WHITE PAPER

K-Band Microwave DACs Driving Quantum Computing Technologies.

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TELEDYNE e2V | Semiconductors
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ABSTRACT

As classical computer developments asymptotically approach fundamental computational speed limits, quantum computing has the potential to be hundreds of millions of times faster, at a fraction of equivalent development costs [1].
This will occur only if quantum computer designers can ensure microwave signal-source Qubit drive capability that is accurate, synchronized, reliable, and consistent [2].
Teledyne e2v provides K-Band microwave DACs (and ADCs) that will drive current and future quantum computing technologies in sourcing and receiving the very precise signals needed to understand, trigger, and evaluate the behaviour of the quantum bits (Qubits) [4].

INTRODUCTION TO QUANTUM COMPUTING

In 1975, Gordon Moore, the co-founder of Fairchild Semiconductor and Intel, theorized a doubling “every two years” of the number of components per integrated device. This prediction called “Moore’s Law” became the target for miniaturization in the semiconductor industry; particularly for classical computer advancements in regards to computational power and speed. Since 2010, microprocessor architects have reported an industry wide slowing below the pace predicted by Moore’s Law. Subsequently, over the last twenty years, quantum computing has also emerged as a companion to on-going classical computing developments.

Quantum computing has the potential to solve complex problems more quickly and efficiently than classical computing. Classical computing power increases linearly as a function of the number of bits/components per integrated device. Quantum computing power increases exponentially as a function of the number of Qubits [1]. A Qubit is a two-state quantum mechanical resonator device that displays the characteristics of quantum mechanics (utilizing the properties of atomic and sub-atomic matter) [5]. In classical computing, a single bit must be in one of two states either a 1 or 0. In quantum computing, a Qubit exhibits wave-like, multi-dimensional characteristics that must be in coherent “superposition” of two states simultaneously (the probability of measuring a 0 is equal to the probability of measuring a 1). Coherent superposition is analogous to the properties of spot noise at a single frequency (various amplitudes contained within a probable range, or in other words, X probability measuring Y value) [1] [3].

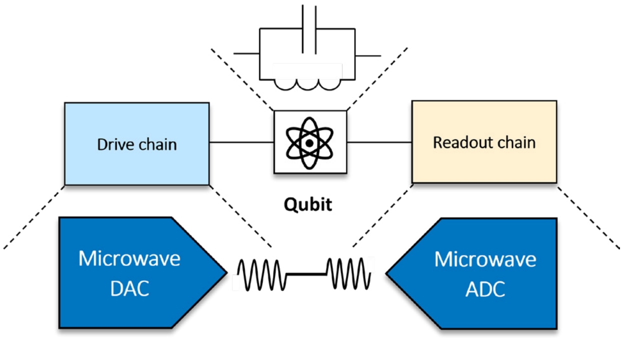


Figure 1—Microwave Mechanical Resonator: Qubit

Qubits can be implemented by a superconducting microwave mechanical resonator (i.e. Josephson junction with a large capacitor) and modelled as a LC tank circuit (see Figure 1) [4] [5]. The LC tank circuit theoretically operates as a perpetual motion machine whereby as the inductor magnetic field eventually collapses while charging the capacitor thereby eventually causing the capacitor to discharge restoring the inductor magnetic field and the cycle repeats. Qubits are driven by a DAC at its resonant microwave LC frequency in order to change from a 0 state to a 1 state (from one energy level to another). Under the driven condition, the probability of being a 1 or a 0 varies sinusoidally over time, under control, and measured by magnitude and phase with an ADC (e.g Teledyne e2v EV10AQ190A). Realistically, losses in the Qubit called “decoherence” result in a damped sine wave output caused by unwanted resistance, magnetic fields, leakage, thermal noise, mechanical vibrations, etc., which then requires feedback injection/compensation of additional drive energy, also driven through the DAC. Decoherence decay corrupts the Qubit’s superposition response requiring feedback for error correction [1].

