A Compact Filter-Bank Waveguide Spectrometer for Millimeter Wavelengths

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Abstract—We present the design and measurements on a 90GHz prototype of a millimeter-wave channelizing spectrometer realized in rectangular waveguide for astronomical instrumentation. The device was fabricated using conventional high-precision metal machining, and the spectrometer can be tiled into a 2D array to fill the focal plane of a telescope. Measurements of the fabricated five-channel device matched well with electromagnetic simulations using HFSS and a cascaded S-matrix approach. This motivated the design of a 54-channel R=200 spectrometer that fills the single-moded passband of rectangular waveguide in the 130-175 GHz and 190-250 GHz atmospheric windows for millimeter-wave spectroscopic mapping and multi-object spectroscopy.

I. INTRODUCTION

The development and optimization of large format bolometric arrays for imaging and polarimetry from ground-based millimeter-wave and sub-millimeter telescopes has helped to revolutionize the fields of cosmology, galaxy evolution and star formation. High resolution imaging and spectroscopy of individual mm-wave sources is now being done by ALMA [1], however spectral surveys over wide sky areas and wide frequency ranges are not practical with ALMA. The next major steps in millimeter-wave imaging and spectroscopy will include several science goals. Large area spectral surveys with moderate spectral resolution (e.g. $R \approx 50-200$) could be used to characterize large scale structure and the star formation history of the universe using intensity mapping of emission lines such as CO [2] and CII [3]. Multi-object mm-wave wideband spectroscopy with moderate spectral resolution would enable galaxy redshift surveys. Further studies of hot gas in galaxy clusters through the Sunyaev Zeldovich (SZ) effect would be enabled by high angular resolution and moderate spectral resolution instruments.

One of the main new technologies required to achieve these science goals is an arrayable wideband spectrometer consisting of a compact spectrometer module coupled to highly multiplexable detector arrays. Several groups are working on developing superconducting on-chip spectrometers (e.g. SuperSpec [4], [5], Micro-Spec [6], DESHIMA [7] and CAMELS [8]) based on either filter banks or on-chip gratings. Existing mm-wave spectrometers in the field include imaging Fourier Transform Spectrometers [9] and the Z-Spec waveguide grating-type spectrometer [10]. Here we present the design and prototype test results for a compact scalable waveguide filter-bank spectrometer. This spectrometer can be manufactured with standard high precision machining facilities, is able to be tested both warm and cold independently from the detectors. It can be coupled to simple-to-fabricate highly multiplexable kinetic inductance detectors (KIDs), or to conventional bolometers. The spectrometer is highly complementary to the on-chip spectrometers in several ways. First, it could be naturally used in the currently undeveloped spectral range from 130-250 GHz, which is optimal for measurements of CO line emission and the kinetic SZ effect. Also, this device can be straightforwardly designed to cover a relatively broad spectral resolution compared to the superconducting filters. Finally, instead of using KIDs as the detector technology, the device could alternately be configured as a room temperature wideband backend for mm-wave and cm-wave cryogenic amplifiers without the need for downconverting mixers.

II. SPECTROMETER CONCEPT AND MEASUREMENTS OF THE PROTOTYPE

The design concept of the filter-bank spectrometer is illustrated in Fig. 1 which shows a drawing of the five-channel prototype filter bank we have fabricated and tested. A direct-drilled circular feed horn [11] followed by a circular to rectangular transition (not shown) couples light from the sky onto the main rectangular waveguide. Each channel connects to the main waveguide through an E-plane tee that uses an evanescent coupling section into a half-wavelength resonating cavity. An identical narrow section on the other end of the resonant cavity defines the resonating length. The radiation then terminates on a detector. The narrow sections of waveguide have a cutoff frequency that is 50% higher than the center frequency of the passband of the channel. Because the light from the sky is below the cutoff frequency of the narrow section, this means the section’s impedance is effectively capacitive. However, on-resonance the cavity section is effectively inductive, which tunes out the capacitive sections, allowing the radiation to pass through to that channel’s detector. At frequencies far from resonance, this cancellation does not take place, and light does not couple to the detector. The center frequency of each channel is tuned by adjusting the length of the resonant section, and the bandwidth is defined by adjusting the length of the narrow capacitive sections.

