An Optoelectronic Pulse Drive for Quantum Voltage Synthesizer

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***Abstract*— An optoelectronic pulse drive system based on commercially available telecoms optoelectronic components and a field-programmable gate array has been developed. In order to allow the use of ac-coupled optoelectronic components, a method of adding and subtracting complementary pulses was developed. The system was used to drive a Josephson junction array to synthesize quantum-accurate voltage waveforms. These waveforms will be used in voltage waveform metrology applications. Results from the synthesis of sinusoidal unipolar voltage waveforms from 3 to 300 kHz are presented. The margin of operation was measured and shown to require an optical pulse height stability better than 0.15 mW. The use of delta–sigma code with repeated sections, suitable for a quantum voltage digitizer was also examined. A test code corresponding to a delta–sigma feedback loop rate of 250 MHz was used to synthesize a 3.125 kHz sinusoidal waveform.**

***Index Terms*— Josephson arbitrary waveform synthesizer, Josephson arrays, measurement, metrology, optoelectronics, voltage measurement.**

I. Introduction

THE synthesis of quantum-accurate voltage waveforms of high spectral fidelity has been demonstrated using pulse-driven Josephson junction arrays (JJAs) with part per million accuracy up to frequencies of the order of 1 MHz (see [1], [2]). By connecting several JJAs in series, rms voltages of up to 2 V have been demonstrated [1]. The pulse drive system (for example, as described in [3]) typically consists of a commercial pulse pattern generator (PPG), used to produce electrical pulse codes at pulse rates in the region of 10 GHz, combined with low-frequency compensation circuits to reintroduce the parts of the signal removed via filtering. Such systems can produce bipolar voltage waveforms as described in [4]. The future requirements of instrument and sensor developers have focused research efforts on increasing output voltage levels and to work toward operation at higher frequencies. In this paper, we present an alternative optoelectronic-based pulse drive system. In this system, the JJA and its microwave termination are galvanically isolated from the pulse drive system. This avoids any common mode voltages, which means that several JJAs can be combined in series without the need for complex electrical compensation circuits. This simplifies the future scaling to large numbers of JJAs in order to increase output voltages. Previously, the use of photodiodes (PDs) to drive JJAs has been investigated both at low temperature [5] and room temperature [6], showing promising results.

An optoelectronic pulse drive system has been designed with preliminary results given in [7]. It is demonstrated in this paper in synthesis mode showing the ability to generate quantum-accurate voltage waveforms. However, the design of the system is such that it can also, in the future systems, be used in the digitization of arbitrary voltage waveforms. The use of delta-sigma electronics [7] and a field-programmable gate array (FPGA) to produce the pulse sequence, combined with the optoelectronic drive, produce a quantum voltage digitizer system. The long-term goal of this paper is to provide new quantum traceability for voltage waveform metrology, with the ability to offer real-time quantum-accurate spectral characterization of waveforms.

II. Design

The optoelectronic pulse drive design for waveform synthesis is shown in Fig. 1(a). A digital code is loaded into an FPGA. A commercial FPGA evaluation board was used for ease of development. The FPGA includes electrical transceivers that operate up to 12 Gb/s. The board also features the ability to connect commercial optical transceivers to convert these electrical pulses into optical pulses [9]. In this way, an optical pulse code can be generated without the use of a commercial PPG. The FPGA also allows the code to be generated in response to an input, e.g., the feedback from a delta–sigma feedback loop, so that the generated code can be updated in real time. This is unlike a commercial PPG where the code must be loaded into the memory before use. This will allow the future integration of the system in a feedback loop for use as a quantum voltage digitizer.

