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Pulse driven Josephson voltage standard using modulated optical comb

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Abstract. We have performed an experiment to drive an overdamped superconductor-insulator-normal-insulator-superconductor (SINIS) Josephson junction array (JJA) with modulated current pulse trains, which are generated by modulated ultra short optical pulses. Averaged voltage outputs of the JJA have been systematically measured for various modulation patterns as a function of the bias voltage of an optical modulator. Quantized voltage steps has been clearly observed in accordance with modulation patterns under certain condition of the bias voltage of the optical modulator.

1. Introduction

Studies of ac voltage metrology based on Josephson digital-to-analog (D/A) converter has attracted considerable attention. The ultimate goal of those studies is to realize a primary ac voltage standard with fundamental accuracy protected by the Josephson frequency-voltage relationship. Several kinds of Josephson D/A converters are proposed so far. Among them a Josephson arbitrary waveform synthesizer (JAWS) has proved to be especially useful in an audio frequency range (10 kHz to 100 kHz) in many experiments [1, 2, 3, 4, 5].

The working principle of JAWS is basically similar to a portable audio player with a 1-bit D/A converter, in a sense that both of them generate 1-bit voltage pulse stream and use the same signal processing technique to reduce noise in the audio frequency range. A marked difference between them is the way to generate output voltage signals. In the case of an audio player, common semiconductor devices are used to generate voltage to drive headphones or speakers, because only relative voltage change is important. On the other hand, JAWS utilizes a Josephson junction array (JJA), which quantizes a current pulse to a voltages pulse whose integral with respect to time exactly equals to an integer multiple of $(\hbar/2e)$, because an absolute value of the signal is essentially important.

In order to generate current pulses injected into Josephson junctions, metrology institutes in European Union applied an intriguing method [6, 7, 8, 9]. Instead of using current pulses directly generated by a semiconductor device, they used optical pulses generated by a semiconductor laser. The optical pulses were delivered to a photo-diode on top of a cryoprobe at room temperature, where the optical pulses were turned into current pulses. The electrical pulse trains are transmitted to the JJA in a cryostat by a coaxial cable. This approach will be more attractive if the Optical/Electrical (O/E) converter is in a cryostat, since this removes the dispersive coaxial cables and reduces thermal flow. Bullzaccelli \textit{et al.} demonstrated optical triggering of a Josephson transmission line (JTL) using a Metal-Semiconductor-Metal photodetector (MSM-PD) embedded into the JTL device [10]. Voltage outputs of the JTL were observed...
in accordance with various modulation patterns up to 20.6 GHz, although the variation of modulation patterns were very limited in principle and cannot be applied to the JAWS.

We have attempted to drive a JJA with current pulses generated by triggering a photo-detector, which is located in the vicinity of the JJA with a decimated optical comb. Unlike ref.[10] an arbitrary modulation pattern is available with the help of a programmable pulse pattern generator. In this paper, first of all, the principle of our system is described in detail with experimental data. Next, we show evidence that the modulation method actually works quite well. Finally, experimentally obtained results were compared with theoretically expected values.

2. Experimental setup

The experimental setup to drive a JJA with optoelectronic pulse trains is schematically illustrated in Fig. 1. The key components of the system are the mode locked fiber laser, the LiNbO$_3$ optical modulator (LN modulator), the pulse pattern generator (PPG), the MSM-PD, and the JJA. The optical pulses are transmitted via an optical fiber to the MSM-PD installed in the vicinity of the JJA.

A commercial erbium-doped fiber-based femtosecond laser with a repetition frequency $f_{\text{rep}}$ of 49.752 MHz was utilized as an optical comb generator. The pulse width was about 100 fs, corresponding to a duty cycle of 100 fs/20 ns = $5 \times 10^{-6}$. The wavelength of the light was 1560 nm. The power was controlled by a neutral density filter (NDF). The polarization of the light was adjusted by a half wave plate (HWP), and then the beam is focused on the core of a single mode optical fiber by a lens. A frequency counter were used to measure the repetition frequency of the optical comb. The counter followed the optical coupler (Coupler 1) which guided 1% of the optical power to the counter. Optical power after the LN modulator was measured by a power-meter. The power-meter was placed after the optical coupler (Coupler 2) which spared 10% of LN modulator output power to the powermeter.

