A gate-tunable graphene Josephson parametric amplifier

With a large portfolio of elemental quantum components, superconducting quantum circuits have contributed to advances in microwave quantum optics. Of these elements, quantum-limited parametric amplifiers are essential for low noise readout of quantum systems whose energy range is intrinsically low (tens of μeV). They are also used to generate non-classical states of light that can be a resource for quantum enhanced detection. Superconducting parametric amplifiers, such as quantum bits, typically use a Josephson junction as a source of magnetically tunable and dissipation-free non-linearity. In recent years, efforts have been made to introduce semiconductor weak links as electrically tunable non-linear elements, with demonstrations of microwave resonators and quantum bits using semiconductor nanowires, a two-dimensional electron gas, carbon nanotubes and graphene. However, given the challenge of balancing non-linearity, dissipation, participation and energy scale, parametric amplifiers have not yet been implemented with a semiconductor weak link. Here, we demonstrate a parametric amplifier leveraging a graphene Josephson junction and show that its working frequency is widely tunable with a gate voltage. We report gain exceeding 20 dB and noise performance close to the standard quantum limit. Our results expand the toolset for electrically tunable superconducting quantum circuits. They also offer opportunities for the development of quantum technologies such as quantum computing, quantum sensing and for fundamental science.

In Fig. 1a, we present the schematic of the designed parametric amplifier. The graphene Josephson junction is embedded at the voltage node of a half-wave microwave resonator with resonant frequency $\frac{\omega_0}{2\pi} = 6.44$ GHz (measured experimentally in the absence of the junction; Extended Data Fig. 1 and Supplementary Information). It provides the lossless non-linearity required to perform wave mixing and necessary for a low noise amplification process.

In Fig. 1b, we present the d.c. resistance of the device as a function of the gate voltage ($V_g$) and bias current ($I_b$). At low d.c. bias current, the device resistance vanishes and a Josephson supercurrent can flow in the graphene. Above the critical current $I_c$, dissipation kicks in and, as a result, we observe a non-zero differential resistance. We observe that the critical current strongly depends on the gate voltage and can be varied from 100 nA up to more than 1.3 μA. Such large critical current...
and the value of the $R_n \times I_c$ product ($R_n \times I_c \approx 1.4 \Delta$, where $R_n$ and $\Delta$ are the normal state resistance and the induced superconducting gap; Extended Data Fig. 2 and Supplementary Information) prove the high quality of the junction.

We also observe that the gate voltage modifies the microwave resonance frequency (Fig. 1c) that is measured with a vector network analyser (VNA) in the low power limit. For gate voltages corresponding to a high critical current, the frequency is close to the measured bare resonance frequency $f_0 = \frac{\Phi_0}{2 \pi L_0} = 6.44$ GHz. For lower critical currents, the frequency is reduced. This is a direct consequence of the relationship between the critical current and the Josephson inductance $L_J$. Assuming for simplicity a sinusoidal current phase relation and zero phase bias across the junction, we have $I_J = \frac{\Phi_0}{2 \pi c}$, where $\Phi_0 = \frac{h}{2e}$ is the magnetic flux quantum. A modulation of $I_d$ with $V_g$ thus translates into a modification of $I_J$ resulting in a change of the resonance frequency:

$$\omega_c(V_g) = \frac{1}{\sqrt{R_0 + I_d(V_g)L_0}},$$

where $L_0$ is the resonator inductance in the absence of the Josephson junction and $C$ the total capacitance.

In Fig. 1d, we compare the prediction of the resonance frequency given by this simple equivalent lumped element model with its experimental determination using microwave measurements (Supplementary Information), showing a good agreement between the two. The discrepancies at low frequencies are attributed to an underestimation of the critical current in the d.c. experiment, which rather measures the switching current and thus overestimate the Josephson inductance. At high frequency, on the other hand, the mismatch can be attributed to deviations of the current phase relation from its assumed sinusoidal form. In this region, our data indicate a larger inductance than the one predicted by the critical current (Supplementary Information).
To model the behaviour of our device, we use the following non-linear Hamiltonian, typical for such superconducting circuits with an embedded Josephson junction\(^2\):

\[
H = \hbar \omega_c A^\dagger A + \frac{K}{2} (A^\dagger A)^2
\]  

(1)

where \(\omega_c\) is the angular resonance frequency in our case can be tuned with \(V_c\). \(K\) is the Kerr non-linearity, and \(A\) (respectively \(A^\dagger\)) is the annihilation (respectively creation) operator of resonator photons. The resonator presents some internal losses (rate \(2\gamma_L\)) and is coupled to an input/output port for measurement (coupling rate \(2\gamma\)). We also include a non-linear loss term, in the form of two photon losses (rate \(2\gamma_P\))\(^2\).

