Demonstration of a compact high-resolution spectrograph for far-infrared astronomy: silicon-based virtually imaged phased array

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***Abstract*—We present the first measurement of the spectral performance of a compact silicon-based Virtually Imaged Phased Array (VIPA) in the far-infrared regime. We cryogenically cooled the VIPA to 4 K and measured its transmission spectrum using a quantum cascade laser operating near 115.7 µm and a pyroelectric detector. The measured spectral resolving power is about 16,500. The demonstrated performance of the VIPA indicates the suitability of this technology to achieve spectral resolving powers of 100,000 and thus shows its great promise for applications in balloon-borne and space-borne velocity-resolved astrophysics and represents a valuable addition to the existing suite of high-resolution far-infrared astronomical instruments.**

***Keywords*—Spectrometer, virtually imaged phased array, far-infrared astronomy, silicon, nanofabrication.**

I. Introduction

The VIPA, a novel spectral disperser capable of achieving extremely high spectral resolution, distinguishes itself from conventional methods due to its compact structure without moving components and cost-effectiveness [1]. Its versatility spans diverse fields like frequency comb spectroscopy [2] and biological imaging [3]. Recently, the use of a VIPA as the prime spectral element to deliver a resolving power of 100,000 has been proposed for direct detection, far-infrared astronomy projects, e.g. POEMM and FIRSST.

As shown in Fig. 1, the VIPA system channels a line-focused beam through an entrance slit, using two highly reflective surfaces to form a resonating cavity. The entrance side, excluding the slit, has a metal film for near-total reflection, while the exit side has a partially reflective film (usually over 90%) to allow a small portion of the beam to pass through with each reflection. An anti-reflection coating can be applied to the entrance slit to enhance transmittance if needed. The incident light, injected at an angle, resonates within the cavity, with each wavelength following its unique path. After multiple reflections, the light exits through the partially reflective surface, and the transmitted beams are focused to create angular dispersion based on their wavelengths.

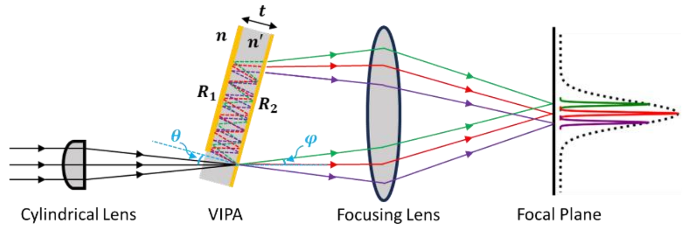

Fig. 1. Schematic of the VIPA system's operation principle. The colored ray traces illustrate how beams of different wavelengths follow distinct paths and disperse on the focal plane.

In this study, we present the development and successful tests of a far-infrared VIPA device, demonstrating the potential of using VIPAs in upcoming high-spectral resolution, velocity-resolved astronomical instruments.

II. Fabrication and Experimental Setup

The VIPA demonstrator was fabricated at the Cornell NanoScale Facility using high-purity silicon from the same boule studied in Wollack et al. [4]. At room temperature, the sample measures 50.020 mm in length, 30.029 mm in width, and 9.907 mm in thickness. This silicon, produced using the float-zone method, has an electrical resistivity of approximately 30-40 kΩ·cm. The entrance side, excluding the slit, is coated with a gold film, while the exit side features gold inductive metal meshes with a pitch of 27.5 µm and an inner opening width of 14.8 µm.

We utilized a cooled THz Quantum Cascade Laser (QCL) coupled with a room-temperature pyroelectric detector to capture the transmitted signal through the VIPA. We tuned the QCL wavelength around 115.7 µm by modifying the operating voltage.

