Second-generation design of Micro-Spec: a medium-resolution, submillimeter-wavelength spectrometer-on-a-chip

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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 chip through the use of superconducting microstrip transmission lines on a single-crystal silicon substrate.

The second generation of µ-Spec is being designed to operate with a spectral resolution of 512 in the submillimeter (500-1000 µm, 300-600 GHz) wavelength range to study the early universe (redshift > 8) and observe the lines of abundant elements (C, N and O) in star-forming galaxies. In addition, µ-Spec would improve the long-wavelength capability of several IR space observatories.

High-altitude balloon missions would provide both the first testbed to demonstrate the µ-Spec technology in a space-like environment and an economically viable venue for multiple observation campaigns.

Instrument layout

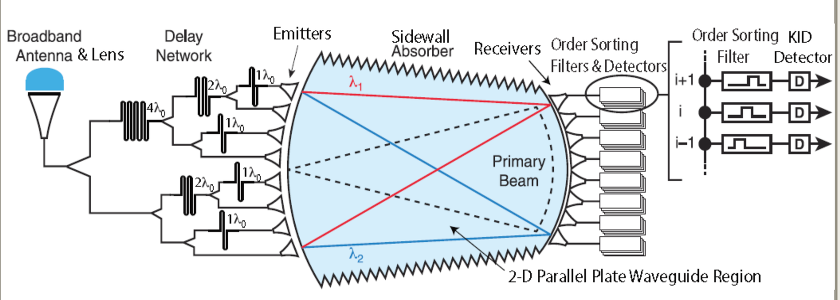
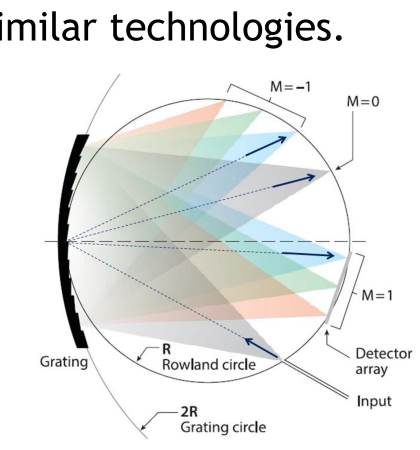


Figure 1. Layout of the µ-Spec module. The light is coupled into the instrument via a broadband antenna and is transmitted through a low-loss superconducting transmission line to a divider and a phase delay network. In the multimode region, the feed horns radiate a converging circular wave, which concentrates the power along the focal surface, with different wavelengths at different locations. To disentangle the various orders, the receiver antennas are connected to a bank of order-sorting filters terminated in microwave kinetic inductance detectors (MKIDs) for readout.

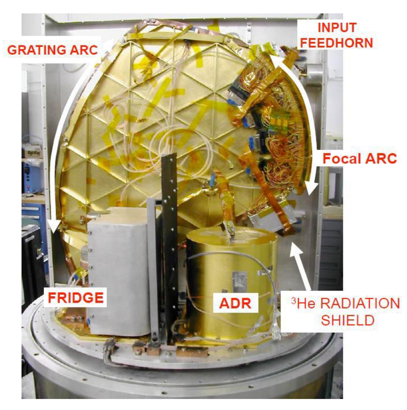
Literature Review

µ-Spec differs from similar technologies.

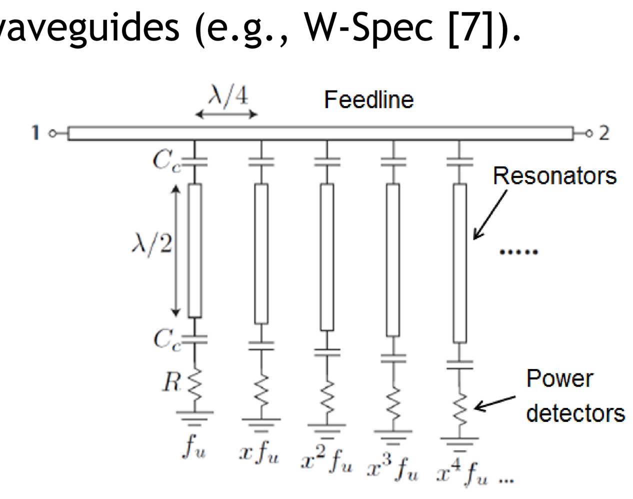
- In a Rowland spectrometer, the required phase retardation is generated by reflection from the grating grooves [1].



