# Second-generation Micro-Spec: Spectrometer design for the Experiment for Cryogenic Large-Aperture Intensity Mapping

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## Introduction

Micro-Spec (µ-Spec) is a direct-detection spectrometer which integrates all the components of a diffraction-grating spectrometer onto a ~10-cm$^2$ , <200-g chip through the use of superconducting microstrip transmission lines on a single-crystal silicon substrate.

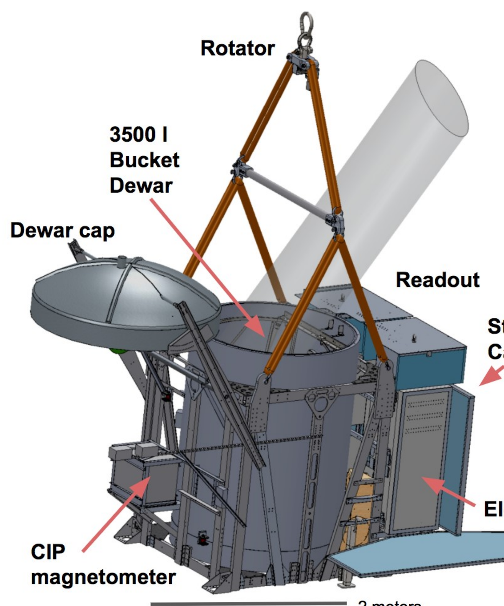
The second generation of µ-Spec was designed and is currently being built to operate with a spectral resolution of 512 over a 714-555 µm (420-540 GHz) wavelength range, a band of interest for NASA's EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM).

## The EXCLAIM mission

EXCLAIM is a balloon-borne telescope that will map the emission of CO/[CII] lines in redshift windows of 0<z<3.5. These lines are key tracers of the gas phases in the interstellar medium involved in star-formation processes.

EXCLAIM will adopt an approach called Intensity Mapping (IM):

- It will measure the statistics of brightness fluctuations of redshifted, cumulative line emissions instead of detecting individual galaxies.
- This enables a blind, complete census of emitting gas in cross-correlation with a rich spectroscopic galaxy catalog such as the Baryon Oscillation Spectroscopic Survey (BOSS) [1].

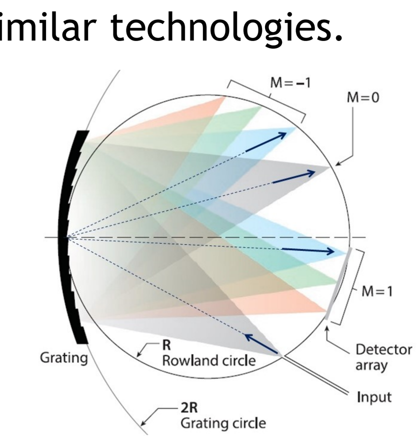



FOR MORE DETAILS, PLEASE SEE POSTER: E. Barrentine et al., "The Experiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM)"

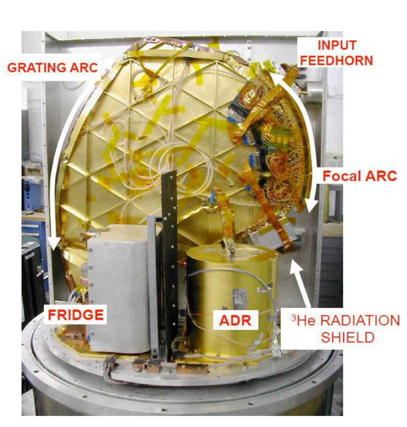
## Literature review

µ-Spec differs from similar technologies.