Fig. 2 provides a simplified schematic of the testbed's main components. The QCL is housed in a separate cryostat, maintaining a stable temperature of approximately 52 by using a liquid nitrogen bath. To produce a clean beam, the QCL laser

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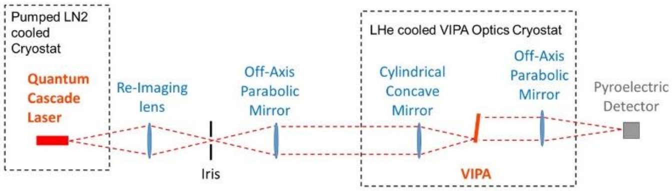

Fig. 2. Simplified schematic of the main components of the testbed

is refocused through a 2 mm diameter iris diaphragm, forming a spatial filter. An off-axis parabolic (OAP) mirror then captures the beam and redirects it as a collimated beam into the liquid helium-cooled cryostat containing the VIPA. Initially, the VIPA stabilized at 26 K due to the thermal background radiation load from room temperature. To reduce this load, subsequent measurements utilized two cooled quartz windows and scatter filters at the entrance and exit of the VIPA cryostat, achieving a VIPA temperature of 4 K. Incoming radiation, upon entering the cryostat, is deflected by a flat mirror and focused onto the VIPA's exit side by a cylindrical concave mirror. The beam is focused on the VIPA's back surface for better radiation coupling to the resonator space. Inside the VIPA, the radiation exits as a system of collimated beams, which are collected by an OAP mirror and directed to a focal plane via two flat mirrors. The radiation then exits the VIPA cryostat and is detected by a single-pixel pyroelectric detector. To record the VIPA's spectral transmission profile, the detector is translated along the dispersion direction in the focal plane.

III. Results

The VIPA was operated at a stable temperature of 4 K. The dispersion measurements obtained from the VIPA are depicted in Fig. 3 as data points with error bars. These measurements are delineated into three discrete sets of data points, each distinguished by distinct colors and acquired at different QCL wavelength settings. The measurements have been normalized to unity to facilitate more effective comparison. The observed wavelength shift of the three recorded spectral peaks in the focal plane aligns with the anticipated VIPA output and QCL tuning.

The solid curves in Fig. 3 represent the normalized model calculations for the three distinct wavelengths. The plot illustrates an impressive consistency between the model predictions and the observed data, with the full width at half maximum (FWHM) measurements differing from the model predictions by less than 10%. The FWHM measurements for the peaks are approximately 7 nm at 115.722 µm and 115.714 µm, and around 8 nm at 115.697 µm. These values correspond to resolving powers of 14,500 and 16,500, and hence, finesses of 25 and 28.5, respectively.

During the optical alignment process, we also measured a single wavelength at 300 K. The resonating peak's resolving

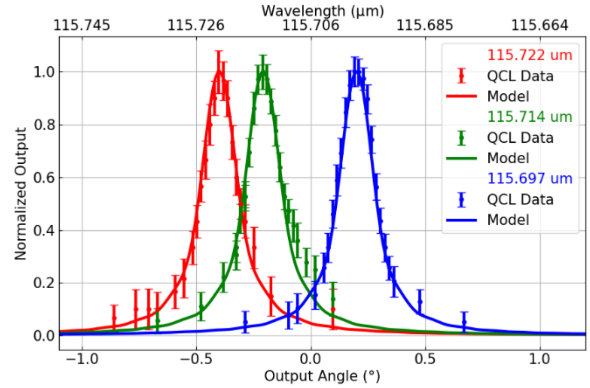

Fig. 3. Measured VIPA transmission profile and corresponding model calculations at three different QCL wavelengths. The measured data is shown as dots with errorbars, and the simulations are shown as solid lines.

power was found to be 5800, with an approximate finesse of 10. As expected, these values are considerably lower than those observed at 4 K, though the signal remains detectable at room temperature.

Differences among the spectral profiles and minor discrepancies in the side wings between measurements and model calculations are likely caused by vignetting in the optical system, non-uniform slit illumination, or stray light. Further investigation into the experimental setup or refining the modeling parameters could provide deeper insights into these small discrepancies.

IV. Conclusions

In this study we presented the tests of a far-infrared VIPA and demonstrated its spectral resolving power of approximately 16,500 at 115.7 µm, 4 K. Our findings establish a robust foundation for future far-infrared VIPA devices. This innovative technology holds potential for diverse scientific applications in velocity-resolved spectroscopy and represents a valuable enhancement to current high-resolution far-infrared astronomical instruments.

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