On-chip filter bank spectroscopy at 600–700 GHz using NbTiN superconducting resonators

A. Endo, C. Sfiligoj, S. J. C. Yates, J. J. A. Baselmans, D. J. Thoen, S. M. H. Javadzadeh, P. P. van der Werf, A. M. Baryshev, and T. M. Klapwijk

Citation: Appl. Phys. Lett. 103, 032601 (2013); doi: 10.1063/1.4813816
View online: https://doi.org/10.1063/1.4813816
View Table of Contents: http://aip.scitation.org/toc/apl/103/3
Published by the American Institute of Physics

Articles you may be interested in

Frequency-tunable superconducting resonators via nonlinear kinetic inductance
Applied Physics Letters 107, 062601 (2015); 10.1063/1.4927444

High optical efficiency and photon noise limited sensitivity of microwave kinetic inductance detectors using phase readout
Applied Physics Letters 103, 203503 (2013); 10.1063/1.4829657

A semiempirical model for two-level system noise in superconducting microresonators
Applied Physics Letters 92, 212504 (2008); 10.1063/1.2937855

Superconducting properties and chemical composition of NbTiN thin films with different thickness
Applied Physics Letters 107, 122603 (2015); 10.1063/1.4931943

Readout-power heating and hysteretic switching between thermal quasiparticle states in kinetic inductance detectors
Journal of Applied Physics 108, 114504 (2010); 10.1063/1.3517152

Low loss superconducting titanium nitride coplanar waveguide resonators
Applied Physics Letters 97, 232509 (2010); 10.1063/1.3517252
On-chip filter bank spectroscopy at 600–700 GHz using NbTiN superconducting resonators

A. Endo,1,a) C. Sfiligoi,1 S. J. C. Yates,2 J. J. A. Baselmans,3 D. J. Thoen,1 S. M. H. Javadzadeh,1 P. P. van der Werf,4 A. M. Baryshev,2,5 and T. M. Klapwijk1

1Delft University of Technology, Kavli Institute of Nanoscience, Department of Quantum Nanoscience, Lorentzweg 1, 2628 CJ Delft, The Netherlands
2SRON Netherlands Institute for Space Research, 9747 AD Groningen, The Netherlands
3SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
4Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
5Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

(Received 18 March 2013; accepted 25 June 2013; published online 15 July 2013)

We experimentally demonstrate the principle of an on-chip submillimeter wave filter bank spectrometer, using superconducting microresonators as narrow band-separation filters. The filters are made of NbTiN/SiN/NbTiN microstrip line resonators, which have a resonance frequency in the range of 614–685 GHz, two orders of magnitude higher in frequency than what is currently studied for use in circuit quantum electrodynamics and photodetectors. The frequency resolution of the filters decreases from 350 to 140 with increasing frequency, most likely limited by dissipation of the resonators. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4813816]

On-chip filter bank spectrometers using superconducting resonators as narrow band-separation filters have been theoretically studied1–3 as one of the promising technologies for enabling multi-object broadband spectrometers on next-generation millimeter/submillimeter wave telescopes4 for astronomy. The advantage of an integrated filter bank spectrometer, such as the proposed instrument DESHIMA (Delft-SRON High z Mapper),1,2 on conventional optical spectrometers5 is the combination of (1) photon-noise limited point-source sensitivity, ultimately equal to a grating spectrometer, (2) compact size of each filter, which is of the order of the wavelength on chip and independent of frequency resolution, and (3) flexibility for increasing the sampling in either frequency space, or in real space, by arranging multiple filter bank units on a focal plane. One of the challenges towards realization is to make resonant filters with $Q \geq 300$, to match the typical line width of distant submillimeter galaxies.6 Unloaded $Q$’s of up to 2000 have been reported7 at 100 GHz ($\lambda = 3$ mm), but so far there has been no experimental study on resonant filters with $Q > 100$ in the submillimeter band (300–1000 GHz), in which the luminous C⋆ line at 1.9 THz can be detected from dusty star-forming galaxies in the redshift range of $1 < z < 5$, including the peak of cosmic star formation history.1,2

Here we prove the principle of performing spectroscopy in the 600–700 GHz submillimeter band, using a superconducting on-chip filter bank. We have developed a chip, onto which 30 spectroscopic channels are integrated. A schematic of the distributed circuit is presented in Fig. 1(q). Each channel is a combination of a submillimeter-wave superconducting resonator, which functions as a band-separation filter, and a microwave resonator coupled to it which functions as a microwave kinetic inductance detector (MKID), indicated with a shaded line in Fig. 1. There are two sets of 15 channels on one chip, which are each designed to have a resolution of $f / df = 1000$, and spaced in frequency with an interval of 20.8 GHz so that they sparsely cover the band of 530–830 GHz. In the case of a real spectrometer, the filters should be packed densely to cover the band with no gaps. In the following, we will show that this chip is indeed capable of detecting submillimeter waves at different channels depending on the frequency and discuss the properties of the resonant filters.