While a single Qubit is the fundamental building block for quantum computing, multiple Qubits (in parallel) are required in order to implement a quantum computer in which each Qubit can then be driven/modulated separately by a corresponding DAC. Linked Qubit pairs then exploit the interference between their wave-like quantum states in what is called “entanglement” in which one Qubit directly affects the other in predictable ways. Qubit pairs entanglement properties mimic an interferometer in which two patterns can constructively (with high density probability) or destructively (with low density probability) create both parallel and a multi-path network of information. Therefore, the inherent architecture of a quantum computer simply allows for a massive number of inputs, with non-discrete/statistical data, being driven by DACs, measured by multiple Qubits; but the correlation and control of each Qubit is the driving factor for a quantum computer [1] [3]. Over the last twenty-five years, quantum computer developers have demonstrated a two-Qubit computer (1998) up to a 54-Qubit machine (2019) that reportedly performs calculations that would be impossible for a classical computer (the validity of these claims are still being researched). Currently, over the last ten years, world-wide public investment funding for quantum computing technology developments have exceeded approximately $16BUSD [6] [7] [8] [9].

DRIVING QUBITS

The global scale and magnitude of public and private funding for the development of viable quantum computers is indicative of the extreme challenges facing quantum computing research and development [9]. The microwave mechanical resonator structure of the Qubit is the most challenging, and many versions are currently under development (see Figure 2). There are a variety of atomic and subatomic particles being used, as well as techniques for manipulating them. These particles and techniques can include trapped ions, photons, electrical stimulation, electron/spin, nuclear/particle spin using lasers, magnetism, etc., in order to control the Qubit [1] [2] [3].

	Photons	**Electrons**				**Atoms**	
	Photons	Superconducting	Silicon	NV centers	Majorana fermions	Cold atoms	Trapped Ions
qubit size	$(100\mu)^2$	$(100\mu)^2$	$(100nm)^2$			atomes	$(1mm)^2$
Two gates fidelities	98%	99,4%	>98%	92%		98%	99,9%
Readout fidelity	50%	95%	98%	93%		99%	99,9%
Speed	1ms	250 ns	≈5µs				100µs
Temperature	4K/10K for photons generators and detectors	15 mK	1K	300K	15mK	15mK	10K
Enyangled qubits	20 (Chine)	65 (IBM)	4 (Delft)	6		51	32(IonQ)
Scalabitily	100s	100s	millions	100s	?	100s	100

Figure 2 - Qubit Technology Developments

Regardless of the type of structure that is utilized, the next problem is driving it with the high- resolution microwave signals that are required to understand, trigger, and evaluate the response of the Qubit. Generally, in the past, driving the Qubit began with a base-band signal source (from a traditional DAC) which is then low pass filtered, upconverted/mixed, band pass filtered, and then amplified (see Figure 3) [4].
In addition, the Qubit microwave mechanical resonator requires extremely low temperatures (near absolute zero) which creates signal-source driving challenges requiring pre-distortion and pre-compensation in order to correct for various losses in the signal chain (electronic, cabling, etc.) [5].

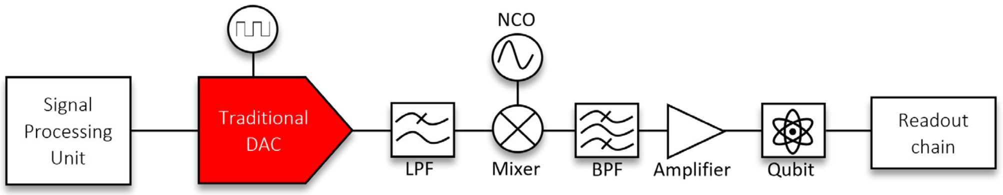


Figure 3 - Traditional Base Band DAC Qubit Driver

Driving the Qubit with an upconverted base-band approach, minimally introduces noise and distortion error components through the NCO and mixer along with cabling mismatches and reflections, etc. State-of-the-art microwave DACs, such as Teledyne e2v's family of 12-bit, K-Band capable DACs (e.g. DAC family EV12DS4x0: https://semiconductors.teledyneimaging.com/en/products/digital-to-analog-converters/ev12ds480), operate at a typical sample rate above 6 GSps and bandwidths beyond 7.5 GHz. Direct drive microwave performance at this level eliminates any requirements for upconversion/mixing, low pass filtering, and local oscillator generation (NCO) as well as simplifying cabling and interconnects (see Figure 4).