Fig. 1(b) shows a system where the pulse code is provided by a unipolar electrical PPG for the purpose of testing the

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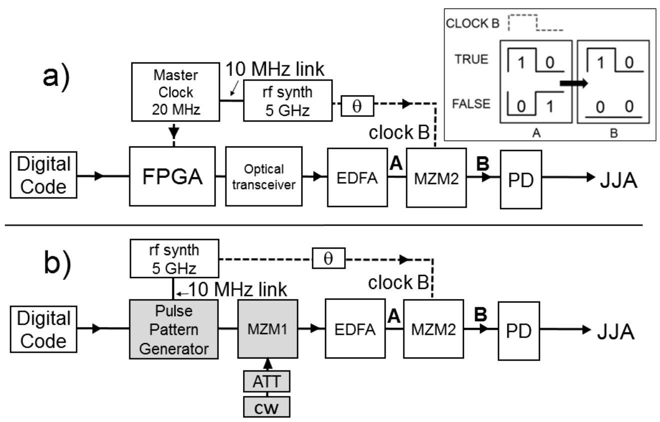

Fig. 1. (a) Schematic of optoelectronic pulse drive based on an FPGA. (b) Similar system using a PPG which is used for testing the optoelectronics. A digital code is loaded onto either FPGA or PPG and converted into optical pulses using either an optical transceiver or continuous wave laser and MZM. Both systems operate at a wavelength of 1550 nm. The optical signal is amplified using an EDFA. An electrically controlled optical attenuator ATT is used for fine adjustment of optical pulse height. A MZM2 is required to remove complementary pulses in code A producing code B. Inset: output of MZM2 at point B for the input of either TRUE (1, 0) or FALSE (0, 1). When clock B is high, the input is passed, and when clock B is low, the input is nulled. An RF synthesizer that is phase locked to the FPGA via a master clock or directly to the PPG is used to provide a clock signal (clock B) to MZM2. The phase between clock B and the pulse code is manually adjusted via a delay line (θ). The optical pulses are incident on a fiber-coupled InGaAs PD that is used to drive the JJA. To integrate system (a) into a delta–sigma feedback loop, the real-time feedback voltage from the JJA is fed to the FPGA instead of the static digital code.

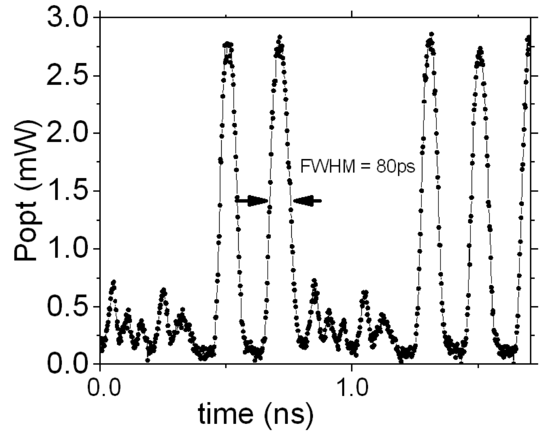

Fig. 2. Typical optical pulses measured at point B shown in Fig. 1(b), shown as optical power (Popt) as a function of time. The structure in between the pulses shows where complementary pulses have been removed by the second MZM2. The size of this structure is reduced by optimizing the phase alignment of clock B with the pulse train, using a delay line to adjust phase. The drive amplitude and bias of MZM2 are also adjusted to minimize the level of signal between pulses. The pulses shown above have a measured full width at half maximum of 80 ps. The extinction of the complementary pulses is sufficient for the structures seen in the zero level not to contribute to a voltage output for the array.

optoelectronics. The PPG clock rate of 10 Gb/s corresponds to a return to zero (RTZ) pulse rate of 5 GHz. A single-channel pulse code was used to produce voltage waveforms of positive voltage only. The electrical code from the PPG is converted into an optical pulse code using a Mach–Zehnder modulator (MZM), denoted MZM1 in Fig. 1(b), to modulate a continuous wave (cw) laser input from a laser diode operating at a wavelength of 1550 nm. The results presented in this paper correspond to the use of the system shown in Fig. 1(b).

