Superconducting Parametric Amplifiers: the Next Big Thing in (Sub)Millimeter-wave Receivers

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***Abstract*—We are developing a new superconducting amplifier technology for radio astronomy instruments called the Traveling-Wave Kinetic Inductance Parametric (TKIP) amplifier. Invented at Caltech/JPL, recent laboratory demonstrations have resulted in near quantum-limited noise performance over more than an octave of microwave bandwidth and operating temperatures as high as 3 Kelvin. These amplifiers have the potential to be used as front-end replacements for ALMA's mm/sub-mm SIS receivers and intermediate frequency (IF) amplifiers, and for multiplexing faint signals from focal-plane arrays of single-photon detectors on space telescopes such as NASA's Origins Space Telescope (OST). The enhanced observational capabilities that would be enabled by TKIP front-end amplifiers on ALMA would tremendously benefit ALMA science across all bands.**

I. Introduction

A recent breakthrough at Caltech/JPL in amplifier technology called the Traveling-Wave Kinetic Inductance Parametric (TKIP) amplifier has resulted in near quantum-limited performance over more than an octave instantaneous bandwidth in the microwave range [1]. Until now the quantum computing community has been the main driver for developing these amplifiers for qubit readout, but their devices have narrow bandwidths, low dynamic range, and operate at sub-Kelvin temperatures. Our collaborators at JPL recently demonstrated a microwave TKIP amplifier with several GHz of bandwidth, and orders of magnitude higher saturation power that maintains quantum-limited noise performance up to an operating temperature of 3K. Similar amplifiers but at higher frequencies up to 1 THz could be designed since the operation principle and physics remain largely unchanged. These qualities make TKIPs suitable candidates for ground-based astronomy with instruments such as ALMA.

II. TKIP amplifier development at NRAO

In a 2-year study we are planning to build a high-frequency TKIP demonstration prototype as a front-end replacement for the ALMA band-3 SIS mixer receivers. Our collaborator has designed and fabricated a TKIP chip that covers a very wide bandwidth of 55-175 GHz, and we are preparing to test this device at NRAO-CDL. Ultimately we envision similar TKIP amplifiers for higher frequency ALMA bands if this device is successful. We also plan to explore TKIP amplifiers as quantum-limited microwave IF amplifiers, which could be applied as a one size fits all replacement for all ALMA IF amplifiers, and would reduce SIS receiver noise typically by 2x. The main challenge in this work is in further optimizing the superconducting thin-film materials to retain their sub-Kelvin properties such as ultra-low loss at temperatures close to 4K.

III. Increased Observation Efficiency with TKIP amplifiers on ALMA

The enhanced observational capabilities that would be enabled by these front-end amplifiers would benefit ALMA science across all bands. For example the Band-3 improved signal-to-noise from a front-end RF TKIP amplifier would be a factor of ~ 5 measured at the receiver input. Including the loss of atmosphere this translates to a doubling of system sensitivity and a factor of ~ 4 increase in array efficiency (speed) enabling the detection of weaker spectral lines and continuum sources and mapping larger fields. The increased sensitivity from the RF front-end relaxes the requirements on IF amplifiers and allows for tradeoff with bandwidth to increase the instantaneous IF bandwidth from the current 4 GHz per sideband per polarization to $\sim$ 10 GHz. For continuum observations, this provides a greater than factor of two increase in efficiency (speed), which combined with the increased RF efficiency would result in a factor of ~ 8 increase in observation efficiency (speed). For spectral observations such a wide bandwidth also enables the detection of various spectral lines simultaneously, removing the need of multiple observations at different LO frequencies to cover the whole band. This is also ideal for obtaining spectral index information on sources in much shorter integration times than is currently possible. In addition, as quoted from the ALMA 2030 roadmap "Bandwidth expansions will, simultaneously, enormously increase the legacy value of the archive while increasing the likelihood of serendipitous discoveries" [2]. The ALMA 2030 roadmap recommends that "Long-term sustained research in better devices or new technologies (such as TKIP amplifiers) has the potential to yield significant breakthroughs that are equivalent to doubling or tripling the collecting area of the array with its present instrumentation". Therefore, because of the potential game changing improvements that might be achieved it is important to further study these amplifiers with a long-term view of what will be possible in 5 to 10 years.

IV. Enhanced Science studies with ALMA

The potential science return from these amplifiers is significant. Studies of regions undergoing star and planet formation, molecular gas surveys, afterglows of Gamma-Ray Bursts (GRB), and objects in the high-redshift Universe are but a few of the current ALMA capabilities which will be vastly improved by these amplifiers. The increased continuum bandwidth will also allow for studies of clusters of galaxies, thought to be tracers of dark energy in the universe.

V. Other application areas for TKIPs

These amplifiers are not only interesting for the NRAO and ALMA community, but are also sought after in the direct detection astronomy community (e.g. MKID detectors, TES detectors etc.) for amplifying or multiplexing signals from large focal-plane arrays of photon detectors for space telescopes such as NASAs Origins Space Telescope and X-ray telescopes. Finally, they are also a powerful general tool for exploring quantum physics and have many experimental applications in research labs (quantum optics, quantum cryptography, nanomechanical sensors, dark matter detectors).

Acknowledgement

We acknowledge support for this study from the Cycle-5 NRAO ALMA Development Study program.

References

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[2] Available at https://go.nrao.edu/Roadmap_for_ALMA