The full non-linear response of the system can then be calculated using input–output theory\(^2\) (Supplementary Information) showing a good agreement with the experiment (Fig. 2b). This allows us to extract the parameters of our non-linear resonator (Fig. 2). We note that the agreement between the model and the experiment depends on the gate voltage. For some gate voltages, we see that the model is not well suited to describing the system (Supplementary Information). We can formulate several hypothesis to account for this. First, this could come from the fact that higher order terms of the non-linearity are neglected in the model. Another possibility could be that the model assumes a sinusoidal current phase relation. With a non-sinusoidal current phase relation, one would need to include additional terms in the non-linearity, in particular a cubic term that could have a contribution comparable to the quartic one. Such analysis nevertheless goes beyond the scope of the current study. Finally, the presence of non-linear losses in the device is only included to first order. The exact power dependence of the losses is likely to be more complicated, and a more realistic model should be developed to take into account the detailed nature of the non-linear losses.

The estimated Kerr non-linearity in the device is weak, with \(|K|/\omega_0 \sim 10^{-4}\), which is typical for Josephson parametric amplifiers\(^1\). Finally, above a threshold power, the resonator bifurcates and enters a bistable regime, characteristic of such a non-linear circuit.

We will now focus on the regime of interest for parametric amplification that is slightly below bifurcation. Here, two signals are sent to the input of the device: a strong pump tone (frequency \(f_p\)) and a weak probe tone (frequency \(f_s\)), whose reflection is measured with a VNA. Both signal frequencies are chosen close to the resonance frequency of the resonator, and we have the relation \(2f_p = f_s + f_r\), where \(f_r\) is the frequency of the complementary idler mode. We are thus in a four-wave mixing scheme of amplification, which is the one expected from the Hamiltonian in equation (1). In Fig. 3a, we see the effect of the pump on the magnitude of the reflection coefficient; in the presence of the pump, the probe signal is amplified by as much as 22 dB. This is the signature of parametric amplification. Amplification is present in a small frequency range near the pump frequency, limited by the resonator bandwidth. We extract a gain-bandwidth product of 33 MHz, which is typical for resonant Josephson parametric amplifier and mainly set by the coupling to the measurement port. The slightly larger gain-bandwidth product than the one that could be inferred from the system parameters (Fig. 2) comes from a small change of setpoint between the two measurements.

In Fig. 3a, we compare the experimentally measured gain with the one predicted by the input–output model using the parameters extracted from the one-tone measurement (Fig. 2). We see that the gain profile is qualitatively described by the formalism of Josephson parametric amplifiers\(^2\) (Supplementary Information, for more details about the modelling of the gain).

In a resonant Josephson parametric amplifier, amplification can typically be achieved only in a narrow frequency range close to the resonance frequency of the superconducting resonator. In our device, the resonance frequency can be tuned with a simple gate voltage as we...
reported in Fig. 1. We now explore the possibility to realize amplification in a broad frequency range and present the main result of this work. In Fig. 3b, we show gain profiles measured across the full range of tunability of the resonance frequency. For each frequency, set by a chosen $V_p$, pump frequency and power are optimized accordingly. We see that we can have a large gain (>15 dB) in a frequency range of about 1 GHz, that is, more than 100× the bandwidth of the amplifier. This gives interesting perspectives for qubit readout as the amplifier could be used to selectively address superconducting circuits at different operating frequencies by choosing the gate voltage. A gate voltage tuning has advantages compared to traditional magnetic flux tuning obtained in a superconducting quantum interference device as the local character of the electrical control will suppress crosstalk issues between different parts of the device. But such advantage will really materialize when fast gate voltage tuning of the amplifier can be demonstrated with the use of an efficient gating design and standard large bandwidth control techniques.

