Significant effort is current going toward the development of new hardware for neuromorphic computing. We have argued in a number of papers that large-scale artificial neural systems will benefit from light for communication combined with superconducting electronics for neural computation. In this work we present a thorough analysis of many aspects of the circuits required to make this new computing paradigm a reality. We are not aware of any work in the field of neuromorphic computing that presents as thorough and comprehensive a treatment of neural circuits, including synapses, dendrites, neurons, plasticity mechanisms, as well as analysis of scaling and power consumption. This work is original in that our group has invented this field of superconducting optoelectronic networks, and this paper is the most complete analysis of the concepts presented to date. A summary of these circuit concepts was previously published in the Journal of Applied Physics (JAP, 124, 152130 (2018)), but the paper submitted here is significantly more complete. It advances the field by presenting important details of circuits and systems that have extraordinary promise to enable very-large-scale neuromorphic systems.

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Reduced abstract:

Superconducting optoelectronic hardware has been proposed for large-scale neural computing. In this work, we expand upon the circuit and network designs previously introduced. We investigate circuits using superconducting single-photon detectors and Josephson junctions to perform signal reception, synaptic weighting, and integration. Designs are presented for synapses and neurons that perform integration of rate-coded signals as well as detect coincidence events for temporal coding. A neuron with a single integration loop can receive input from thousands of synaptic connections, and many such loops can be employed for dendritic processing. We show that a synaptic weight can be modified via a superconducting flux storage loop inductively coupled to the current bias of the neuron. Synapses with hundreds of stable states are designed. Spike-timing-dependent plasticity can be implemented using two photons to strengthen and two photons to weaken the synaptic weight via Hebbian and anti-Hebbian learning rules. In addition to the synaptic receiver and plasticity circuits, we describe an amplifier chain that converts the current pulse generated when a neuron reaches threshold to a voltage pulse sufficient to produce light from a semiconductor diode. This light is the signal used to communicate between neurons in the network. We analyze the performance of the elements in the amplifier chain to calculate the energy consumption per photon created. The speed of the amplification sequence allows neuronal firing up to at least 20\,MHz, independent of connectivity. We consider these neurons in network configurations. By modeling the physical size of superconducting optoelectronic neurons, we calculate the area of these networks.