RECENT ADVANCES IN SOFTWARE-DEFINED RADARS: CHIRPED IMPULSES

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ABSTRACT

The software-defined radio (SDR) paradigm can be applied to radars. Novel radio-frequency (RF) chains and architectures can lead to enhanced radar schemes. After a brief review of SDR-based schemes, this work concentrates on the relevant topic of impulse-radio ultra-wideband (IR-UWB) radars. By emitting extremely-narrow impulses in time domain, these systems can achieve a great range resolution. However, one drawback is their difficulty to control their narrow waveform. On the other hand, because of its many advantages, the chirped waveform has been extensively used in radars and has become the standard employed signal. Here, for the first time, the chirped waveform is exploited in SDR-inspired IR-UWB radars, thus bringing together the benefits of both worlds. The key element in this radar architecture is a passive device shaped by smoothly-chirped coupled lines (SCCL) to produce the chirped signal. Through a developed circuit, very-narrow chirped pulses have been generated and measured.

Index Terms— Chirped waveform, cognitive radars, impulse-radio ultra-wideband radar, smoothly-chirped coupled lines, software defined radio (SDR).

1. INTRODUCTION

Acquiring multi-standard/multi-band services may come to light from the software-defined radio (SDR) paradigm [1]. The current evolution of generation and acquisition blocks tries to move the processing to the digital domain, which simplifies the implementation of the SDR concept [2]. Nevertheless, available sampling rates, bandwidths and resolutions—of the necessary analog-to-digital and digital-to-analog converters—do not currently permit large radio-frequency (RF) bandwidths to be handled [1].

Because of the previous limitation, intensive investigations on novel RF front-end configurations for SDR applications are nowadays being carried out. Radars and communication systems can benefit from this active research trend. Different approaches for SDR-based schemes which may be exploited in radars are:

- The superheterodyne architecture [3] – [5]. This solution usually employs several mixing stages, which confers it a large dynamic range. Drawbacks are its great size and the need for careful designs regarding image bands and spurious signals.
- The zero- and low-intermediate-frequency (IF) schemes [6] – [8]. In the zero-IF solution, a direct conversion to baseband is required, so that the In-Phase/Quadrature (I/Q) components must be extracted. Imbalances and possible direct-current (DC) offsets are critical in this scheme. In low-IF alternatives, these problems are more easily circumvented, but the image band issue is reinstated.
- Direct-sampling solutions [9] – [11]. Here, a sub-Nyquist frequency can be employed to acquire sparse-spectrum signals. The sampling frequency must be properly chosen so that aliasing effects are avoided. Nevertheless, problems related to jitter noise are to be highlighted.
- Innovative mixed-mode architectures [12], [13]. These schemes, both in transmission or reception, employ a hybridization of the analog and digital domains with intensive channelization and digital compensation of analog imperfections. The main drawback of these approaches is their large size.
- Six-port schemes [14], [15]. By employing six-port transceivers, these architectures can avoid the employment of mixers. Nevertheless, the acquisition of simultaneous channels can be an issue for them.

In this paper, the effort is made on impulse-radio ultra-wideband (IR-UWB) radar systems. A novel SDR-inspired scheme, which combines very narrow pulses and chirped waveforms, is proposed. IR-UWB systems use extremely-narrow temporal pulses with nanosecond or subnanosecond widths [16]. They are obtained by means of the employment of impulse generators which push towards the analog approximation of the Dirac delta function [17]. In fact, the bandwidth of the obtained impulses is very large and usually goes from DC to a high frequency value (say 10 GHz).

In the context of IR-UWB radars, many short-range applications have arisen [18]. Note that these systems can achieve

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an extremely-high range resolution, which is inversely proportional to the transmitted bandwidth. Radar imaging, target range profiling, ground penetrating schemes, microwave surveying, and through-the-wall vision are good exponents of scenarios where these very-narrow time-domain impulses are exploited. Even, IR-UWB radars can also be employed for biomedical and healthcare purposes [19].

On the other hand, if a look is taken at commercial radar prototypes—e.g., surveillance, synthetic aperture, tracking, phased array radars, etc., which have a larger range and, thus, employ longer more-energetic pulses—, it is discovered that the preferred signal is the chirp—i.e., the linear-frequency-modulated (LFM) waveform [20]. This is due to its many advantageous features when compared to other kinds of signal [21].