In both systems shown in Fig. 1, the optical pulses must be amplified to provide a sufficient pulse area to operate the JJA on the first Shapiro step. Therefore, an erbium-doped fiber amplifier (EDFA) is used to provide optical amplification up to a gain of 20. The ac coupling of both the MZM1 drive [not shown in Fig. 1(b)] and the optical power amplifier means that a constant mark to space ratio in the pulse code is required at all times. Therefore, complementary pulses must be inserted into the pulse code to maintain a constant pulse density at point A in Fig. 1. These unwanted pulses are then removed by a second MZM (MZM2) to produce the desired code at point B. As shown in Fig. 1 inset, the code at point A is either 1, 0 or 0, 1. The clock is provided by an RF synthesizer, locked to the PPG [Fig. 1(b)] or FPGA [Fig. 1(a)] via the 10 MHz timing link. An electronic delay line is used to manually adjust the phase of the clock so that it aligns with the pulse code at point A. The MZM2 then acts to pass "1"s in code A that align with the clock "1" and to suppress "1"s in code A that align with clock "0."

The resultant optical pulse code at point B in Fig. 1(b) was examined using an optical sampling scope. A typical pulse pattern with a pulse area corresponding to operation on the first Shapiro step is shown in Fig. 2. The features in between the pulses show the extinction of unwanted complementary pulses that have been removed by MZM2. The height of these structures is reduced by optimizing the alignment of the phase of clock B with the pulse train at point A and by adjusting the MZM2 drive amplitude and bias. However, provided the pulse area of the remaining structure is below that required to produce a quantized voltage pulse, it does not result in any voltage output from the array. In Fig. 2, the average pulse height is 2.8 mW with a full width at half maximum (FWHM) of 80 ps.

A commercial InGaAs PD operating at room temperature was used to convert the optical pulses into electrical pulses to drive the JJA. The responsivity of the PD was 0.9 A/W. The PD is reverse biased with an isolated power supply in order that the JJA and its termination are galvanically isolated. The PD is mounted at room temperature at the top of a cryoprobe, the end of which is located in a liquid helium bath at 4.2 K. Rf coax is used to connect the PD output to a JJA. A distributed JJA with 1000 junctions of superconductor– normal metal–superconductor type with a critical current of 0.3 mA and normal resistance R_N of 16 mΩ was used. The single ended voltage output across the JJA is accessed via on-chip low-pass filters. The voltage was measured using a digitizer with an input impedance of 1 MΩ and with sampling rates between 100 kSs^{-1} to 15 MSs^{-1}.

III. Results

Sinusoidal waveforms were encoded using single bit second-order delta–sigma modulation. A unipolar waveform was used since a single PD provides only a single polarity voltage pulse. The complementary pulses were then added to the delta–sigma code by doubling the code so that "1"

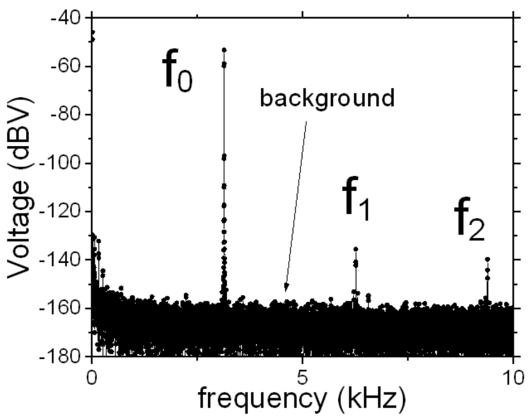

Fig. 3. Fast Fourier transform (FFT) of a 3.125 kHz sine wave where the optical pulse height is set just below the value required to reach the first Shapiro step. The harmonics f_1 (6.250 kHz) and f_2 (9.375 kHz) are present in the FFT when not all the pulse areas are within the margin for output of a quantized $V(t)$ pulse, due to pulse height variation. A typical value for the background voltage level is measured between the peaks at a frequency of $1.5 * f_0$. In this example, the background level is of the order of -160 dB corresponding to an rms voltage of 10 nV.

was replaced by "1, 0" and "0" was replaced by "0, 1" to fit the scheme described earlier. Typically, the amplitude of the waveform was set to 60% of the full-scale delta–sigma amplitude. Note that the optoelectronic system does not require a compensation signal to reintroduce the dc level, since the PD is directly connected to the JJA rather than ac coupled. For the results presented below, the digital code was loaded into the memory of the PPG shown in Fig. 1(b).

