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A four-pole power-combiner design for far-infrared and submillimeter spectroscopy ☆

Giuseppe Cataldo [a,b,*], Samuel H. Moseley [a], Edward J. Wollack [a]

[a] NASA Goddard Space Flight Center, United States of America
[b] Massachusetts Institute of Technology, United States of America

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ABSTRACT

The far-infrared and submillimeter portions of the electromagnetic spectrum provide a unique view of the astrophysical processes present in the early universe. Micro-Spec (μ-Spec), a high-efficiency direct-detection spectrometer concept working in the 450–1000-μm wavelength range, will enable a wide range of spaceflight missions that would otherwise be challenging due to the large size of current instruments and the required spectral resolution and sensitivity. This paper focuses on the μ-Spec two-dimensional multimode region, where the light of different wavelengths diffracts and converges onto a set of detectors. A two-step optimization process is used to generate geometrical configurations given specific requirements on spectrometer size, operating spectral range, and performance. The canonically employed focal-plane constraints for the power combiner were removed to probe the design space in its entirety. A new four-stigmatic-point optical design solution is identified and explored for use in far-infrared and submillimeter spectroscopy.

1. Introduction

Far-infrared (IR) and submillimeter (15 μm to 1 mm) spectroscopy provides a powerful tool to probe a wide range of environments in the universe. In the past thirty years, discoveries made by several space-based observatories have provided unique insights into physical processes leading to the evolution of the universe and its contents. This information is encoded in a variety of molecular and fine structure lines; observations of such spectral lines enable the exploration of galaxies at high redshifts. The fine structure lines of abundant elements (carbon, nitrogen, and oxygen), for example, allow tracing the obscured star formation and Active Galactic Nuclei (AGN) activity into the high-redshift universe. One can measure galaxy redshifts and determine their elemental abundances and physical conditions out to redshifts $z > 5$. In spite of this, a number of questions remain unanswered regarding the very early steps of the universe as well as galactic, stellar, and planetary formation. The ability to explore this rich spectral region has been limited by the size and cost of the cryogenic spectrometers required to carry out these measurements. The work proposed here specifically addresses the need for integrated spectrometers and background-limited far-IR direct detectors. For space-borne astrophysics systems, the specific requirements are shown in Table 1 and compared against the current state of the art [1].

In order to realize the goals outlined in Table 1, a high-performance integrated spectrometer module, Micro-Spec (μ-Spec), operating in the 450–1000-μm (300–650-GHz) range is proposed. μ-Spec can be compared to a grating spectrometer [2–6], in which a plane wave is reflected from the grating and the phase of each partial wave scattered

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* Corresponding author at: NASA Goddard Space Flight Center, United States of America.

E-mail addresses: Giuseppe.Cataldo@nasa.gov, gcataldo@mit.edu (G. Cataldo).

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from the rulings is a linear function of position across the grating. An example of planar Rowland grating architecture is Z-Spec, in which propagation occurs in parallel-plate waveguides [7–10]. Another comparison can be made with one-dimensional bootlace lenses found in microwave practice [11–14], which μ-Spec builds upon for submillimeter wave applications. Finally, another variation used at millimeter wavelengths, which does not rely on optical interference as in grating spectrometers, is a narrow-band filter-bank spectrometer. Examples realized in superconducting transmission lines are SuperSpec [15–17] and the Delft SRON High-Z Mapper (DESHIMA) [18].

μ-Spec differs from these approaches by the order of processing of the light in the spectrometer. In μ-Spec (Fig. 1), the incoming radiation collected by the telescope is coupled to the spectrometer via a broadband dual-slot antenna used in conjunction with a hyperhemispherical silicon lens and directed to a series of power splitters and a delay network made of superconducting microstrip transmission lines. Analogous to the Rowland grating [2], the delay network creates a phase retardation across the input to a planar-waveguide multimode region, which has two internal planar antenna arrays, one for transmitting and one for receiving the radiation as a function of wavelength. Absorber structures lining the multimode region terminate the power emitted into large angles or reflected from the receiver antenna array. An array of planar feed structures is employed to couple the radiation to the multimode region and concentrates the power along the focal surface with different wavelengths at different locations. The outputs are connected to a bank of order-sorting filters which terminate the power in an array of microwave kinetic inductance detectors (MKIDs) for detection and read-out. The entire spectrometer circuit is integrated on a $\sim$10-cm^2 silicon chip (i.e., the hyperhemispherical lens, relay optics, and telescope are not on the chip and are part of the instrument system). This compact footprint is accomplished through the use of single-mode microstrip delay lines, which can compactly be folded on the silicon wafer and reduce the required physical line length by a factor of the medium's effective refractive index.

