μ-Spec: An Efficient Compact Integrated Spectrometer for Submillimeter Astrophysics

Omid Noroozian*, Emily Barrentine, Ari Brown, Giuseppe Cataldo, Negar Ehsan, Wen-Ting Hsieh, Thomas Stevenson, Kongpop U-yen, Edward Wollack, and Samuel Harvey Moseley
NASA Goddard Space Flight Center, Greenbelt, MD, USA
*Contact: omid.noroozian@nasa.gov, phone +1-301-286-8960

Abstract— **We are developing an extremely compact (~10 cm^2) sub-millimeter spectrometer instrument called μ-Spec for application on a space or balloon telescope. We use low-loss superconducting microstrip transmission lines on 0.45 μm single-crystal silicon to produce a synthetic grating with spectral resolution and efficiency only limited by the intrinsic loss of Si. The photon detectors are superconducting micro-resonator MKIDs that are produced by patterning a layer of superconducting thin film such as Al on Si. We have built a prototype version of μ-Spec with resolution R=64 that operates in the 400—600 GHz band. We have measured the spectral response of the channels and obtained good agreement with the expected resolution of 64 and band center frequency locations within ±1 GHz of design values. We have also designed and characterized Al resonators and obtained quasi-particle lifetimes of order ~ 1ms and internal quality factors of order ~ 2 million, which are necessary for producing ultra-sensitive MKIDs for a space or balloon instrument.**

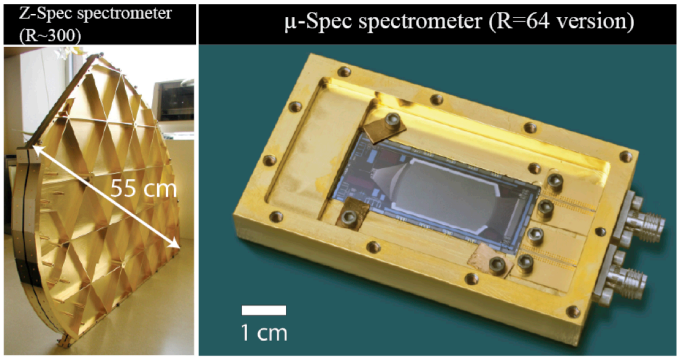

Fig. 1 A prototype μ-Spec instrument with R=64 (right) compared in size to the state-of-the-art submillimeter spectrometer Z-Spec (left)

I. INTRODUCTION

High-resolution submillimeter and far-IR spectroscopy is a powerful tool for probing the early universe in the epochs of initial galaxy formation and reionization. The observation of the fine structure lines of the abundant elements C, N, and O allow us to trace obscured star formation and AGN activity into the high redshift universe, and enable the exploration of the physical conditions during the time when many of the elements are being formed. We can observe molecular lines, such as the CO ladder, from the nearby universe to z>5.

Our ability to fully explore this rich spectral region has been limited, however, by the size and cost of the cryogenic spectrometers necessary to perform these measurements with the required resolution and sensitivity from space. For example, the current ground-based state-of-the-art submillimeter spectrometer Z-Spec [1], with R ~ 300, uses a parallel-plate waveguide grating architecture and has a cold mass of ~ 4 kg of aluminum at 0.1 K, clearly a challenge to adapt for a space instrument (see Fig 1(left)). We are developing an extremely compact (~10 cm^2), submillimeter spectrometer, called μ-Spec for operation on a space or balloon instrument with R ~ 1500 in the 350-700 GHz band. All elements of the spectrometer - the dispersive element, filters, and detectors - are fully integrated on a single Si chip (see Fig. 1(right)). We achieved orders of magnitude reduction in the mass and volume of our spectrometer by using superconducting microstrip transmission lines combined with the very low loss [2] and high refractive index of single-crystal silicon as the dielectric. We use Microwave Kinetic inductance Detectors (MKIDs) [3, 4, 5] to sensitively detect photons in each spectral channel. Arrays of these μ-Spec modules can enable high performance spectroscopic surveys opening a wide range of new science.

We will describe an overview of the instrument and critical components, and then present laboratory measurement results on a prototype μ-Spec with resolution R=64. We also describe on-going detector development and characterization work for our aluminum MKIDs, and characterization of our ultra-low background testbed.

