Broadband Scanning Spectrometer with Heterodyne SIS (Superconductor-Insulator-Superconductor) Receiver

K. Kikuchi[a], S. Kohjiro[a], M. Maezawa[a], and H. Ozeki[b]
[a] National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
[b] Department of Environmental Science, Faculty of Science, Toho University, Funabashi, Japan

***Abstract*—We are developing a heterodyne receiver based on an SIS (Superconductor-Insulator-Superconductor) mixer, aiming to realize a highly sensitive, broadband, and precise measurement system at terahertz frequencies. The receiver noise temperature is less than ~20 times of the quantum limit in the frequency range of 0.2-0.5 THz. Combining of the heterodyne SIS receiver, a frequency scanning system of local oscillator, and a high-resolution back-end spectrometer, we demonstrated a spectroscopic measurement of CH_3CN gas, with the frequency resolution of 61 kHz in a 418-430 GHz range.**

I. Introduction and Background

HETERODYNE receivers with Superconductor-Insulator-Superconductor (SIS) mixers are widely used for scientific applications, such as radio astronomy and atmospheric research to achieve both high frequency resolution and quantum-limited sensitivity. Taking advantage of the heterodyne SIS receiver, we are aiming to apply this technique to practical spectrometers, such as "spectrum analyzers" at terahertz frequencies.

In general, frequency resolution of the SIS heterodyne receiver is as high as $f/\Delta f > 10^6$, depending on the frequency precision of local oscillator (LO) and the resolution of back-end spectrometer. One of the issues that need to be overcome for the practical application is a small instantaneous bandwidth, typically less than several GHz, which is limited by both SIS mixers and back-end spectrometers. Although some novel type of SIS mixers achieve a very large instantaneous bandwidth of ~20 GHz,[1] here we propose a simple approach to realize a highly sensitive broadband spectrometer keeping the high frequency resolution. Our system consists of an SIS mixer with an octave RF bandwidth,[2] a frequency scanning system of LO, and a high-resolution back-end spectrometer. Rapid scan of the LO frequency may compensate the small instantaneous bandwidth.

II. System Description

Schematic view of the spectrometer system is shown in Fig. 1. The heterodyne SIS mixer is at 4.2-K stage in a liquid helium cryostat. THz signals emitted by both LO source and "Device Under Test" (DUT) come from outside of the cryostat through a vacuum window and an infrared cut filter, and couple quasi-optically to the SIS device through an elliptical silicon lens. At the SIS mixer, the THz signal is down-converted to intermediate frequency (IF) of 0.2-1 GHz, and finally detected by a back-end spectrometer.

A digital Fast Fourier Transform (FFT) spectrometer[3] is used as a back-end. The FFT spectrometer has a remarkable total bandwidth of 1 GHz, resolved into 16k channels (i.e. 61 kHz resolution for 1 GHz bandwidth), in continuous real-time.

The LO frequency should be electronically tunable for a frequency scanning system. Our LO source is commercially available, consists of a microwave amplifier and a series of broadband frequency multipliers, and generates a signal in ~380- 490 GHz range.[4] The total frequency multiplication is 36, so the output THz frequency is controllable by a standard microwave synthesizer.

To realize a high coupling efficiency in such a large bandwidth, quasi-optical lenses are arranged to produce a frequency-independent image of the LO horn aperture at the SIS mixer. In the path to DUT, a Martin-Puplett interferometer is placed in the optics to be used as a single sideband (SSB) filter. A movable roof-top mirror of the SSB filter and the synthesizer for controlling the LO frequency are synchronously controlled by a PC. The total spectrometer system shows a noise temperature less than ~20 times of the quantum limit in

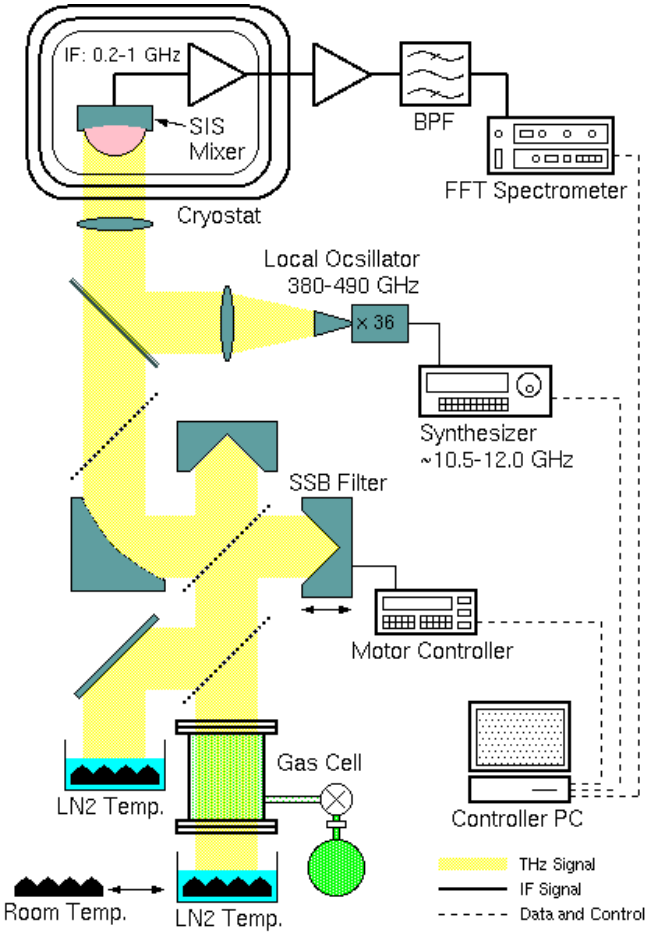

Figure. 1: Schematic view of the spectrometer system.

the frequency range of 0.2-0.5 THz[5], and the stability measurements give an Allan time of several tens of seconds.

