Kinetic Inductance Traveling Wave Amplifiers For Multiplexed Qubit Readout

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We describe a kinetic inductance traveling-wave (KIT) amplifier suitable for superconducting quantum information measurements and characterize its wideband scattering and noise properties. We use mechanical microwave switches to calibrate the four amplifier scattering parameters up to the device input and output connectors at the dilution refrigerator base temperature and a tunable temperature load to characterize the amplifier noise. Finally, we demonstrate the high fidelity simultaneous dispersive readout of two superconducting transmon qubits. The KIT amplifier provides low-noise amplification of both readout tones with readout fidelities of 83% and 89% and negligible effect on qubit lifetime and coherence.

Fast and high-fidelity readout of superconducting qubits is essential to implementing complex quantum algorithms [1, error correction [2, 3] and quantum feedback [4, 5]. The low-noise amplification of readout signals is usually achieved via Josephson parametric amplifiers and ring modulators [6-9]; however lumped-element Josephson parametric amplifiers (JPAs) typically have low saturation power and bandwidths of a few megahertz that can be extended up to 700 MHz with suitable impedance matching techniques [10-13]. As the size and complexity of superconducting quantum circuits increases [11-14, 15], it is desirable to extend the amplifier bandwidth and saturation power in order to achieve higher measurement speeds by performing the simultaneous dispersive readout of a large number of qubits, while simultaneously increasing the power of each individual readout tone. Traveling-wave parametric amplifiers provide such an option because of their wide bandwidth, typically spanning several gigahertz, high saturation power and near quantum limited noise performance. In this case, amplification is obtained by injecting the input signal together with a strong co-propagating pump into a nonlinear transmission medium, consisting of either a long array of Josephson junctions or SQUIDs [16-21, or of a high kinetic inductance material [22-25]. In both cases the propagating pump modulates the inductance per unit length of the line and parametrically amplifies the weak input signals. Kinetic inductance traveling-wave (KIT) amplifiers further provide an extremely high saturation power ($\geq$ -60 dBm), in addition to the broad ($\sim$4 GHz) bandwidth, that make them a desirable tool for the simultaneous readout of superconducting qubits. Moreover, recent demonstrations of the KIT amplifier have significantly lowered the required pump power, thus enabling operation near sensitive quantum devices [23].

In this work we characterize the gain, return loss and noise temperature of a KIT amplifier at 10 mK optimized for superconducting qubit readout. The amplifier has relatively low pump power $\sim$30 dBm, 12 dB gain with low ripple and wide bandwidth. Moreover we obtain an in-band gain ripple lower than 3 dB between 4 and 12 GHz and system noise temperature as low as 1.5 K. This is about a factor of ten lower than the system noise of a typical superconducting qubit measurement chain with HEMT amplifiers only, which is 10-20 K. We further demonstrate the simultaneous readout of two superconducting transmon qubits with readout fidelities up to 89% and show that the amplifier has no effect on qubit lifetime and coherence within our measurement errors. Furthermore the large saturation power [23] (-40 dBm) of the KIT amplifier makes it a suitable candidate for the multiplexing of superconducting qubit readout tones.

For our measurements we operated a KIT amplifier in three-wave mixing mode [23, 24]. The device consists of a meandered superconducting coplanar waveguide lithographically defined on a silicon chip. The superconductor exhibits a high kinetic inductance that depends non-linearly on the current:

$$L_k(I) \approx L_k(0) \left[1 + \frac{I}{I_s} \right]^2,$$

(1)

where the current $I_s$ is comparable to the critical current $I_c$ of the superconductor [22]. By injecting a strong microwave pump at frequency $\omega_p$ into the line we induce a radio-frequency modulation of the current $I_{rf} = a_p \cos(k_p x - \omega_p t + \phi)$ and, therefore, of the line inductance $L_k(x, t)$. In three-wave mixing operation we further introduce a bias current $I = I_{rf} + I_{dc}$, so that the signal and idler mode frequencies satisfy the constraint $\omega_s + \omega_i = \omega_p$. The amplifier gain grows exponentially with the device length under the phase matching condition $k_s + k_i = k_p - \Delta \theta$, where $\Delta \theta$ is the nonlinear phase shift of the pump due to self- and cross-phase modulation. For $I_{dc} \ll I_s$, the gain is $G \approx 1 + \sinh^2(gL)$, with [22, 24]:

$$g = \sqrt{k_s k_i I_{dc}} \frac{a_p}{2 t^2},$$

(2)

