Final report on

"Development of ultra-wideband quantum limited amplifiers for millimeter and submillimeter receiver frontends"

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Introduction

The proposed project was to investigate a promising new amplifier technology that exploits the very large non-linear inductance of NbTiN superconducting transmission lines to produce parametric amplifiers with near quantum limited noise and greater than octave bandwidths. The upper frequency limit for amplifiers using this technology is expected to only be limited by superconducting band gap at ~1.4 THz. The focus of the development for this proposal is ALMA band 3, 84-116 GHz, where Caltech and JPL have good test equipment for characterizing the devices. This band is also a good match for the wideband 3-mm MMIC receiver development being carried out at CARMA.

The team working on this project has accomplished more than was proposed for this early stage investigation a new receiver technology. The group at JPL has completed the design of the design and simulation of a TKIP (traveling-wave kinetic inductance parameter) amplifier over the 55-175 GHz. This in centered on ALMA band 3 but also covers most of bands 2 and 4. The first version of the amplifier chip has been fabricated and the amplifier block and cryogenic test set up has been designed and is currently under construction.

The main effort has been to push towards demonstrating that a TKIP amplifier can be built and tested in the 3-mm band and much less effort was spent on the more expansive questions of the implementation and impact of this technology on the ALMA system. The impact on the ALMA system will be significant and we felt that it was important to address the difficult technical issues and demonstrating that low noise, octave bandwidths and large gain can be achieved before embarking an extensive design study that could have a large impact on the ALMA system.

Progress on receiver development

The previous work on designing, fabricating and evaluating a TKIP amplifier operating in the 9-13 GHz is described in Eom et al, Nature Physics 8, 623 (2012). Building upon this work, a TKIP amplifier chip for the 3-mm band was designed by Peter Day at JPL using the analysis software developed for analyzing parametric gain in non-linear transmission lines. The design package calculates the nonlinear conversion of pump power to signal power as the signal and pump propagate along the transmission line. The transmission line has a periodic structure that suppresses the 3^{rd} harmonic of the pump frequency (which can be a serious problem for traveling-wave parametric amplifiers) and also provides the correct dispersion in the propagation characteristics as a function of frequency to maximize the gain across the useable bandwidth. The simulation results are shown in fig. 1. The gain is >15 dB over 55-175 GHz, except for a notch around the designed pump frequency at ~115 GHz. This frequency was chosen so that the engineered dispersion at the pump frequency is within the band accessible by the vector network analyzer available in the Caltech Radio Astronomy Lab (CRAL). The gain curve can be shifted toward higher of lower frequencies by adjusting the NbTiN film thickness and the pump frequency. Once the dispersion and performance have been verified, future designs will move the designed dispersion curve and pump to higher frequencies so that the important CO1-0 transition is in the good gain region.

This design has been fabricated and is ready for testing. Fig. 2 shows a photograph of the chip. The signal and pump propagate from the left through the three double spirals and out the right side of the chip. The chip is designed to fit into a block with Anritsu W1 coaxial connectors to be compatible with JPL test equipment. Commercial W1 coax to WR-10 waveguide adapters are used for connection to the Caltech network analyzer and test set up.

The test setup is well along in construction. The required waveguide components have been ordered with delivery expected this month. The pump oscillator is in hand. The evaluation amplifier block has been designed. Most of the parts for the test cryostat have been machined at OVRO and shipped to campus. It now remains to assemble the components and start testing.

The initial tests will be measurements of the transmission through and reflection from the amplifier chip. Another critical measurement is the phase delay as a function of the DC current in the transmission line. This will be measured over the accessible frequency range of the test equipment. The phase delay vs. current determines the available gain which will also be measured as a function of pump power across the 75-115 GHz band.