II. OVERVIEW OF SPECTROMETER AND COMPONENTS

A photograph of a complete prototype μ-Spec chip designed for R=64 is shown in Fig. 2. The sub-mm signal is captured with a broadband single slot antenna on chip (Fig. 2 (A)) that is at the focus of a semi-hemispherical silicon lens glued on the backside of the chip and AR coated, and is then coupled onto a microstrip transmission line. The light is then split into N equal beams, with a linear phase gradient across

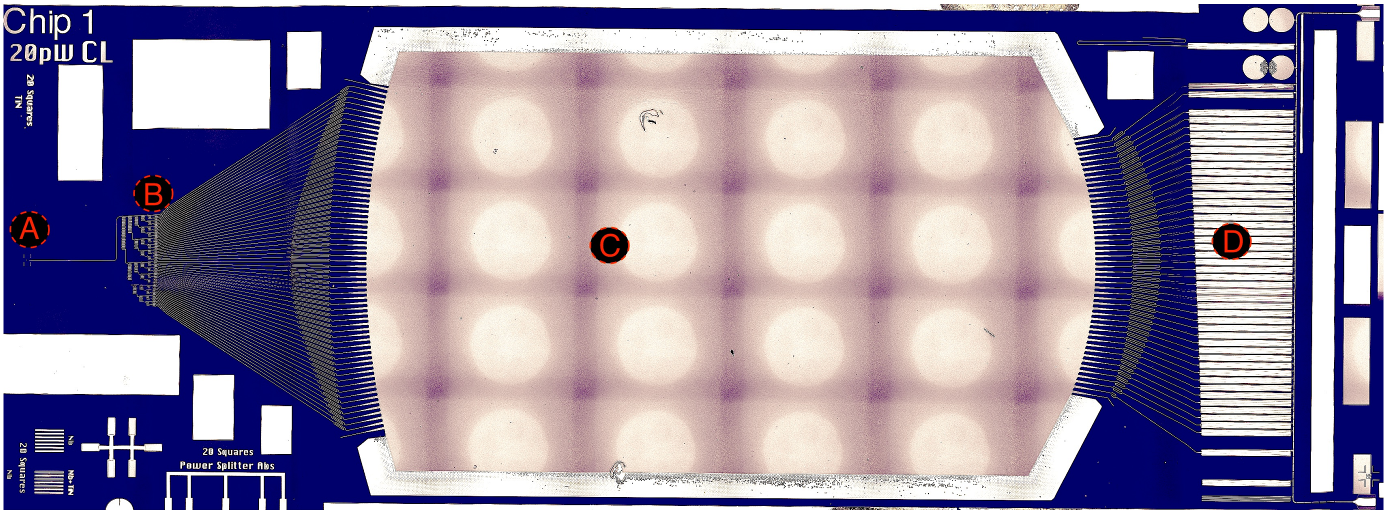

Fig. 2 Photograph of a fabricated prototype μ-Spec chip with R=64 optimized for an optical loading power of ~ 20pW for low-background testing. Key components indicated are (A) slot antenna, (B) phase delay microstrip network, (C) parallel-plate waveguide region, (D) Microwave Kinetic Inductance Detectors. Note the white circles in the parallel-plate region are an image artifact caused by the microscope.

the arced pupil introduced in the 'delay network' portion of the spectrometer (Fig. 2(B)), which is made from a series of meandered microstrip lines. The N outputs radiate into a 2-D parallel-plate waveguide region where convergent circular wavefronts from the different wavelengths of light focus at different locations along the opposite focal curve, producing the desired dispersion.

The optical signals at the focal curve are coupled to MKIDs in our implementation. An MKID is a microwave resonator circuit in which light is detected by a change in the microwave resonance behavior. Thus, all the spectral channels are intrinsically frequency multiplexed and can be simultaneously observed and readout by a single microwave feedline. In our devices the MKIDs were optimized for two specific background power loading conditions depending on the test environment (cryogenic blackbody source or external monochromatic source). MKIDs have the advantage that they are naturally frequency multiplexed, are lithographically compatible and integrated with the rest of the spectrometer elements on the same wafer, and have demonstrated low NEP performance by several groups [6, 7].

