Broadband squeezed microwaves and amplification with a Josephson travelling-wave parametric amplifier

Squeezing of the electromagnetic vacuum is an essential metrological technique used to reduce quantum noise in applications spanning gravitational wave detection, biological microscopy and quantum information science. In superconducting circuits, the resonator-based Josephson-junction parametric amplifiers conventionally used to generate squeezed microwaves are constrained by a narrow bandwidth and low dynamic range. Here we develop a dual-pump, broadband Josephson travelling-wave parametric amplifier that combines a phase-sensitive extinction ratio of 56 dB with single-mode squeezing on par with the best resonator-based squeezers. We also demonstrate two-mode squeezing at microwave frequencies with bandwidth in the gigahertz range that is almost two orders of magnitude wider than that of contemporary resonator-based squeezers. Our amplifier is capable of simultaneously creating entangled microwave photon pairs with large frequency separation, with potential applications including high-fidelity qubit readout, quantum illumination and teleportation.
with respect to the current traversing them. This is the nonlinearity that enables parametric amplification. However, the relatively large circulating field in JPAs strongly drives the nonlinearity of individual junctions, leading to unwanted higher-order nonlinear processes and saturation that impact squeezing performance. Moreover, photon number fluctuations in the pump tone could lead to additional noise that reduces squeezing performance.

Several alternative approaches have been developed that address some of these limitations. For example, the impedance engineering of resonator-based JPAs has increased the bandwidth to the 0.5–0.8-GHz range, but these devices still have a dynamic range limited to ~10 to ~100 dBm and sub-gigahertz bandwidth. Alternative approaches using superconducting nonlinear asymmetric inductive elements (SNAILs) for both resonant and travelling-wave parametric amplification feature a higher dynamic range in the ~100 to ~90-dBm range. However, both architectures require a magnetic field bias, making them subject to magnetic-field noise. Furthermore, the resonant version remains narrowband, and one travelling-wave approach requires additional shunt resistors, which introduce dissipation and unwanted noise. So far, both approaches have been limited to 2–3-dB single-mode and two-mode squeezing.

High kinetic inductance wiring has been used in place of Josephson junctions to realize the nonlinearity needed for both resonant and travelling-wave parametric amplification with higher dynamic range. However, the relatively weak nonlinearity of the wiring translates to a much larger requisite pump power to operate the devices, and the travelling-wave parametric amplifiers have larger gain ripple due to impedance variations on the long (up to 2 m) lines. Furthermore, although a single-mode quadrature noise (variance) reduction has been demonstrated in narrowband resonant nanowire devices, their degree of squeezing in decibels has yet to be quantified using a calibrated noise source. Squeezing always involves two modes, a ‘signal’ and an ‘idler’. We note that there are finite bandwidths associated with measurement in experimental settings. To clarify the terminology used in this Article and draw comparison with other previous works, we define ‘two-mode’ as when the signal and idler are non-degenerate and their mode separation is much larger than the measurement bandwidth $|\omega - \omega_0| \gg B_{\text{meas}}$ and ‘single-mode’ as when the signal and idler are both nominally degenerate and within the measurement bandwidth $|\omega - \omega_0| \leq B_{\text{meas}}$.

In this Article, we demonstrate a broadband single-mode and two-mode microwave squeezer using a dispersion-engineered, dual-pump Josephson travelling-wave parametric amplifier (JTWA). As shown in Fig. 1b, the JTWA contains a repeating structure called a unit cell, comprising a Josephson junction (red) – a nonlinear inductor – and a shunt capacitor (orange). Because their physical dimensions (tens of micrometres) are small compared to the operating wavelength (tens of micrometres) are small compared to the operating wavelength (tens of micrometres) are small compared to the operating wavelength (tens of micrometres) are small compared to the operating wavelength (tens of micrometres) are small compared to the operating wavelength.
of millimetres) in the gigahertz regime, the junctions and capacitors are essentially lumped elements, constituting an effective inductance ($L$) and capacitance ($C$) per unit length. With the proper choice of $L$ and $C$, the lumped LC ladder network forms a broadband 30-50 GHz transmission line, circumventing the bandwidth constraint of the JPA\(^{25}\) and thereby enabling broadband operation. The use of many junctions—here we use more than 3,000—in a travelling wave architecture accommodates larger pump currents before any individual junction becomes saturated\(^ {26}\), resulting in a substantially higher dynamic-range device. Therefore, with proper phase-matching, the JTWA has the potential to generate substantial squeezing and emit broadband entangled microwave photons through its wave-mixing processes.

