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A MINIATURE REAL-TIME RE-CONFIGURABLE RADAR WAVEFORM SYNTHESIZER FOR UAV BASED RADAR

M. Y. Chua*, H. S. Boey, C. H. Lim, V. C. Koo, H. S. Lim, Y. K. Chan, and T. S. Lim

Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Melaka 75450, Malaysia

Abstract—Radar waveform synthesizer is a key component in radar system as it determines the best achievable resolution. In this paper, a miniature and low cost radar waveform synthesizer is proposed. The synthesizer is targeted for Unmanned Aerial Vehicle (UAV) based radar system applications that require miniaturized equipment due to limited space in aircraft's fuselage. The waveform synthesizer has been developed using Altera DE3 development board (Stratix III FPGA) and a custom made dual-channel 420 MSPS HS-DAC board. The proposed system is capable of generating various types of radar waveforms: a) Linear Frequency Modulated (LFM) or *chirp* pulse, b) Frequency Modulated Continuous Wave (FMCW), and c) Calibration Tone (Cal-Tone), for use in different types of radar applications. The distinguishing feature of the proposed synthesizer is its capability in re-configuring the signal properties in real-time. The performance of the synthesizer has been benchmarked with commercially available radar waveform synthesizer and comparable performance has been observed.

1. GROUND SURFACE DEFORMATION MEASUREMENT AND MONITORING

Radar is a common tool in remote sensing. It has been long used for wide range of applications such as imaging for earth monitoring application, missile guidance in military application and remote sensing for environmental and weather forecast applications [1–8]. In principle, radar is an active sensor. The system generates its own source

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* Corresponding author: Ming Yam Chua (mychua@mmu.edu.my).

of illumination, allowing day and night operations [9, 10]. The illumination source is generated in the radar transmitter and radiated in the form of electromagnetic wave in the air through a transmitting antenna.

Radar waveform synthesizer (RWS) is the key component in a radar system as it determines the best achievable radar system resolution. Radar system bandwidth is one of the key parameters in RWS design as in modern chirp radar, the achievable range resolution (ΔR) can be addressed as

$$\Delta R = \frac{c\tau}{2} = \frac{c}{2B} \tag{1}$$

where the range resolution (ΔR) is inversely proportional to the bandwidth (B) of the transmitted signal, τ is the round-trip delay and c is the speed of the electromagnetic wave propagation in air. It would be the ultimate goal for all of the radar system designer to generate as high as possible the transmitting signal's bandwidth to improve the radar system's resolution [11].

In general, radar waveforms can be generated using two approaches, namely i) the analog microwave circuit approach, or ii) the digital approach. In the analogue microwave circuit approach, a Voltage Controlled Oscillator (VCO) is used [12] where the output frequency of the VCO is adjustable by changing the applied tuning voltage. The drawback for this approach is that, VCOs readily available in the market have limited frequency sweep rate (frequency settling time), which is in the range of milli-seconds.

In modern radar system, the digital approach is the preferred choice due to the fact that digital electronics offer better stability, repeatability, and flexibility over an equivalent analogue approach [13]. With the advancement of semiconductor manufacturing process (22 nm in 2011), and the introduction of Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP) to the consumer market, the technique of Direct Digital Synthesis (DDS) has become a popular approach for synthesizing complex waveforms for application in radar and communication systems.

Unmanned Aerial Vehicle (UAV) is a popular choice for radar system platform as it is capable of operating without the presence of pilot or crew in the aircraft's cabin. As compared to conventional airborne or space-borne radar systems, UAV-based radar systems has lower operation cost, lower risk, and suitable for *in-situ* measurement where frequent revisit is required [14]. However, UAV-based radar requires miniature and light instruments due to its limited space and carrying weight in the vehicle [15–17]. This adds a trade-off between the signals quality and the instrument size, and it has to be properly considered in the design of an UAV-based radar system.

Most of the radar waveform generators in the market were exclusively designed for specific radar configuration. Re-configuration of the radar waveform would require an engineering re-working of the radar waveform generator. Commercially available instrument-based Arbitrary Waveform Generator (AWG) such as Agilent N8241A and Agilent 33250A are suitable for arbitrary radar waveform synthesis [18]. However, such implementation is bulky and expensive, and hence, it is not suitable for UAV based radar due to limited workspace in the aircraft.