III. PROTOTYPE MEASUREMENTS

We have measured the spectral response of our first prototype μ-Spec designed for R = 64. We used a tunable photomixer diode THz source to produce monochromatic light and scanned the output frequency over the bandwidth of the spectrometer. Measurements of three adjacent channels are shown in Fig. 3 where they are compared to expected line profiles (solid lines). These first measurements demonstrate the design resolution and frequency location (±1 GHz) of channels on the spectrometer, with a null response outside of the expected channel bands, and confirm that the spectrometer is operating as expected. The observed fine structure in the lines was caused by an unaccounted for impedance mismatch inside the MKIDs and not the spectrometer itself. This is because these initial MKIDs employed a newly developed Mo/Mo$_2$N/Mo trilayer material whose properties were not well understood. We are now using aluminum for our new devices, which is a widely used material for MKIDs, and we have characterized its properties.

IV. ALUMINUM MKID CHARACTERIZATION

We have designed and fabricated several resonator test devices to characterize and evaluate the qualities of our aluminium films on Si for use in MKIDs. One of the qualities that impact the performance of an MKID is the internal quality factor Q_i, which determines the internal losses inside the resonator and affects the sensitivity. Our latest Al devices indicate a $Q_i \sim 2$ million at intermediate microwave readout powers (~95 dBm). We also measured the quasi-particle lifetime τ_{qp} in these devices using a cryogenic optical LED as a photon source and observed $\tau \sim 1$ ms. We believe that based on published literature [6] these observed values for Qi and τ_{qp} are sufficiently good to allow realization of an MKID with sensitivity of order $\sim 10^{-19}$ W/√Hz as required for balloon operation of μ-Spec.

Our resonator measurements were performed inside a closed cycle dilution refrigerator that was customized for ultra-low background testing. We used custom-made in-line coaxial filters for stray light rejection and confirmed immunity to stray light by performing various loading tests, and cross-comparing ultra-high Q devices borrowed from several collaborators.

V. FUTURE PLANS

As a next step in this technology development, we plan to extend our spectrometer demonstration to resolutions of R=256 and R=512. In doing so we will also demonstrate optically-coupled aluminum MKIDs with the sensitivities required for balloon flight conditions. An R=256 and R=512 balloon μ-Spec instrument would be capable of returning the

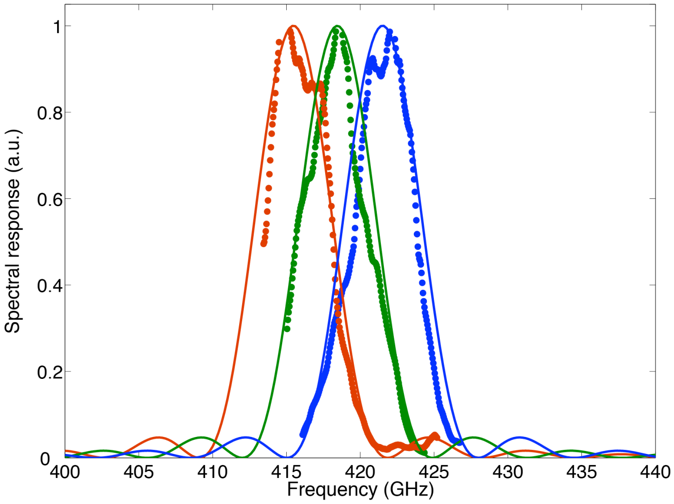

Fig. 2 Optical measurements of three adjacent spectral channels on a R=64 µ-Spec chip. The expected line profiles are shown with solid lines. These first measurements demonstrate the design resolution and frequency location (±1 GHz) of channels on the spectrometer, with a null response outside of the expected channel bands.

first significant science results. For example, an R=512 µ-Spec instrument on a cold balloon would have a line sensitivity better than the Herschel SPIRE or HIFI instruments by an order of magnitude.

VI. CONCLUSIONS

We have designed, developed, and measured the basic operation of a prototype µ-Spec with R=64 in the lab. The spectral response agrees well with the design resolution and frequency location (±1 GHz) of the channels, and confirms that the spectrometer is operating as expected. We fabricated MKID resonators made from aluminum films on Si and measured internal Q's of ~ 2 million and lifetimes of ~ 1 ms, which are required for sensitive MKIDs for µ-Spec. We plan to extend the resolution to R=512 and demonstrate operation with ultrasensitive aluminum MKIDs.

ACKNOWLEDGMENT

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