switching of the carrier to emit a pulse, and carrier phase reset when emitting the pulse, is to clock the DDS with a multiplied output of the microcontroller clocking oscillator (Fig. 1).

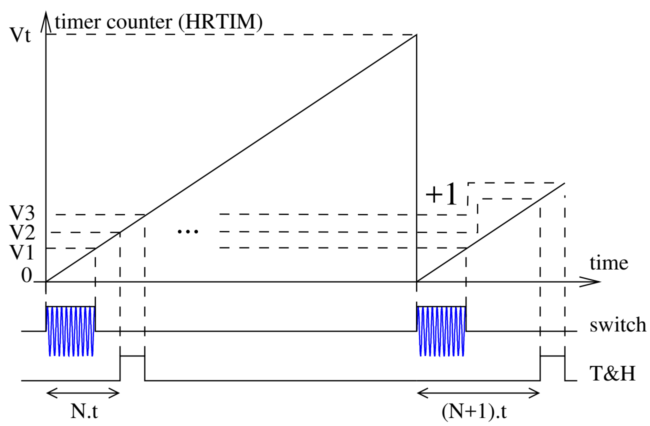

FIG. 1. Signals triggered by interrupt events synchronized on a common high resolution timer counter.

Hence, all signals needed for the stroboscopic measurement – triggering the sources, and phase coherence of the generated signal including clearing a phase register and clocking the DDS – are all generated from interrupts triggered by a single timer. As shown in Fig. 1, the pulse triggering the switch is generated at the reset (value 0) of the timer counter. This same signal also resets the DDS phase accumulator to guarantee phase coherence of all successive emitted pulses. The duration of the excitation pulse is set by an interrupt once the timer counter reaches V1. After a variable duration incremented by a multiple of the timer unit from one measurement to the next, the ADC track-and-hold is set to memorize the voltage at time V2, after which the ADC starts converting and, upon assessing the completion of the conversion, the result is transferred through a synchronous bus to the microcontroller. The trigger signal is reset at time V3 whose exact value is of little impact on the measurement sequence, as long as it occurs before the next measurement cycle defined by the timer period set by Vt. The fast equivalent sampling rate is thus provided by the fine resolution of the timer: in the case of the HRTIM peripheral of the STM32F334C8 (Fig. 2), the timer resolution (named timer unit above) is 217 ps.

Fig. 3 demonstrates one typical acquisition using such a scheme, in which two echoes returned by an acoustic delay line, delayed by more than one microsecond to differentiate the sensor response from clutter, are well resolved. The center frequency is 100 MHz to be com-

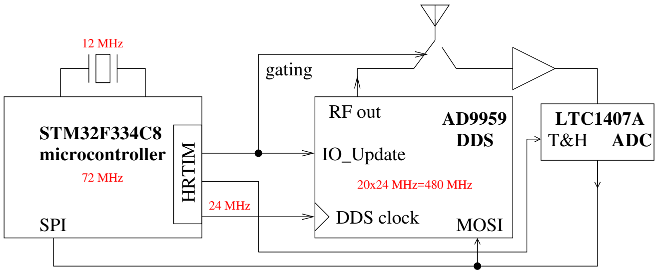

FIG. 2. Experimental setup, with frequencies of the (PLL-multiplied) clocks distributed by the microcontroller.

patible with typical GPR applications, so that in this example more than 46 samples are acquired for each radiofrequency signal period, more than needed for a precise phase measurement.

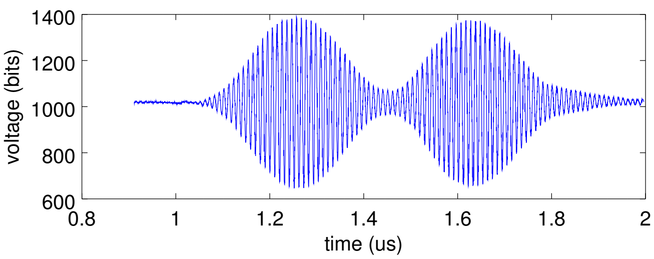

FIG. 3. Time-domain plot of the echoes returned by the acoustic wave transducer. Notice the chart only starts after 900 ns – as do the data acquisitions – since sensor design yields no signal prior to this time offset.