- In Z-Spec, propagation occurs in parallel-plate waveguides [2].



- Bootlace lenses are a 1-dimensional analog of Z-Spec [3], 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 [4, figure below], the Delft SRON High-redshift Mapper (DESHIMA) [5], the CAMbridge Emission Line Surveyor (CAMELS) [6], and similar alternatives made in rectangular waveguides (e.g., W-Spec [7]).



Building on demonstrated technology

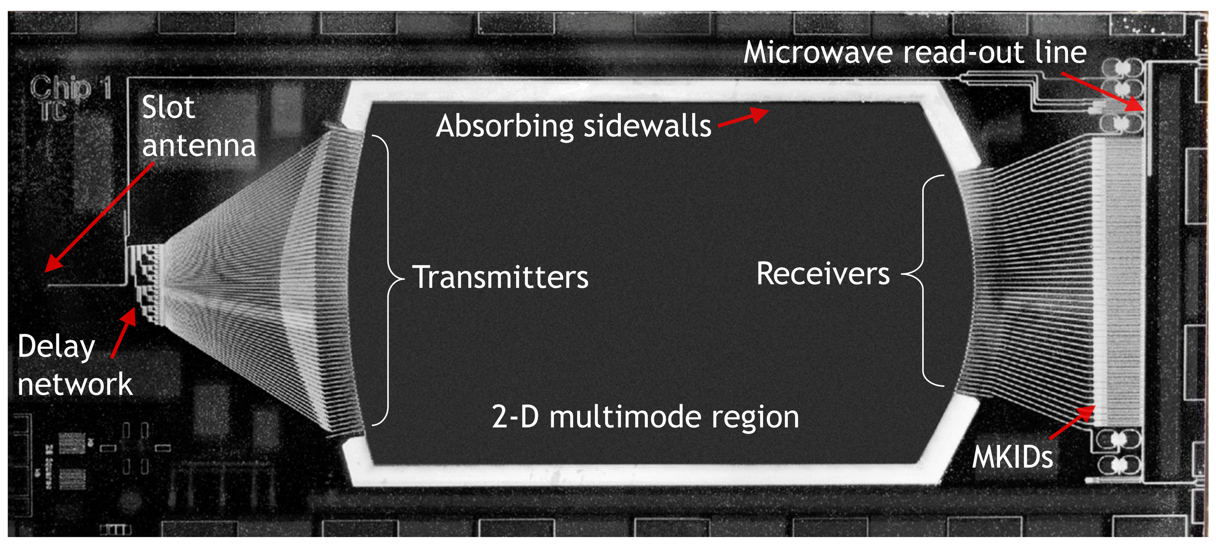


Figure 2. A test version with resolving power equal to 64 was designed [8], built and tested at NASA GSFC. The fabrication process developed [9 and Fig. 7] was employed to build several prototypes. The successful instrument optical performance tests have enabled us to demonstrate the µ-Spec technology [10].