Like a centrosymmetric crystal, the JTWA junction nonlinearity features a spatial-inversion symmetry (in the absence of a d.c. current) that results in $\chi^{(3)}$-type nonlinear electromagnetic interactions. These support both degenerate-pump four-wave mixing (DFWM) and non-degenerate-pump four-wave mixing (NDFWM).

As shown in Fig. 1c, the DFWM process \((2\omega_s = \omega_i + \omega_i)\) converts two frequency-degenerate-pump photons \((\omega_i)\) into an entangled pair of signal \((\omega_s)\) and idler \((\omega_i)\) photons. When $\omega_s = \omega_i$, energy conservation places the idler photon at a different frequency than the signal photon. This leads to two-mode squeezed photons and entanglement. However, DFWM has two drawbacks when considering single-mode squeezing. In contrast, we use here (Fig. 1d) a NDFWM process \((\omega_s + \omega_i = \omega_i + \omega_i)\) that generates both single-mode and two-mode squeezed states far from the pump frequencies $\omega_i$ and $\omega_s$. To do this, we introduce a JTWA that uses two pumps and dispersion-engineering to achieve the desired NDFWM interaction.

The dual-pump JTWA is fabricated in a niobium trilayer process on 200-mm silicon wafers. It exhibits a meandering geometry of its nonlinear transmission line with 3,141 Josephson junctions and shunt capacitors (Fig. 1e). These are parallel-plate capacitors with silicon dioxide as their dielectric material. In addition, the JTWA features two sets of interleaved phase-matching resonators, one (purple) at $\omega_1 = 2\pi \times 5.2$ GHz and the other (blue) at $\omega_2 = 2\pi \times 8.2$ GHz (Fig. 1f). The phase-matching resonators comprise lumped-element parallel-plate capacitors with niobium pentoxide dielectric and meandering geometric inductors. As shown in Fig. 2a, the undriven JTWA transmission $S_{11}$ is normalized with respect to the radiofrequency (RF) background of the experimental set-up, utilizing a pair of microwave switches for signal routing (inset). The transmission characterization informs us of important JTWA parameters, including the frequency-dependent loss, and the frequencies and linewidths of the phase-matching resonators, which guide us in choosing the pump frequencies.

Pumping the JTWA at two angular frequencies $\omega_{1,2}$ generates parametric amplification that satisfies the energy conservation relation $\omega_s + \omega_i = \omega_i + \omega_i$ and leads to the desired single-mode and two-mode squeezing. However, NDFWM also creates unwanted photons through the frequency conversion process $|\omega_i - \omega_i| = |\omega_1 - \omega_2|$, where $\omega_i$ is an extraneous idler angular frequency. This unwanted by-product does not participate in the desired two-mode squeezing, but rather, it is effectively noise that undermines squeezing performance. Fortunately, these unfavourable conversion processes are susceptible to phase mismatch and can be effectively reduced through dispersion-engineering for a wide range of pump powers.

The efficiency of parametric amplification is determined by momentum conservation, that is, phase-matching\(^ {25}\). To this end, we define a phase-mismatch function for the parametric amplification (PA) process associated with NDFWM:

$$\Delta k_{PA}^{(2)} = \frac{1}{2} \left( 2 \beta_1^2 + 2 \beta_2^2 \right) \left( k_1 + k_2 - k_i - k_i \right) - \beta_1^2 k_1 - \beta_2^2 k_2. \tag{1}$$

where $k_i$ and $\hbar$ are the Boltzmann and reduced Planck constants, respectively. For example, $T_{sys}$ from the output of the JTWA at 30 mK in the
dilution refrigerator to the room temperature detectors is ~2.5 K at 6.7037 GHz, corresponding to a measurement efficiency of $\eta_{\text{meas}} \approx 6\%$.

