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Integrated Filterbank for DESHIMA: A Submillimeter Imaging Spectrograph Based on Superconducting Resonators

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Abstract An integrated filterbank (IFB) in combination with microwave kinetic inductance detectors (MKIDs), both based on superconducting resonators, could be used to make broadband submillimeter imaging spectrographs that are compact and flexible. In order to investigate the possibility of adopting an IFB configuration for DESHIMA (Delft SRON High-redshift Mapper), we study the basic properties of a coplanar-waveguide-based IFB using electromagnetic simulation. We show that a coupling efficiency greater than 1/2 can be achieved if transmission losses are negligible. We arrive at a practical design for a 9 pixel $\times$ 920 color 3 dimensional imaging device that fits on a 4 inch wafer, which instantaneously covers multiple submillimeter telluric windows with a dispersion of $f/df = 1000$.

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1 Introduction

Submillimeter galaxies (SMGs) are massive star forming galaxies found in the early universe. The distribution of SMGs across a wide range of redshifts $z$ is of great importance for studies of the cosmic history of star- and galaxy-formation, and the evolution of the cosmic large scale structure.$^1$ While SMGs are expected

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to be found in vast quantities in the coming years, by virtue of large format 2D submillimeter imaging cameras, the measurement of the third dimension—redshift $z$ containing the history—would most likely become the rate-limiting step. An ideal instrument for quickly measuring the $z$ of SMGs would be a submillimeter direct detection spectrometer with a dispersion $f/df \sim 1000$, to match the typical line width of SMGs with rotation velocities of $\sim 300$ km s$^{-1}$. Although the first-generation of these so-called $z$-machines has successfully detected lines from high redshift sources, the instantaneous bandwidth and number of pixels are limited by both the number of detectors and the optics. Moreover, the spatial sampling has been limited to 0 or 1 dimensions.

DESHIMA (Deel SJRON Hi-redshift Mapper) is a project to build a submillimeter imaging spectrograph using the advantage of multiplexability of microwave kinetic inductance detectors (MKIDs). The number of detectors for MKID cameras are quickly exceeding 10,000. If these detectors are to be used for an imaging spectrograph, it is enough for tens of pixels to instantaneously cover multiple submillimeter telluric windows with sufficient frequency resolution. Such an instrument would be ideal for submillimeter telescopes such as the Atacama Pathfinder EXperiment (APEX) and the Cornell Atacama Submillimeter Telescope (CCAT). However, it is challenging to build such a spectrometer using grating optics, from the perspective of size, complexity, and also to achieve a convenient spatial sampling.
Fig. 2 (Color online) 3-port, 2.5 dimensional model used for the numerical simulation of the transmission of the filters. The model consists of coplanar waveguides (CPWs) made of a perfect electric conductor (PEC, white) on 500 µm of Si (gray, blue in color), suspended in air. The vertical CPW on the left with ports 1 and 2 represents the line from the antenna carrying the signal. The vertical CPW on the right connected to port 3 represents the shorted end of the quarter wavelength microwave kinetic inductance detector (MKID). The center strip and the slots of these two lines are all 3 µm wide. In between the two lines is the filter, which consists of a pair of half wavelength resonators. The CPW for the filter has a center strip and slots which are all 1 µm wide. The length of the entire resonator, the coupler, and the width of the ground plane between the two resonators are defined as $L_{res}$, $L_c$, and $G$, respectively. The dotted rectangles represent airbridges, also made of PEC.

One of the alternative frequency-selecting elements is a filterbank. Filterbanks have been commonly used at microwave frequencies, and it is known\(^2\) that a pair of coupled coaxial cable resonators can be used as a band pass filter with an attractive dispersion of 1000. At submillimeter wavelengths, such a filterbank will scale down in size to where the entire filterbank will fit onto a single chip, together with the MKIDs. Such an integrated filterbank (IFB) could take advantage of the compactness, flexibility and mass-production capability that superconducting thin-film technology offers also to MKIDs.

In this study, we investigate the possibility of adopting an IFB design for DESHIMA. We use numerical simulation to study the transmission of the IFB, and subsequently develop a layout in combination with MKIDs to be tested in laboratory and used on the sky.

2 Numerical Simulation of the Integrated Filterbank

The integrated filterbank design considered in this study is depicted in Fig. 1a, b. We select here a structure based on coplanar waveguides (CPWs) because lens-antenna coupled, NbTiN/Al hybrid MKIDs have demonstrated photon noise limited sensitivity under loading powers as low as 100 fW: the single-channel loading power expected for a typical observation using DESHIMA. The signal shining on the antenna will transmit through a CPW line (signal line, hereafter) to which multiple filters are coupled. Each channel of the filterbank consists of two sections; the first is a pair of lossless resonators which act as a narrow bandpass filter, and the second is a lossy resonator which functions as an MKID. The MKID is a quarter wave resonator, coupled to the filter on its shorted end and to the readout CPW line on its open end. At the end of the signal line is a long, lossy CPW that absorbs the uncaptured signal to suppress standing waves. The lossless section can be made of superconductors with gap frequencies higher than 1 THz, such as NbTiN or NbN. NbTiN is also preferable for the MKID section because of its low two level...
Fig. 3 (Color online) a) Calculated transmission $S_{31}$ of filters with 1 (dashed) and 2 (solid) halfwave resonators. The geometry of the simulated model is described in Fig. 2, with $G = 3 \ \mu$m and $L_c = 15 \ \mu$m. $L_{res}$ has been adjusted so that the center frequency is equal in both cases. b) Transmission $S_{31}$ of a filter with 2 coupled resonators with varying gap width $G$.

system noise. In the lossy sections, the center strip of the CPW is replaced by a superconductor with a gap frequency lower than the signal, such as Al or TiN.