A. Operation Margin of the System

In a quantum voltage waveform synthesis system, it is important to quantify the margin of operation. To establish the range of optical power corresponding to the pulse area required to operate the JJA on the first Shapiro step, the JJA output voltage was measured as a function of pulse height.

A 3.125 kHz sine wave was synthesized using the method described earlier and the height of optical pulses was adjusted using an electrically controlled optical attenuator (ATT), as shown in Fig. 1(b). For each pulse height, a voltage waveform of 100 k samples was recorded at a sampling rate of 100 kSs^{-1}. A typical fast Fourier transform (FFT) of a representative voltage waveform is shown in Fig. 3, for operation at a pulse height just below the first Shapiro step. In this case, the system is not producing a quantum accurate output. The FFT was used to obtain the height of the fundamental (f_0) and first two harmonics (f_1, f_2) as well as a representative value of background (measured at a frequency of $1.5 * f_0$). In Fig. 3, the f_1 and f_2 harmonics are clearly visible and the background level is of the order of -160 dB (corresponding to an rms voltage of 10 nV).

The optical pulse height was increased from 0 to around 4 mW and an FFT measured at various optical pulse heights. For each FFT, the height of the peaks and background (as defined in Fig. 3) were measured. The variation of the spectral features with an increasing optical pulse height is shown in Fig. 4, with the region corresponding to the first Shapiro step shown in more detail in Fig. 5. As seen from Fig. 4,

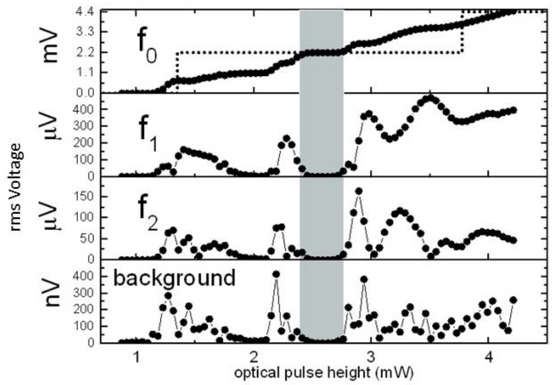

Fig. 4. 3.125 kHz sine wave was synthesized and an FFT of the resultant voltage waveform was obtained as a function of optical pulse height. The height of the FFT peaks, as described in Fig. 3, was measured at each pulse height. The optical pulse height was varied from 0 to 4 mW. The first Shapiro step, (shown in the shaded box) occurs at an rms voltage of 2.2 mV (corresponding to a peak-to-peak voltage of 6.2 mV). For pulse heights within the shaded box, the harmonics f_1 and f_2 decrease below the digitizer noise level. The signal level between the peaks, denoted background level, also decreases when the system is operating in the quantized region. The dotted line shows the output voltage as a function of pulse height for an ideal pulse drive system [10], with the step width chosen so that the measured data is at the center of the step.

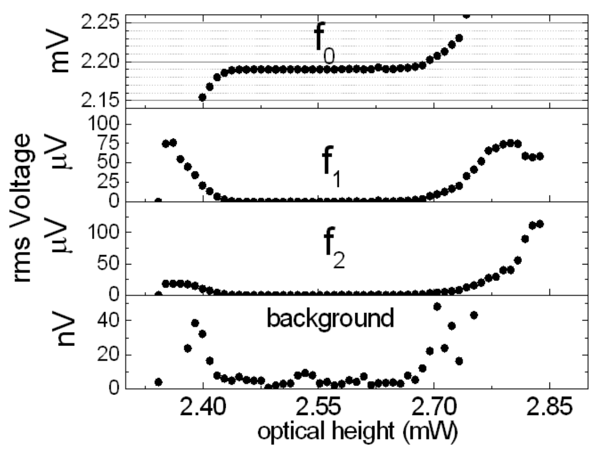

Fig. 5. Height of the FFT peaks, given as rms voltages against optical pulse height. The shaded box in Fig. 4 was measured with smaller steps in optical pulse height to show the flatness of the voltage step which is of the order of 100 nV across the flat region. The background level is seen to reduce to below 10 nV in the quantizing regime.

when the pulses are within the operating margin of the first step (shown in the shaded box in Fig. 4), the background level is seen to drop to below an rms voltage of 10 nV and f_1 and f_2 decrease below the noise level. This provides evidence that the JJA is producing a quantum-accurate output.

