A new coding technique in serial data transmission and demodulation with Josephson junctions array

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Abstract. We have developed a coding technique to drive an overdamped Josephson junction array (JJA) using modulated optical pulses for voltage standard applications. Our system is composed of a multi-channel pulse pattern generator (PPG), a LiNbO$_3$ (LN) modulator with an electrical multiplexer (MUX), a photodiode (PD), and an over-damped JJA cooled with 4 K GM cryocooler. The modulated optical pulses are transmitted via an optical fiber to a PD that is installed close to the JJA on a cold stage, and they are then converted into an electrical current pulse train in order to drive the JJA. To avoid a problem in our LN modulator system, i.e., the duty-ratio dependence of the output pulse waveform, pseudo signals that maintain the duty ratio at approximately 50% are inserted in the original bit stream. We demonstrated that this technique is applicable for arbitrary return-to-zero (RZ) binary bit streams.

1. Introduction
Arbitrary waveform synthesis using overdamped Josephson junction arrays (JJA) has recently been increasingly investigated. The ultimate goal of those studies is to realize a primary ac voltage standard with fundamental accuracy guaranteed by the nature of Josephson junctions [1]. Pulse-driven-type voltage synthesizer using an overdamped JJA proposed by Benz et al. [2] is a promising device for obtaining arbitrary waveforms over a wide range from several tens hertz to several mega hertz without transition errors [4]. The generation of waveforms with an rms voltage of 275 mV and a noise floor of $-113$ dBc has already been demonstrated by NIST using an ac-coupling technique for two 6400-junction JJAs [4].

A waveform synthesizer using a pulse-driven JJA is a kind of a digital-to-analog converter (DAC). An input current pulse applied as digital data causes one switching (i.e., $2\pi$ phase leap) of each junction under a suitable condition. The optimum conditions under which an
input pulse causes the $2\pi$ phase leap are as follows [2]: $I_p \sim 2.6I_c$, $\tau \sim 1/2f_c$, where $I_p$ and $\tau$ are the pulse height and width, $I_c$ and $f_c$ ($= I_cR/\phi_0$) are the junction critical current and characteristic frequency, respectively, $R$ is the junction normal resistance, and the flux quantum $\phi_0 = h/2e \sim 2.07\text{ mVps}$. When the junctions switch, the quantized voltage pulse $V$ is produced at each junction such that $\int V\,dt = \phi_0$, which results in the generation of an accurate average analog voltage output. By suitably modulating the input digital data, we can obtain arbitrary voltage waveforms. The available frequency range of the output signals is limited by the record length of the PPG used and the bandwidth of the low-pass filters attached to the output terminals.

For the proper operation of pulse-driven JJAs, transmission of wideband pulse trains is one of the crucial matters. For example, dispersion of a pulse waveform due to the presence of long transmission lines between room-temperature (RT) and low-temperature environments narrows the operating margins of the JJAs. Enabling pulse-signal transmission using optical fibers, which we used in this study, is one of the useful solutions for solving the above problem. This solution allows us to achieve both low-dispersion pulse transmission and low-thermal inflow to a cryogenic environment, in addition to the generation of short pulses [5].

In this paper, we study the operation of an overdamped JJA used as an arbitrary waveform synthesizer driven by optical pulses. A technical problem caused by the auto bias control (ABC) of an optical modulator and its solution is described.

2. Experimental setup
The key components of our system are a 4-channel pulse pattern generator (PPG), a multiplexer with an electrical/optical (E/O) converter, and a mechanical cryocooler in which a uni-traveling-carrier photodiode (UTC-PD) and an over-damped JJA are contained (Fig.1). The UTC-PD is installed close to the JJA on the cold stage cooled with a 4 K GM refrigerator, enabling a 40 Gbps pulse data transmission to the cryogenic environment [6].

Binary bit data pattern are stored in the memories of the 4-channel PPG clocked at 10 GHz, and then converted to 40 Gbit/s optical pulse trains by the 4-channel MUX with an E/O converter. An optical amplifier and an optical attenuator are used to optimize the amplitude of the optical pulses. The modulated optical pulse trains are transmitted via an optical fiber to the UTC-PD, and are then converted into electric current pulse trains to drive the JJA. Averaged output voltage of the JJA was measure with a digital nano voltmeter. Synthesized waveforms were characterized by a high resolution digitizer with an input impedance of 1 MOhm. At the moment the output voltage is unipolar, because single optical channel is available.

As over-damped Josephson junctions, Superconductor (S) - normal metal (N) - Superconductor (S) (SNS) JJA chip was fabricated using an AIST NbN process [7]. The 480 SNS type Josephson junctions were arranged in the center line of a 50-Ohm coplanar waveguide to transmit high frequency pulse trains. A 5 mm × 5 mm JJA chip is flip-chip-bonded on a 16 mm × 16 mm carrier chip, and it is mounted on a wideband prober module placed on the cold stage.

