A fully integrated nanosecond burst RF generator for quantum technologies

Carlos Sánchez-Azqueta,[1,✉] Concepción Aldea,[2] and Santiago Celma[2]
[1]Group of Electronic Design, Aragón Institute of Engineering Research (I3A), Department of Applied Physics, University of Zaragoza, Zaragoza, Spain
[2]Group of Electronic Design, Aragón Institute of Engineering Research (I3A), Department of Electronic and Communications Engineering, University of Zaragoza, Zaragoza, Spain
✉ E-mail: csanaz@unizar.es

Quantum technologies is an emerging field of physics and engineering based on exploiting properties of quantum mechanics such as entanglement, superposition, or tunneling, and which is expected to impact many applications, such as communications, simulation, computation, or sensing and metrology. The operation of quantum technologies is based on the manipulation of the quantum states of certain devices, either to induce transitions between states or to detect the transitions. Irrespective of the practical realization of these quantum devices, their manipulation requires interacting with their quantum resonant states, for which very narrow radio-frequency (RF) bursts in the range of the GHz are required. Arbitrary waveform generators are used to generate these signals for test purposes, but this is not suitable for practical quantum technology applications, which will need to produce the required bursts by specific circuit building blocks with low power and small dimensions. Here, an integrated RF burst generator capable of producing GHz bursts shorter than 1 ns is presented. The proposed architecture is tested using a 5 GHz quadrature LC-tank voltage-controlled oscillator (LC-VCO), showing that the four equally spaced phases can be switched every 500 ps, which allows the generation of more complex RF bursts for optimized quantum state manipulation.

Introduction: The application of the quantum properties of entanglement, superposition, and tunneling to the development of practical systems is an emerging field of research generally referred to as quantum technologies. Its many foreseen applications are usually divided into four main fields, namely quantum communications, quantum simulation, quantum computation, and quantum sensing and metrology [1]. What all four share is that their operation is based on manipulating the quantum states of certain devices to produce a set of desired transitions, or conversely to couple to the devices to detect those transitions.

Despite particular realizations of quantum systems such as trapped ions or nitrogen vacancies, which can operate at room temperature due to their weak coupling to the environment [2], quantum technologies typically require low-temperature environments, in the deep cryogenic regime, to manipulate the extremely unstable and fragile quantum states, minimizing the effect of thermal noise. Even in that case the time required to carry out the operations, called coherence time, is very short, typically in the range of hundreds of ns [3].

In this context, the manipulation of the quantum states of interest for the desired quantum technology applications needs to be done using RF bursts lasting for a fraction of the coherence time of the quantum states, and with a carrier signal tuned to their resonant frequency, which, despite implementations such as mechanical quantum states or quantum spin, with a lower value [4], is typically found in the GHz range. For instance, it ranges from 0.1 to 1 GHz for photon quantum devices [3], from 1 to 10 GHz for charge quantum devices, or from 1 to 50 GHz for electron spin quantum devices. This is, in the majority of cases, the interactions with the quantum states needs to be done with RF bursts of some GHz lasting for a few ns.

For testing and characterization purposes, these bursts are usually created using state-of-the-art arbitrary waveform generators (AWG), which allow the generation of the desired pulses [5, 6]. However, this approach is not valid for the expected practical applications of quantum technologies, which will require the simultaneous manipulation of large numbers of quantum devices in industrial or even home environments, where the access to sophisticated pieces of instrumentation is not feasible.