For an ideal pulse drive system, the output of the JJA is predicted to follow a "staircase" structure [10] as the pulse area is increased. An example of ideal performance is indicated by the dotted line in Fig. 4 in order to compare with the measured performance. We note that the values of the fitting parameters were selected so that the measured Shapiro step data is at the center of the fit step, and the onset and width of the step follow the theory outlined in [10]. The fitted system parameters deviate from the ideal case, because in the optoelectronic system presented in this paper, it is found that the presence

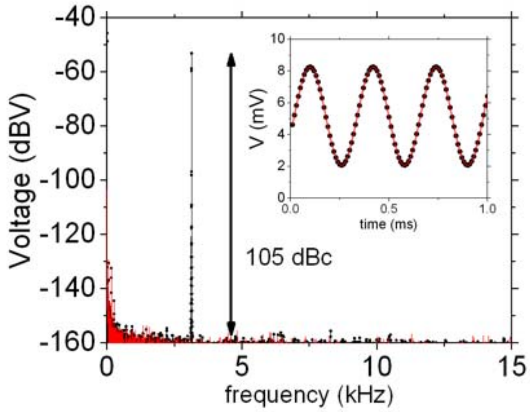

Fig. 6. FFT of a 3.125 kHz sine wave (black points and line) synthesized using the optoelectronic drive system shown in Fig. 1(b). A delta–sigma code with a delta–sigma amplitude that is 60% of full scale was used. The noise level with no input (red line in color version) is of the order of −160 dB which is 105 dBc. Inset: corresponding voltage waveform. The waveform is unipolar with a measured peak-to-peak voltage of 6.2 mV.

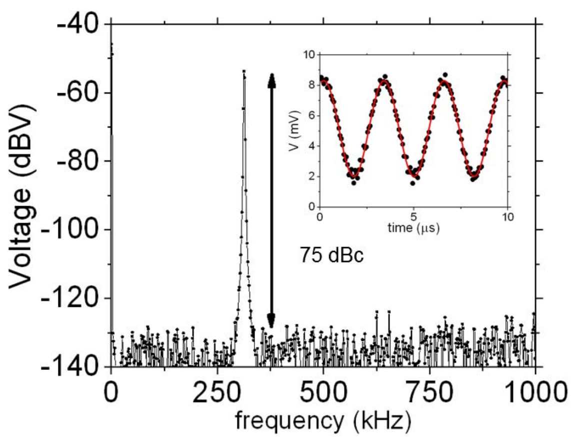

Fig. 7. FFT of a 312.5 kHz sine wave synthesized using a delta–sigma code with a delta–sigma amplitude that is 60% of full scale. The noise level is 75 dBc. Inset: corresponding voltage waveform with a measured peak-to-peak voltage of 6.30 mV (points) and a fit sine wave (line).

of the second MZM (MZM2) and the features introduced in the pulse train in the extinction region (shown in Fig. 2) lead to the additional features shown in Fig. 4. This acts to reduce the operating margins. From Fig. 5, it can be seen that there is a region from approximately 2.4 to 2.7 mW pulse height, where the pulse areas are within the quantizing regime and the extinction features are not large enough to contribute an output voltage. Therefore, in order to operate the system on the center of the step and within the quantizing regime, the optical pulse height stability must be controlled to better than ±0.15 mW, which is achievable with the commercial telecoms components used in this system. The flatness of the constant voltage step (Fig. 5, top) is measured to be 100 nV across the width of the flat region.

