PHYSICS

Pumping up the quantum

A superconducting amplifier is used to boost quantum signals

By **Andrew N. Cleland**

The detection of quantum signals from electronic devices requires exquisite instrumentation: The energy of a single photon from a cell phone, for example, is more than five orders of magnitude smaller than that of a visible-light photon. However, experiments on superconducting and semiconducting quantum bits require this level of sensitivity, as these quantum systems operate in the same band of frequencies as cell phones and microwave ovens. On page 307 of this issue, Macklin *et al.* (*1*) demonstrate a new kind of microwave amplifier that achieves the requisite sensitivity: a traveling-wave parametric amplifier, which uses a chain of superconducting amplifying elements, linked together in a nonlinear transmission line. This device can amplify microwave signals over a broad range of frequencies, while adding an extremely small amount of noise—close to the minimum amount of noise as set by quantum mechanics. This innovation represents an improvement over the previous amplifiers, which while achieving roughly equivalent performance in terms of quantum-limited noise (*2*), only work over a narrow range of frequencies and for very small microwave powers. The latter two limitations have now been substantially lifted.

The way a parametric amplifier works can be understood by using the example of a child on a swing. Sensing the motion of the swing, the child increases (amplifies) the motion by pumping with her legs, slightly increasing the motion of the swing on each pass. The swing is a type of resonator, storing the energy pumped into it by the child; this energy increases as long as the child's pumping action matches the motion of the swing. A peculiarity of the swing is its nonlinearity: As its amplitude of motion increases, its frequency falls, so the child must adjust the rate that she pumps her legs to stay in phase with the swing. If the child were replaced by a motor that pumped at regular intervals, matching the swing's frequency for small motions, the swing's amplitude would increase, and its frequency fall, only until it was out of phase with the motor's pumping action, thereby limiting the maximum amplitude of motion of the swing.

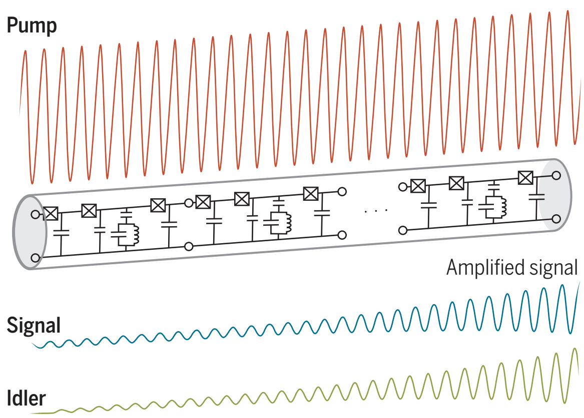
A similar problem is encountered in electrical resonant amplifiers. Here, however, the nonlinearity usually appears as a result of the amplification process itself: It is difficult to get sufficient amplification with just one resonator driven by a single amplifier. In high-power electronic amplifiers, such as the klystron (*3*), one solution is to use a traveling-wave amplifier, distributing the amplification process among a series of amplifiers positioned along the length of a transmission line. In a sense, the single motor on a swing is replaced by a series of motors on swings, where the motor-driven swings are linked together so that the motion of one swing is passed to its neighbor, and each motor slightly amplifies the motion as it is passed along the chain. This reduces the demand on each motor.

A challenge, then, is to make sure that the pumping action occurs at the proper phase of motion, so that each pump increases the motion. This can be achieved by careful design of the swings and the links between them. In addition to this design allowing much larger amplification, it also greatly increases the range of frequencies that can be amplified: The strongly linked resonant elements, such as the coupled swings, greatly increase the effective frequency range compared to that of a single swing. Macklin *et al.* take this concept, previously used for high-power electronics such as those in radio satellites or microwave transmitters, to demonstrate a quantum-limited microwave amplifier. Their amplifier relies on a linked chain of Josephson parametric amplifiers, placed at regular intervals along a superconducting transmission line, where each amplifier slightly increases the signal as it travels down the transmission line (see the figure).

The amplifier involves three transmitted microwave tones: a pump, provided by an external microwave source; the signal to be amplified; and, owing to the action of the parametric elements, a third signal, the "idler" (the signal and idler frequencies sum to twice the pump frequency). The pump tone acts with each nonlinear Josephson element to increase the energy in both the signal and idler as the three tones travel down the transmission line. A critical requirement was to work out how to achieve the requisite phase matching so that the three tones remain in the appropriate phase relation to achieve amplification—an especially difficult task because the wave speed of these tones changes with the amplitude of the waves. The prior theoretical development (*4*) showed that this could be done with an approach termed "resonant phase matching," involving a careful design of the nonlinear transmission line, including the amplifiers.

The immediate application for this new amplifier is in quantum measurement of microwave frequency qubits used for quantum computation. Measurement of quantum systems (such as quantum bits or qubits) needs to be fast and accurate both for correcting errors and for evaluating a result, and is presently a resource-intensive process. This amplifier, providing a means to measure many qubits in a short time, would reduce those resource requirements. More broadly, however, a simple, plug-and-play quantum-limited microwave amplifier with broadband response will simplify quantum measurements in general, providing a straightforward means to develop quantum electronic devices, and possibly for exploring the quantum measurement process itself. ■

Crank it up some more. Schematic of a Josephson traveling-wave parametric amplifier, with a pump tone (red) amplifying a signal (blue) and idler (green) as all three signals travel through the nonlinear transmission line.



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10.11263/science.aad0858

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