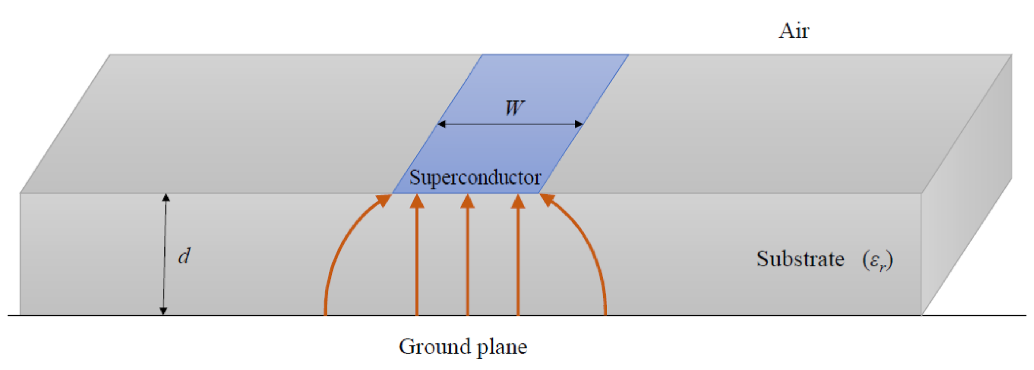


Figure 3. Geometry of a microstrip transmission line. In orange are the electric field lines indicating their dominant modal symmetry [11]. This structure can be fabricated by photolithographic processes and integrated with other active or passive microwave devices. It is mass producible and enables reducing the instrument size by a factor of the medium's effective index.

Multimode region design methodology

The design methodology results in an optimized geometry arrangement for the transmitting and receiving antennas (red arc in Fig. 4) through the minimization of the root-mean-square (RMS) phase error on the focal plane (Fig. 5) [12].

1) INPUT PARAMETER SELECTION

Table 1: Spectrometer design parameters for the configuration selected to fit 4 spectrometers in a 10-cm-diameter silicon wafer. This choice has enabled several designs to be studied as well as the development of the required fabrication process.

Input parameter	Value
Min frequency in vacuum	300 GHz
Max frequency in vacuum	600 GHz
Resolving power	512
Grating design order	8
Number of transmitters	64
Number of receivers	311
Multimode region radius	1.25 cm
Silicon relative permittivity	11.55
Silicon relative permeability	1
Kinetic inductance	ON

2) FOCAL PLANE OPTIMIZATION

3a) Outputs:
1) Antennas' optimal coordinates
2) Optimal delay-network electric path lengths in silicon