Determining the nose performance requires putting the TKIP amplifier into a demonstration receiver system and performing the normal 300K_hot/77K_cold load or Y-factor system temperature measurements. The demonstration receiver will utilize the CARMA wideband receiver system as shown schematically in fig. 3 with the TKIP amplifier as a low-noise preamplifier. This system has 34 GHz of RF bandwidth, is currently under development for CARMA and is well suited to characterizing the TKIP amplifier over all of ALMA band 3.

There are several design challenges that are being worked on; 1) developing a thin-film air-bridge for suppressing of unwanted slot line modes in the transmission line, and 2) developing absorptive diplexers to avoid out of band resonant oscillations and 3) pushing the required operating temperature closer to 4 K to be compatible with the ALAM cryocoolers. The significance of these issues will be evaluated during the initial testing.

Most of the work at this point has been carried out at JPL using their internal funding. The NSF/NRAO funds are only used for staff at OVRO working on the testing of the devices and some equipment to be used on the Caltech campus to build the prototype test set up. This work is continuing at JPL and Caltech using limited internal funds while funding is sought from other sources.

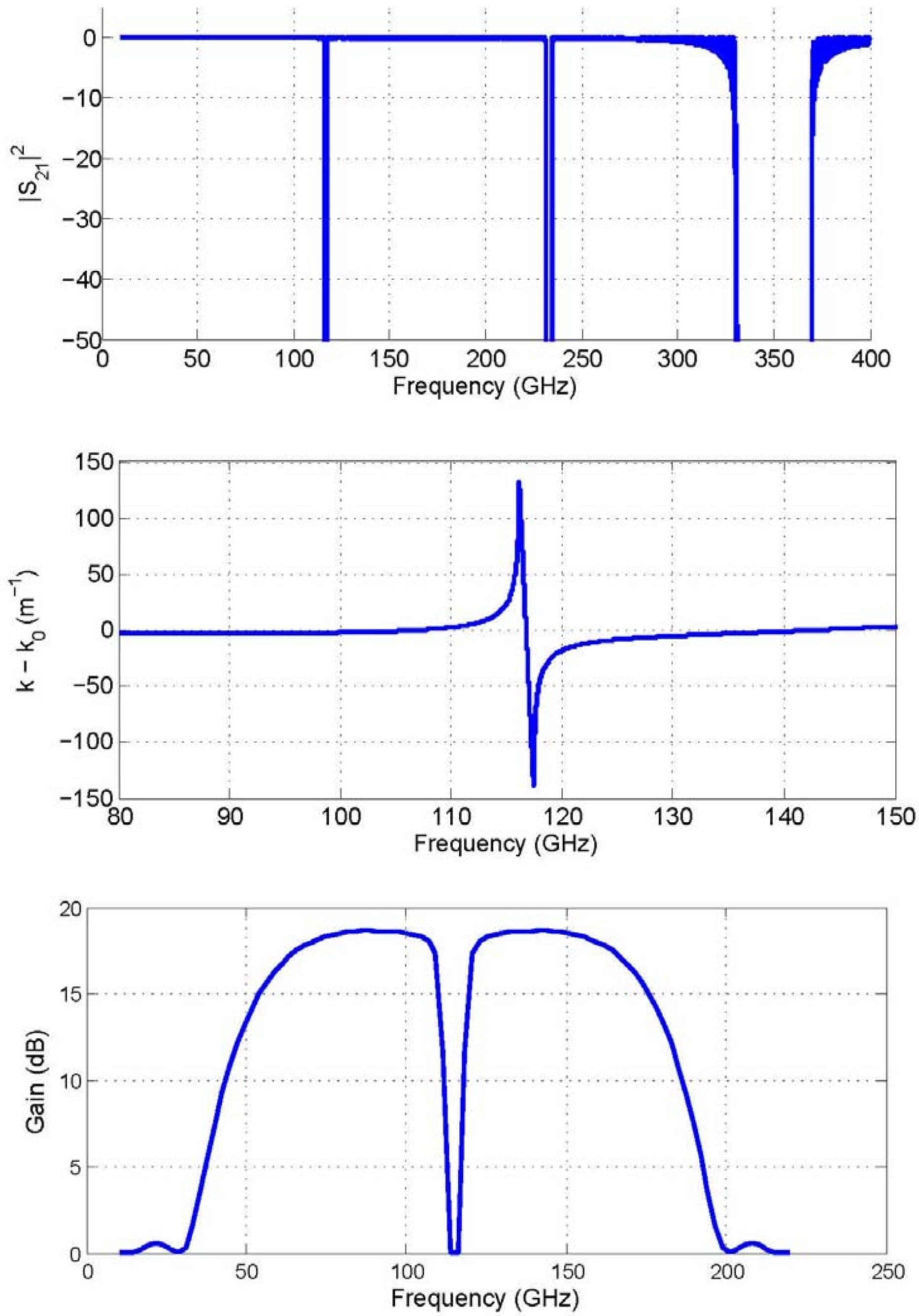

Fig. 1. Simulated performance. a) Calculated transmission through the TKIP amplifier chip with no applied pump showing the narrow stop band near the pump frequency of 115 GHz, at the $2f_{pump}$ harmonic, and a much wider stop band around at $3f_{pump}$, ~350 GHz. b) The difference in the propagation constant, resulting from the periodic loading, and linear (~ f) dispersion. c) Calculated gain of the amplifier assuming a pump power roughly half of which was used with a microwave version of the device.