To verify this concept, we constructed and tested a prototype five-channel spectrometer machined from aluminum for the WR10 band. This band was chosen to allow testing using a WR10 VNA extender. The dimensions were chosen based on simulations in HFSS. Because this spectrometer is realized in waveguide, it can operate at both room and cryogenic temperatures, which enabled simple and rapid testing. The

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prototype device has one channel with a center frequency $f_c$ at 80 GHz, three closely spaced channels near 90 GHz, and a fifth channel at 105 GHz, each with $R \equiv f_c/\Delta f \sim 200$ resolution. Just as would be possible with a larger multichannel spectrometer, we used E-plane split block construction with conventional alignment pins. Nominally no RF current flows across the split. This prototype was machined on a 5-micron tolerance CNC milling machine. The 1-2 micron tolerances that would be needed for operation at 200-300 GHz are regularly achieved on standard high-precision CNC milling machines.

We measured the passbands of each channel by terminating all but one channel using standard gain horns from Quinstar to dump the power onto absorbing AN-72 foam. We then used a diode detector from Pacific Millimeter Products to measure the passband of the remaining channel, and put a second detector on the thru port. We generated millimeter waves using the source component of a VNA extender driven by a microwave frequency generator. The passband of each channel was measured by sweeping the frequency at the source, and recording the signal on the detector mounted to each channel in succession, while terminating all the other channels with the horns.

To guide the design of the initial prototype, and for comparison with the measurements, we simulated the entire five-channel structure in HFSS. The results of the measurements and the simulation are shown in Fig. 2. The measured center frequencies agree with the calculation to better than 0.5%, and the measured spectral resolutions agree to within 30%. Out of band coupling is observed at the -25 dB level. The standing wave pattern in the thru detector suggests an optical path length of roughly 30 cm, which could suggest a standing wave between imperfect terminations in the horns or detectors, and another imperfect match somewhere inside the VNA extender. Overall, there is good agreement between the measurement and the HFSS simulation, suggesting that we can use HFSS to design a spectrometer with more channels.

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III. CASCaded HFSS SIMULATION METHOD

Having verified the spectrometer concept, we designed a spectrometer that has a large number of channels spread across a wide passband. Here we consider two bands, 130-175 GHz and 190-250 GHz. At a spectral resolution of $R=200$, 54 spectrometer channels are needed to fill the single-moded passband of rectangular waveguide, assuming we place the center frequencies of each channel at the half-power points of each of its nearest neighbors. A full 54-channel structure would be so large that it would require too much RAM and too much CPU time to reasonably simulate in a single HFSS run on a workstation. However, we found that cascading the S-matrices of single-channel HFSS simulations was as accurate as a full simulation, and can be done for a device with a large
number of channels. We verified the accuracy of this cascade method by using it to simulate the five-channel prototype device, and comparing that simulation with the full HFSS simulation of the entire five-channel structure.

An overview of the cascade method is shown in Fig. 3 We start by drawing the structure of an individual spectrometer channel, and simulating it in HFSS. The full 3D simulation is necessary to calculate the effects of the rounded corners left by the machining process, and the fringing fields around the waveguide tee. These simulations yield the S-matrix of an individual channel. Since the field distribution at each of the three ports of an individual channel is nearly identical to the fundamental mode of rectangular waveguide, the S-matrices of the individual channels can be cascaded together, both to each other and to sections of rectangular waveguide, to yield an accurate model of the total S-matrix of the entire system. We used a function in the scikit-rf module in python to perform the cascade, which is an implementation of the subnetwork growth algorithm. The S-matrix of a section of rectangular waveguide is composed of simple analytic functions, which makes the cascade simulation fast. Cascading is much more accurate than naively multiplying the individual transmission and reflection values, since it properly treats multiple reflections among the internal sub-structures in the system.

A comparison of the simulated spectrometer passbands using both methods for the five-channel device is shown in Fig. 4 We found that we could reproduce all the details of the five-channel full simulation down to the -60 dB level by using the cascade method. Using this equivalent method for the 54-channel structure makes it possible to simulate and design the device needed for the full instrument. Simulating an entire 54-channel structure with the cascade method takes only 3 hours of workstation CPU time to generate the single-channel HFSS simulations, and 2 minutes to cascade them together.