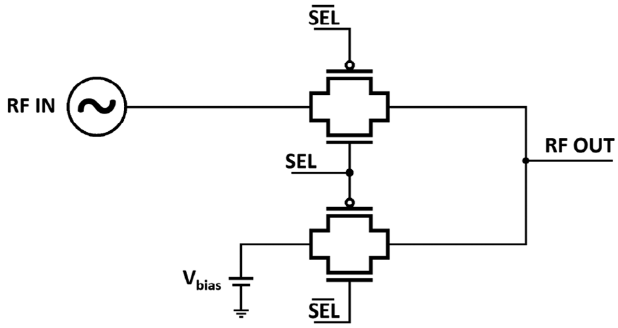

Fig. 1 *Block diagram of a single-phase RF burst generator*

For example, in the field of quantum computation, today's largest quantum computer, IBM's Osprey, encompasses 433 quantum devices (called qubits in quantum computing), but practical quantum computers are expected to require up to one million qubits [7]. Even more challenging, recent advances of the manipulation of quantum states indicate that their optimal operation will be achieved by the generation of nanosecond bursts of different RF signals or different phases of a given RF signal, similarly to current digital communication modulation schemes but with symbols with a duration orders of magnitude shorter [8].

This letter presents an integrated RF burst generator capable of producing bursts of RF signals in the GHz range shorter than 1 ns, with a power consumption of 10 nW. The architecture proposed here has been tested using a quadrature LC-VCO that outputs two quadrature differential outputs of 5 GHz, showing that the four equally spaced phases can be switched at a speed of 10 GHz, which allows an efficient way to integrate the generator of complex RF bursts for optimized manipulation of quantum devices.

Circuit description: The RF burst generator is formed by two independent building blocks. On the one hand, there is the RF signal generator, which can be implemented as a phase-locked loop (PLL) with a temperature-compensated crystal oscillator together with an LC-VCO to achieve the spectral purity required for the manipulation of quantum systems [9]. The RF signal generator can be designed to fine tune the particular characteristics of the quantum system, which adds high modularity to the proposal, even allowing the implementation of multi-quantum system generators by expanding the tuning range of the PLL, for instance using a switched capacitor tank for the LC-VCO [10]. On the other hand, the circuitry in charge of switching the RF signals is formed by a set of transmission gates connected to each of the outputs of the PLL, with a dedicated logic to select only one of them, leaving the rest in a high impedance state.

This scheme is shown in Figure 1, where a simplified generator of only one phase is shown. The switching of the signal is carried out by two transmission gates: one of them drives the synthesizer and the other one a direct-current (DC) level matching that of the RF signal provided by the synthesizer so that the ON–OFF switching of the system can take place immediately and without introducing any undesired voltage step, which would translate in spurious frequency components that could alter the manipulation of the quantum system. In this case, the logic that controls the switching of the RF signal can be implemented by only an inverter so that the control inputs of the transmission gates oppose each other.

The architecture that can provide the ns bursts of different phases of an RF signal that are expected to manipulate quantum states in practical systems is shown in Figure 2. It is formed by four transmission gates placed in parallel, each one driving one of the four phases of the synthesizer, and controlled by a two-to-four line binary decoder, which sets only one of the transmission gates active at a time. In this case, the RF input signal is provided by frequency synthesizer based on a quadrature LC-VCO [11], but the architecture is flexible and it can be expanded to accommodate the necessary phases. It is worth noting that, because the signal of the synthesizer is driven to the output by means of the transmission gates, the RF signal can be stabilized prior to being driven to the output, eliminating the issues associated with the oscillator start-up.

