Optoelectronic generation and detection of single-flux-quantum pulses

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We report on the direct observation of a single-flux-quantum (SFQ) pulse. The response of a metal–semiconductor–metal (MSM) photodiode to a femtosecond laser pulse was used to switch Josephson junctions and to generate an SFQ voltage pulse on a superconducting microstrip line. The detailed shape of the pulse was measured optoelectronically, using a cryogenic electro-optic sampling system. The measured SFQ pulse had a width of 3.2 ps, an amplitude of 0.67 mV, and a total pulse area of 2.1±0.2 mV×ps, corresponding to the quantum of magnetic flux $\hbar/2e$. With larger excitation, multiple SFQ pulses were observed. Numerical simulations are shown to be qualitatively similar to our experimental results. © 1995 American Institute of Physics.

Superconducting circuits based on single-flux-quantum (SFQ) pulses provide a new family of digital electronics with ultrahigh speed and very low-power dissipation. This family of digital logic currently has a clock rate exceeding 10 GHz and is a promising technology for hundreds-of-gigahertz operation speed, much faster than any semiconductor logic.

In these circuits, an SFQ voltage pulse, the basic information “carrier,” is generated when a nonhysteretic Josephson junction is switched by a magnetic-flux quantum. The pulse area is quantized; the integral of the voltage over time is equal to one flux quantum, $h/2e$, or 2.07 mV×ps. The SFQ pulses are regularly generated, processed, and detected in many different superconducting circuits. In addition, a soliton fluxon propagating in a Josephson transmission line has been measured by a Josephson sampler, by means of the pulse convolution with the sampler’s internal response (of the order of a few picoseconds). However, because of its small amplitude and the picosecond time scale, an SFQ pulse has never been directly observed, i.e., having its voltage and temporal evolution accurately determined.

We have directly observed superconducting SFQ pulses. These time-domain measurements were based on an electro-optic (EO) sampling system with 200 fs temporal resolution and submillivolt sensitivity. In our experiments, a silicon metal–semiconductor–metal (MSM) photodiode was used as an optoelectronic switch. Its output is coupled to a two-Josephson-junction transmission line. The response of the MSM diode to a femtosecond laser pulse was shaped to SFQ pulses by these junctions, acting as a “pulse shaper.”

Sample chips were fabricated using conventional Nb technology. The MSM diode was made with an Al/Nb bilayer on n-type silicon with a detection area of 30×30 μm² and an electrode separation of 2 μm. The MSM diode was mounted in-line on a Nb superconducting microstrip line (SML) and connected to the two-junction pulse shaper, as shown in Fig. 1. Each junction of the pulse shaper had a critical current $I_c$ of 150 μA at 2 K and the McCumber parameter $\beta_c$ of 1.5. The inductance between junctions was estimated to be 6.5 pH. To generate SFQ pulses, the junctions were biased at $\sim 0.7I_c$, and the MSM diode was biased at 5 V and illuminated with blue light. By changing the light intensity, different switching amplitudes from the MSM diode were generated and subsequently fed into the pulse shaper. As a result, different numbers of SFQ pulses were generated.

The time-domain observation of SFQ pulses was made using an EO sampling system. In its cryogenic version, reflective sampling was made by attaching a lithium tantalate (LiTaO₃) crystal to cover the superconducting circuit. The crystal had a high-reflectivity (HR) dielectric coating facing the device under test (DUT). A titanium-doped sapphire mode-locked laser, with ~150 fs pulses, tuned to 800 nm, was used for the EO sampler. The frequency-doubled (blue) light penetrating the dielectric coating was used as the switching beam to activate the MSM diode mounted in-line on the DUT, as shown in Fig. 1. The fundamental light, serving as the sampling beam, passed through the LiTaO₃ crystal, experienced the refractive-index change caused by the fringe electric field from the SML, and was reflected by the HR coating to the analyzer. Both the switching and sam-

FIG. 1. Microphotograph of the experimental structure, showing an MSM photodiode coupled to a microstrip line and followed by a two-junction pulse shaper.
pling beams were focused by a single microscope objective and delivered through an optical window to the DUT, which was immersed in superfluid helium.

The detection process is noninvasive because only the fringe field of the microstrip line is probed. To convert the measured EO signal to the “real” voltage transient on the transmission line, the calibration process was accomplished using a passive SML that contained no Josephson junctions and was separated from the DUT by 300 μm. A known electrical signal was applied to the passive transmission line to determine the voltage scale factor. The sampling beam was then moved back to the DUT. Sensitivities at the two measurement points were assumed equal, justified by knowing that the crystal was in uniform contact with the chip to within 250 nm (as verified by interference fringes observed through the crystal).

Figure 2 shows a series of the measured results. The response of the MSM diode, i.e., the input signal of the pulse shaper, is shown in Fig. 2(a) to have a saw-toothed-like waveform. Responses of the pulse shaper to different input amplitudes are shown in Figs. 2(b)–2(d). As a comparison, simulated results using JSPICE are shown in Fig. 3. A waveform similar to the MSM diode response was used in these simulations, as shown in Fig. 3(a). Circuit parameters were chosen to approximate the experimental conditions. It is seen that measured and simulated results are in qualitative agreement.

For a certain range of light intensity, only one SFQ pulse was generated, as in Fig. 2(b) (solid line). The measured pulse had a width of ~3.2 ps and an amplitude of ~0.67 mV. The time-averaged integral of the measured SFQ pulse, as shown by the dashed line in Fig. 2(b), shows a total pulse content of 2.1±0.2 mV·ps, corresponding to a single quan-
tum of magnetic flux. To reduce the noise level down to subhundred microvolt, the trace presented in Fig. 2(b) represented ~15 min of data acquisition.

With a larger input signal, three SFQ pulses were obtained; the first two were closely placed and the third entered about 6 ps after the second, as indicated by arrows in Fig. 2(c). The time-averaged integral (dashed line) shows that the total content of pulses was ~6 mV×ps. For even larger input signals (e.g., the peak amplitude $I_p = 4.3I_c$), the output begins to acquire the overall shape of the input with Josephson junction pulsing superimposed, as is visible in Fig. 2(d). However, one SFQ pulse can still be clearly identified at the end of the transient [cf. Fig. 3(d)].

In conclusion SFQ pulses generated by switching non-hysteretic Josephson junctions have been directly observed by EO sampling techniques. The measurement system had a temporal resolution of 200 fs and a noise level down to sub-hundred microvolt. A single SFQ pulse, as well as multiple pulses, were generated by a two-junction pulse shaper, fed by the signal from an MSM photodiode. The measured single SFQ pulse had a pulse width of ~3.2 ps and a peak amplitude of ~0.67 mV, with a total pulse content of 2.1±0.2 mV×ps. Simulations using JSPICE were qualitatively in agreement with our experimental results.

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