B. Synthesis of Quantum Accurate Waveforms

The system was optimized to operate with the pulse height at the center of the first Shapiro step, shown in Fig. 5 to correspond to an optical pulse height of approximately 2.6 mW. We note that the optical pulse height required depends on the settings of MZM2 and must, therefore, be adjusted in conjunction with setting the MZM2 drive parameters for each measurement run. In particular, the phase difference between the input to MZM2 and clock B drifts over time and requires hourly adjustment. However, it is expected that the use of a higher performance master clock will increase stability. The results presented here indicate the typical performance of the system and are typically obtained with a data collection time of 1 s. A sine wave of frequency 3.125 kHz was synthesized using a code length of 3.2 M points per period. The resulting waveform is shown in the inset of Fig. 6 and the corresponding FFT in Fig. 6. The voltage waveform has a measured peak-to-peak value of 6.2 mV corresponding to the value expected for 1000 Josephson junctions operating at an RTZ pulse rate of 5 GHz and a 60% of full-scale delta–sigma code. The harmonics are suppressed to about 105 dBc. The use of a JJA with a factor of 10 increase in the number of junctions would increase the output voltage by a factor of 10, increasing the ratio of signal to background obtained with the optoelectronic pulse drive system close to the performance obtained using a typical commercial electrical pulse drive [2]. Using the same method, a sine wave of 312.5 kHz was synthesized. In this case, a code length of 32 k points was used. The waveform is shown in Fig. 7 inset and the corresponding FFT in Fig. 7. The calculated peak-to-peak amplitude was 6.22 mV and the measured value obtained from fitting the data was 6.30±0.02 mV. In this case, the background level was 75 dBc. The discrepancy between calculated and measured values and the increase in background noise level is believed to be due to high-frequency reflection effects in the cables connecting to the JJA, and the calibration of the digitizer used to measure the output voltage. Reducing these discrepancies is the subject of future investigation. The system quantization was checked by examining the suppression of harmonic components as a function of optical pulse height as described earlier. The synthesis of a 300 kHz sine wave shows the advantage of pulse-driven JJA system over programmable systems, where operation is limited to a few kHz [11]–[13] due to the time required for the output to stabilize after the state of the junctions is switched.

C. Synthesis With Repeat Sections of Delta–Sigma Code

As described in Section I, the synthesis of quantum-accurate voltage waveforms using delta–sigma encoding to produce an electrical pulse code to drive JJAs is a well-developed technique [1], [2]. These systems employ a configuration where every data bit of the code is controlled, or in the case presented earlier (shown in Figs. 6 and 7), where every pair of bits is controlled (in order to add complementary pulses). However, in order to construct a quantum voltage digitizer, it is necessary to synthesize quantum-accurate waveforms using the delta–sigma code that is updated in real time at the feedback loop rate. A delta–sigma feedback loop will operate at a lower frequency than the JJA drive pulses, with 100 MHz being a challenging target for such a loop. In the above-mentioned optoelectronic system, the RTZ pulse rate is 5 GHz, therefore, for example, if the feedback loop rate was 250 MHz, this would require a segment of 20 data bits at a

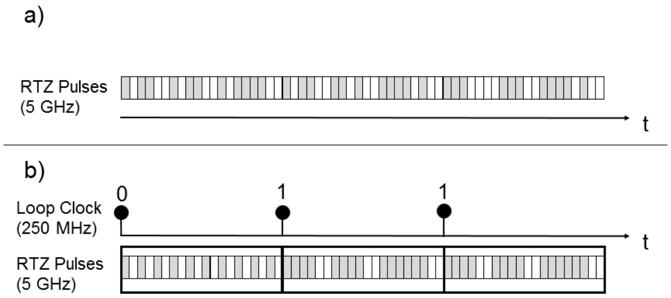

Fig. 8. Schematic comparing two methods of using delta–sigma code to generate waveforms. (a) Delta–sigma code is produced where every data bit can be controlled and set to either a pulse (gray) or no pulse (white). The pulses are 5 GHz RTZ pulses generated using the PPG at 10 Gb/s. The complementary pulses (not shown) are added as described earlier. (b) Pulse sequence is only updated at the slower loop clock rate (250 MHz in this example). This means that the code must be constructed in segments of 20 pulses. A delta–sigma code is produced at the 250 MHz rate. For a value of "0" in the code, a segment containing 10 pulses (gray) and 10 zeros (white) is generated. For a value of "1," a segment containing 14 pulses and 6 zeros is generated.