IV. SIMULATION RESULTS FOR A 54 CHANNEL DEVICE

Each channel in the spectrometer has three dimensions: the length of the resonator section, the length of the coupling sections, and the width of the coupling section. For a 54-channel device, that means there are 162 free parameters that needed to be adjusted to achieve the target center frequency and \( R = 200 \) resolution for each channel. Tuning all 162 parameters individually by hand is not feasible, so instead we determined the optimal parameters by interpolating between hand-tuned designs. Here we illustrate this process for selecting the resonator length dimensions, the coupling section lengths and widths were chosen in an identical fashion. First, we hand-tuned the dimensions of six channels spread evenly across the desired passband by interactively running HFSS simulations. The set of center frequencies \( f_{\text{design}} \) of the hand-tuned channels was

\[
f_{\text{design}} = \{80.00 \, \text{GHz}, 85.42 \, \text{GHz}, 89.79 \, \text{GHz}, \ldots, 95.18 \, \text{GHz}, 100.46 \, \text{GHz}, 105.26 \, \text{GHz} \} \quad (1)
\]

and the resonator lengths corresponding to those center frequencies determined by hand-tuning were

\[
l'_{\text{design}} = \{2.355 \, \text{mm}, 2.068 \, \text{mm}, 1.905 \, \text{mm}, 1.739 \, \text{mm}, 1.617 \, \text{mm}, 1.523 \, \text{mm} \}. \quad (2)
\]

The coupling section widths were set such that their cutoff frequency is 50% higher than the center frequency, and the coupling section lengths were adjusted to yield the desired \( R=200 \) resolution. These sets of hand-tuned dimensions can
be thought of as a “dataset” of designs with known center frequencies and the desired resolution.

We then scaled these designs to center frequencies across the entire band. Putting center frequencies across the whole passband and at the half-power points of their nearest neighbors yielded a set of 54 desired center frequencies

\[ f_{NChn}^i = \{80.00 \text{ GHz}, 80.41 \text{ GHz}, 80.82 \text{ GHz}, \ldots, 103.93 \text{ GHz}, 104.46 \text{ GHz}, 105.00 \text{ GHz} \}. \]  

This can be thought of as Nyquist-sampling the spectral band. The hand-tuned designs needed to be scaled somehow to determine the resonator lengths to yield these desired center frequencies. Since all channels will use the same WR10 waveguide, the designs were scaled by the in-guide wavelengths corresponding to each center frequency. For rectangular waveguide in the fundamental mode, the in-guide wavelength \( \lambda_g \) for a frequency \( f \) is

\[ \lambda_g(f) = \frac{2}{\sqrt{\left(\frac{2f}{c}\right)^2 - \left(\frac{1}{a}\right)^2}}, \]  

where \( c \) is the speed of light, and \( a \) is the width of the waveguide. To generate the resonator lengths \( l_{NChn}^i \) corresponding to the desired center frequencies, we linearly interpolated between the hand-tuned channels, using the guide wavelength. The lengths are therefore

\[ l_{NChn}^i = \text{interp}(\lambda_g(f_{\text{design}}^i), l_{\text{design}}^i, \lambda_g(f_{NChn}^i)), \]  

where the function \( \text{interp}(x_{\text{data}}, y_{\text{data}}, x) \) linearly interpolates between the datapoints \( (x_{\text{data}}, y_{\text{data}}) \) to estimate the \( y \) value corresponding to the input \( x \). The dimensions for the coupling section widths and lengths were interpolated similarly from the hand-tuned designs.

Once we had those dimensions, we ran HFSS simulations for each single channel. This process was automated using the Matlab API for HFSS, and the individual S-matrices for each individual channel were stored to disk. This method yielded center frequencies that were fairly close to the desired values. We took the results of this simulation run as “data” and interpolated between them to get designs which are even closer to the desired center frequencies. This process, and slightly tweaking a few of the channels by hand, yielded a set of dimensions where the center frequencies of the final 54-channel cascaded simulation matched the design goal to within an RMS of 0.05% and the spectral resolutions were within an RMS of 25% of \( R = 200 \).

To determine the optimal physical spacing between channels along the main waveguide, we cascaded the 54 individual channel simulations together to yield the 56 port S-matrix that simulates the performance of all of the channels in the full device. Since changing the spacings only requires repeating the cascade step in the simulation, not resimulating in HFSS, changing the spacings only takes 2 minutes of workstation CPU time to recompute. We were therefore able to simulate many spacings and choose the best one. We chose to arrange the channels from low to high frequency, and have a constant spacing between each channel. Resimulating over a range of spacings showed that the optimal channel spacing is 3.065 mm, which is 3/4 of a wavelength in WR10 guide at 94.2 GHz. Initial simulations using a different spacing between each pair of channels did not yield better performance than using constant spacing, but we are investigating this more to see if further performance improvements are possible.