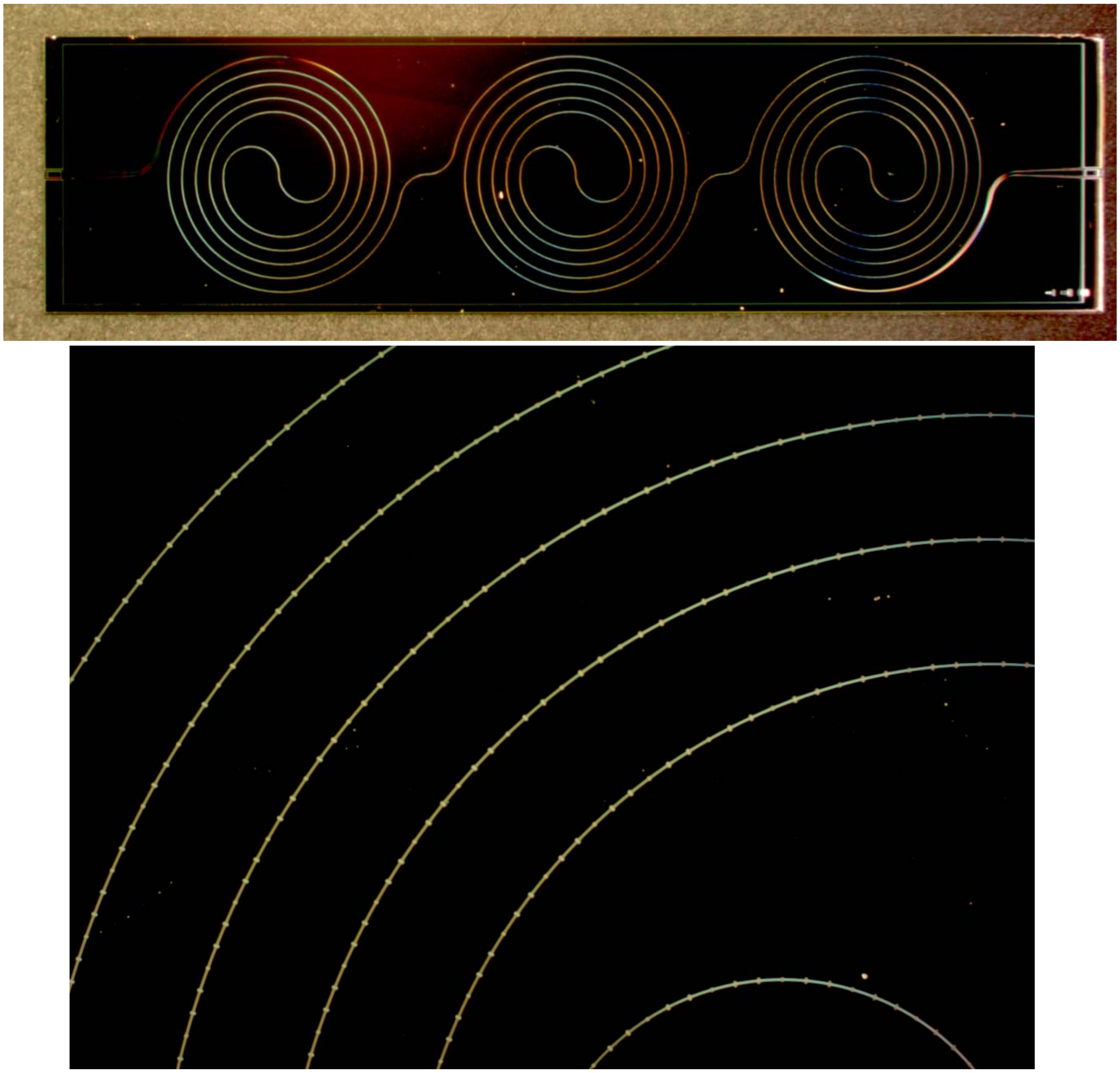

Fig. 2. Top panel is a photograph of the TKIP amplifier chip. The bottom panel shows an enlarged section of the traveling wave transmission line. The TKIP amplifier consists of a 0.15 m length of NbTiN CPW line arranged in three double spirals. The thickness of the thin-film NbTiN is 35 nm and the center conductor and gap widths are 1 micron. At the input and output of the line, the CPW geometry tapers from center strip and gap widths of 30 micron and 5 micron to adiabatically transform the characteristic impedance of the line from close to 50 to 300Ω. The line is periodically loaded by widening a short section after every length D, producing a transmission stop band and dispersion characteristics tuned to increase the parametric gain.