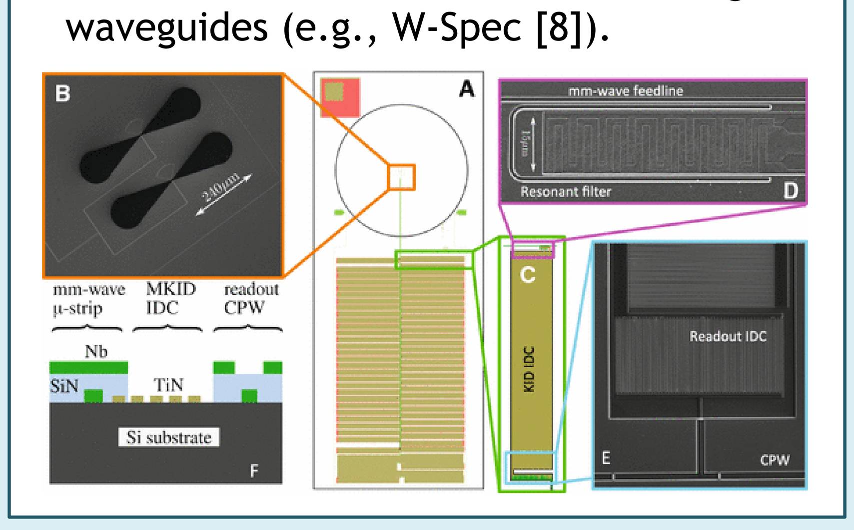
- In a Rowland spectrometer, the required phase retardation is generated by reflection from the grating grooves [2].




- In Z-Spec, propagation occurs in parallel-plate waveguides [3], which remains a bulky option (55-cm length scale and 4-kg mass).




- Bootlace lenses are a 1-dimensional analog of Z-Spec [4], which µ-Spec builds on for submillimeter wave applications.
- Narrow-band filter-bank spectrometers do not rely on optical interference as in grating or Fabry-Perot spectrometers. Some examples are: SuperSpec [5, figure below], the Delft SRON High-redshift Mapper (DESHIMA) [6], the CAMbridge Emission Line Surveyor (CAMELS) [7], and similar alternatives made in rectangular waveguides (e.g., W-Spec [8]).




## Instrument layout

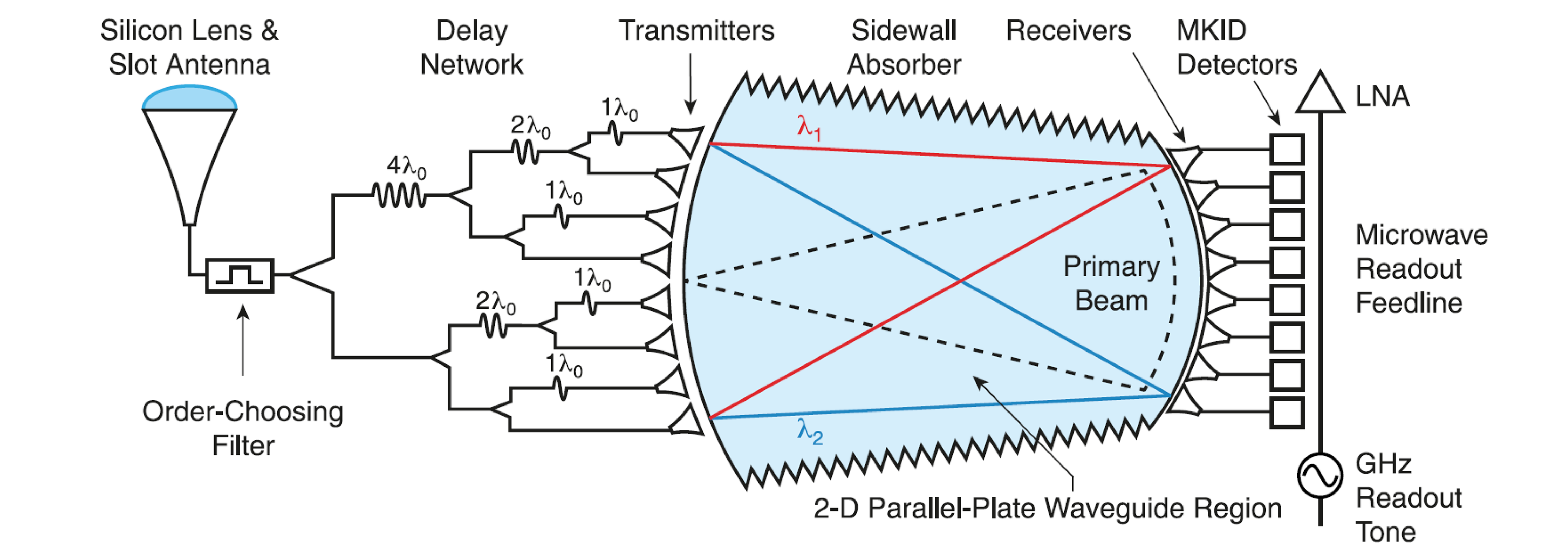



**Figure 1. Layout of the µ-Spec module.** The light is coupled into the instrument via a lens and a broadband antenna. An order-choosing filter selects the design order before the light is transmitted through a low-loss superconducting transmission line to a phase delay network (Fig. 7). The spectrum enters the planar diffractive region through an array of feed horn structures (transmitters), which concentrate the power along the focal surface as a function of wavelength. The receivers terminate in microwave kinetic inductance detectors (MKIDs) for readout. Sidewall absorbers terminate any power emitted into large angles or reflected from the receivers.