We will begin by describing the working principle of a single band-separation filter, using transmission line theory.8 The configuration of a single filter is represented by a 3-port transmission line model in Fig. 1(a). The submillimeter wave signal enters the circuit from port 1 (we denote port 1 as P1 hereafter, and accordingly for P2 and P3) and flows towards P2. We will call the line between P1 and P2 the “signal line.” Along the signal line is a half wavelength resonator which is capacitively coupled to the line. On the other side, it is capacitively coupled to P3, which we will later connect to a matched MKID detector. The loaded quality factor of the resonator, $Q_l$, consists of 3 components

$$1/Q_l = 1/Q_1 + 1/Q_{c1} + 1/Q_{c2}. \tag{1}$$

Here, $Q_1$ is the unloaded (internal) quality factor that reflects dissipation loss in the resonator, $Q_{c1}$ is the quality factor set by the power that leaks from the resonator to P1 and P2, and $Q_{c2}$ is the quality factor set by the power leaking to P3. Hereafter we will assume $Q_{c1} = Q_{c2} = Q_c$, because we have designed the two capacitors symmetrically to achieve maximum coupling. Using these definitions, the normalized magnitude of power transmitted from P1 to P3 can be written with a Lorentzian function as

$$|S_{31}|^2 = \left| \frac{Q_l}{\sqrt{\frac{2Q_1^2Q_l^2}{(Q_1 - Q_l)^2} + 2iQ_l(f - f_0)/f_0}} \right|^2. \tag{2}$$

---

1Electronic mail: A.Endo@tudelft.nl.
The configuration of a single spectroscopic channel, which is a combination of a filter and an MKID detector, is presented in Fig. 1(b). At the top of the diagram is the submillimeter wave filter that we discussed in the previous paragraph. The signal line and the filters are made of NbTiN, which typically has a gap frequency of \( \sim 1.1 \text{ THz} \) (Ref. 9) and should therefore behave as a superconductor for a signal of 600–700 GHz. Now P3 is connected to the center of an MKID which is open-ended on both sides. The MKID is itself a half wave resonator for a microwave readout tone in the range of 6–7 GHz and is capacitively coupled on one of its open ends to a through-line made of a NbTiN microstrip line. This resonator showed an unloaded quality factor of \( Q_i = 10^5 \). We have also fabricated a single microwave resonator with a NbTiN wire to measure the microwave losses of the NbTiN/SiN\(_x\)/NbTiN microstrip line. This resonator showed an unloaded quality factor of 2.5 \( \times 10^3 \). These values show that the SiN\(_x\) dielectric has a microwave loss in the range of \( \tan \delta = 2 \sim 10 \times 10^{-6} \), which is comparable to or even lower than the best values found in literature.10

The microwave losses of the transmission lines have been measured using a vector network analyzer while the chip was cooled to 350 mK using a \(^3\)He sorption cooler. All 30 Ta/SiN\(_x\)/NbTiN microstrip MKIDs have a resonance frequency in the range of 6–7 GHz as designed and have an unloaded quality factor of \( Q_i = 1 \sim 5 \times 10^5 \). We have also fabricated a single microwave resonator with a NbTiN wire to measure the microwave losses of the NbTiN/SiN\(_x\)/NbTiN microstrip line. This resonator showed an unloaded quality factor of 2.5 \( \times 10^3 \). These values show that the SiN\(_x\) dielectric has a microwave loss in the range of \( \tan \delta = 2 \sim 10 \times 10^{-6} \), which is comparable to or even lower than the best values found in literature.10

We have measured the submillimeter wave frequency-dependent response of the channels using a measurement setup as shown in Fig. 1(j). The filter bank chip is shown in the grey rectangle. On the back side of the chip, we have glued an elliptical lens made of Si, which has a diameter of 8 mm. The chip and the lens are cooled down to 250 mK using a \(^3\)He sorption cooler. The lens looks straight out of the cryostat through a 1.1 THz micro mesh low pass filter and a GORE-TEX infrared blocker. Outside the window is a multiplier-based narrow-band submillimeter source with a tunable frequency in the range of 600–700 GHz, which shines radiation from a feed horn into the cryostat window. The polarisation of the feed horn is tilted by 45° with respect to the window.
to the polarisation of the antenna on the chip. By turning the orientation of a linear polarising grid in the optical path, we can make the polarisation of the signal entering the cryostat either parallel or perpendicular to the designed polarisation of the antenna on the chip.