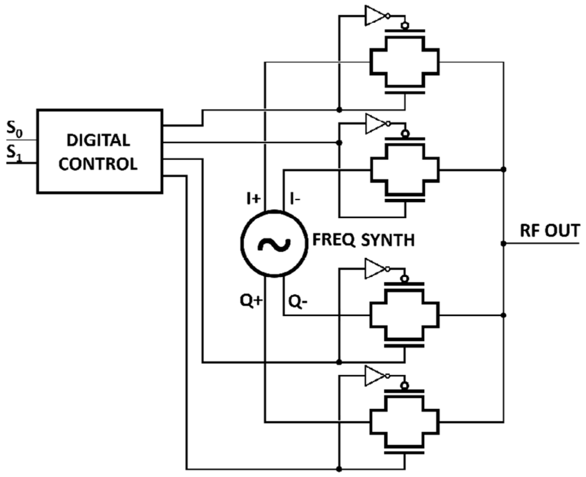

Fig. 2 *Block diagram of a quadrature four-phase RF burst generator*

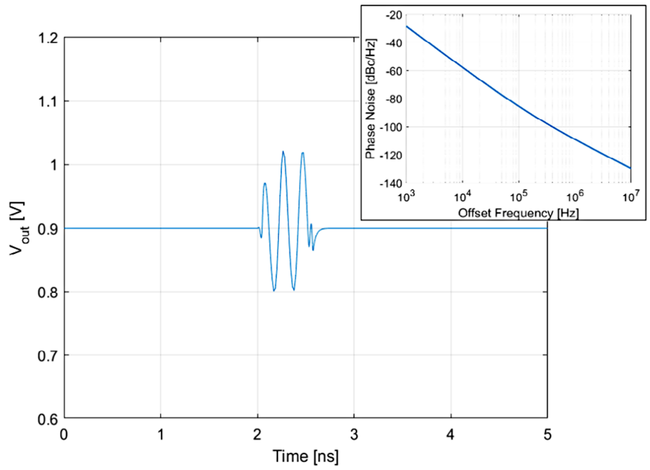

Fig. 3 *The 500 ps single pulse of the 5 GHz local oscillator signal. The DC level is 0.9 V to match that of the oscillator. The inlay shows the phase noise of the free-running LC-VCO, which is −110 dBc/Hz at 1 MHz from the carrier*

Results: The proposed system has been implemented using a 65 nm complementary metal-oxide-semiconductor (CMOS) process. In the first place, the switching capabilities of the burst RF generator have been tested using the architecture shown in Figure 1. Once the oscillator has started and provides a stable 5 GHz signal, the control bit *SEL* has been set to logic 1 for a duration of 500 ps. As can be seen in Figure 3, the output of the generator stays at the desired DC level, fixed in this case at 0.9 V to match that of the synthesizer, and it provides an RF burst for the desired 500 ps. Figure 4 further illustrates this behaviour, presenting a train of 500 ps pulses with 2 ns spacing, controlled by the digital *SEL* signal, which can be fed externally to the IC.

The operation of the architecture shown in Figure 2 to switch between different phases of an RF signal is shown in Figure 5, where the four 90° shifted phases at 5 GHz provided by the frequency synthesizer are driven sequentially to the output every 500 ps. As can be seen, the transition between phases is produced instantaneously as expected. Finally, to demonstrate the feasibility to use the proposed architecture as an RF generator for the realization of quantum algorithms, the system shown in Figure 6 has been operated using a randomized pattern to drive the switching of the phases, replicating the sequence of phases that would be necessary to implement quantum algorithms, in which, as has been indicated before, the switching of the different RF phases is produced as required by the application in bursts of duration in the order of ns [8]. Finally, a key parameter in the operation of cryo-CMOS in quantum technologies is power dissipation, since it needs to be kept low enough so that refrigerators can keep the cryogenic temperature. A common accepted estimation is that it should be well below 1 mW/qubit [12]. In the case of this work, the electrical power consumed is 3.47 mW for