Unmodulated optical comb was decimated by means of a Mach-Zehnder type optical interferometer based on LiNbO$_3$. Output optical power can be controlled by applying appropriate dc bias voltage $V_{\text{bias}}$ and a modulation signal to the LN modulator. A commercial PPG was utilized in order to generate modulation signal.

A commercial InGaAs based MSM-PD, operating at wavelength below 1650 nm, was used as an O/E converter. The MSM-PD was placed in a can with an SMA (Sub Miniature type A) output. Although a dark current of the MSM-PD at room temperature was not small (7 µA at 10 V), it was reduced to a negligible level in liquid helium due to suppression of excited carriers at 4.2 K.

Superconductor-insulator-normal-insulator-superconductor (SINIS) Josephson junctions consisting of Nb/AIO$_x$/Al/AIO$_x$/Nb multilayers were fabricated by using a conventional Nb-junction technology [11]. The junction was composed of a Nb base electrode (200 nm), a lower Al layer (8 nm), a lower AIO$_x$ barrier, a middle Al layer (20 nm), an upper AIO$_x$ barrier, an upper Al layer (8 nm), and a
Nb counter electrode (125 nm). The upper and lower AlO$_x$ barriers were formed with the same oxidation conditions of the O$_2$ pressure and oxidation time, so that the junctions were nominally symmetric. Details of fabrication process is described elsewhere [12]. An array of 100 SINIS Josephson junctions was arranged in the center line of a 50 Ω coplanar waveguide. The Josephson junctions were located between a matching load of 50 Ω and ground in order to prevent common mode noise from contaminating the output waveform. The output voltage was filtered by part of the voltage taps formed as meanders.

Before pulse-drive experiments basic $I - V$ characterization was done. The critical currents $I_c$ s was 340 µA and the normal state resistance $R_n$ was 116 mΩ for the 100-junction array. A characteristic frequency $f_c$ estimated by the $R_n$ and $I_c$ become $f_c = 18.5$ GHz. The JJA characteristics were in good agreement with an RSJ model for small capacitance.

3. Results and discussion

Averaged output voltage of the JJA, $V_{out}$, was measured as a function of averaged optical power, $P_{out}$, of the optical comb by changing optical attenuation (Fig.2(a)). The result qualitatively agreed with that of a JJA with a higher $f_c$ [13]. Quantized voltage steps of $n = 0, 1, 2$ were clearly observed at multiples of about 10 µV, corresponding to frequency of 49.7 MHz multiplied by the junction number of 100.

For optical-pulse-modulation tests using LN modulator, the optical attenuator was adjusted so that averaged power of the optical comb was just below the upper edge of the 1st voltage step in Fig.2 (i.e., at around 175 µW) in order to maximize the voltage margin of the PPG. Optical output power of the LN modulator was then measured as a function of the dc bias voltage $V_{bias}$ of the LN modulator (Fig.2(b)). This curve, so called $V_n$ curve, exhibited a sinusoidal behavior with a period of 8.4 V. For example, when $V_{bias}$ was set to 0.7 V, the output optical power became 80 µW, resulting in averaged output voltage of 0 V. On the other hand, if $V_{bias}$ was set to 2.3 V, the output voltage was 10 µV because the optical power was within the first voltage step. If dc bias voltage is 0.7 V and voltage amplitude of modulation signal given by PPG is 1.6 V ($= 2.3$ V-0.7 V), a quantized voltage pulse pattern will be logically the same as the modulation pattern from the PPG.