## Building on demonstrated technology

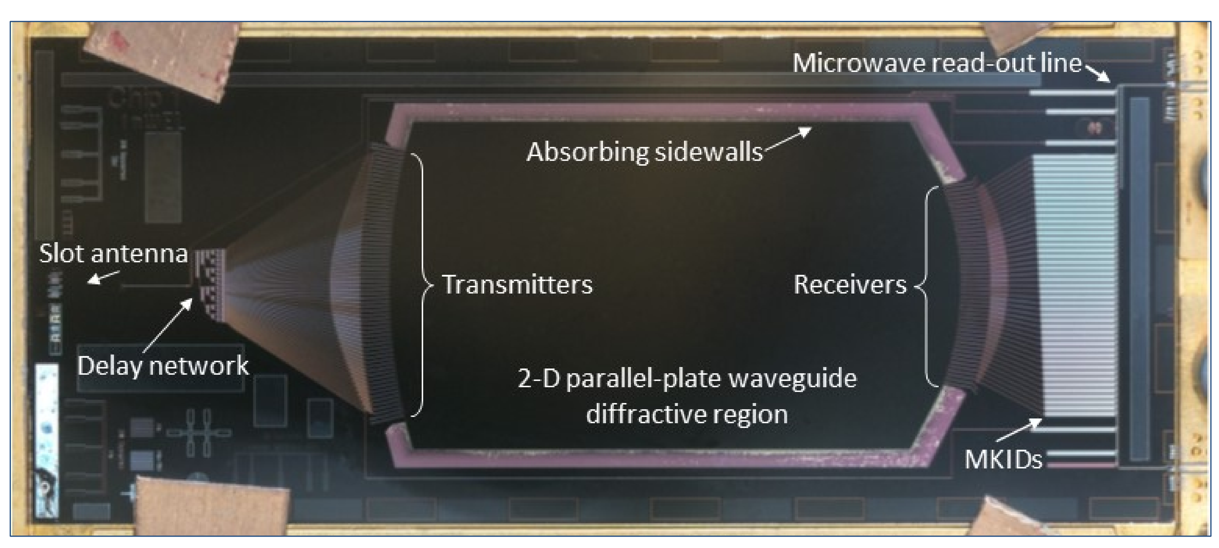



**Figure 2.** A test version with resolving power *R*=64 was designed [9], built and tested at GSFC. The fabrication process developed [10] was employed to build several prototypes. The successful instrument optical performance tests have enabled us to demonstrate the µ-Spec technology [11].

## Diffractive region design methodology

An optimized geometry is found for the transmitting antennas (red arc in Fig. 4) and the delay network extra lengths in silicon (not shown) through the minimization of the root-mean-square (RMS) phase error on the spectrometer focal plane (Fig. 5) [12]. The receiving antennas (green arc in Fig. 4) are laid to Nyquist-sample the combined power beam.

The design methodology was updated from [9,13] to account for the dispersive effects due to the superconductor's kinetic inductance (KI) in the silicon dielectric. The KI fraction is determined by the niobium, of which the transmission lines are made. The dispersive effects are quantified through the frequency dependence of the ratio of the phase velocity without KI to the phase velocity with KI following the Mattis-Bardeen theory [14].