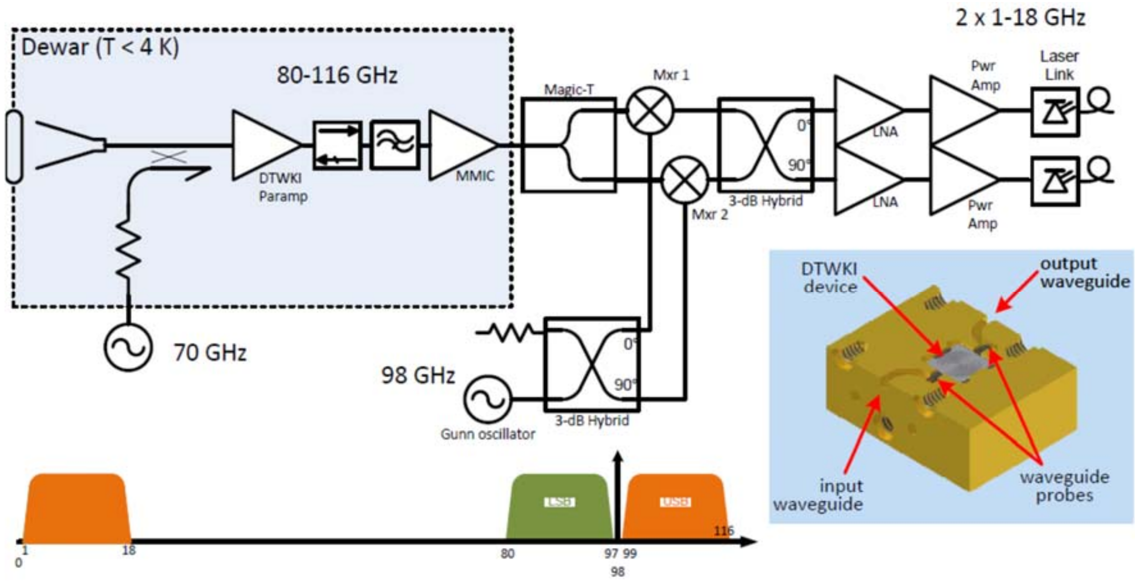

Figure 3. (Left) A schematic of a receiver that can be built with existing components (other than the TKIP amplifier). The planned frequency range covers many of the interesting molecular transitions in the 3mm band, as well as the high-transparence atmospheric window for high continuum sensitivity. A standard corrugated horn will cover this range with close to optimum efficiency. Pump power for the TKIP amplifier is injected through a waveguide directional coupler (though a dielectric beamsplitter could also be considered). The amplifier is mounted in a split-block with input and output WR-10 waveguides and channels for broadband waveguide probes. A high-pass waveguide filter is used to block the pump power from the MMIC to avoid saturation, and the reflected power is terminated in the isolator between the amplifier and the filter. The cooled MMIC amplifies the signal level high enough that the solid-state mixer and subsequent amplifiers add negligible noise. To process the required bandwidth, a sideband separation mixer is used to deliver two 1-18 GHz IF bands (34 GHz of instantaneous bandwidth), which is a standard frequency range for microwave components and optical links. The inset shows the expected configuration of the TKIP amplifier chip (denoted as DTWKI device in the figure) in a block with waveguide input and output.

ALMA system impact

The use of TKIP amplifiers for ALMA could significantly improve the system noise temperature, particularly in the lower bands that are not atmospheric noise limited, and increase the instantaneously available bandwidth on the sky. The current band 3 receiver noise temperature would be reduce from ~5hν/k, ~25 K, to ~2hν/k, ~10 K and the instantaneous bandwidth would increase from 16 GHz to >32 GHz. Realizing these improvements will require changes to some parts of the existing front-end cryogenics and receiver cartridges.

The initial measurements of the 10 GHz TKIP amplifier were done at ~0.2 K but optimization of thin-film NbTiN material should allow good performance at temperatures as high as 3 K and fabrication on a sapphire substrate should allow operation as high as 4

K and be compatible with the ALMA cryocoolers. If the performance is not satisfactory at this higher temperature there would be a very large impact on the ALMA cryostat and cooler. Although it may be possible to add micro-coolers to cool just the TKIP amplifier chips in the bands which use them it is probably more practical to change out the Sumitomo GM type coolers for commercial pulse tube coolers can achieve these lower temperatures and cool all front-ends to the lower temperature.

Making use of the very large instantaneous bandwidth will require modifications to the whole receiver and IF chain. Wideband MMIC and discrete component amplifiers exist for bands below 120 GHz and can be built into the receiver chain to provide extra gain at the RF frequency before down converting and sampling. MMIC amplifiers are being developed that operate up to ~300 GHz and show good promise. This would allow capturing of octave wide RF bands in ALMA bands 5 and lower. TKIP amplifiers for ALMA bands 6 or higher would be followed by mixers. The existing SIS or even Schottky mixers could be used. The astronomically useable bandwidth for the TKIP amplifiers will be limited by the feedhorns. Development of greater than half-octave wide feedhorns for all bands would be a separate development project.

Note that TKIP devices can also be used for low noise and very wideband IF amplifiers. The performance of some SIS mixers are limited by the IF amplifier noise and bandwidth. Thus TKIP amplifiers may be useful as IF amplifiers for some of the existing SIS mixers to improve the noise temperature and bandwidth.