In this paper, a miniature, low cost, re-configurable RWS is proposed. The waveform synthesizer is able to generate three types of commonly used radar waveforms: the chirp pulse is typically employed for SAR systems, the FMCW configuration is suitable for near-range imaging and non-imaging systems, while the Cal-Tone is widely used for calibration and internal testing. The synthesizer has the capability to switch in-between the generating radar waveform type without system re-configuration, in real-time.

2. RADAR WAVEFORMS

There are several types of radar waveforms used, serving different purposes in different types of radar configurations. These include: i) Linear Frequency Modulated Pulse (LFM or *Chirp* pulse), ii) Frequency Modulated Continuous Wave (FMCW), and iii) Calibration Tone. This following section will briefly discuss characteristics of these waveforms.

2.1. Linear Frequency Modulated Pulse

Linear Frequency Modulated pulse (LFM) is a commonly used waveform in Synthetic Aperture Radar (SAR). It is more well-known as the *chirp* pulse among SAR researchers. A chirp is a signal in which the frequency increases ('up-chirp') or decreases ('down-chirp') with time. The instantaneous frequency of the baseband chirp signal, $f(t)$, with B as the bandwidth of the signal, can be expressed as [14],

$$f_i\left(t\right) = \frac{B}{T}t - \frac{B}{2} \tag{2}$$

By applying integration to Equation (1), the instantaneous phase of the baseband chirp signal can be expressed as,

$$\phi_i\left(t\right) = 2\pi \int f_i\left(t\right)dt = \pi\left(\alpha t^2 - Bt\right) \tag{3}$$

where α is the chirp rate (in hertz per second) of the chirp signal.

From the instantaneous phase Equation (2), the baseband chirp signal can be modeled as,

$$x_b(t) = A \cdot \mathrm{rect}\left[\frac{t}{T_p}\right] \cdot \exp[j\phi_i(t)] = A \cdot \mathrm{rect}\left[\frac{t}{T_p}\right] \cdot \exp\left[j\pi\left(\alpha t^2 - Bt\right)\right] \quad (4)$$

with T_p as the pulse duration of the chirp signal and A is the peak voltage of the signal.

Up-converting the baseband chirp signal to carrier band yields,

$$\begin{aligned} x(t) &= A \cdot \mathrm{rect}\left[\frac{t}{T_p}\right] \cdot \exp[j\phi(t)] \\ &= A \cdot \mathrm{rect}\left[\frac{t}{T_p}\right] \cdot \exp\left[j\pi\left(\alpha t^2 - Bt\right)\right] \cdot \exp[j2\pi f_c t] \end{aligned} \quad (5)$$

2.2. Frequency Modulated Continuous Wave (FMCW)

The Frequency Modulated Continuous Wave (FMCW) is commonly used in FMCW radar as it possesses a large bandwidth [18]. By convention, a FMCW waveform is generated using a Voltage Controlled Oscillator (VCO) by changing the applied tuning voltage in which the tuning voltage is linearly proportional to the VCO's output frequency. The baseband FMCW waveform can be mathematically expressed as,

$$x\left(t\right) = A \cdot \exp\left[j\pi\left(\frac{B}{T}t^2 - Bt\right)\right] \quad (6)$$

where $\frac{B}{T}$ is the FMCW sweep rate.

2.3. Calibration Tone (Cal-tone)

The Calibration Tone is commonly used as a single tone reference signal in radar systems for calibration and testing purposes. The signal can be mathematically expressed as,

$$x(t) = A \cdot \exp\left[j2\pi f t\right] \quad (7)$$

where f is the instantaneous frequency of the signal.

3. RADAR WAVEFORM SYNTHESIS USING DDS TECHNIQUE

Direct digital synthesizer is a method of producing an analog waveform, usually a sinusoid, by generating a time-varying signal in digital form and then performing a digital-to-analog conversion. DDS offers fast switching between output frequencies, fine frequency resolution, and operation over a broad spectrum of frequencies.