In a uniform coplanar waveguide (CPW) line in general $k_p \approx k_s + k_i$ and the phase matching condition is not satisfied unless artificial dispersion is introduced by periodically modulating the CPW line width to introduce
FIG. 1. KIT scattering parameters: forward gain and input return loss (left) and reverse gain and output return loss (right). The return loss increases when the gain is turned on, because the device reverse transmission and gain create a feedback mechanism that amplifies the reflected signals.

a bandgap near the pump frequency. Finally we observe that, even when operating the KIT amplifier under a nonzero dc current bias, 4-wave mixing and other parametric processes are present and impact the device characteristics [24]. Our KIT amplifier is fabricated on a 20nm NbTiN film over a 2.0 × 2.2 cm, 381 µm thick silicon chip. The meandered CPW line is 2 m long, has a gap of 2 µm and width of 3 µm, which is increased to 6 µm at the periodic loadings used for dispersion engineering. Since the line characteristic impedance is 180 Ω, we use 50 to 180 Ω triangular tapers for impedance matching. Furthermore, we coat the ground plane with gold to suppress parasitic microwave modes and thermalize the device.

We characterize the amplifier gain and return loss in our dilution refrigerator at a temperature T∼10 mK. The KIT amplifier is connected on both sides to single-layer Nb superconducting microwave diplexers to separate the signal (4-12 GHz) from the parametric pump (17 GHz), while the bias current $I_{dc}$ is provided via commercial external bias tees. The superconducting diplexers are fabricated in a single Niobium layer on a 6×8.5 mm silicon chip. They consist of a low-pass stepped-impedance microstrip filter (dc-12 GHz, with <0.2 dB insertion loss up to 9 GHz) and a band-pass parallel coupled-lines (hairpin) filter (14-20 GHz with 0.4 dB of insertion loss at the pump frequency) [26]. The lowpass filter suppresses the pump power by more than 50 dB.

We use a set of cold thru-reflect-line (TRL) coaxial calibration standards to deembed the intervening components in the measurement chain and obtain the device scattering parameters [27]. A pair of 6-port mechanical dc-18 GHz switches mounted onto the mixing chamber plate allows the selection of different calibration standards without needing to warm up the system. We connect the KIT and calibration standards to the switches via short (~6 in) identical coaxial cables to minimize calibration errors due to variations in the standard measurement lines. We then measure all four scattering parameters via two independent attenuated input lines (90 dB loss) and two amplified output lines. By measuring three calibration standards, we extract an error model for the intervening components before and after the device under test and de-embed the scattering parameters of the KIT amplifier: the error model consists of 8 independent terms determined by a constrained interior-point nonlinear optimization algorithm [27].

When the parametric pump is turned off and the KIT is biased with a bias current of $I_{dc} = 1.5 mA$, we measure the insertion loss of the CPW line and obtain 0.5 dB at 2 GHz up to 3 dB at 8 GHz. We then turn the pump on and obtain the scattering parameters shown in Figure 1. We measure a peak forward gain of 12 dB at 7.6 GHz with a 3dB bandwidth of 8 GHz and ±1.5 dB ripple. The reverse gain of the device is independent on the pump power and equal to the device insertion loss measured with no parametric pump, as expected. In Figure 1 we also show the device return loss, which, interestingly, is a function of the pump power. With no microwave pump applied to the KIT, we measure a return loss of around 20 dB on both ports, with a maximum return loss of 10 dB above 8 GHz. However, as soon as the microwave pump is turned on, the device reflection coefficients increase up to ~0 dB around 8 GHz, as shown in Figure 1. We can understand this behavior by observing that the amplifier impedance mismatch is due to the interference of multiple reflections at the taper junctions as well as at the multiple bends of the CPW line. When we tune the amplifier up, the signal is amplified before each reflection, causing an increase in the total return loss. If we further increase the pump power we obtain increase in gain ripple. Therefore, the low reverse isolation (> −2.5 dB) and impedance match effectively limit the maximum amount of gain that can be extracted from the device. Neverthe-
FIG. 2. Amplifier noise temperature measurement acquired with a variable temperature load tuned between 300 mK and 3 K. The system noise temperature without the amplifier (blue line) is compared to the noise temperature measured with the amplifier turned off (black line) and on (red line). The KIT amplifier provides a factor of 10 improvement in system noise. The figure on the right shows a detail of the system noise and the KIT noise after removing the effect of the external components (blue line).