Variations in the apparent gain and deviations from an ideal Lorentzian shape are attributed to non-optimal pump parameters that can come from gate voltage instability (Supplementary Information). Nevertheless, maximum gains are expected to be reduced when the graphene Josephson junction non-linearity is not optimal, for instance, too large, close to the Dirac point, that is, at low frequency. We also observe that the non-linear losses seem to increase at high frequency, above 6.2 GHz, which could explain the lower gains in this region. While identifying the exact mechanism to explain the losses would require further investigations, it is possible that it comes from the reduced non-linearity at higher frequency. The reduction of the non-linearity imposes that a larger working power is necessary to reach gain. Such larger working power, which in a simple picture means an exploration of the current phase away from zero phase, could be the reason of the apparent larger losses.

Having demonstrated large gain and tunability, we now turn to two essential characteristics of a superconducting parametric amplifier: dynamic range and noise. The dynamic range indicates the input power that can be sent to the amplifier before the gain is appreciably reduced. To measure it experimentally, we measure the gain as a function of probe power for fixed frequency and pump power. In Fig. 4a, we see that the gain is reduced by 1 dB for an input power of −123 ± 3 dBm: this is the 1 dB compression point $P_{\text{comp}}$ for our device. Such a value is comparable to the best values obtained with a single Josephson junction Josephson parametric amplifier (JPA)\cite{note2}. It is intrinsically related to the junction non-linearity, critical current and the exact resonator design. This can be improved in future realizations by using arrays of junctions with larger critical currents\cite{note2}.

The noise of a measurement chain designed to measure very low microwave signals is one of its key characteristics. As such, amplifiers in this chain, and especially the first one, which will often determine the noise figure of the full chain, should add as little noise as possible. Quantum mechanics states that at least half a photon of noise, that is, an energy of $\frac{\hbar \omega}{4}$, will be added for each additional mode involved in the amplification process. In a perfect Josephson parametric amplifier, working in a phase-preserving mode, one can then expect a minimal added noise level of $\frac{\hbar \omega}{4}$ because of the presence of the idler mode. This is the standard quantum limit (SQL) and corresponds to a noise temperature of about 145 mK at a frequency of 6 GHz.

We have seen previously that our device presents some internal losses, especially at strong pump power (non-linear losses) that means that energy is transferred to other modes. In principle, this coupling to other modes, if large enough, could degrade the noise figure of the amplifier as these modes will inject their vacuum noise into the amplifier\cite{note2}. In this case, the resulting noise is expected to be increased by a factor $\frac{P_{\text{tot}}}{P_1}$, where $\gamma_{\text{tot}}$ is the total internal loss rate. In our case, considering the internal losses of the device, we thus expect this mechanism to enhance the noise by about 10% above the SQL.

We measure the noise of the amplifier using a shot noise tunnel junction (SNTJ), which serves as a self-calibrated broadband noise source when voltage-biased (see Extended Data Fig. 3 and Supplementary Information, for details about the setup) and replaces the VNA input tone. The broadband SNTJ output amplified by the device, and we measure the resulting signal with a spectrum analyser. Studying the power spectral density of the output signal as a function of the SNTJ bias voltage, we are able to extract, for each frequency, the system gain and the noise added by the system (Supplementary Information). In Fig. 4b,c, we present the frequency dependence of the fitted gain and added noise, when the amplifier is set to operate at a centre frequency of 6.13 GHz. We see that there is a clear anticorrelation between the two. When the gain of the parametric amplifier is low, the noise added by the system is, as expected, close to 15 photons. It is limited by the noise of the high electron mobility transistor (HEMT) amplifier thermalized at 4 K and additional losses in the system. When the gain of the amplifier increases, getting closer to the pump frequency, the system added noise decreases dramatically and reaches a value close to the SQL. The fact that the full system does not reach the SQL is mainly due to the limited gain in the accessible measurement range (Extended Data Fig. 4 and Supplementary Information). Because the setup does not allow to measure the
noise very close to the pump frequency, the gain is limited to about 15 dB, which is not enough to overcome the HEMT noise on the next amplification stage. We can thus conclude that our graphene-based Josephson parametric amplifier adds a minimal amount of noise, set by quantum mechanics, which is comparable to the state of the art of quantum-limited amplifiers. In this regard, it compares favourably to travelling wave parametric amplifiers. In such amplifier, which has the advantage of intrinsically presenting a very large amplification bandwidth, the reported noise are typically limited to about twice the SQL.