The bandpass characteristics of the filters are measured by observing the response of each MKID while sweeping the submillimeter source frequency. We use an FFTS-based multi-tone readout electronics\(^ {1,2,13}\) with 400 MHz bandwidth, which allows us to simultaneously measure the response of 16 MKIDs, of which 5 have (1) MKID resonance frequencies within a single readout bandwidth, (2) designed filter resonance frequencies in the 600–700 GHz band, and (3) situated consecutively on the chip. A common background signal is seen for all 16 MKIDs, as shown in the inset of Fig. 2, where the response of one channel is compared with a trace of a channel with a filter tuned to outside of the 600–700 GHz band. Because there was no systematic dependence of the common signal on the positions of the resonators on the chip, we conclude that it is due to stray light leaking from around the lens into the sample holder, which forms an integration cavity to couple the stray light directly to the MKIDs. In a future experiment the amount of stray light can be reduced by a better design of the sample box\(^ {14}\)

FIG. 2. Normalized phase response of the MKIDs behind consecutive filters in the range of 600–700 GHz. All 5 curves have been normalized so that the average background response outside the filter band is equal to unity, and each curve has been given an offset for clarity. The stepped plots indicate the measured data, where the solid curves are Lorentzian fits to each set of data. (Inset) Example of spectra for two channels before dividing out the common stray light component. The vertical axis shows the phase response of the MKIDs in units of milliradians. One of the spectra (solid blue curve) has a filter with a frequency within the measured band at 614 GHz, where the other one (dashed black curve) has, by design, a filter centered at 759 GHz, which is outside the measured frequency band. The spectrum of the 614 GHz channel after dividing out the stray light component is included also in the main figure, as indicated by the arrows.

FIG. 3. (Left axis, points) Normalized peak height plotted against the loaded quality factor \(Q_l\), where both values are taken from the fitted curves presented in Fig. 2. (Right axis, curve) Normalized filter transmission \(|S_{31}(Q_l)|^2\) as a function of \(Q_l\), where both \(|S_{31}(Q_l)|^2\) and \(Q_l\) are calculated by varying \(Q_l\) as a parameter in Eq. (2). (Inset) Inferred \(Q_l\) for each filter, plotted against the resonance frequency.
reported therein increase by only ~15% over the range of 600–700 GHz. This is strikingly slow compared to the rapid increase by a factor of 3 in our experiment.

If we next assume that the superconducting NbTiN is responsible for the loss, the sheet resistance inferred from the $Q_i$ values are in the range of 0.7–2 m$\Omega$, which is lower than epitaxial NbN and NbCN films measured at 4.2 K.\textsuperscript{16,17} If we would treat NbTiN in the framework of the BCS and Mattis-Bardeen theory, as a superconductor with $T_c = 14.2$ K and hence a gap energy of 2.2 meV, the $Q_i$ of a resonator for 600–700 GHz at a temperature of 250 mK should be many orders of magnitude higher than what can be probed in this experiment. One possibility is that there is a layer of reduced $T_c$ at the surface of the NbTiN, produced either during the 300 °C-deposition of SiNx, or the initial stages of the deposition of the wire, as has been argued for Nb strip lines.\textsuperscript{19} In order to explain the $Q_i$ which we measure, one would have to assume such an interface layer with a $T_c$ of 8 K or lower.

In conclusion, we have experimentally demonstrated submillimeter-wave on-chip spectroscopy using a superconducting filter bank, in the submillimeter wave band of 600–700 GHz. The achieved resolution is in the range of $Q_i = 140–350$, which is found to be limited by losses in the transmission line. The estimated transmission across the filters is 1%–6%, which can be increased by bringing $Q_i$ closer to the $Q_s$ at the cost of a lower resolution. Development of transmission lines with losses lower by a factor of 4–10 ($Q_i \geq 2000$), sample packaging with better stray light control, and antennae with a high efficiency over a broad bandwidth\textsuperscript{10} are required for the realization of on-chip filter bank spectrometers with sufficient resolution and photo-efficiency to be useful for extragalactic astronomical science at these high frequencies.