The Qubit is driven with a specific frequency, and the reaction of the Qubit's output frequency is the result of the calculations. The Qubits resonant frequency generally varies between 4 and 12 GHz. This resonator can only be maintained under a certain period-of-time due to energy loss in the system. Therefore, the goal is to generate as many microwave pulses creating as many Qubit interactions as possible during a limited period-of-time; minimizing noise introduced by the driver to improve performance and reliability of quantum computing operations. Direct synthesis microwave DACs with high precision, short latency, and low phase noise are essential in quantum computing to control the Qubit [4].

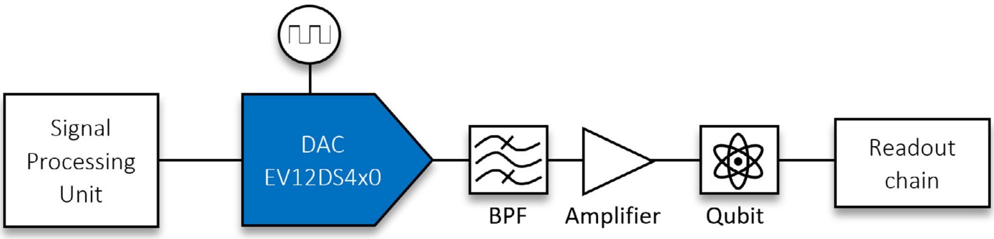


Figure 4 - EV12DS4x0 Microwave DAC Qubit Driver

Additionally, a realistic Qubit network requires scaling (multiple Qubits simultaneously operating in parallel in states of superposition and entanglement). This requires synchronization and triggering of the microwave DAC drivers (see Figure 5). Control, speed, correlation, repeatability, and reliability of each Qubit (and Qubit network) is the driving factor for a quantum computer. Synchronized microwave DAC drivers allow the quantum computer designer to meet these requirements in both performance and cost constraints [1] [2] [3].

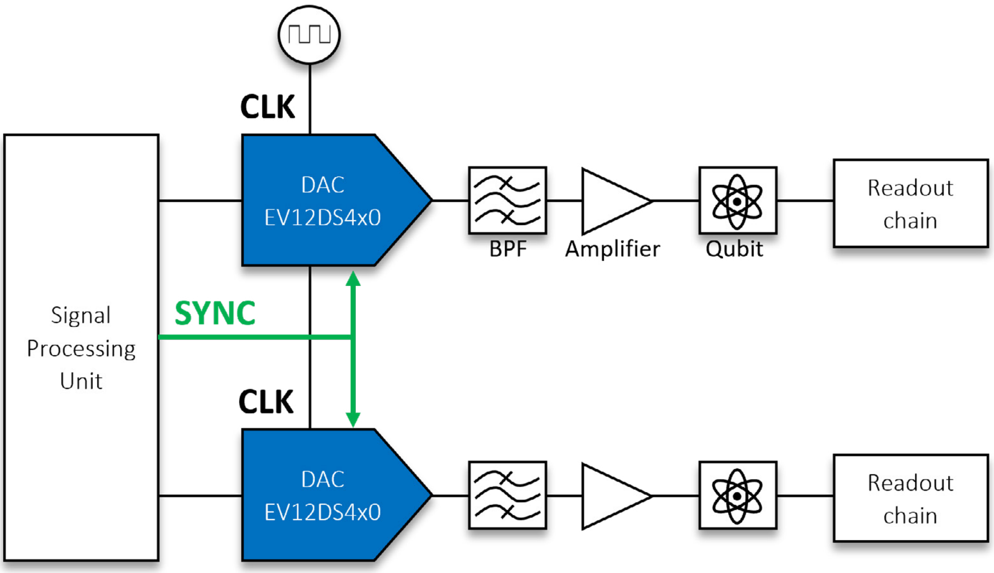


Figure 5 - EV12DS4x0 Synchronized Qubit Drivers

TELEDYNE E2V DAC QUBIT DRIVERS AND APPLICATIONS

As mentioned before, quantum "entanglement" effectively impacts other Qubit's outputs contained within the local quantum computer network. Qubit pair's/network's output entanglement performance can therefore also be input referred, in which each Qubit's input is essentially affected by other Qubit's inputs. Entanglement creates an environment, within a Qubit network, where it is capable of receiving a massive number of inputs (of statistical data) for processing and analysis.