1) INPUT PARAMETER SELECTION

**Table 1: Spectrometer design parameters** for the configuration selected to fit 2 spectrometers in a 15-cm-diameter silicon wafer.

| Input parameter | Value |
|---|---|
| Min frequency | 420 GHz |
| Max frequency | 540 GHz |
| Resolving power | 512 |
| Grating design order | 2 |
| Diffractive region radius | 1.35 cm |
| Stigmatic points' coordinates | See Fig. 4 |
| Stigmatic points' frequencies | See Fig. 4 |
| Silicon relative permittivity | 11.55 |

2) DIFFRACTIVE REGION OPTIMIZATION

3a) Optimized design variables:
1) Transmitting antennas' x-y coordinates
2) Delay-network extra lengths in silicon

3b) RMS phase error minimization

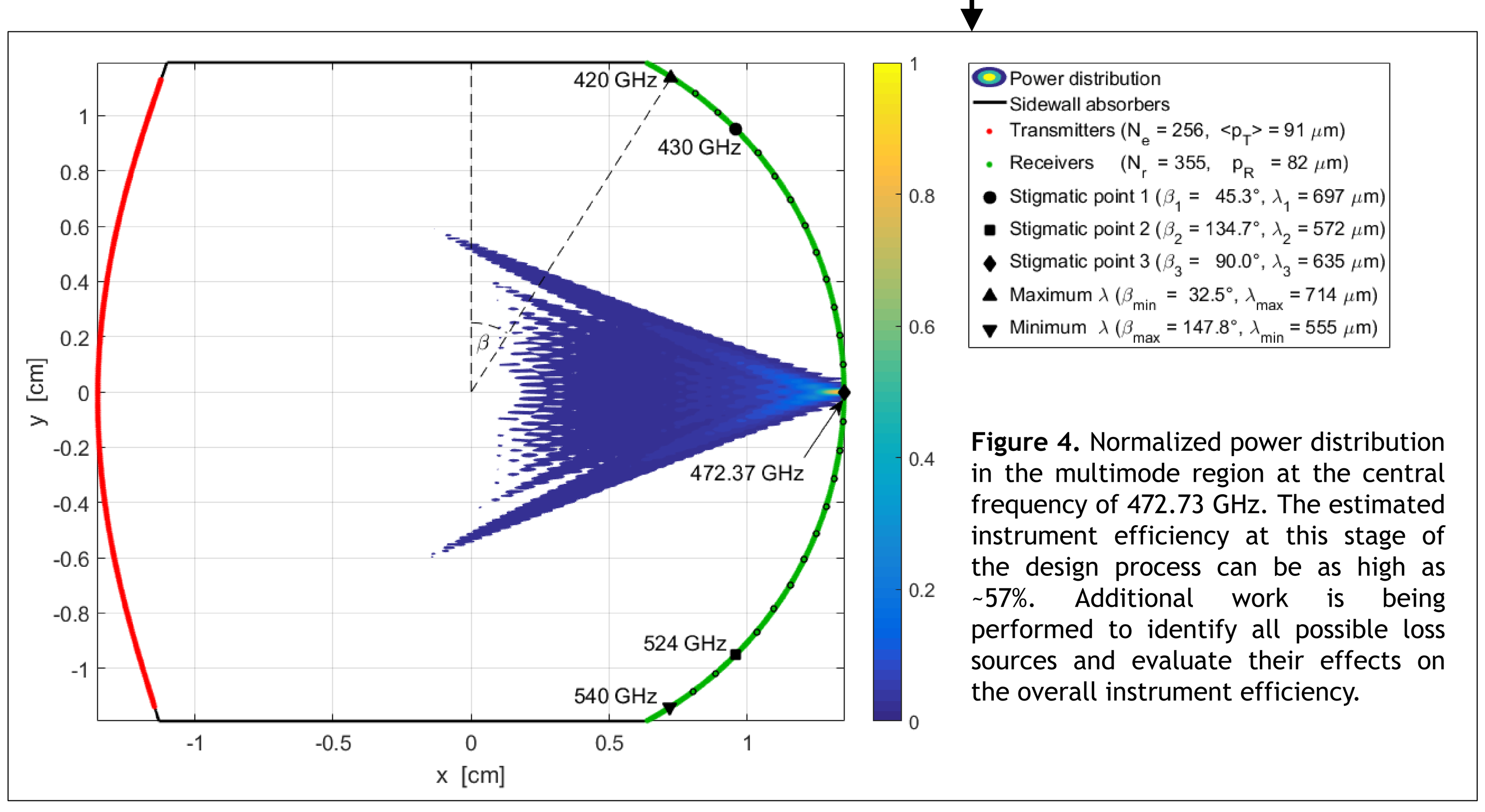



**Figure 4.** Normalized power distribution in the multimode region at the central frequency of 472.73 GHz. The estimated instrument efficiency at this stage of the design process can be as high as ~57%. Additional work is being performed to identify all possible loss sources and evaluate their effects on the overall instrument efficiency.