It would be then desirable to combine the two previous ideas in order to develop a chirped IR-UWB radar. Moreover, the captured UWB returned signal could be processed by different receiver philosophies, such as a matched-filter-based scheme or the hybrid-domain channelized SDR configuration of [13]. Unfortunately, the chirping process of such extremely-narrow temporal pulses is not trivial at all. That is, the techniques employed in long-pulse radars for chirp generation can hardly be extrapolated to these impulses due to technological limitations. In this paper, for the first time to the authors' knowledge and by making use of smoothly-chirped coupled lines (SCCL), this concept becomes attainable. Narrow 3-ns-width chirps sweeping from 8.2 GHz to 3.2 GHz have been generated and measured through a built proof-of-concept circuit. This opens the way to the complete development of an innovative SDR-inspired chirped IR-UWB short-range radar sensor prototype based on this philosophy.

2. BASIC PRINCIPLES: IR-UWB RADARS AND CHIRPS

2.1. IR-UWB Radars

Very-narrow time-domain pulses are a good approximation to a train of ideal impulses—i.e., Dirac deltas—and, hence, their transmitted instantaneous bandwidth B is very large. By noting that the general expression for range resolution ΔR of a radar is $\Delta R = c/2B$, where c is the speed of light, it comes to light that an IR-UWB radar has a very-high range resolution [22]. Furthermore, the spectrum of the transmitted signal is located into the microwave region, which makes that such high-resolution performance comes together with some advantageous extra features, such as penetrating capabilities.

On the other hand, some drawbacks of these radar systems must be expounded, as follows:

- It may be possible that the impulse generator obtains pure impulses, but some doubts can arise about their spectral purity in the air. Note that the amplification stages and, of course, the antenna modify the frequency appearance of the radiated impulses. This reflects the difficulty in the control of the desired transmitted waveform.
- The Federal Communications Commission (FCC) has defined several transmission masks for UWB emissions [23]. The spectral confinement for these radar impulses is not trivial at all. Nevertheless, to meet these spectral requirements, some proper modifications on the transmitted pulses have been engineered and reported [17].
- Regarding technical radar issues, the transmitted waveform for IR-UWB radars may be not adequate. For example, among others, coherence aspects, extraction of the phase/Doppler history, implementation of the matched filter to improve detection performance, control of temporal secondary lobes, and ambiguity-function considerations are important issues to be addressed when designing a radar waveform. The discussion of these very important topics is usually omitted in IR-UWB literature.

2.2. Chirps

As mentioned, the LFM waveform is broadly used in all-type radar systems [21]. The main reasons for it are as follows:

- The spectral confinement for a chirp is very efficient. In fact, its spectrum is almost flat in the corresponding frequency-sweep region, especially for a high value of the "time-bandwidth product" (TBP) parameter.
- The pulse compression technique can be applied to effectively get the range resolution given by equation $\Delta R = c/2B$. As a consequence, energetic long pulses can be generated, thus guaranteeing a larger range, while obtaining a high range resolution at the same time [24].
- The matched filter to improve detection performance is implemented by means of the pulse compression method. That is, the matched filter simultaneously enables to compress the chirps.
- The level of the secondary lobes of the compressed pulse can be easily controlled through a weighting process in the frequency domain. This control is not possible for other waveforms, such as a Barker code.
- The matched filter and the sidelobe control can be carried out at the digital level after the corresponding acquisition. Moreover, the analog-to-digital converter (ADC) can be very simple for short-range applications—i.e., the sampling-speed requirements can be noticeable relaxed—by making use of the analog "deramping" technique [25].
- The phase history can be easily extracted, if the coherence of the radar is maintained. This makes this kind of waveform very adequate to get Doppler information.

Chirp generation for these radars usually consists in the use of a voltage controlled oscillator (VCO). If a high ramp linearity is required, then a direct digital synthesizer (DDS) as a reference for a phase locked loop (PLL) is utilized.

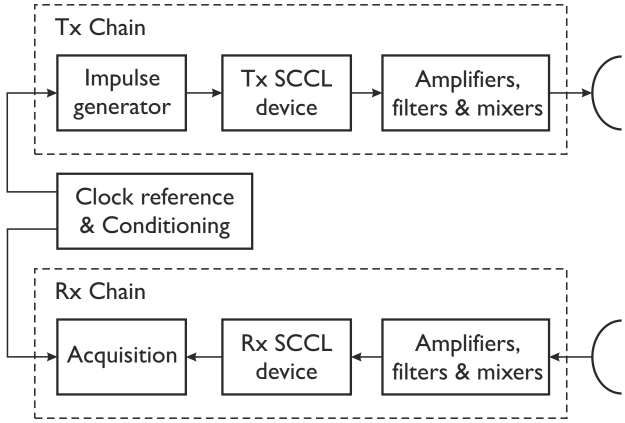

Fig. 1. Proposed architecture for a chirped IR-UWB radar.