The WR10 design was simulated without any conductor loss in the model. The good agreement between the lossless simulations and the measurements of the WR10 prototype suggest that ignoring conductor loss is a valid approximation. This means that in principle we can scale the dimensions and the simulation to other passbands. Two bands lying in atmospheric windows that are interesting for observing the SZ effect and CO/CII spectroscopy are the 130-175 GHz band, and a 190-250 GHz band. The gap between the two bands is to avoid a strong atmospheric absorption line. This scaling of the lossless simulation is valid as long as conductor loss continues to be negligible in the higher passbands. For a rectangular waveguide, the attenuation constant due to conductor loss is

\[ \alpha_c = \sqrt{\frac{\pi f \mu_0}{\sigma} \frac{b + 2a^3 \left(\frac{f}{c}\right)^2}{a^3 b^2 \left(\frac{f}{c}\right)^2 - \left(\frac{1}{a}\right)^2}}, \]  

where \( a \) and \( b \) are the width and height of the waveguide, \( \sigma \) is the metal conductivity, and \( \eta \) is the free space impedance [13].

For the WR10 prototype with aluminum’s room temperature conductivity [14], the calculated attenuation constant of aluminum WR10 waveguide at 105 GHz is 0.3 m\(^{-1}\), already a low enough value for good performance of our prototype. Scaling up to a maximum operating frequency of 250 GHz, and the corresponding reduction in the waveguide dimensions, could both make the loss worse. However, we also plan to switch from aluminum to gold-plated OFHC copper, and the device will likely operate with cryogenic detectors. For instance, if KID detectors are employed, they will operate well below 1 K. The material change and the cryogenic cooling, both taken together, will actually improve the loss relative to our already low-loss prototype. The loss constant is calculated to improve to 0.1 m\(^{-1}\) for OFHC copper cooled below 10 K, or 0.02 m\(^{-1}\) for a gold-plated device cooled below 10 K, using literature [14] conductivity values. Sputter coating a superconducting niobium layer onto the device would eliminate conductor loss altogether. This indicates that designing the higher frequency devices with our current simulations should be a good approach.

The simulated passbands of the individual channels of both a 130-175 GHz band device and a 190-250 GHz device are shown in Fig. 5. The passbands of neighboring channels cross at the half-power point, which Nyquist samples the entire bandwidth. The entire 130 GHz to 250 GHz passband does not fit in the single-moded bandwidth of a rectangular waveguide, so we will use either a single horn with a diplexer, or two independent feed horns, to place the full bandwidth into a lower Band A and an upper Band B, on either side of the atmospheric line at 180-185 GHz. Since the device is small enough to fit under the footprint of the feed horn, a
Fig. 5. Simulated passbands of a 54-channel spectrometer. The top panel is on a linear scale and shows the 54 Band A passbands which cover 135-170 GHz and the 54 Band B passbands which cover 190-245 GHz. The black curve shows the sum total of all the passbands. The optical efficiency of the individual channels ranges from roughly 0.25 to 0.4, which compares favorably to the idea-impedance-match case of 0.5. The bottom panel shows the simulation down to -60 dB, with selected channels highlighted. Band A is indicated on the top x-axis, and Band B is on the bottom x-axis. Out of band coupling is simulated to be at the -20 to -30 dB level, or better.

linear array of these spatial pixels is formed in one direction, which all feed a single wafer of KID detectors. These linear arrays can then be tiled in the other direction, like vertical cards in a motherboard, to form a filled focal plane array of spectrometers.

A schematic of a 2 × 2 array of spatial pixels is shown in Fig. 6. For a single spatial pixel in the focal plane, the light will come in from the horn, down the main waveguide, and be directed into the 54 individual spectral channels. In the prototype WR10 design, the physical center-to-center spacing between channels is a constant 3.065 mm. Scaling the design to Band A gives a total device length of 96 mm, and Band B will have a length of 68 mm. These dimensions are small enough that fabricating the corresponding detector array cards in standard cleanroom processes will be feasible.

V. Conclusions

Compact spectrometers that can be tiled into focal plane arrays are an important enabling technology for the next generation of millimeter-wave and sub-millimeter astronomy. Complimentary to the other technologies currently under development, the measurements and modeling of the waveguide filter-bank spectrometer presented here show that it is a promising approach for future instruments. Measurements of the prototype show that cascading the S-matrices from HFSS simulations of individual channels is a good way to model this class of device. This enabled us to design a full R=200 spectrometer that fills single-moded passband of rectangular waveguide. We are currently scaling up our prototype to a five-channel test device for the WR5 band (160-210 GHz). We will then test it with another VNA extender at room temperature to verify that conductor loss and machining tolerances do not limit the performance at higher frequencies. We then plan to fabricate and test a full 54-channel device with cryogenic detectors for the 130-175 GHz and 190-250 GHz bands to verify that the optical efficiency and spectral performance are as good as the modeling predicts.

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