The working principle of the DDS is based upon the phase-frequency relationship in a sinusoidal signal [19]. A complete sine-wave oscillation can be visualized as a rotating vector that rotates around a phase circle from 0° to 360°. When the rotating vector is rotating at constant speed, sine-wave linear phase information is produced. Since the output frequency is a function of the number of steps to complete a wheel cycle, the number of discrete phase points contained in the wheel (the length of the phase accumulator) is determined by the resolution, a modulus 2^n, of the phase accumulator [18].

The phase accumulator increments its stored number each time it receives a clock pulse. The magnitude of the increment is determined by a digital tuning word, M. The tuning word forms the phase step size between reference clock updates. The relationship of the phase accumulator and tuning word forms the basic tuning equation for the DDS architecture, which gives the output frequency [14],

$$f_{\mathrm{OUT}} = \frac{M \times f_c}{2^n} \tag{8}$$

where f_c is the internal reference clock.

The output of the phase accumulator is linear and cannot be directly used to generate a sine-wave or any other waveform except a ramp. Therefore, a phase-to-amplitude lookup table is used to convert the phase accumulator's instantaneous output value into the sine-wave amplitude information that is presented to the D/A converter.

The radar waveforms described in Equations (4), (6), and (7) can be generated using the above said DDS architecture. The instantaneous frequency of the radar waveforms can be altered by changing the tuning word, M, in the DDS core in the elapse of every clock tick. The instantaneous tuning word, M_i, can be derived from Equations (2) and (8) as

$$M_i = \frac{\left(\alpha t - \frac{B}{2}\right) \times 2^n}{f_c} \tag{9}$$

4. PROPOSED WAVEFORM SYNTHESIZER CORE

Figure 1 depicts the functional block diagram of the proposed waveform synthesizer core. The proposed synthesizer core can be divided into three major sections; namely the input, the digital logic platform, and High Speed DAC. Two external inputs are required for operation, which are, analog 10 MHz external reference clock signal, and digital configuration data from external controller through a UART interface.

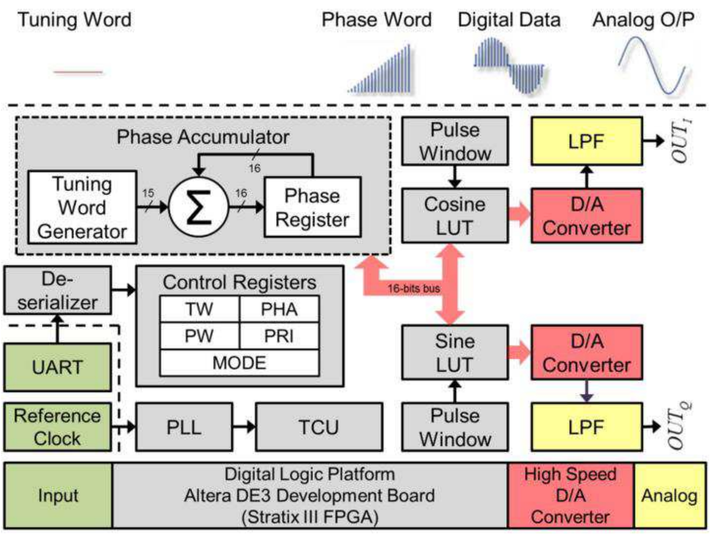


Figure 1. Proposed waveform synthesizer core.

A digital Phase Locked Loop (PLL) is used to multiply the reference signal to two higher frequency (200 MHz) clock signals, with 90° phase difference. The leading clock signal will be used as internal clock in digital logic platform while the lagging clock signal will drive the external DACs for data conversion.

The digital logic platform comprises several functional logic blocks serving the purpose of generating digital waveform data. The functional blocks are Phase Accumulator (PA), De-serializer, Control Registers (CRs), Timing and Control Unit (TCU), and two Look-Up Tables (LUTs). PA is an essential block in the core whereby it generates the phase word of the desired waveform. The phase word changes in every elapse of internal clock cycle. The new phase word is obtained by summing the phase word from the previous clock cycle in the phase register, with the tuning word generated by the tuning word generator. Instantly, the newly generated phase word will be used as an address pointer pointing to the two Cosine and Sine LUTs (for In-phase and Quadrature phase channel) for phase-to-amplitude conversion. At last, the two DACs convert the digital amplitude data into analog signal and quantization noise is filtered using Low Pass Filter (LPF).