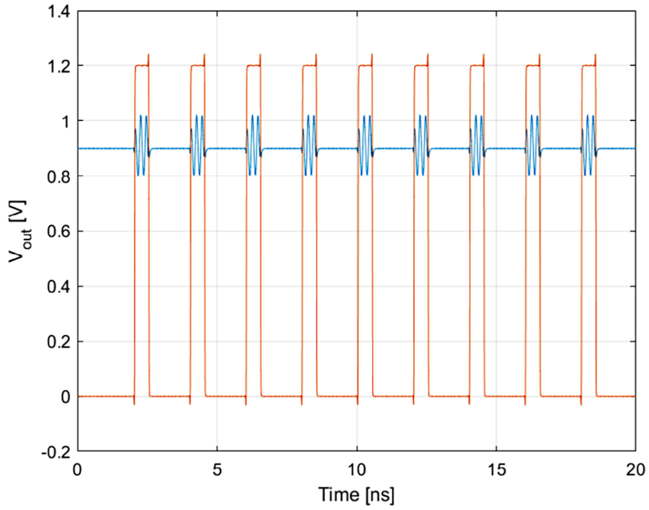

Fig. 4 *Train of 500 ps pulses of the 5 GHz local oscillator test signal*

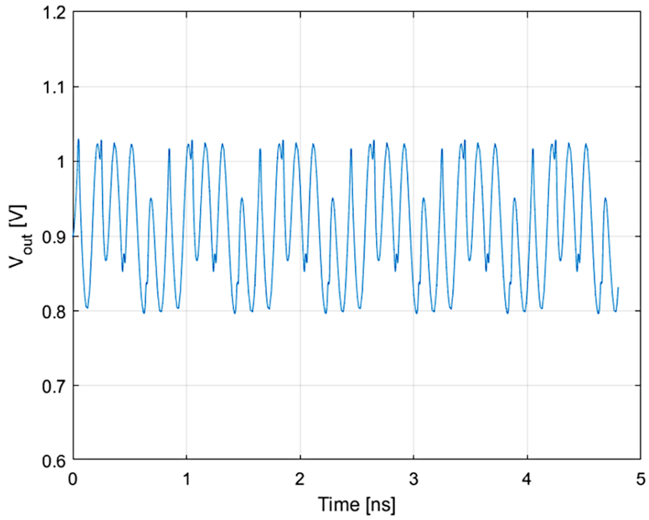

Fig. 5 *Sequential switching of the 90° phases at 5 GHz, separated by 500 ps*

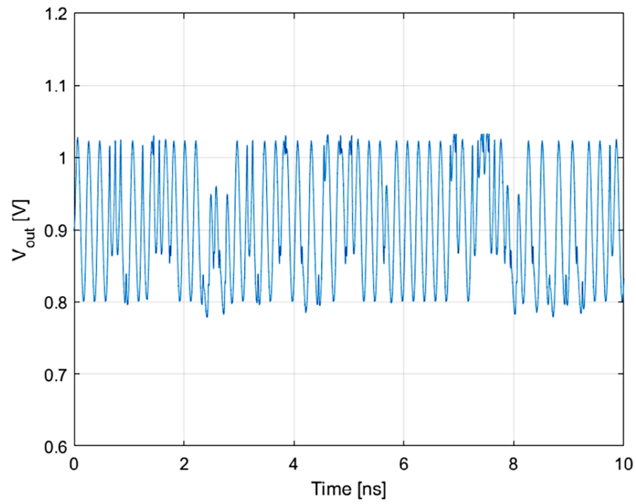

Fig. 6 *Four 90° phases at 5 GHz switched randomly every 500 ps to emulate the signals required by quantum algorithms*

the LC-VCO and 27.5 μW for the logic that generates the pulses. This proposal, estimating a scaled quantum system with 100 qubits, would translate in an average power of about 0.035 mW/qubit, well within the desired range.

Conclusion: This work presents the realization of an integrated RF burst generator capable to produce bursts of RF signals in the GHz range shorter than 1 ns, suitable for its use in the implementation of quantum algorithms. The system proposed here is small size and low power, thus alleviating the need to use external AWG, the solution used today for testing purposes, which is not suitable for practical quantum systems expected to operate thousands or even millions of quantum devices, each one requiring its own interaction signals. To test the architecture proposed in this letter, a quadrature LC-VCO that outputs two quadrature differential outputs of 5 GHz previously designed by the authors has been used. The results show that the four equally spaced phases can be switched in any order with burst times lower than 1 ns, which allows an efficient way to integrate the generator of complex RF bursts for optimized manipulation of quantum devices.

Author contributions: **Carlos Sánchez-Azqueta**: Conceptualization; investigation; validation; writing—original draft; **Concepción Aldea**: Formal analysis; visualization; writing—review and editing; **Santiago Celma**: Formal analysis; visualization; writing—review and editing.

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Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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