3b) RMS phase error minimization

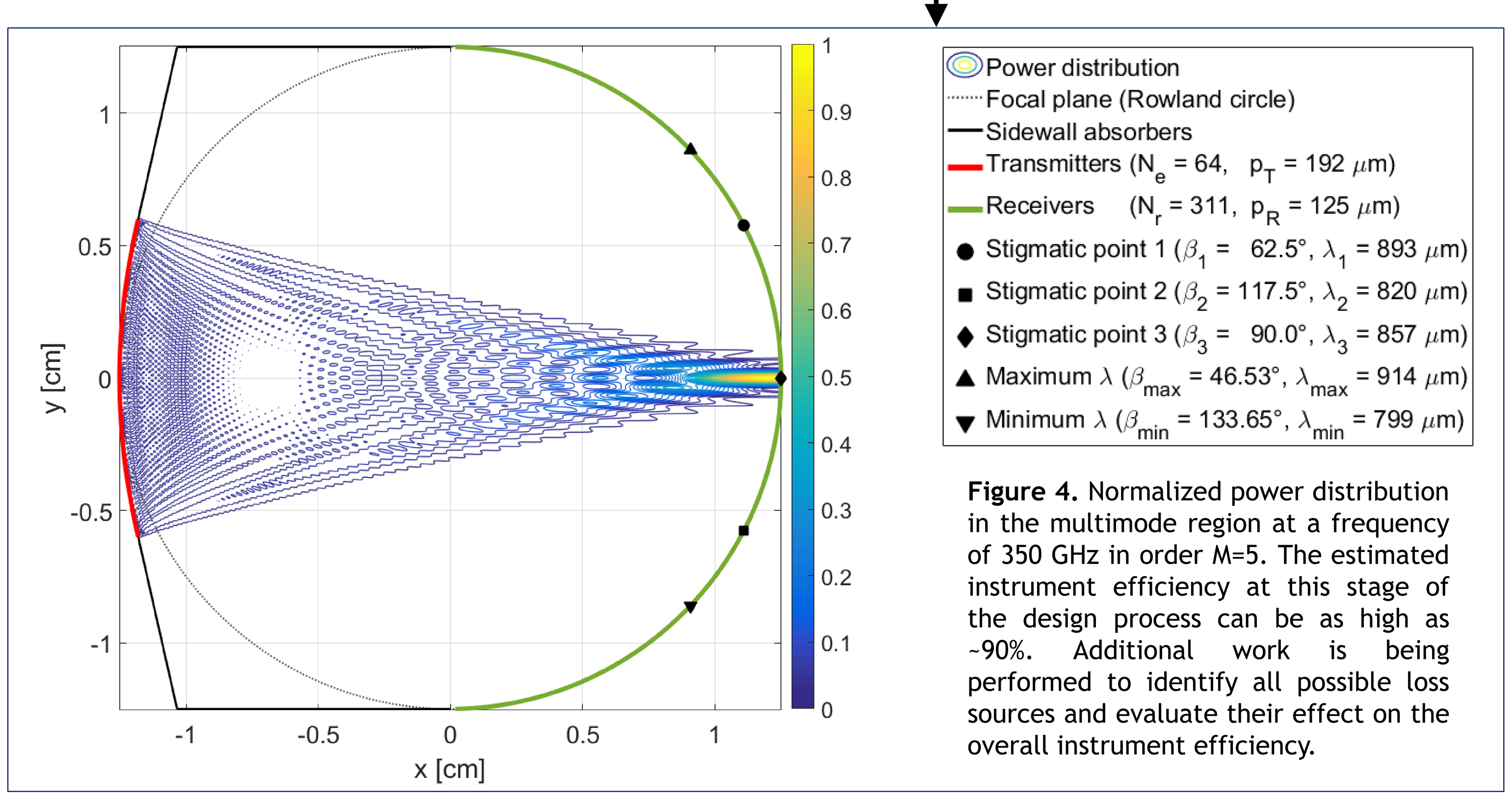


Figure 4. Normalized power distribution in the multimode region at a frequency of 350 GHz in order M=5. The estimated instrument efficiency at this stage of the design process can be as high as ~90%. Additional work is being performed to identify all possible loss sources and evaluate their effect on the overall instrument efficiency.