less, we show below that our KIT amplifier still provides a substantial improvement in qubit readout fidelity.

To characterize the noise temperature, we perform a hot/cold load measurement by use of a variable temperature load noise source, which is heated by injecting a dc current and measured by a thermocouple. The source is anchored to the cold plate via a low thermal conductivity platform. The temperature of the noise source can be continuously tuned from 100 mK to 3 K, unlike a traditional hot/cold measurement where only two temperature points are available, thus leading to improved accuracy. We measure the output noise spectral density $S(\omega, T)$ of the amplifier as a function of frequency $\omega$ and temperature $T$ in a spectrum analyzer and compute the system noise via a minimum least squares fit to:

$$S(\omega, T) = G \left( \frac{\hbar \omega/k_B}{e^{\hbar \omega/k_B T} - 1} + T_{sys}(\omega) \right)$$

Note that the system noise is characterized over the entire amplifier band in a single measurement, which is important for devices such as the KIT that amplify over several GHz of bandwidth. In Figure 2 we show the measured system noise in Kelvin as a function of frequency: we measure $T_{sys}^{off}$ = 6-15 K between 4-12 GHz when the KIT is removed (blue line) and a lower system noise $T_{sys}^{on}$ = 3-1.7 K when the KIT is inserted. The noise is referred to the input of the amplifier chain. We also observe a noise temperature increase when the amplifier is off (black line), due to the insertion loss of the diplexers and bias tees (3 dB at 8 GHz) and the amplifier itself (1 dB at 8 GHz). In future device implementations these components could be placed into the same package to minimize insertion loss and improve impedance match. At 9 GHz, where the gain is maximum, the system noise $T_{sys}^{on}$ = 1.5 K ($\pm$0.17 K) corresponds to 3.5 noise photons. We attribute the excess noise to losses in the measurement chain, particularly in the diplexers and bias tees, HEMT amplifier noise and thermal heating of the KIT amplifier. We use a distributed model [16] of the KIT internal gain and loss to estimate the intrinsic am-
plifier input noise and obtain 1.4 photons of added noise at 10 GHz (close to the standard quantum limit) and 4.1 photons at 6 GHz. Finally, we test the performance of the KIT amplifier in a single and two-qubit dispersive readout experiment. In our measurement setup, shown in Figure 3(a), we replace the noise source in the previous experiment with a qubit circuit. This circuit (Figure 3(b)) consists of four transmon qubits dispersively coupled to quarter-wave CPW readout resonators (center frequencies 7.1-7.4 GHz, coupling strength $g = 38$ MHz).

The readout resonators are in turn capacitively coupled to a quarter-wave resonator Purcell filter [28], with readout resonator damping rate $\kappa^{-1} = 33$ ns to achieve fast readout while preserving qubit coherence. The filter is weakly coupled to an input line via a small (15 fF) coupling capacitor and strongly inductively coupled (external quality factor $Q=22$) to an output line to enable measurements in transmission. We measured fixed frequency qubit $Q_2$ with 0-1 transition frequency 4.518 GHz and tunable $Q_3$ with 0-1 transition frequency 5.772 GHz. Both qubits have an anharmonicity of $-310$ MHz. Typical qubit coherence times measured for this device are $T_1 = 12 \mu s$, $T_2 = 14 \mu s$ and Hahn echo time $T_{\text{echo}} = 19 \mu s$.