The waveform synthesizer core was built with UART de-serializer and control registers enabling waveform re-configuration capability by external controller. UART de-serializer reads binary serial commands

Table 1. Summary of waveform synthesizer's re-configurable specifications.

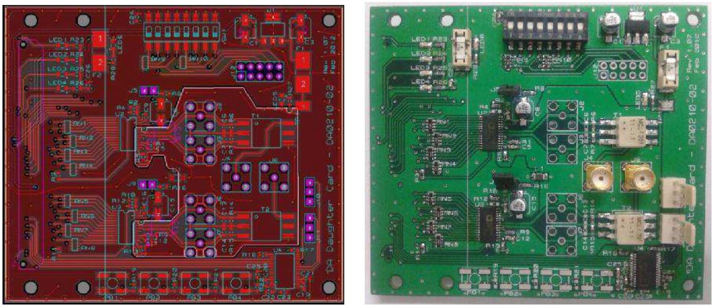
Operating Mode	**Signal Properties**	**Operating Range**	**Resolution**
Linear Frequency Modulated or *chirp* pulse	Bandwidth	1 to 200 MHz	1 MHz
	Pulse width	5 ns to 10 μs	5 ns
	Pulse repetition frequency	1 Hz to 10 kHz	1 Hz
	Starting phase	0° to 360°	0.1°
Frequency Modulated Continuous Wave	Bandwidth	1 to 200 MHz	1 MHz
	FM Rate	10 Hz to 1 kHz	1 Hz
	Starting phase	0° to 360°	0.1°
Calibration Tone	Frequency	0.1 MHz to 100 MHz	0.1 MHz
	Starting phase	0° to 360°	0.1°

from a Personal Computer (PC) or controller, decode the commands, and update the control registers. Updating the control registers will switch the operating mode (MODE) and change the generating signal properties such as bandwidth (TW), pulse width (PW), starting phase (PHA), and pulse repetition interval (PRI) in real-time, without FPGA re-configuration. Table 1 lists the supported operating modes of the proposed core and its re-configurable specifications.

Timing and control unit (TCU) is a custom designed sub functional module for timing and control signals generation. It is built from counters and combinational logics to generate high precision adjustable (in accordance to PRI and PW control registers) pulse. The generated pulse controls the operating of the PA and enabling/disabling the digital output data to the D/A converter through the pulse window logic.

5. HARDWARE DESIGN AND IMPLEMENTATION

The proposed waveform synthesizer was implemented on Altera DE3 development board and a HS-DAC board. Altera DE3 development board features a high-end FPGA device (Stratix III EP3SL150 — 2 ns speed grade) with eight High Speed Terasic Connectors (HSTC), allowing the board to interface with multiple Altera High Speed Mezzanine Card (HSMC) compatible card. The HS-DAC board is a dual-channel, 14-bits, 420 MSPS Digital-to-Analog Converter board



(a) (b)

Figure 2. (a) HS-PCB layout design for HS-DAC board, (b) HS-DAC board

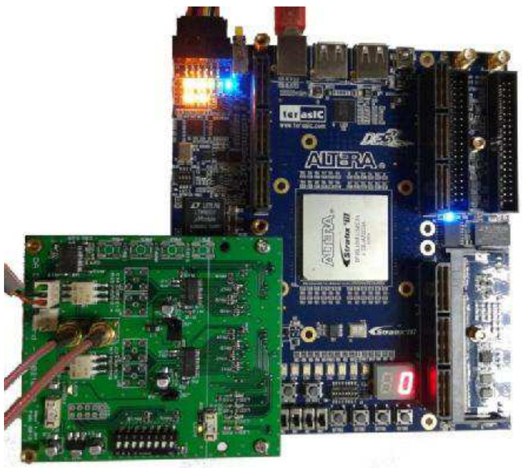


Figure 3. Altera DE3 development board and custom made HS-DAC board.

compatible to Altera HSMC interface. The design layout and the assembled HS-DAC board are shown in Figure 2. The board employs 4-layer FR4 stack-up configuration and were designed with High Speed Printed Circuit Board (HS-PCB) consideration. Besides DACs, the board has several on-board peripherals such as RS232 to TTL level converter, 4 User LEDs, 8-way User DIP Switch, and 8-way Parallel IO, which enables interfacing with external devices. Table 2 summarize the specifications of Altera DE3 and HS-DAC. System parameters were determined in the early design stage and Table 3 lists the parameters.