By accounting for the gain and loss in the entire measurement chain, we determine an 'input-referred' noise at the JTWPA reference plane. See Supplementary Information for details on the calibration methods and results.

We first characterize the single-mode squeezed vacuum of the dual-pump JTWPA. To do this, we apply vacuum to the JTWPA input using a cold 50-Ω resistive load. We measure and compare the output field of the JTWPA for two cases: (1) the output with both pumps off (that is, vacuum) and (2) the output with both pumps on (that is, squeezed vacuum). In both cases, the JTWPA output field propagates up the measurement chain to a room-temperature heterodyne detector comprising an IQ mixer that downconverts the signal into its in-phase (I) and quadrature (Q) components at 50 MHz. These two components are then sampled using a field-programmable gate array (FPGA)-based digitizer with a sampling rate of 500 MS$^{-1}$ (S, sample). The components are then digitally demodulated to obtain an I–Q pair from which one can derive the amplitude and phase of (S, sample). The components are then digitally demodulated to obtain an I–Q pair from which one can derive the amplitude and phase of (S, sample). The components are then digitally demodulated to obtain an I–Q pair from which one can derive the amplitude and phase of (S, sample). The components are then digitally demodulated to obtain an I–Q pair from which one can derive the amplitude and phase of (S, sample).

To acquire I–Q pairs, the pumps—and thus the squeezing—are periodically switched on and off with a duration of 10 μs each. For each 10-μs acquisition, only the inner 8 μs is digitally demodulated to eliminate sensitivity to any turn-on and turn-off transients. The 8-μs signal is integrated, corresponding to a measurement bandwidth $B_{\text{meas}} = 125$ kHz, and yields a single I–Q pair. We interleave the squeezer-on and squeezer-off acquisitions to reduce sensitivity to experimental drift between the measurements. When the squeezer is off, we extract an isotropic Gaussian noise distribution for the vacuum state with variance $\Delta X_{\text{SQZ,off}}^2$. When the squeezer is on, the squeezed vacuum state exhibits an elliptical Gaussian noise distribution as shown in Fig. 3a. In total, we acquire six million I–Q pairs to reconstruct each histogram. We then extract the variance along the squeezing axis $\Delta Y_{\text{SQZ,off}}^2$ and along the anti-squeezing axis $\Delta X_{\text{SQZ,off}}^2$, Comparing the values $\Delta X_{\text{SQZ,off}}^2$ and $\Delta X_{\text{SQZ,off}}^2$ to the vacuum level $\Delta X_{\text{SQZ,off}}^2$ along with the measurement gain and efficiency enables us to determine the degree of squeezing and anti-squeezing, respectively (see Supplementary Information for further details on the measurement protocol).

The squeezing process is sensitive to the power of both pumps due to the desired phase-matching condition for parametric amplification (for example, $\Delta k_{\text{PA}} \approx 0$ in equation (1)) and also residual parasitic processes such as frequency conversion. To maximize the degree of squeezing, we perform a coarse measurement of the $\Delta X_{\text{SQZ,off}}^2$ (plotted relative to vacuum) as a function of pump powers. This enables us to empirically identify the pump powers $P_1$ and $P_2$ that correspond to higher squeezing levels. For six such near-optimal values (the six different colours in Fig. 3d), we carry out finer scans of squeezing, anti-squeezing and parametric gain as a function of $P_1$ for fixed $P_2$. Accounting for the measurement efficiency $\eta_{\text{meas}}$ at the output, we extract a squeezing level of ~11.35 to 15.7 dB and an anti-squeezing level of 15.7 to 15.7 dB at the optimal pump conditions, comparable with the best performance demonstrated by resonator-based squeezers in superconducting circuits18,42,43,44,45.