3. CHIRPED IR-UWB RADAR ARCHITECTURE

The chirping of a very-narrow temporal pulse is the key feature of the conceived chirped IR-UWB radar scheme. The combination of chirps and impulses would merge all the aforementioned advantages into a single prototype. If a large bandwidth (say 4 GHz) is to be swept during a very short time (say 1 ns), classic techniques for long pulses cannot be used[1].

Figure 1 shows an example of chirped IR-UWB radar architecture. As can be seen, the majority of the elements here are identical to those found in conventional IR-UWB radars. For example, important modules are the impulse generator and the acquisition stages. The impulse generator is supposed to produce subnanosecond impulses—tenths of ps—, whereas the acquisition process can be implemented by means of expensive real-time sampling—i.e., through very complex techniques such as those used in new-generation digital oscilloscopes—or by considering much cheaper solutions, such as sequential sampling or sweeping impulse correlation procedures [19]. The clock reference is usually common in transmission (Tx) and reception (Rx). Local oscillators locked to this reference may be necessary to generate a chirp every period or to perform an I/Q demodulation.

The main difference in the devised chirped IR-UWB radar is the use of a SCCL device both in Tx and Rx. Regarding the Tx chain, the input to this linear time-invariant (LTI) pulse-shaping block—the SCCL structure as shown below—are the impulses from the generator. At its output, chirped pulses are created. As a result, the obtained chirp can be understood as the impulse response $h(t)$ of the LTI SCCL system and its frequency response $H(j\omega)$ as the Fourier transform of the desired chirp. In fact, by making use of specific techniques, an analog device with any given $H(j\omega)$ can be synthesized and constructed [26]. Regarding the Rx chain, the input to the LTI SCCL block are the received chirps, whereas the compressed pulses constitute its output. Hence, this device acts both as the matched filter and the pulse compressor [20]. As well known, the frequency response for this Rx system should be $H^*(j\omega)$, where $(\cdot)^*$ denotes complex conjugate, which again can be properly designed and physically implemented with wiggly-line-based synthesis approaches or by the particularization of such techniques for linearly-chirped delay lines [26].

Finally, note that the compressed-pulse sidelobe control can be easily incorporated as a frequency-dependent attenuation—i.e., a frequency window—into the SCCL devices.

[1]Perhaps the most expensive DDS can put the correct number of samples of the chirp in such short times. Here, it is assumed that a low-cost portable short-range chirped IR-UWB radar sensor is under research.

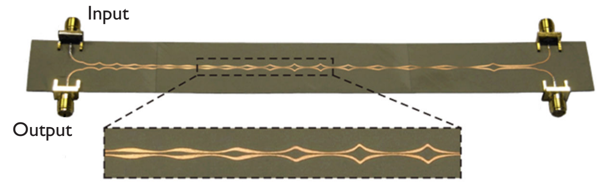

Fig. 2. Photograph of the Tx SCCL device.

4. EXPERIMENTAL RESULTS

To attest the practical usefulness of the engineered method to generate very-narrow chirped pulses, a SCCL dispersive coupler was built and tested [27]. As a proof-of-concept, only the transmission chain—i.e., the chirp generation—has been made. A photograph of the prototype is shown in Fig. 2.

An impulse generator has been connected to the input of the pulse shaping block. The width of these impulses is 70 ps. As output, chirps are obtained. Fig. 3 depicts the obtained LFM waveform in the time domain, after its acquisition with the digital oscilloscope Agilent-86116C. If the oscillations highlighted with arrows in Fig. 3 are considered, the chirp sweeps from 8.2 GHz to 3.2 GHz in a time interval of 2.9 ns, which implies a very-high chirp rate $\gamma = 1.7 \cdot 10^{18}$ Hz/s.

The frequency spectrum $H(j\omega)$ of the chirp, estimated after a fast Fourier transform (FFT) of the time-domain chirp, is given in Fig. 4. As observed, the spectrum is far from being well confined in the 3.2-8.2-GHz interval. Specifically, low-frequency components are clearly visible, which can be attributed to double-bounce echoes inside the SCCL device—that is, possibly the signal components around 4 ns in Fig. 3.

Figure 5 shows the spectrogram of the obtained chirped impulse. A 256-point Hamming window and a zero-padded 2048-point FFT have been used in the short-time Fourier transform (STFT). As shown, a linear trend in the spectrogram of the chirped impulse can be guessed.