Figure 3 shows the complete waveform synthesizer implementation using Altera DE3 development board and the HS-DAC board.

Table 2. Specifications of Altera DE3 and HS-DAC.

<table>
<tr><th>Board</th><th colspan="2">Specifications</th></tr>
<tr><td rowspan="2">Altera DE3</td><td>FPGA</td><td>– 142,000LEs
– 5,499 kbits total memory
– 384 18 × 18-bit multipliers
– 736 user I/Os</td></tr>
<tr><td>Peripherals</td><td>– DDR2 SO-DIMM socket
– SD Card socket
– 4 push-button switches,
1 DIP switch (×3),
4 slide switches,
3 RGB LEDS,
2 seven-segment displays
– USB Host/Slave Controller
– 3 HSTC (4 male, 4 female)
– Two 40-pin Expansion Header</td></tr>
<tr><td rowspan="2">HS-DAC</td><td>DAC</td><td>– 210 MSPS
– 2 channels
– 14-bits</td></tr>
<tr><td>Peripherals</td><td>– 2 × UART
– 4 × User LED
– 1 × 8 way DIP Switch
– 1 × 8 way GPIO</td></tr>
</table>

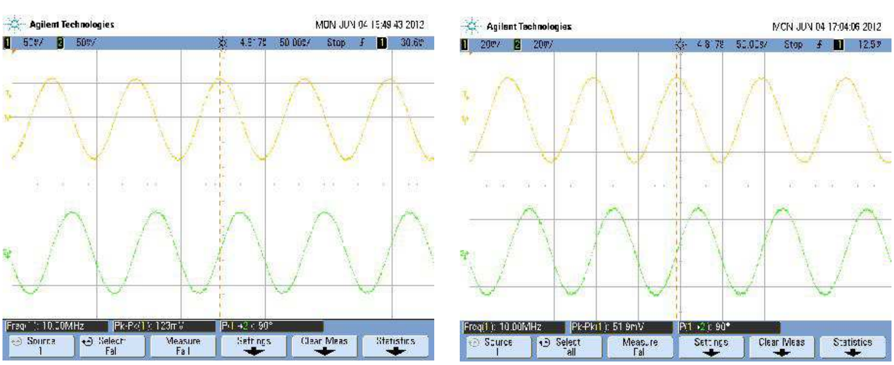
6. SIGNAL QUALITY MEASUREMENT

A series of in-lab measurements have been carried out for verification and signal quality analysis purposes. The generated signals have been benchmarked with Agilent N8241A Arbitrary Waveform Generator (AWG) for comparison purposes. The waveforms were captured using Agilent InfiniiVision 7032A MSO for time domain signal analysis and Agilent N9320B for spectral analysis. The waveforms and spectral recorded are shown in Figures 4–8.

Figure 4 shows the 10 MHz calibration tone in time domain while Figures 5 and 6 show the power spectral density of the calibration tone, all generated by both the equipment. The time domain analysis shows that both the calibration tone are oscillating at 10 MHz and I

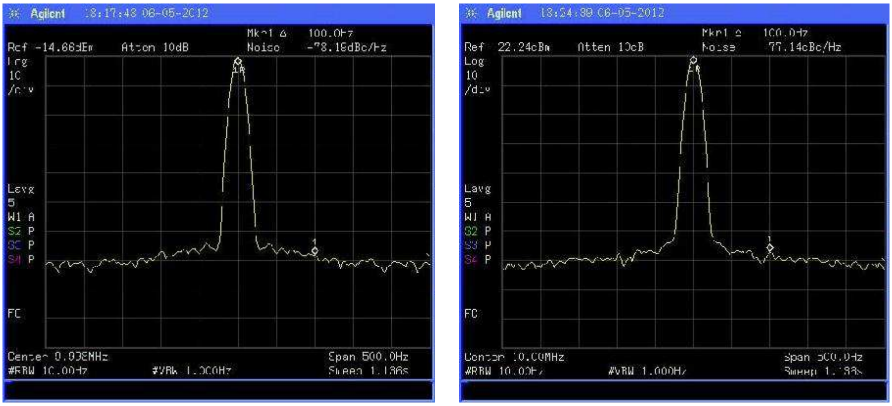
Table 3. Waveform synthesizer design parameters.