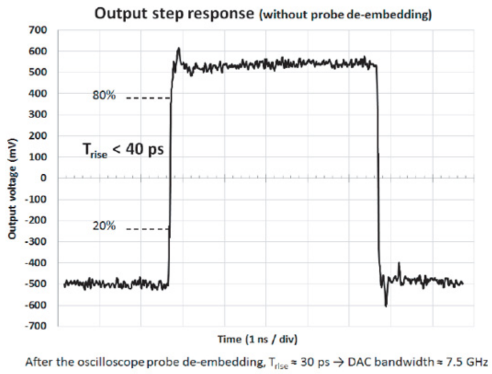
This is how a quantum computer thinks and operates, it is a true parallel processing networking machine. Cases involving a large number of complex data inputs also require software algorithms that can handle superposition, entanglement, feedback error correction, and calibration, all at temperatures approaching absolute zero [1] [2] [3].

True parallel processing opens the door to numerous applications that involve large data sets that can require near instantaneous calculations (see Figure 6). For instance, cybersecurity and cryptography require the sharing of information within a secure environment. Classical computers store "bits" in parallel with a linear number of processors and use classical algorithms to transfer secure data. Quantum computers store parallel "Qubits" in a truly exponentially processing network and use quantum algorithms to transfer data. This is also true for all other applications [9].

Figure 6 - Quantum Computing Applications

Of course, each quantum computer application fundamentally requires a microwave DAC capable of driving an individual Qubit (within the network) with high precision, short latency, and low phase noise. Teledyne e2v's DAC DS4x0 family can be utilized to control one or multiple Qubits. Capable of sampling at 6GHz, with an output bandwidth of greater than 7.5 GHz (and flat response at higher frequencies); the DAC DS4x0 family is able to directly synthesize high precision Qubit driving requirements which simplifies both design architecture and calibration/correlation requirements (removing the need for an up-conversion stage) [4].

The DACDS4x0 time domain step response is shown in Figure 7 with symmetrical rise and fall times of 30 ps. Figure 8 shows the ultra-low latency of <1nsec. Both enable fast, and short, microwave pulse generation [4].



After the oscilloscope probe de-embedding, T_{rise} ≈ 30 ps → DAC bandwidth ≈ 7.5 GHz

Figure 7 - DACDS4x0/EV12DS460A Time Domain Step Response

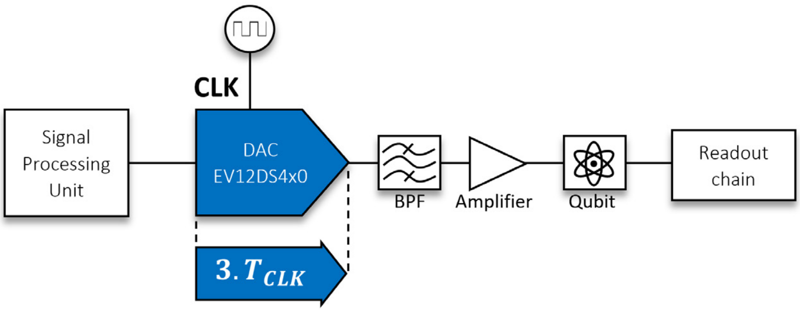


Figure 8 - DACDS4x0/EV12DS460A Latency (3 Clock Cycles)

Figure 9 shows the DACDS4x0 family phase noise characteristics. Of course, ultra-low phase noise measurements also include measuring the clock phase noise as well. Therefore, it is important to design and characterize a low phase noise clock generator in conjunction with the intrinsically low phase noise of the DAC (see Figure 9 right) [4].