From Figs. 3, 4, and 5, it comes trivial that there is much necessity for improvement, so that the generated chirps are purer. For example, the pulse envelope should be better adjusted to get a proper control of the secondary lobes of the

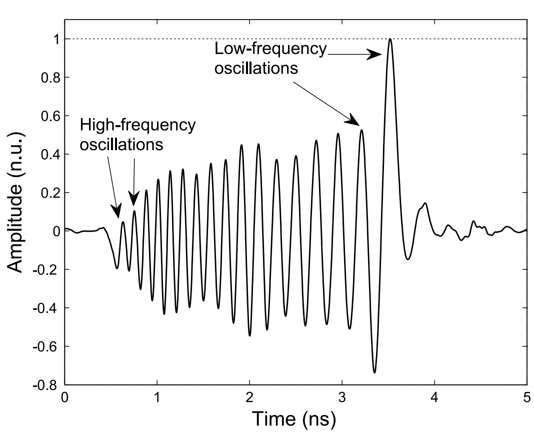

Fig. 3. Measured chirped impulse.

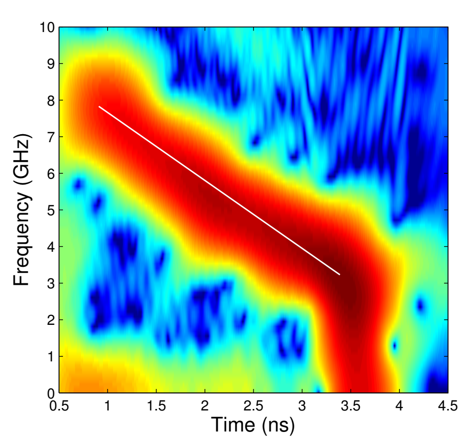

Fig. 5. Spectrogram of the chirped impulse.

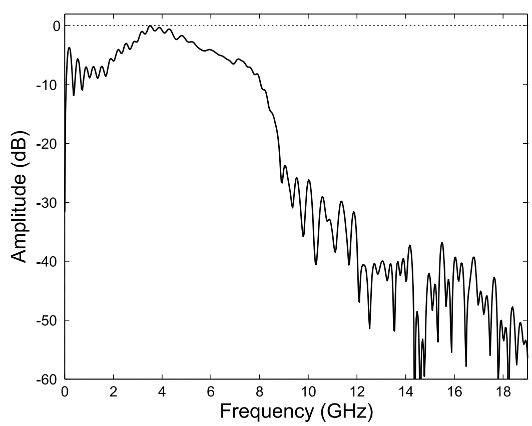

Fig. 4. Magnitude of the spectrum of the chirped impulse.

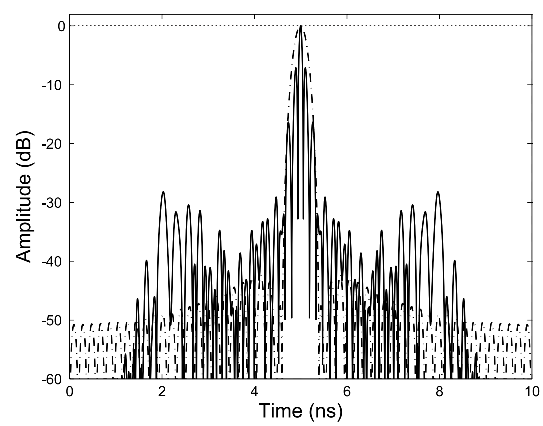

Fig. 6. Compressed pulse for the chirp (continuous line) and ideal Hamming-weighted compressed pulse (dashed line).

compressed pulse. Fig. 6 depicts the compressed pulse in a logarithmic scale, after a digital autocorrelation of the chirp of Fig. 3. This compressed pulse would be the result after the matched filter. For comparison purposes, a Hamming-weighted compressed pulse with a 3-dB width of 0.2 ns ($B =$ 5 GHz) is shown. The extra lobules appearing at the main lobe may be easily canceled by an I/Q demodulation. Nevertheless, it is obvious that a better adjustment of the chirp amplitude is mandatory for the control of the level of the secondary lobes. Besides, the linearity of the generated ramp has to be enhanced, as Fig. 5 suggests. These issues are challenging goals for the proposed analog generation scheme and remain as further research work to be addressed.

5. CONCLUSION

A concept of SDR-inspired chirped IR-UWB radar architecture has been presented. This radar should combine the advantages of IR-UWB radars and chirps into a single prototype. A better spectral conformation, secondary-lobe control, and phase-history extraction are very important features for radar sensors that chirped impulses can provide. The core of the conceived IR-UWB radar scheme are two SCCL devices, which respectively enable the generation of the chirps and their matched filtering. As a proof-of-concept, the experiments regarding 3-ns-width chirps sweeping from 8.2 GHz to 3.2 GHz were reported. To the authors' knowledge, the use of such creation of very-narrow chirped pulses has not been previously demonstrated in the literature for radar applications.

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