Squeezing performance is sensitive to dissipation (loss), which acts as a noise channel. Within our JTWPA, loss primarily originates from defects—modelled as two-level systems (TLSs)—within the plasma-enhanced chemical-vapour-deposited (PE-CVD) SiO$_2$ dielectric used in the parallel-plate shunt capacitors. Previous studies have shown a quality factor $Q=10^3$ associated with this dielectric in the single-photon regime, observed at low power and low temperature. In this limit, the TLSs readily absorb photons from the JTWPA and cause relatively high loss.

We observe high levels of squeezing despite the use of such lossy materials in the JTWPA. We conjecture that the reason for this is TLS saturation. At sufficiently high powers (large photon numbers), the TLSs saturate and the loss is reduced17. We can understand the net impact of TLSs on squeezing performance by considering the JTWPA to be a cascade of individual squeezers. The amount of added squeezing becomes position-dependent and increases with the increased gain at the output end. The TLSs are also distributed along the JTWPA, and they become saturated towards the output end due to the larger number of photons associated with the higher gain. Therefore, the impact of loss on squeezing performance is reduced towards the output where the marginal squeezing is the largest15. As a result, we expect loss saturation at large signal gain to improve squeezing performance, as we observe in our experiment (Fig. 3d at higher pump power $P_2$).
To verify this conjecture, we independently measure the JTWPA loss as a function of photon number by varying the JTWPA temperature. The loss at small thermal photon numbers (<50 mK) is around −5 dB. This reduces to −1 dB for large photon numbers (>800 mK). These two limits are shown as dashed lines using a constant-loss model in Fig. 3d. For low pump power $P_2$, our data are closer to the −5-dB line. At higher powers, where we see maximal squeezing, the data are more consistent with the −1-dB line corresponding to saturated TLSs. We then use numerical simulations to calculate the photon number in the JTWPA from its input to its output. The photon number is converted to loss from the independent loss-temperature measurement, and we plot the corresponding squeezing due to this distributed loss (solid line).
It starts at $-5\,\text{dB}$ for low powers, and reduces toward $-1\,\text{dB}$ at high powers due to loss saturation. The high degree of squeezing observed in this device is consistent with the loss saturation model to within $-1\,\text{to}\, -2\,\text{dB}$ at high powers. (See Supplementary Information for more details.) At intermediate powers, the agreement is not as good. This is probably due to our optimizing for maximum squeezing at high pump powers. Parasitic processes that are largely absent at high powers may not be completely suppressed at intermediate powers. There is ongoing research to better understand and suppress these unwanted modes\textsuperscript{39}, but this is outside the scope of this Article.

Using the same optimized pump configuration, we generate and characterize two-mode squeezed vacuum as a function of the frequency separation $\omega_s - \omega_i$ between the two modes. We switch to a dual-readout configuration\textsuperscript{30} that simultaneously demodulates the signal and idler using two separate FPGA-based digitizers, circumventing bandwidth limitations of the digitizer and other components in the experiment, such as IQ-mixers, low-frequency amplifiers and so on. We directly measure up to a separation of 373 MHz with the maximum squeezing of $-9.54\pm 1.11\,\text{dB}$, an average squeezing of $-6.71\,\text{dB}$, and an average anti-squeezing of $16.12\,\text{dB}$. The noise characterization method limits the measurement efficiency calibration to a frequency range of $500\,\text{MHz}$, and therefore we cannot directly calibrate the degree of squeezing beyond this range. Nonetheless, squeezing is expected to continue beyond 500 MHz (ref.\textsuperscript{46}). As shown in Fig. 4d, we characterize the variance change between the squeezed and the vacuum quadratures. Below 373 MHz, the results are consistent with the squeezing measured in Fig. 4c. Above 373 MHz, the JTWA exhibits a consistently low variance out to 1,500 MHz, beyond which we are again limited for technical reasons, in this case, by the onset of a filter roll-off. Because the signal and idler photons propagate at different frequencies, frequency-dependent variations of the loss and nonlinear processes can lead to frequency-dependent two-mode squeezing performance\textsuperscript{38}. However, based on the flat and broadband gain profile observed in our JTWA, we infer consistent squeezing levels out to 1.5-GHz total signal-to-idler bandwidth, and net squeezing out to 1.75-GHz total signal-to-idler bandwidth. These results represent an almost two-orders-of-magnitude increase in two-mode squeezing bandwidth compared to conventional resonator-based squeezers\textsuperscript{9,11,31,41–43}.