In a first experiment we measure coherence and dephasing times $T_1$ and $T_2$ of qubit $Q_2$ with the KIT pump turned on and off for identical readout drive parameters. We measure a slight decrease in $T_1$ when the KIT is turned on, and no change in $T_2$ ($T_2^{\text{off}} = 13.6 \pm 0.57 \mu s$, $T_2^{\text{on}} = 12.85 \pm 0.42 \mu s$, see Figure 4(c)). We fit to two frequency components in the Ramsey fringe experiments used to measure $T_2$ and we ascribe a small splitting $\Delta f \sim 600$ kHz, consistent with charge dispersion of a transmons with $E_j/E_C = 30$ to $\pm \delta$ offsets induced by background fluctuations. [29] [30]. We note that the distribution of $T_2$ measured through Ramsey interferometry is not affected by turning the KIT on, see Figure 4(b), and verify that the Hahn echo time is also preserved ($T_{\text{echo}}^{\text{off}} = 18.52 \pm 1.27 \mu s$, $T_{\text{echo}}^{\text{on}} = 21.19 \pm 3.38 \mu s$). Finally, we do not observe a measurable Stark shift induced by the amplifier pump leaking into the readout resonator, consistent with the pump being far from the readout resonator center frequency and pump leakage being further suppressed by the diplexer, isolator and Purcell filter.

In a second experiment we perform single shot readout measurements of the same qubit to determine readout fidelity. We prepare the qubit in its $|0\rangle$ or $|1\rangle$ states $3 \times 10^4$ times, and monitor the transmission across the Purcell filter while driving the qubit cavity on the dressed $|0\rangle$ with a 1 $\mu$s long readout pulse. We use an optimal matched filter approach [31] to integrate the digitized heterodyne signal and rotate qubit state information into the real quadrature of the signal. Binning this data, we measure well separated histograms corresponding to the two state preparations (Figure 4). We then extract the readout fidelity, defined as $F = 1 - (P_{1|0\rangle} + P_{0|1\rangle})/2$, where $P_{0|1\rangle}$ is the probability of erroneously identifying the qubit state as $|0\rangle$ instead of $|1\rangle$, by integrating the two histograms and taking the difference. We obtain a fidelity of $F = 71.7\%$ with the KIT turned off, compared to 90.3% with the KIT turned on, corresponding to a 18.6% improvement.

Finally we perform a simultaneous readout of two qubits $Q_{2,3}$ by probing their respective readout cavities at the same time. From the measured histograms (Figure 5) we extract readout fidelities of 89.4% and 83.3%. While these fidelities do not match the best results achieved for other quantum-limited amplifiers [32] [33], we believe that they demonstrate the KIT promise for superconducting qubit readout, particularly for those situations that benefit from its broad bandwidth and high saturation power. The fidelities reported here are limited by the low gain of present KIT devices and the use of a qubit device not optimized for high-fidelity readout ($\kappa \gg 2\chi \approx 2$ MHz). In conclusion we characterized the gain and noise temperature of a KIT amplifier at 10 mK, demonstrating 12 $\pm 1.5$ dB gain and 1.5 K of system noise at 9 GHz. Furthermore, we demonstrated the single shot readout of superconducting qubits with a KIT amplifier and measured
FIG. 5. Two qubit fidelity histograms for 30,000 ground and excited state preparations for \( Q_2 \) (top) and \( Q_3 \) (bottom). Measurement fidelity is \( F = 89.4\% \) for \( Q_2 \) and \( F = 83.3\% \) for \( Q_3 \). The individual error probabilities are \( P_{1|0} = 7.01\% \) and \( P_{0|1} = 13.6\% \) for \( Q_2 \) and \( P_{1|0} = 14.5\% \) and \( P_{0|1} = 17.8\% \) for \( Q_3 \).

more than 90% fidelity (single qubit) and 83-89% (two-qubit). Further improvements need higher amplifier gain to further overcome microwave losses and HEMT noise. The maximum gain is limited by the insulation of instability as the pump power is increased past a critical threshold. Higher gains require a further investigation into the effect of impedance fluctuations in the superconducting line, increasing the nonlinearity at low pump powers and use 50 Ω artificial lines \[34\] that achieve better impedance match by reducing overall device size and eliminating impedance transformers.

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