The integrated filterbank is modeled using a commercial 2.5 dimensional electromagnetic simulator Sonnet. We model the filterbank alone by replacing the antenna, the absorber, and the connection from the shorted end to the rest of the MKID, by matched ports. The NbTiN film is replaced by a perfect electric conductor (PEC), assuming that the ohmic loss in NbTiN is negligible. The geometry of a single channel filter is shown in Fig. 2. As seen in Fig. 3(a), the use of two coupled halfwave resonators adds a flat-top transmission and a sharper passband, compared to the case where a single resonator is used as a filter. While the center frequency of the filter is determined mainly by the total length of the resonators, $L_{res}$, varying the inter-resonator ground plane width $G$ influences the frequency splitting between the symmetric- and anti-symmetric modes in the coupled resonators, as shown in Fig. 3(b). The airbridges across the filters are required for suppressing the slotline mode, which are observed to create an additional transmission peak when the bridges are absent. In practice, airbridges of Al can readily be made across NbTiN groundplanes.

Using the calculated scattering parameters of the single-channel transmission, we construct a 70 port network model of a 68 channel filterbank. In doing this we assume that the inter-coupling between each filter through free space and the substrate is negligible. The geometry of each channel is described in Fig. 2, with $G = 3 \ \mu$m and $L_c = 15 \ \mu$m, and $L_{res}$ varying from 91.75 $\mu$m to 96.775 $\mu$m with a step of 75 nm. After calculating the scattering parameters of individual channels, a network model is constructed by connecting the signal line ports of each channel with an ideal transmission line of half wavelength in between. Ports 1 and 2 of the network model are placed at each ends of the signal line, and ports 3-70 are placed at the MKID-ends of the 68 filters.

The scattering parameters of the complete network are plotted against frequency in Fig. 4. The amplitude of $S_{31}$ representing the power flowing into the MKID is similar from channel to channel across a bandwidth of 30 GHz, except for the few channels at the edge. Strikingly, the transmission to the MKID has sig-
Fig. 4 (Color online) Calculated scattering parameters $S_{nn}$ for a 70-port model of a filterbank with 68 channels. Curve $S_{11}$ represents the fractional power reflected back to the direction of the antenna. Similarly, curve $S_{21}$ represents the power that passes all filters and flows into the absorbing termination. The remaining curves are $S_{nn}$ ($n = 3, 2, ... , 70$), which represent the power that flows into the individual channels to be absorbed by the microwave kinetic inductance detectors.

significantly increased from the case of a single isolated filter; compare Fig. 3(a) with Fig. 4. This can be understood as a result of multiple reflections between channels. The unabsorbed fractional power ($S_{11} + S_{21}$) is less than $−3$ dB throughout the entire band, implying that more than half of the signal will be coupled to the MKIDs. Note that the frequency spacing of the filters has been chosen rather arbitrarily to simplify the simulation, and the spectral shape and inter-pixel overlapping of the transmission can be further optimized.

Finally, leakage from the readout line to the signal line through the filter and the MKID at resonance has been calculated to be $<-50$ dB.

3 Design of an Integrated DESHIMA chip

Based on the simulated results, we construct a prototype design for an integrated DESHIMA chip. In Fig. 1(b) we present an example of a 9 pixel $\times$ 920 color layout on a 4-inch wafer, which includes the antenna, the IFB, the MKIDs, the signal line, and the readout line. In the center of the wafer are 9 CPW-fed log-periodic antennas, spaced 2 mm away from the nearest-neighboring pixels. The number of channels is enough to instantaneously cover 320-475 GHz and 600-950 GHz with a dispersion of 1000. In order to avoid the higher order mode of the low frequency channels from interfering with the high frequency channels, quarter wave resonators are used instead of the half wave resonators as filters. In order to achieve a high channel density, while keeping the channels neighboring in frequency $n \times \lambda / 2$ apart from each other, the high- and low-frequency bands are interwoven as shown in the inset of Fig. 1(b). The remaining empty space on the wafer is enough to double the number of pixels. The area per channel is limited mainly by the length of the MKID, which could be significantly reduced by replacing the distributed CPW resonators with parallel plate lumped element resonators. While our primary aim is to bring this IFB-based DESHIMA to ground-based submillimeter wave telescopes, the compactness and flexibility of
the device compared to a grating-optics spectrometer makes it suitable for space- and air-born missions as well.

Finally, we consider the issues that have not been taken into account in the simulation. Effects such as the transmission loss of the CPW and frequency shift due to crosstalk and/or fabrication errors need to be addressed experimentally. The difference in length of the filters of neighboring channels are $\sim 50$ nm at 950 GHz, which is still much greater than the resolution of electron beam lithography.

4 Conclusion

The result of electromagnetic simulation yields a straight-forward solution for integrating the entire filterbank and detector array of DESHIMA onto a single chip. The technology required for fabrication is largely in common with lens-antenna coupled NbTiN/Al hybrid MKIDs, which have shown photon-noise limited sensitivity down to optical loading powers expected for spectroscopy on ground. Though the concept needs further demonstration through experiments, which are under preparation, such an integrated filterbank configuration could yield a new generation of $z$-machines with full-3D spectral imaging capability.

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