Module	Parameter		Value
Clock	Input reference clock		10 MHz
	Internal clock		200 MHz
UART	Baud rate		115200 baud
	Format		1 start, 8 data, 1 stop, no parity
Phase Accumulator	Phase wheel width		15 bits
	Tuning word width		15 bits
Look up table (LUT)	Cosine (I)	Table size	32768 entry
		Data width	16 bits
	Sine (Q)	Table Size	32768 entry
		Data width	16 bits
Timing and Control Unit	Timing Precision		5 ns
HS-DAC	Number of channel		2 channel
	Sampling speed per channel		200 MSPS (210 MSPS max)
	Data width		14 bits



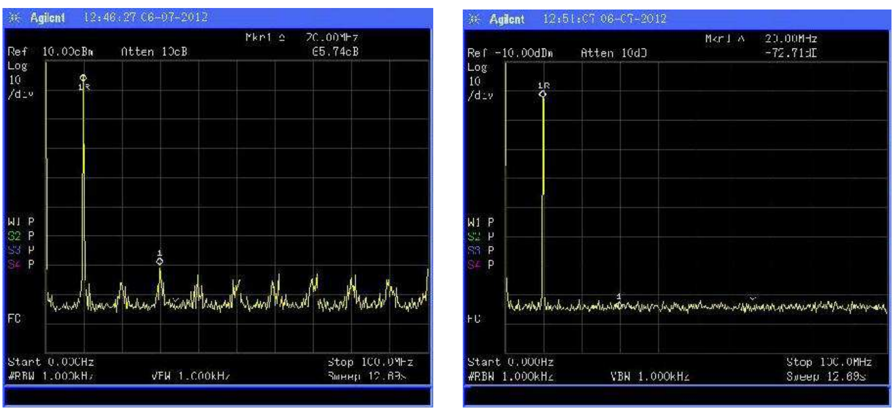
(a) (b)

Figure 4. Calibration tone — time domain. (a) Proposed RWS, (b) Agilent N8241A AWG.



(a) (b)

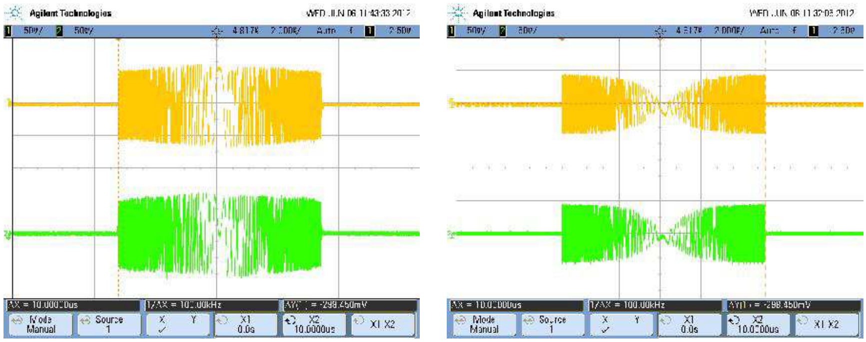
Figure 5. Calibration tone — phase noise. (a) Proposed RWS, (b) Agilent N8241A AWG.