3. Results and discussions
The averaged output voltage of the SNS array was measured at a sampling frequency $f_s = 2.5$ GHz as a function of the averaged optical power of the optical pulse trains by changing the optical attenuation. Hereafter, this curve is called as a $P - V$ curve. The modulation pulse paterns were used with 64-bit resolution, and are shown in Fig.2 in Hexadecimal expression. Since the output current pulse of the UTC-PD has negative polarity, the output voltage of the JJA is negative and unipolar. Quantized voltage steps of $n = -1$ and 0 were clearly observed when the averaged duty ratio of the pulse patterns were 48.4375%, 43.75% and 37.5%. The voltage
step values were consistent with the number of pulses per second and number of the Josephson junctions of 480.

However, voltage steps for \( n = -1 \) collapse for the pulse patterns with duty ratio below 35\%. Using an optical sampling oscilloscope we confirmed that our optical pulse generator works correctly only when averaged optical pulse were in the range between 35\% and 65\%. This is probably due to the malfunction of the auto bias controller installed in the MUX with E/O to suppress the effect of the drift of the modulation curve. This limitation of the duty ratio give rise to a serious problem, because the Return-to-Zero data patterns obtained for ac waveforms without dc component have a duty ratio of 25\%, while the bare Non-Return-to-Zero data have a duty ratio of 50\%.

This kind of strict limitation in a duty ratio is very common in high speed optical communication and it is necessary to use some kind of data modulation technique to guarantee the quality of the data transmission. For instance, the 64B/66B protocol is used in the optical ethernet to maintain the duty ratio as high as 50\%. However, these kind of protocols are not applicable in our case, because the decoders are too large to implement on a JJA chip.

To avoid above mentioned problem, we developed a new data coding method suitable for our JJA devices. The technique is made up of “over-sampling” and “insertion of short dummy pulse”. One of the modulation rules for over-sampling ratio of 4 is shown in Fig.3. As shown in Fig.3(b), short dummy pulses “1” are inserted in the modulated signal for the original data of “0”. The duration of the dummy pulse is determined so that it \((1/4f_c)\) is smaller than \(1/f_c\). By contrast, the duration of the succeeding “1”s in the modulated signal for “1” in the original data should always be greater than \(1/f_c\). Furthermore, the number of the dummy pulse have to be adjusted so that the averaged duty ratio is in the range between 35\% and 65\% to guarantee the proper operation of the optical pulse generator. Due to a pulse quantization mechanism of a JJ described in the introduction, dummy current pulse is quantized to zero by a JJ, while on the other hand succeeding “1” which is longer than \(1/f_c\) leads to a quantized voltage of \(h/2e\), as summarized in Fig.3(c).

In order to verified the validity of the new coding technique with dummy pulses measurement of the \(P-V\) curves were performed again for the pulse patterns whose duty ratio were originally below 35\% (Fig.4). In spite of such low duty ratios such as 31.25\% and 25\%, quantized voltage steps of \( n = -1 \) and 0 were clearly seen not only for short pulse pattern with 64 bit but also for a longer data pattern with 131072 bit/Channel, which is intended for the generation of a sine wave. The voltage step values agreed well with the pulse patterns and number of the Josephson junctions, indicating that the coding technique works properly.

Fig.5 shows a spectrum of a sine wave generated at \(f_{\text{sample}} = 2.5\) GHz. The measured frequency of the fundamental at 76.3 kHz agrees well with the value estimated by the clock frequency of the PPG (10.0 GHz) and the memory length of the PPG (131072 bit/Channel). The noise floor is as low as \(-75\) dBc. This results strongly support that the new coding technique functions well as we had intended.

4. summary
We are developing an arbitrary waveform synthesizer using an overdamped Josephson junction array driven by optical pulse trains. A new coding method based on the quantization properties of Josephson junctions has been developed in order to solve the problem associated with our LN modulator system which has something to do with the duty ratio of of the pulse pattern. Using this method, we succeeded in correct operation of the LN modulator for the optical-pulse-driven JJA system.
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Figure 1. A block diagram of the system for an optical-pulse-driven JJA. PPG, ABC, EDFA and UTC-PD stand for a pulse pattern generator, an auto bias controller, an Er-doped fiber amplifier and a uni-traveling-carrier photo diode, respectively.

Figure 2. Averaged output voltage of the JJA measured as a function of averaged power of optical pulse trains with various averaged duty ratio. The pulse patterns are expressed in Hexadecimal.
Figure 3. (a) Original data before modulation with sampling frequency of $f_s$. (b) The coding rule for each type of data. These patterns correspond to optical pulses. (c) Demodulated data obtained by a Josephson junction.

Figure 4. Averaged output voltage of the JJA measured as a function of averaged power of optical pulse trains. A waveform observed at an optical power of 14 mW is shown in the inset.

Figure 5. The spectrum of a single tone 76.3 kHz sine wave generated by a SNS array containing 480 JJs.