III. Experiment and Result

We have demonstrated a gas-cell measurement with our spectrometer system. The same kind of measurements have been performed without LO frequency scanning, and succeeded in getting some physical parameters of the gas molecules, such as pressure broadening parameter, for low-pressure (i.e. narrow line-width) samples.[6] For the demonstration of frequency scanning, we chose a relatively high pressure CH_3CN (acetonitrile) gas as a DUT, whose line width is much larger than the instantaneous bandwidth of the spectrometer.

Firstly, an intensity calibration using black-body radiators was carried out to derive the brightness temperature of thermal emission from CH_3CN. A 0.2-m long, empty gas cell was put in front of a hot (room temperature, 300 K) or cold (liquid nitrogen, LN_2) temperature (77 K) terminator. After the hot and cold calibration observations, a ~3-hPa CH_3CN gas is installed into the gas-cell in front of LN_2 temperature terminator. At each observation, the LO frequency was swept from 418 to 430 GHz in a stepwise, and the IF output is accumulated by the FFT spectrometer.

The brightness temperature of the gas (T_{gas}) is calculated as,

$$T_{\mathrm{gas}} = \frac{P(T_{\mathrm{gas}}) - P(T_{\mathrm{cold}})}{P(T_{\mathrm{hot}}) - P(T_{\mathrm{cold}})}(T_{\mathrm{hot}} - T_{\mathrm{cold}}) + T_{\mathrm{cold}},$$

where $P(T)$ is the detected power when observing a object whose radiation temperature is T , and T_{hot} and T_{cold} are radiation temperatures corresponding to room and LN_2 temperature, respectively.

Fig. 2 shows an example of measured spectrum of CH_3CN at 418-430 GHz band. In spite of the instantaneous bandwidth as small as ~350 MHz, the spectroscopy of 12-GHz bandwidth was achieved due to 35-times stepwise scanning of the LO frequency. The FFT spectrometer integrated the measured signal at each step with the frequency resolution of 61 kHz.

IV. Conclusions

We have succeeded in developing a wideband, high-frequency resolution, and high-sensitivity spectrometer operates at 0.2-0.5 THz range. The gas-cell measurement demonstrated that the spectrometer had an ability to observe a broader spectrum than the instantaneous bandwidth of the spectrometer.

Further increase of the tuning range and frequency agility of LO is under development. One of the most promising candidate is a photonic local oscillator using an uni-traveling-carrier photodiode (UTC- PD).[5,7]

This work was supported in part by the National Institute of Information and Communications Technology, Japan.

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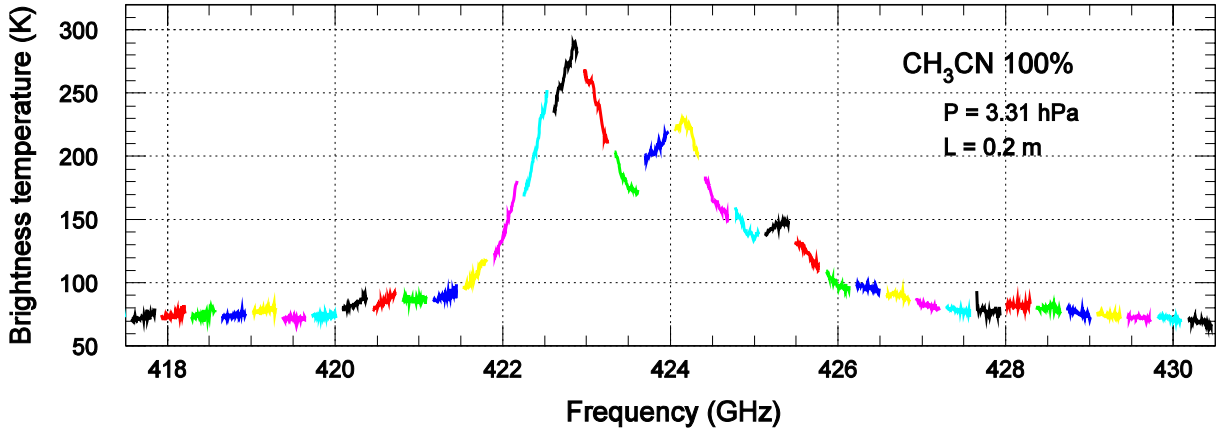

Figure. 2: Emission spectrum of CH_3CN detected by 35-times stepwise scanning of LO frequency. Each color corresponds to the instantaneous band of each step.