In conclusion, we have demonstrated a Josephson parametric amplifier using an electric field tunable Josephson junction made of graphene. The amplification bandwidth of the device is tunable over about 1 GHz with a simple electric field in addition to presenting a gain >20 dB and noise close to the SQL. This experimental demonstration of a gate-tunable semiconductor weak-link Josephson parametric amplifier opens interesting perspectives for different amplification schemes. For example, pumping the gate voltage at twice the signal frequency would modify the critical current and thus directly modulate the kinetic inductance. In practice, such a scheme should produce a three-wave mixing amplification process, similar to flux pumping in superconducting quantum interference device-based Josephson parametric amplifiers. The three-wave mixing process, which has the advantage of frequency separation between signal and pump, could also be observed in graphene-based Josephson parametric amplifier using other strategies. The possibility to bias the junction with a d.c. current, as is demonstrated in this work, could naturally give access to the non-linearity necessary to achieve three-wave mixing. In addition, in Josephson junctions presenting a non-sinusoidal current phase relation, which has been reported in graphene, three-wave mixing terms are present even at zero d.c. current bias and could be directly used. Together with the recent developments regarding qubits and bolometers and the use of van der Waals materials in superconducting quantum circuits, the demonstration we report here for quantum-limited amplifiers, and the related work of Sarkar et al., position semiconductor-based Josephson junctions as key elements for future integrated superconducting quantum circuits.

**Online content**
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Methods

Devices fabrication
We use a van der Waals heterostructure made of graphene encapsulated in hexagonal boron nitride (h-BN), connected to two superconducting leads (Ti/Al) to build the Josephson junction. h-BN encapsulation and one-dimensional side contacts ensure high charge carrier mobility and low contact resistance that are both needed for reaching large critical currents. The h-BN encapsulated graphene stacks were made using a polymer-free assembly technique on a high-resistivity Si substrate. Devices were processed with two steps of e-beam lithography (80 kV) using positive resists (poly(methyl methacrylate)) and an additional layer of conductive resist for the contact step (AllResist/Electra). The first step allows to expose all the elements of the device (transmission line, resonator, d.c. lines and gate) and is followed by an etching step giving access to the graphene edges. Etching was performed using reactive ion etching and a mixture of O2 and CHF3. Right after the etching step, the sample is installed into the e-beam evaporation chamber for metal deposition (Ti/Al, 5/60 nm). The second lithography step is also followed by an etching step and allows to define the shape of the gj and separate it from the side gate. The size of the gj is 300 nm between the superconducting contacts and 1.5 μm in the transverse direction.

Design of the resonator
The schematic of the device is shown in Extended Data Fig. 1. The external quality factor was set by design (that is, coupling capacitance) with the help of electromagnetic simulations. We target a value of 100, which is typical for a resonant JPA. Experimentally, we measured external quality factors in the range of 100 to 200 depending on the resonance frequency because of variations in the environment impedance. The internal quality factor was measured in different configurations. In a design with higher external quality factor, we checked that the use of a Ti layer was not a limiting factor and measured internal quality factors in the range of 2,000 to 10,000. In the amplifier design, we measured that the bare internal quality factor, that is, without the graphene junction, was more than 1,000. In the presence of the junction, this was reduced to lower values (400–1,000 depending on the frequency, with the lower values being measured close to the neutrality point) that indicates that the junction has some non-negligeable losses. Nevertheless, since the internal quality factor remains above the external one, we expect a limited effect on the added noise.

A side gate allows to control the carrier density in the graphene junction. We chose to use a side gate instead of a traditional backgate or topgate to limit potential sources of loss. State of the art backgate are indeed usually done with a graphite flake. Graphite is a normal conductor and CHF3. Right after the etching step, the sample is installed into the e-beam evaporation chamber for metal deposition (Ti/Al, 5/60 nm). The second lithography step is also followed by an etching step and allows to define the shape of the gj and separate it from the side gate. The size of the gj is 300 nm between the superconducting contacts and 1.5 μm in the transverse direction.