In order to confirm that the modulation scheme described above works correctly, we have measured the averaged output voltage of the JJA, $V_{out}$, as a function of $V_{bias}$ of the LN modulator, instead of direct measurement of time- or frequency-domain signals. The voltage amplitude of PPG was fixed to 1.6 V
during the experiment. Results for five modulation pulse patterns are shown in Fig.3. They are periodic functions with a cycle of 8.4 V due to periodic nature of the \( V_\pi \) curve of the LN modulator. Each curve can be divided into 4 segments depending on the dc bias voltage of the LN modulator, as indicated by (i)-(iv) in Fig.3. Let us take a modulation pattern of 0x000F in the hexadecimal expression, i.e. 0000 0000 0000 1111 in the binary expression, for example. First, \( V_{\text{out}} \) is totally zero for all modulation pulse patterns when \( V_{\text{bias}} \) is in the segment (i), because the optical output power of the LN modulator is below the optical threshold of 110 \( \mu \)W regardless of the modulation signal as might be easily recognized in Fig.2. \( V_{\text{out}} \) displays a voltage step corresponding to the modulation signal of 0x000F in the segment (ii). Note that the rising edge of the voltage step in the segment (ii) appears at around \( V_{\text{bias}} = 0.4 \) V, not at around \( V_{\text{bias}} = 2.0 \) V which can easily be read from Fig.2. This is because in the former case the total bias voltage applied to the LN modulator is not 0.4 V but 2.0 V (=0.4 V [from DCVS] + 1.6 V [from PPG]), whereas in the latter case that is 2.0 V because PPG is off. In contrast to the first phase, \( V_{\text{out}} \) displays the plateau corresponding to the pulse pattern of 0xFFFF regardless of the modulation pulse pattern in the segment (iii). In this bias voltage range modulated optical power change within 130 – 175 \( \mu \)W, yielding undecimated quantized voltage pulse trains. With further increasing the bias voltage, the voltage step corresponding to a complement of the modulation pattern, i.e. 0x000F = 0xFFFF, is observed in the segment (iv). In this domain the LN modulator functions as an inverter due to negative slope of the \( V_\pi \) curve. Segment (i) appears again in the higher voltage range next to the segment (iv) due to the periodicity of the \( V_\pi \) curve.

\[
\begin{align*}
\text{Segment (i)} & \quad \text{Segment (ii)} & \quad \text{Segment (iii)} & \quad \text{Segment (iv)} \\
0x0000 & \quad 0x000F & \quad 0x0FF0 & \quad 0xFFFF
\end{align*}
\]

\( V_{\text{out}} \) in the bias voltage range of (ii) should increase linearly with increasing duty cycle of the modulation signal, defined by a ratio of number of “Hi”s to total bit number in a period. By contrast, \( V_{\text{out}} \) in the segment (iv) should linearly decrease with increase of duty cycle. In order to verify the precision of modulation, \( V_{\text{out}} \) were measured against duty cycle for various pulse patterns in the segment (ii) and (iv). Modulation signals used in this test was made up of 16 bits. Generated signals are square wave of 3.1 MHz (= 49.752/16 MHz) with duty cycle of \( n/16 \), where \( n \) is number of “Hi”, or “1”, in the modulation pulse pattern. As shown in Fig.4(a), experiments agree well with the calculation. Note that thermal emf values were subtracted assuming that they are constant during measurement for each pattern. Voltage difference between experimental values and theoretically expected values is shown in the inset to Fig.4(b). The voltage errors for all points are within almost 1 \( \sigma \) uncertainty bars of the order of 10 nV. In principle, over 500,000 level of voltage output up to about 10 \( \mu \)V, corresponding to voltage spacing of 0.02 nV, can be generated by modulating optical comb with PPG in the same way.

4. Conclusion
We have operated an overdamped Josephson junction array with current pulse trains triggered by optical pulse trains. A zero-crossing averaged voltage curve, showing quantized voltage plateaus at every 10 \( \mu \)V, has been measured to decide modulation conditions. Unmodulated optical pulse trains have been
decimated by a LN modulator with a PPG, averaged output voltage has displayed 4 phases depending on the dc bias voltage of the LN modulator. The output voltages corresponding to the modulation pattern show good agreement with theoretical values within 10 nV.

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Figure 4. (a) Averaged output voltages of the JJA in the segment (ii) and (iv) are plotted against the duty cycle of modulation signal. (b) Voltage differences between experimental and theoretical value. Solid- and open-circles indicate data for segment (ii) and (iv), respectively. The error bars correspond to 1σ type A uncertainties. Data for segment (iv) is shown with offset of +0.02 for clarity.