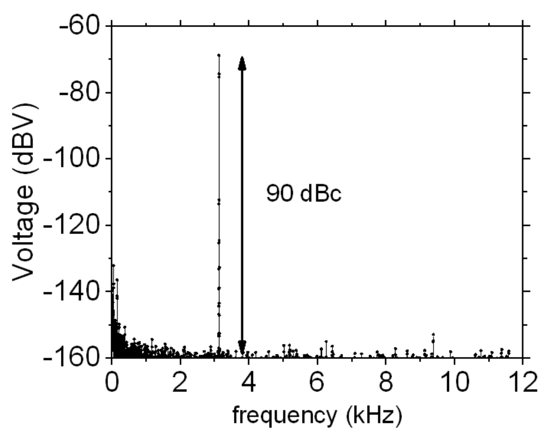

Fig. 9. FFT of a 3.125 kHz sine wave synthesized using a delta–sigma code, where the pulse code is controlled in segments of repeated code of 20 bits rather than controlling every pulse. To avoid long runs of "1"s or "0"s, sequences containing 14 pulses and 10 pulses are used for the true and false codes, respectively. This reduces the peak-to-peak voltage of the waveform to 1.04 mV.

time to be output to the JJA (as shown in Fig. 8). The use of longer code segments requires more careful construction of the delta–sigma code to avoid creating unwanted spectral features. In addition, it provides the opportunity for multilevel delta–sigma coding, which can be used to increase resolution.

In order to investigate the response of the JJA to a delta–sigma code that contains segments of code, a 3.125 kHz sinusoidal waveform was encoded at a data rate of 250 MHz. This value was chosen a starting point for loop rate. In the final system, the loop rate will be slower. Each data bit obtained at the 250 MHz rate was then replaced with a segment of 20 data bits (given the 5 GHz RTZ pulse rate). Two codes were used, corresponding to a single-level delta–sigma encoding so that a "1" was replaced by 14 RTZ pulses and a "0" was replaced by 10 RTZ pulses. This was required to minimize long runs of "0"s and "1"s in the final code which were generated if 20 and 0 RTZ pulses were used for the two codes. This choice of codes reduced the amplitude of the synthesized waveform to 20% of full scale in addition to the 50% amplitude used in the delta–sigma code generation leading to a final value of amplitude of 10% of full scale corresponding to a peak-to-peak voltage of 1.04 mV. The resultant FFT of the voltage waveform is shown in Fig. 9. The background level was of the order of 90 dBc. Further work is required to optimize the pulse patterns, particularly as the loop rate is reduced. It is expected that this optimization will allow the corresponding output to be increased above 10%.

IV. CONCLUSION

An optoelectronic pulse drive system has been developed to drive a JJA. The system has demonstrated synthesis of quantum-accurate voltage waveforms up to a frequency of 300 kHz. Use of a complementary pulse technique is required to allow the use of commercial optoelectronics components. The operational margin for optical pulse height has been investigated and found to be sufficient despite structure introduced in the pulse train by the complementary pulse technique. The design of the system is such that it can be used as the basis for a quantum voltage digitizer system via use of an FPGA to provide the pulse code. Results from an example of a code that could be used for a ratio of 1:20 loop to pulse rate provide proof of concept.

This paper will be further extended in two ways. First, the system will be developed to synthesize bipolar, larger voltage waveforms. To achieve this, two PDs will be used for opposing polarities. To generate larger voltages, JJAs with more junctions will be used and JJAs will also be combined in series by using multiple PDs. An advantage of this optoelectronic drive system is that a single optical drive signal can be split in order to drive several PDs that are all electrically isolated from the drive circuit and, therefore, have no need for compensating electronics. Improved pulse code patterns will be investigated to increase the signal amplitude. Second, the system will be combined with analog delta–sigma electronics such that the JJA output is feedback around a feedback loop and follows an input arbitrary voltage waveform, hence providing quantum-accurate digitization of the input waveform. Use of multilevel delta–sigma processing to encode the repeated sections of code is the subject of future work.

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