Electrical power consumption in this system is divided as follows: the receiver stage made of the microcontroller and the ADC consume 350 mW under 3.3 V, while the DDS (680 mW), radiofrequency switch and linear amplifiers acting as emitter use 2450 mW under 5 V.

IV. SAW SENSOR PROBING AND TEMPERATURE MEASUREMENT

Having demonstrated the ability to record a trace representative of the echoes returned by the SAW sensor, we consider the fine phase analysis – by computing the phase of the Fourier transform at the maximum of the magnitude of the Fourier transform of the echoes – to recover the acoustic velocity and hence temperature. Because the distance between the short range RADAR system and the sensor is unknown, a differential measurement in which the phase difference between two echoes returned by the same delay line is mandatory to get rid of the distance contribution to the delay (Fig. 4).

Considering the $f = 100$ MHz operating frequency and the typical temperature sensitivity of YXl/128 lithium niobate of $S = 70 \pm 5$ ppm/K, a 2π phase rotation is observed for temperature variations ΔT for echoes separated by a time interval τ of

$$\varphi = 2\pi \cdot f \cdot \tau \cdot S \cdot \Delta T \Rightarrow \Delta T|_{\varphi=2\pi} = 1/(f \cdot \tau \cdot S)$$

where φ is the phase shift induced by the temperature variation ΔT. Numerical application shows that in our case $\Delta T = 385$ K if $\tau = 0.37$ μs as designed in our chip between the first and second echoes. Hence, phase unwrapping will not be needed in most civil engineering applications such a sensor might be applicable in.

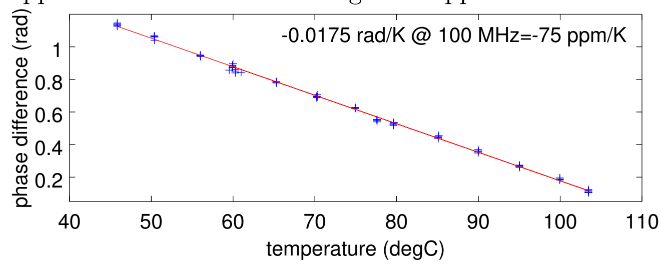

FIG. 4. Experimental phase difference versus temperature plot.

One classical drawback of stroboscopy lies in the long duration of the measurement: acquiring N samples in a T_{echo} long time-window defined by the longest echo expected to be detected, a total duration of $N \cdot T_{echo}$ is needed to acquire the full trace. In the case of sensing, a very strong assumption is introduced by the knowledge of the echo position in time. Stroboscopy is well suited to define sub-windows centered on the regions of interests – namely the echoes returned by the sensor – and in preventing the acquisition of samples known to lie in time intervals where no echo is expected from the sensor. Thus, N can be greatly reduced, down to a minimum of two samples if only two echoes are considered and only one sample is acquired in each echo, at the expense of signal to noise ratio.

V. CONCLUSION

We have presented an alternative to the classical programmable delay line for implementing a stroboscopic RADAR receiver system, here using a high resolution timer provided by the latest microcontroller peripheral evolution. The pulse emission scheme was adapted from a single pulse to a pulse length matching the number of radiofrequency periods to the transfer function of the cooperative target used as sensor, namely a Surface Acoustic Delay line. Phase coherence between successive pulses needed to acquire the complete time-domain response of the RADAR environment, including the sensor related echoes, is met by synchronizing all clocks, direct digital synthesizer accumulator clearing and digital functionalities as well as track-and-hold triggering, on a common signal generated by the microcontroller timers.

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