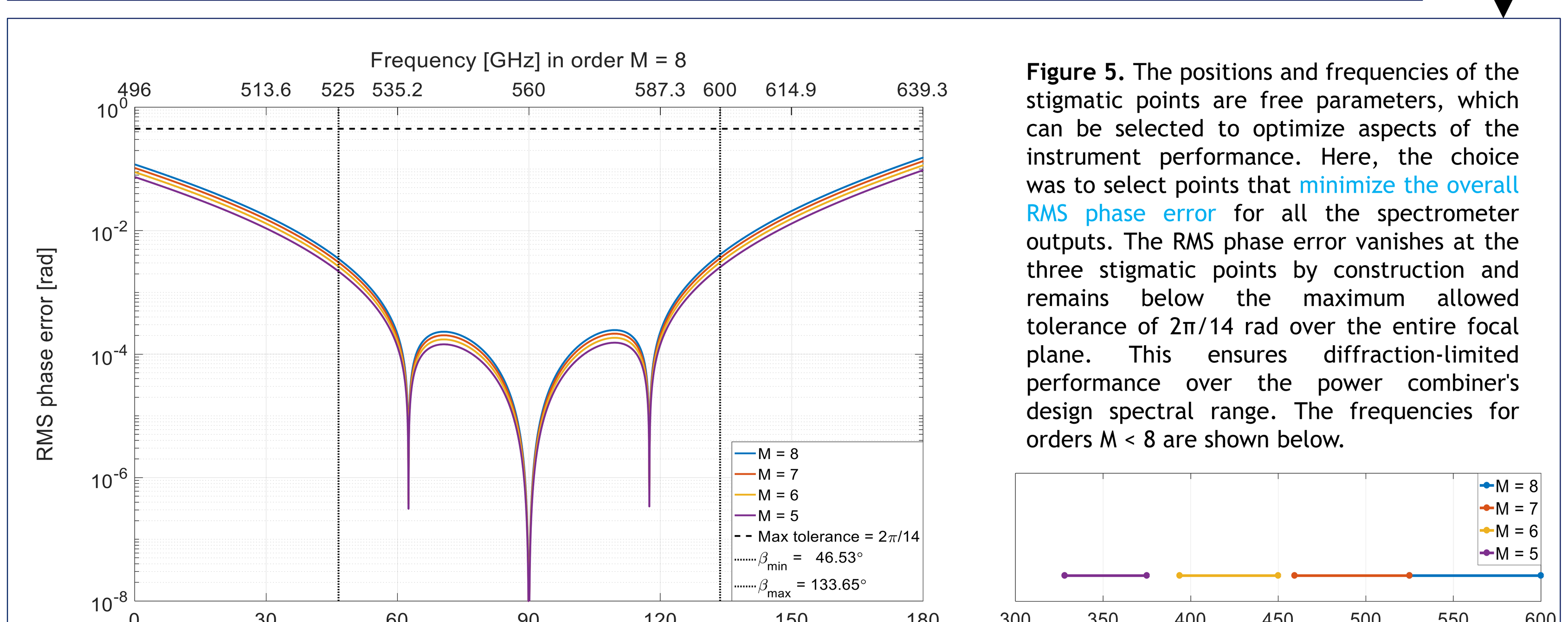


Figure 5. The positions and frequencies of the stigmatic points are free parameters, which can be selected to optimize aspects of the instrument performance. Here, the choice was to select points that minimize the overall RMS phase error for all the spectrometer outputs. The RMS phase error vanishes 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. The frequencies for orders M < 8 are shown below.

Antenna feed horn design

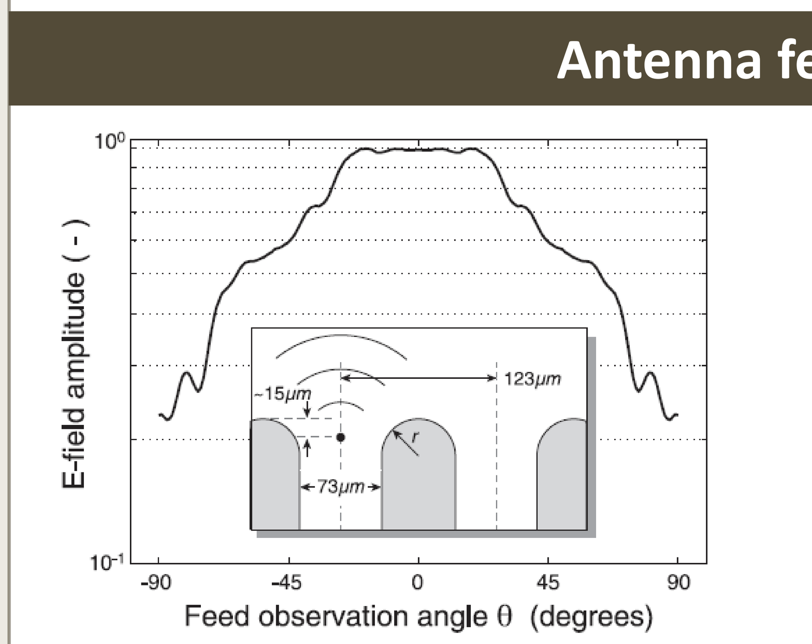


Figure 6 (Adapted from [8]). (Left) Computed feed horn angular response at 430 GHz. The response of an emitting feed is evaluated in the far field (r~6λ = 438 µm) and normalized to the magnitude of the E field at 0°. The feed array geometry is provided in the figure insert. The feed's phase center is indicated by a black filled circle.

Work is in progress to explore a different design, which employs magnetically coupled antennas.