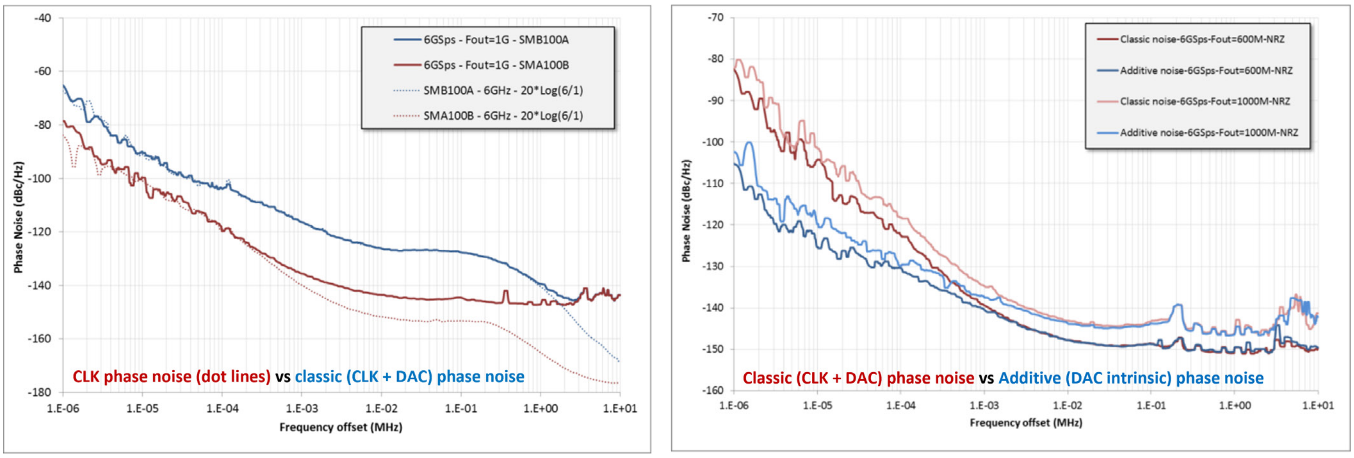
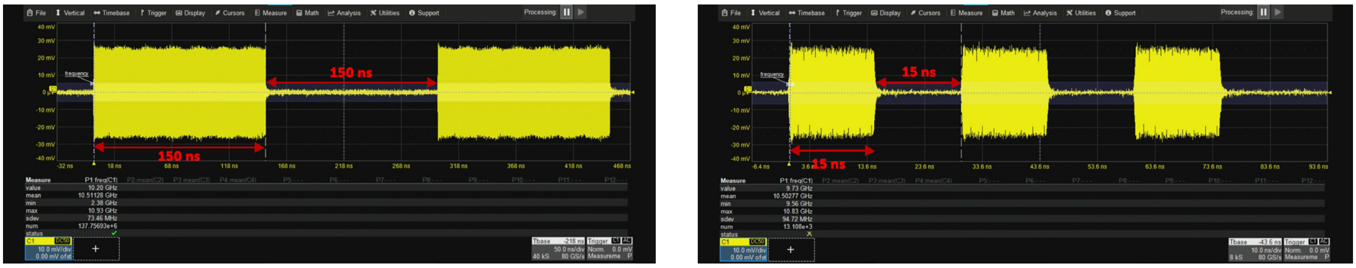


Figure 9 - DACDS4x0/EV12DS460A Phase Noise Performance

Figure 10 shows the DACDS4x0 time domain measured performance utilizing a DAC DS400 evaluation board. A signal generator drives the 6 GHz DAC input clock. The DAC output drives a Marki (BAL0036) microwave balun to convert from a differential to single ended signal, and then a Marki (B1050) microwave band pass filter is used to select the band of interest. A band centred at 10.5 GHz was used for these measurements to directly generate short consecutives pulses of 150 ns at 10.5 GHz (left) and even smaller pulses of 15 ns also at 10.5 GHz (right) [4].