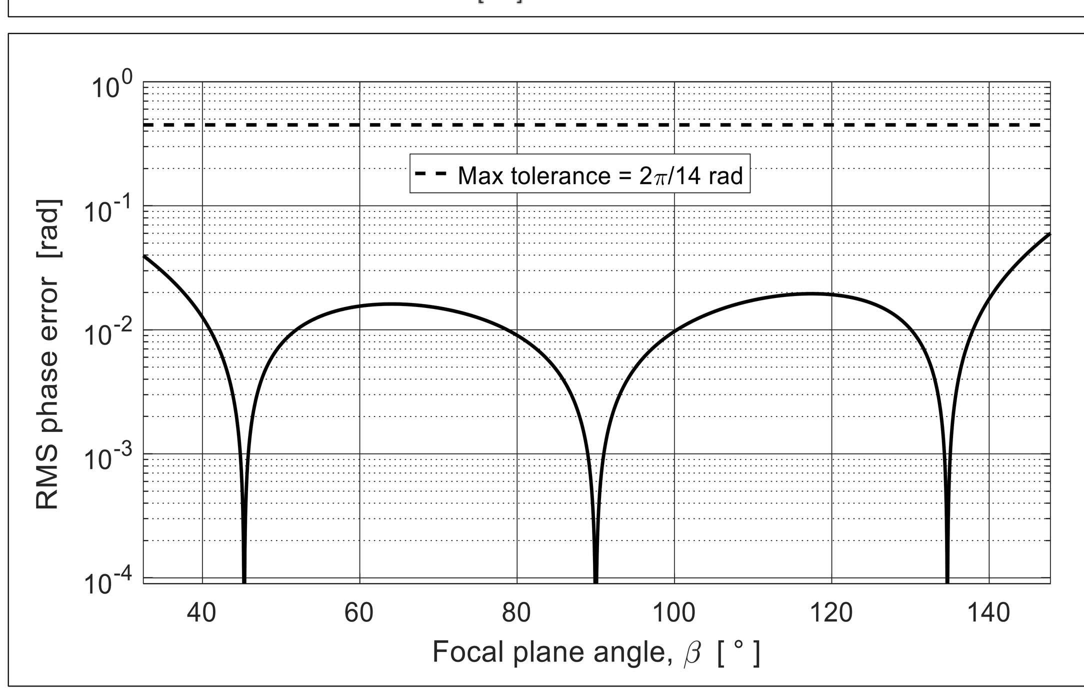



**Figure 5.** The positions and frequencies of the stigmatic points are selected so that the average pitch of the transmitting and receiving antenna arrays does not differ by more than approximately ±10%. This ensures the two antenna arrays have the correct coupling. The RMS phase error vanishes at the three stigmatic points by construction and remains below the maximum allowed tolerance of 2π/14 rad over the entire focal plane. This ensures diffraction-limited performance over the power combiner's design spectral range.

## Delay network

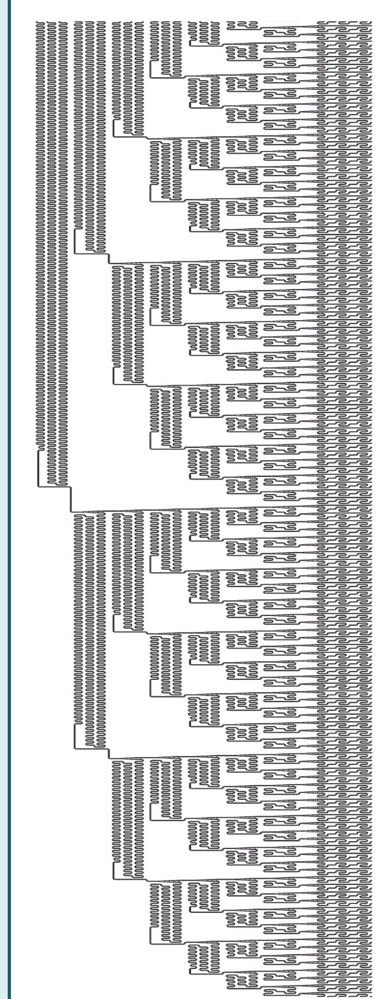
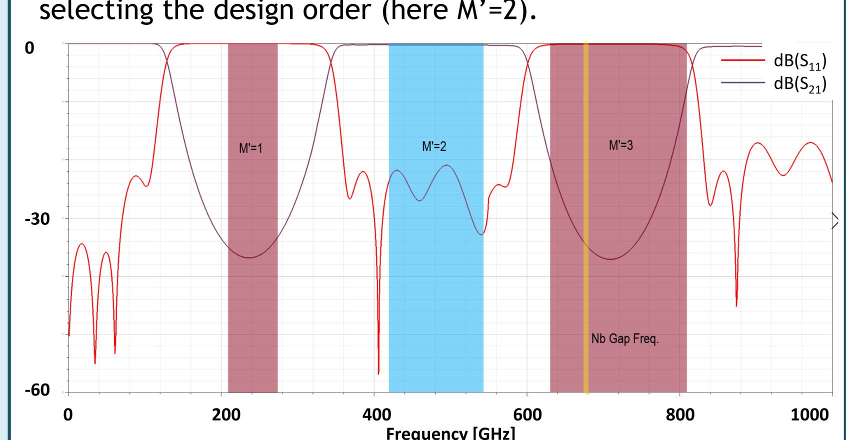