FOR FURTHER DETAILS, PLEASE SEE: B. Bulcha et al., "Electromagnetic Design of a Magnetically-Coupled Spatial Power Combiner," LTD17 #2312245.

Fabrication process

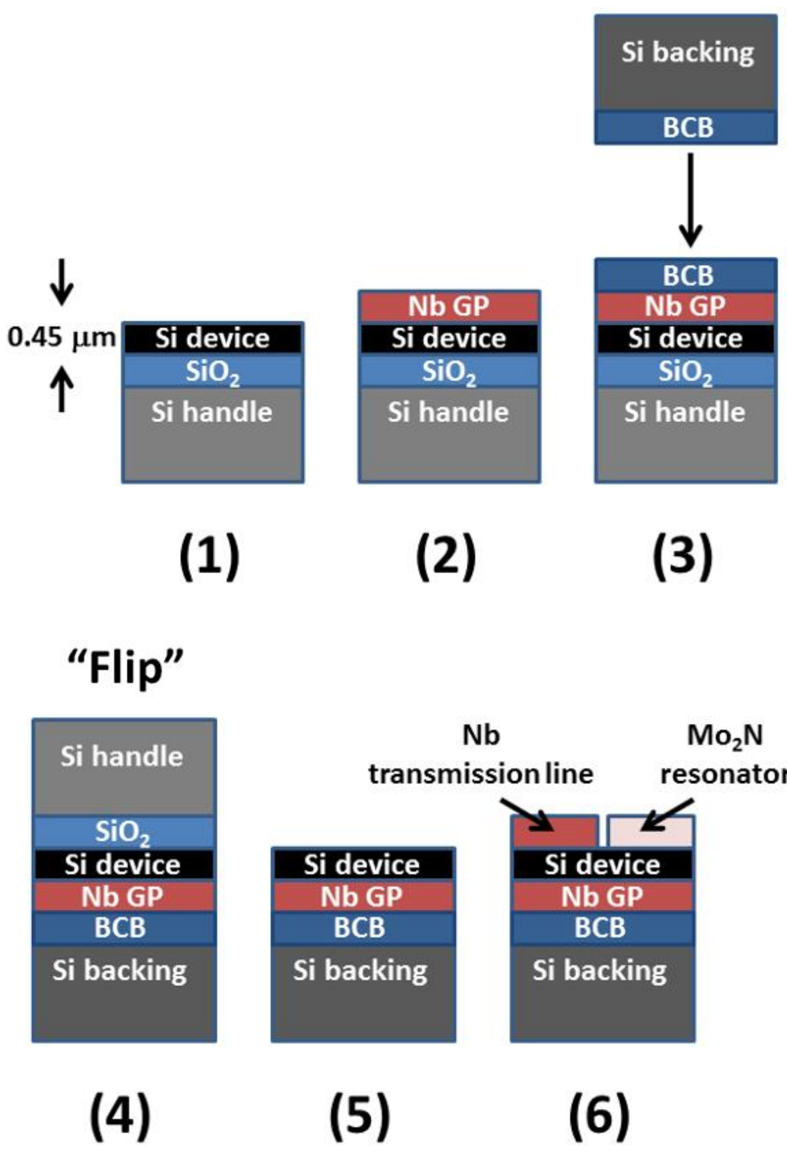


Figure 7 (Adapted from [13]). (1) Clean a silicon-on-insulator (SOI) wafer. (2) Sputter-deposit the niobium (Nb) ground plane (GP) with argon. (3) Spin-coat bisbenzocyclobutene (BCB) on the Nb-coated surface of the SOI wafer. (4) Manually flip the wafer stack upside down to start processing the SOI wafer backside. (5) Etch the silicon handle wafer by mechanical lapping, followed by deep reactive ion etching using the Bosch process. (6) Deposit molybdenum nitride (Mo_2N), pattern the resonators and sputter-deposit the Nb transmission lines.

References

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Acknowledgments

G. Cataldo would like to acknowledge the University of Maryland Baltimore County for administering his appointment at the NASA Goddard Space Flight Center.

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