Measure	P1:freq(C1)
value	10.20 GHz
mean	10.51128 GHz
min	2.38 GHz
max	10.93 GHz
sdev	73.46 MHz
num	137.75693e+6
status	✓

C1 DC50 10.0 mV/div 0.00 mV ofst
Tbase -218 ns 50.0 ns/div 40 kS 80 GS/s
Trigger C1 AC Norm. 0.0 mV Measureme P

Measure	P1:freq(C1)
value	9.73 GHz
mean	10.50277 GHz
min	9.56 GHz
max	10.83 GHz
sdev	94.72 MHz
num	13.108e+3
status	✕

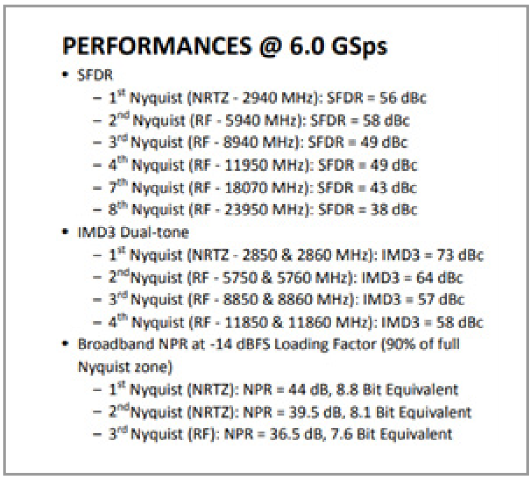
C1 DC50 10.0 mV/div 0.00 mV ofst
Tbase -43.6 ns 10.0 ns/div 8 kS 80 GS/s
Trigger C1 AC Norm. 0.0 mV Measureme P

Figure 10 - DACDS4x0/EV12DS460A Time Domain Performance

Specifically, Teledyne e2v's EV12DS460A is a K-Band microwave 12-bit 6.0 GSps DAC with an integrated 4:1 or 2:1 multiplexer and 7.5 GHz output bandwidth, allowing easy interface with standard FPGAs. It embeds 4 different output modes (NRZ, RTZ, NRTZ and RF) that allow performance optimizations depending on the Nyquist zone of interest. The EV12DS480A is similar to the EV12DS460A, but it operates up to 8.0 GSps also with a 7.5 GHz output bandwidth and beyond [4].

CONCLUSION

The core element in a quantum computer is the Qubit. Fabricating Qubits that have both sufficient quantum-coherence timeframes (how long Qubits retain their information), and the means for producing and controlling their superposition and entanglement, remains the principal roadblock to building a large-scale quantum computer. As Qubit fabrication technologies continue to advance on many fronts, the requirements to drive and control the Qubit actually remains relatively constant: K-Band Microwave DACs that are accurate, low phase noise, synchronized, reliable, and consistent. Teledyne e2v's DACDS4x0 family offers the current and future performance required to drive ever changing Qubit development technologies (see the performance of the EV12DS460A in Figure 11).



PERFORMANCES @ 6.0 GSps

- SFDR
  - 1st Nyquist (NRTZ - 2940 MHz): SFDR = 56 dBc
  - 2nd Nyquist (RF - 5940 MHz): SFDR = 58 dBc
  - 3rd Nyquist (RF - 8940 MHz): SFDR = 49 dBc
  - 4th Nyquist (RF - 11950 MHz): SFDR = 49 dBc
  - 7th Nyquist (RF - 18070 MHz): SFDR = 43 dBc
  - 8th Nyquist (RF - 23950 MHz): SFDR = 38 dBc
- IMD3 Dual-tone
  - 1st Nyquist (NRTZ - 2850 & 2860 MHz): IMD3 = 73 dBc
  - 2ndNyquist (RF - 5750 & 5760 MHz): IMD3 = 64 dBc
  - 3rd Nyquist (RF - 8850 & 8860 MHz): IMD3 = 57 dBc
  - 4th Nyquist (RF - 11850 & 11860 MHz): IMD3 = 58 dBc
- Broadband NPR at -14 dBFS Loading Factor (90% of full Nyquist zone)
  - 1st Nyquist (NRTZ): NPR = 44 dB, 8.8 Bit Equivalent
  - 2ndNyquist (NRTZ): NPR = 39.5 dB, 8.1 Bit Equivalent
  - 3rd Nyquist (RF): NPR = 36.5 dB, 7.6 Bit Equivalent

Figure 11 - EV12DS460A Freq. Performance

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