**Figure 7. Layout of the µ-Spec delay network.** The delay network consists of a binary splitting network of meandered microstrip transmission lines made of niobium (Nb) on a 0.45-µm-thick silicon (Si) dielectric substrate. This configuration reduces the required area by a factor of $\log_2(N)/(N-1)$ = 0.03.

Each delay line's length is designed to generate the required phase retardation at the input to the planar diffractive region.

Given measured uniformities in the patterned Nb transmission lines and in the Si dielectric layer, our studies show we can achieve the phase control necessary to provide resolving powers ≥ 2300.

**Figure 8. Order-choosing filter passband.** Before the light propagates through the delay network, an on-chip microstrip stepped-impedance bandpass filter enables selecting the design order (here M'=2).




## References

[1] S. Alam et al., "The eleventh and twelfth data releases of the Sloan Digital Sky Survey: final data from SDSS-III," Astrophys. J. Suppl. Ser. 219(1), 2015.
[2] H. A. Rowland, "On concave gratings for optical purposes," Philos. Mag. 16, 1883.
[3] L. Earle et al., "Z-Spec: a broadband, direct-detection, millimeter-wave spectrometer - instrument status and first results," Proc. SPIE 6275, 2006.
[4] W. Rotman and R. F. Turner, "Wide-Angle Microwave Lens for Line Source Applications," IEEE T. Antenn. Propag. 11(6), 1963.
[5] J. Wheeler et al., "SuperSpec, The On-Chip Spectrometer: Improved NEP and Antenna Performance," J. Low Temp. Phys. 193(3-4), 2018.
[6] A. Endo et al., "Design of an Integrated Filterbank for DESHIMA: On-Chip Submillimeter Imaging Spectrograph Based on Superconducting Resonators," J. Low Temp. Phys. 167(3-4), 2012.
[7] C. N. Thomas et al., "Progress on the CAmbridge Emission Line Surveyor (CAMELS)," 26th Int. Symp. Space THz Technol., 2015.
[8] S. Bryan et al., "A compact filter-bank waveguide spectrometer for millimeter wavelengths," IEEE Trans. Terahertz Sci. Technol., 5(4), 2015.
[9] G. Cataldo et al., "Micro-Spec: an ultracompact high-sensitivity spectrometer for far-infrared and submillimeter astronomy," Appl. Opt. 53(6), 2014.
[10] A. Patel et al., "Fabrication of MKIDs for the Micro-Spec Spectrometer," IEEE T. Appl. Supercon. 23(3), 2013.
[11] O. Noroozian et al., "µ-Spec: An Efficient Compact Integrated Spectrometer for Submillimeter Astrophysics," 26th Int. Symp. Space THz Technol., 2015.
[12] G. Cataldo, "Second-generation Micro-Spec: A compact spectrometer for far-infrared and submillimeter space missions," Acta Astronaut. 162, 2019.
[13] G. Cataldo et al., "Micro-Spec: an integrated direct-detection spectrometer for far-infrared space telescopes," Proc. SPIE 9143, 2014.
[14] D. Mattis and J. Bardeen, "Theory of the anomalous skin effect in normal and superconducting metals," Phys. Rev. 111 (2), 1958.

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