We would like to thank A. Bruno and M. Bruijn for film deposition and D. Cavallo and L. Ferrari for advice on the antenna design. A.E. is financially supported by NWO (Veni Grant No. 639.041.023) and JSPS Fellowship for Research Abroad. This research was partially supported by the NWO Medium Investment grant (No. 614.061.611), and the ERC starting grant (ERC-2009-StG Grant 240602 TFPA).

A. Endo, P. P. Werf, R. M. J. Janssen, P. J. de Visser, T. M. Klapwijk, J. J. A. Baselmans, L. Ferrari, A. M. Baryshev, and S. J. C. Yates, \textit{J. Low Temp. Phys.} 167, 341 (2012).

A. Endo, J. J. A. Baselmans, P. P. van der Werf, B. Knoors, S. M. H. Javadzadeh, S. J. C. Yates, D. J. Thoen, L. Ferrari, A. M. Baryshev, and Y. J. Y. Lankwarden, \textit{Proc. SPIE} 8452, 84520X (2012).

A. Kovacs, P. S. Barry, C. M. Bradford, G. Chattopadhyay, P. Day, S. Doyle, S. Hailey-Dunsheath, M. Hollister, C. McKenney, H. G. LeDuc, N. Llombart, D. P. Marrone, P. Maukof, R. C. O’Brien, S. Padin, L. J. Swenson, and I. Zmuidzinas, \textit{Proc. SPIE} 84522G (2012).

D. Woody, S. Padin, E. Chauvin, B. Clavel, G. Cortes, A. Kissil, J. Lou, P. Rasmussen, D. Redding, and J. Zolwoker, \textit{Proc. SPIE} 8444, 84442M (2012).

G. J. Stacey, \textit{IEEE Trans. Sci. Technol.} 1, 241 (2011).

C. Carilli and R. Wang, \textit{Astron. J.} 131, 2763 (2006).

J. Gao, A. Vayonakis, O. Norouzian, J. Zmuidzinas, P. K. Day, and H. G. LeDuc, \textit{AIP Conf. Proc.} 1185, 164 (2009).

D. M. Pozar, \textit{Microwave Engineering}, 2nd ed. (Wiley, New York, 1998).

B. D. Jackson, N. N. Iosad, G. de Lange, A. M. Baryshev, W. M. Lauwren, J. R. Gao, and T. M. Klapwijk, \textit{IEEE Trans. Appl. Supercond.} 11, 653 (2001).

B. A. Mazin, D. Sank, S. Mchugh, E. A. Lucero, A. Merrill, J. Gao, D. Pappas, D. Moore, and J. Zmuidzinas, \textit{Appl. Phys. Lett.} 96, 102504 (2010).

P. A. R. Ade, G. Pisano, C. Tucker, and S. Weaver, \textit{Proc. SPIE}, Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III 6275, 62750U (2006).

B. Klein, S. Hochgärtel, I. Krämer, A. Bell, K. Meyer, and R. Güsten, \textit{Astron. Astrophys. (A&A)} 542, L3 (2012).

S. J. C. Yates, A. M. Baryshev, J. J. A. Baselmans, B. Klein, and R. Güsten, \textit{Appl. Phys. Lett.} 95, 042504 (2009).

J. J. A. Baselmans, S. J. C. Yates, P. Diener, and P. J. de Visser, \textit{J. Low Temp. Phys.} 167, 360 (2012).

G. Cataldo, J. A. Beall, H.-M. Cho, B. McAndrew, M. D. Niemack, and E. J. Wollack, \textit{Opt. Lett.} 37, 4200 (2012).

A. Kawakami, S. Miki, and Z. Wang, \textit{Physica C} 378, 1295 (2002).

S. Kohjiro, S. Kiriya, and A. Shoji, \textit{IEEE Trans. Appl. Supercond.} 3, 1765 (1993).

D. Mattis and J. Bardeen, \textit{Phys. Rev.} 111, 412 (1958).

S. Zhu, T. Zijlstra, A. A. Golubov, M. van den Bent, A. M. Baryshev, and T. M. Klapwijk, \textit{Appl. Phys. Lett.} 95, 253502 (2009).

A. Neto, \textit{IEEE Trans. Antennas Propag.} 58, 2238 (2010).