(a) (b)

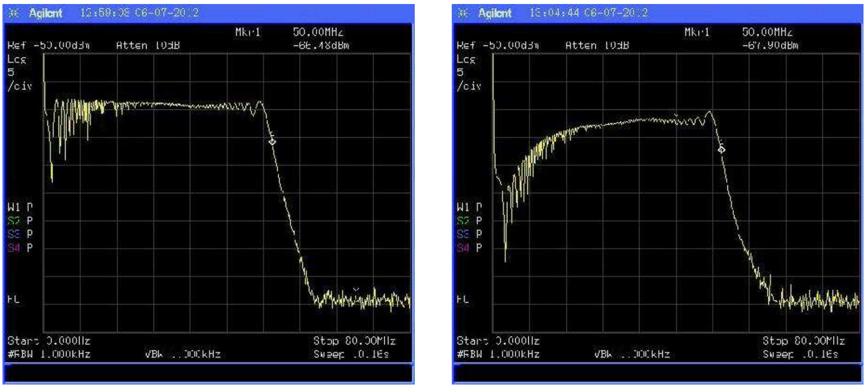
Figure 6. Calibration tone — broadband spurious harmonics. (a) Proposed RWS, (b) Agilent N8241A AWG.

channel is leading Q channel precisely at 90° phase difference. Phase noise for both the signals are less than -77 dBc/Hz at 100 Hz offset as illustrated in Figure 5. Harmonics and spurious does not exist (greater than -72 dBc) for Agilent N8241A AWG while for calibration tone generated by the proposed waveform synthesizer, several significant harmonics could be seen, with highest spurious exist in 2nd harmonics at power level of -65.74 dBc. The main source of spurious observed is from the quantization noise of the DACs and it could be eliminated using an analog Low Pass Filter (LPF).



(a) (b)

Figure 7. LFM waveform — time domain. (a) Proposed RWS, (b) Agilent N8241A AWG.



(a) (b)

Figure 8. LFM waveform — frequency domain. (a) Proposed RWS, (b) Agilent N8241A AWG.

As for wideband signal generation in baseband, the proposed RWS has better performance as compared to Agilent N8241A AWG. Frequency swept signals generated by the proposed RWS possesses good amplitude flatness across the frequency sweep band while Agilent N8241A AWG has poor amplitude flatness especially in low frequency. Both the equipment shows good noise floor, flooring at $> 90\,\mathrm{dBm}$.

Apart from the signal quality comparison, the proposed RWS is smaller and lighter than Agilent N8241A AWG. In terms of cost comparison, the proposed RWS is much lower compared to (in 2012) the cost for Agilent N8241A AWG. Table 4 concludes the benchmark of the developed waveform synthesizer with Agilent N8241A AWG.

Table 4. Benchmark on the developed waveform synthesizer with Agilent N8241A AWG.

Benchmark Parameters	**RWS**	**Agilent N8241A AWG**
Amplitude (Peak-to-Peak Voltage)	123.0 mV	51.9 mV
Phase Difference (between I channel & Q channel)	90°	90°
Phase Noise (offset at 100 Hz)	78.19 dBc/Hz	77.14 dBc/Hz
Broadband Spurs	Highest spurs observed: −65.74 dBc @ 30 MHz	No spurs were observed
LFM Amplitude Flatness	Flat across the LFM band	Poor amplitude response at low frequency, fluctuates across the band
Noise Floor	$>$ 90 dBm	$>$ 90 dBm
PRF Precision	$\pm$5 MHz	$\pm$0.8 MHz
Pulse Width Precision	$\pm$5 MHz	$\pm$0.8 MHz
Radar Waveform Switching	Real-time	Requires waveform re-configuration
Dimension	2.5 inch (H)× 6.5 inch (W)× 6.5 inch (D)	3.5 inch (H)× 8.4 inch (W)× 16.6 inch (D)
Weight	$<$ 0.5 kg	5.66 kg
Estimated Cost	USD 3,500	USD 70,000

7. CONCLUSION

This paper presents a miniature, light, and low cost real-time re-configurable RWS suitable for radar applications in UAV platform. A waveform synthesizer core were proposed with the capability of re-configuring the radar waveform's properties in real-time. The proposed system was built using Altera FPGA and the performance was benchmarked with high-end commercial instrument. A series of in lab signal quality measurement has been conducted on the proposed system and the commercial instrument. The signal quality analysis clearly indicate that the waveform synthesizer is comparable to high-end commercial instrument. As a conclusion, the proposed waveform synthesizer has demonstrated its capability of generating complex radar waveforms. In future, the waveform synthesizer will be further enhanced to achieve ultra wideband (in the range of $> 1000\,\text{MHz}$).

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