In conclusion, we have designed and demonstrated a dual-pump JTWA that exhibits both phase-preserving and phase-sensitive amplification, and both single-mode and two-mode squeezing. We have measured 20-dB parametric gain over more than 3.5 GHz of total instantaneous bandwidth (1.75 GHz each for the signal and idler) with a 1-dB compression point of $-98\,\text{dBm}$. This gain performance is comparable with the single-pump JTWA, yet it features minimal gain ripple and gain roll-off within the frequency band of interest. This advance alone holds the promise to improve readout of frequency-multiplexed signals\textsuperscript{46}. In addition, the favourable performance of this device enabled us to measure a 56-dB phase-sensitive extinction ratio, useful for qubit readout in quantum computing and phase regeneration in quantum communications. We have also achieved a single-mode squeezing level of $-11.35\pm 1.60\,\text{dB}$, and two-mode squeezing levels averaging $-6.71\,\text{dB}$ with a maximum value of $-9.54\pm 1.11\,\text{dB}$ measured directly over 400 MHz and extending to over more than 1.5-GHz total bandwidth (signal to idler frequency separation). The results enable direct applications of the JTWA in superconducting circuits, such as suppressing radiative spontaneous emission from a superconducting qubit\textsuperscript{39} and enhancing the search for dark-matter axions\textsuperscript{41}.

We have observed high levels of squeezing, despite the presence of dielectric loss from the SiO\textsubscript{2} capacitors, which we attribute predominantly to distributed TLS saturation in the high-gain regions of our JTWA. Nonetheless, squeezing performance can be further improved by introducing a lower-loss capacitor dielectric. Performance can also be improved by exploring distributed geometries and Floquet-engineered JTWPAs that reduce the impact of unwanted parasitic processes\textsuperscript{39}.

The broad bandwidth and high degree of squeezing demonstrated in this device represent a resource-efficient means to generate multimode, non-classical states of light with applications spanning qubit-state readout\textsuperscript{35,47}, quantum illumination\textsuperscript{38,49}, teleportation\textsuperscript{29,34,50} and quantum state preparation for continuous-variable quantum computing in the microwave regime\textsuperscript{45,52}. In addition, the technique of using dispersion-engineering to phase-match different nonlinear processes can be extended to explore dynamics within superconducting
Josephson metamaterials with engineered properties not otherwise found in nature.

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41567-022-01929-w.

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Data availability
The data supporting the findings of this study are available from the corresponding author upon reasonable request and cognizance of our US Government sponsors who funded the work.

Code availability
The code used for the analyses is available from the corresponding author upon reasonable request and with the permission of the US Government sponsors who funded the work.

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Author contributions
J.Y.Q., K.P.O., I.S. and W.D.O. conceived the experiment. J.Y.Q., K.P.O., S.G. and W.D.O. designed the experimental procedure. J.Y.Q. designed the devices and conducted the measurements with assistance from B.K., B.L., Y.S. and P.K. J.Y.Q. analysed the data with assistance from A.G., K.P.O. and W.D.O. A.G. and K.P. provided theory support. J.Y.Q., T.P.O., K.P.O. and W.D.O. wrote the manuscript. V.B., G.C., D.K., A.M. and B.M.N. performed sample fabrication. J.Y., M.E.S., T.P.O., I.S., S.G., K.P.O. and W.D.O. supervised various aspects of the project. All authors discussed the results and commented on the manuscript.

Competing interests
The authors declare no competing interests.

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