The d.c. and microwave measurements
Measurements were performed in dilution refrigerators with base temperatures of 25 mK. The resonator is probed at microwave frequencies in a reflection geometry. The scattering parameter S11 is measured while additional probes allow us to characterize the junction low-frequency (d.c.) properties. The position of those probes, close to centre of the resonator, was chosen to minimize their effect on the microwave properties and in particular any microwave leakage. The d.c. measurements were performed using low-frequency lock-in techniques. We have removed a constant baseline resistance of 1.207 Ω from the two-probe measurement. This corresponds to the resistance of the measurement wires. The microwave measurement setup is presented in details in Extended Data Fig. 3 and in the Supplementary Information. One-tone microwave measurements were performed with a VNA. Two-tone measurements (for instance, to measure the amplifier gain) were performed using an additional microwave source. The reflected signal is split with a circulator or a directional coupler depending on the setup and amplified at 4 K and again at room temperature. For noise measurement, the signal is measured with a spectrum analyser using a resolution bandwidth of 2 MHz (3 dB bandwidth).

Influence of the SNTJ packaging attenuation on the added noise estimation
The attenuation between the SNTJ and the graphene Josephson parametric amplifier (gJPA) was not taken into account in the added noise fitting procedure (Supplementary Information). This has the effect of overestimating the intrinsic noise added by the gJPA. We estimate the total attenuation in between the SNTJ and the gJPA to be 2.2 dB meaning that the fitted intrinsic added noise by the gJPA is 2.2 dB higher than its real value. For example, the minimum added noise measured is 0.8 photon including 0.5 photon coming from the vacuum noise in the idler channel. It means that the corrected intrinsic added noise by the gJPA is reduced by 2.2 dB from the measured 0.3 photon value, making the total added noise 0.68 instead of 0.8 photon.

Data availability
The data that support the findings of this study are available in Zenodo with the identifier https://doi.org/10.5281/zenodo.7025633.

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Author contributions
K.W. and T.T. grew the h-BN crystals. G.B. and J.R. designed the samples. G.B. and N.A. fabricated the devices. G. B., A.J. and J.R. performed d.c. measurements. G.B. performed the microwave measurements with help from K.R.A. and J.R. Noise measurements were realized by G.B., A.R. and M.E. with help from N.R. and J.R. Data analysis was performed by G.B. with help from A.R., N.R. and J.R. The project was supervised by F.L. and J.R. G.B. prepared the figures of the manuscript. J.R. wrote the manuscript with input from all authors.

Competing interests
N.R. is founder and shareholder of Silent Waves.

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Extended Data Fig. 1 | Design of the device. a) Schematic of the device (to scale). A resonator (purple) is capacitively coupled to a transmission line (red) as shown in the left inset. A side gate (green) is used to tune the graphene Josephson junction (gJJ) (located in the center of the resonator) critical current. The right inset shows an optical picture of the gJJ. Additional lines (blue) are connected close to the center of the resonator to perform d.c. measurements on the gJJ. They are located 20 μm away from the junction. Lines between the pads and the thick lines are bonding wires. (b) Phase of $S_{11}$ measured and fitted for a bare device where the gJJ is replaced by a short between the two parts of the resonator.
Extended Data Fig. 2 | Graphene Josephson junction d.c. properties. (a) Differential conductance with respect to the bias voltage. The dark line indicates the position of the first multiple Andreev reflection (MAR) peak at a voltage value of 2Δ/e. (b) Differential resistance as a function of the gate voltage measured at 25 mK with a bias current of 7μA. (c) eRnIc/Δ product with respect to the gate voltage.
Extended Data Fig. 3 | Experimental setups. Noise measurement setup (a) and d.c. measurement setup (b). Both the setups use a dilution fridge and allow for standard microwave measurements.
Extended Data Fig. 4 | Added noise of the graphene Josephson parametric amplifier. (a) and (b) extracted added noise with respect to the frequency. The blue curve represents the extracted added noise from the graphene Josephson parametric amplifier (gJPA) measurement. The purple curve represents the added noise extracted by the printed circuit board (PCB) measurement, that is, the chain noise without the JPA. The red curve represents the added noise computed from the added noise extracted by the PCB measurement and the measured gain of the gJPA in the limit where the JPA does not add noise, that is, the expected noise at the standard quantum limit (SQL).