Table 1
Summary of far-IR cryogenic spectrometer and detector array requirements and comparison with current state of the art [1].

Metric	State of the art	Requirements
Wavelength, λ (μm)	250–700	220–2000
Noise equivalent power, NEP (W/$\sqrt{\text{Hz}}$)	10^{-19}	$< 10^{-20}$
Spectral resolution, $\mathcal{R}$	≥ 100	≥ 1200
Detective quantum efficiency, DQE (%)	~ 15	> 90
Time constant, τ (ms)	100	< 10

The frequency range of the implementation presented here is limited to wavelengths $\lambda > 250\ \mu$m by the gap frequency of currently available low-loss superconductors. These include niobium (Nb) and niobium-titanium nitride (NbTiN) for the transmission line structures, and molybdenum nitride (MoN) for the detectors. This paper will describe the design process of the μ-Spec multimode region and illustrate the results in terms of geometry, imaging quality, and efficiency.

2. Multimode region design

In designing a spectrometer, it is possible to define points on the focal plane where the phase error of the diffracted light is identically equal to zero. These points are called stigmatic points. Increasing the number of such points on the focal surface presents the advantage of improving a spectrometer's imaging quality, which results in lowering the overall phase error on the entire focal plane and increasing the usable spectral bandwidth. As a consequence, the number of spectrometer channels and the resolving power can grow.

Examples of designs with two stigmatic points can be found in the literature [4,6,7]. We built upon these designs to generate spectrometer concepts with an increased number of stigmatic points. A three-stigmatic-point prototype version with a resolving power $\mathcal{R} = 65$ in first order ($M = 1$) was designed [19] and built, and is currently under evaluation at the NASA Goddard Space Flight Center. Additional designs are described in [20] for configurations with resolving powers equal to $\mathcal{R} = 260$ and $\mathcal{R} = 520$ in higher order ($M > 1$). These designs were obtained through a constrained optimization process in which zero phase error was imposed on three preselected points. However, a fourth stigmatic point was observed beyond the angular range in use. It is the purpose of the work presented in this paper to show how to

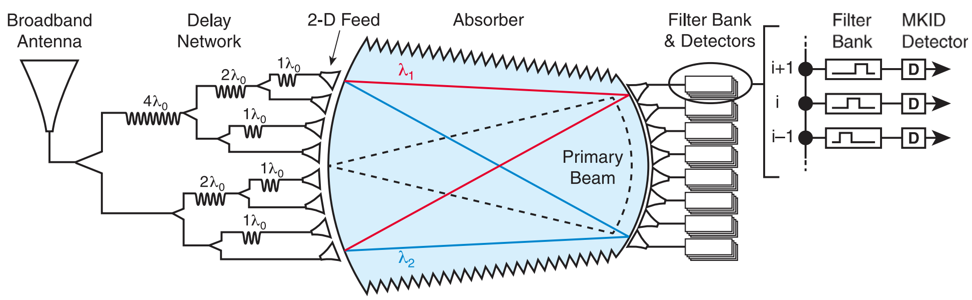

Fig. 1. Layout of an individual μ-Spec wafer. The radiation is coupled into the instrument through a broadband antenna and is then transmitted through a superconducting transmission line to a divider and a phase delay network. The spectrum enters the multimode region through an array of feeds which concentrates the power along the focal surface with different wavelengths at different locations. The receivers are connected to a bank of order-sorting filters and MKID detectors [19]. Multiple spectrometer wafers can be packaged and potentially used in defining an instrument system.