Preserving the low system noise requires image rejection or sideband separating mixers to convert to the IF band. Achieving good image rejection over the full bandwidth delivered by TKIP amplifiers will be challenging. The IF sideband separating system being developed for the CARMA 3-mm MMIC receivers will ultimately be capable of delivering 34 GHz of bandwidth band and this is just sufficient to capture the full ALMA band 3 but less than the TKIP amplifiers can deliver. This will become more difficult at higher frequencies while maintaining the fractional bandwidth on the sky.

As with most millimeter interferometers, when you increase the delivered bandwidth you also want to increase the processed bandwidth which means wider band samplers and more digital filtering and a larger correlator. This is an active area of development and Moore's law will help with the digital processing. As an example of this type of development, CARMA is finishing the development of a system that will sample ~10 GHz of bandwidth in a single ADC and process 8 GHz of bandwidth for 23 telescopes and dual polarization.

Follow on work

The next step in this development is to finish the test setup and evaluate the gain and bandwidth of the first prototype 3-mm TKIP amplifier chip. This would be followed by converting the setup up into a receiver configuration to evaluate the noise performance. Assuming no series difficulties are encountered, a second version of the chip would be designed and fabricated that would fit into a block with waveguide probes, internal bias circuitry, etc. suitable for construction of an astronomically useful receiver. The receiver would then be deployed on a CARMA telescope to verify its performance for astronomical observations. This is approximately two years of effort.

Successful results from astronomical observations using the 3-mm band TKIP amplifier would justify a full system design of how these devices could be implemented on ALMA. This design effort along with refinement of the design and solving the various problems that are bound to arise in this type of cutting edge development is likely to take another 3-5 years of development effort.

The development of TKIP amplifiers from microware up through submillimeter wavelengths is of great interest to Caltech and JPL. Funding is being sought from internal JPL/Caltech funds as well as from NSF and other sources. All projects contributing to this development effort will be leveraging funding and effort from the other projects to produce the next generation of low noise and wideband amplifiers throughout the microware to submillimeter range.

Summary and conclusion

The design and fabrication of the first version of an ALMA band 3 (84-116 GHz) TKIP amplifier chip has been completed. The test setup is under construction and results are expected in the next several months. The simulations indicate that greater than an octave of bandwidth is possible although it is not clear at this point how to cope with this much bandwidth in an astronomical system. The noise temperature is expected to be less than a few times the quantum limit in all bands, a factor of two lower than existing MMIC amplifiers or SIS mixers.

Exploiting the performance improvement that can be expected for using TKIP amplifiers on ALMA will have a large impact on the ALMA system. In particular much wider RF, IF and processing bandwidth systems will be needed. The cost of these changes is hard to estimate but will be on the order of the cost of the existing front end and IF system and Moore's low would say that the larger processing bandwidth will cost roughly the same as the existing lower bandwidth system. One of the goals of follow on development would be to develop TKIP amplifiers that can operate at the temperatures produced by the existing Sumatomo coolers, avoiding major changes to the existing ALMA cryostat and cooling system.

Although the TKIP amplifiers could be developed for all ALMA bands the performance gain will be largest for the lower bands which have a relatively small sky noise contribution. Band 5 and below will be able to use MMIC amplifiers for the gain stages after the TKIP amplifier, offering simpler and more robust system.

To quote from the proposal:

"The improved noise performance of the receiver translates directly to a ~70% increase in sensitivity across the band, resulting in increased efficiency of the array and enabling the detection of weaker spectral lines. Provided the antenna response pattern is well measured, this leads directly to the ability to map larger fields. Moreover, it allows for the use of weaker calibrators which are nearer to the source, improving not only image fidelity but also reducing the slew-time associated with calibrator observations.

"The increase in instantaneous bandwidth to over 40 GHz is powerful for both continuum and spectral line observations. For continuum observations, this results in a greater than factor of three increase in imaging efficiency. 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."

It is too soon to start system design around TKIP amplifiers but the "game changing" potential of these devices justifies continuing the development to understand their performance over the full millimeter and submillimeter bands of interest to ALMA.