Development of a Waveguide-Type Dual-Polarization Sideband-Separating SIS Receiver System in 100 GHz Band for the NRO 45-m Telescope

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***Abstract*— We developed a waveguide-type dual-polarization sideband-separating SIS receiver system of the 100-GHz band for the 45-m radio telescope at the Nobeyama Radio Observatory, Japan. This receiver is composed of an ortho-mode transducer and two sideband-separating SIS mixers, which are both based on the waveguide technique. The receiver has four intermediate frequency (IF) bands of 4.0--8.0 GHz. Over the radio frequency range of 80--120 GHz, the single-sideband receiver noise temperatures are 50--100 K and the image rejection ratios are greater than 10 dB. The new receiver system was installed in the telescope, and we successfully observed the ^{12}CO, ^{13}CO, $C^{18}O$ and the other emission lines simultaneously toward the Sagittarius B2 region to confirm the performance of the receiver system.**

I. Introduction

The 45-m telescope (Fig.1) is located at Nobeyama Radio Observatory (NRO) in Nagano, Japan and is one of the largest millimeter-wave telescopes in the world (e.g., [1], [2]). The 45-m telescope is equipped with low-noise high electron mobility transistor (HEMT) and superconductor-insulator-superconductor (SIS) receivers covering the observing frequency range of 20 to 115 GHz, along with powerful spectral-line and continuum back-ends.

The 100-GHz band SIS receivers are the most important receivers for the 45-m telescope, because they cover the highest frequency range among the heterodyne SIS receivers installed in the telescope. From a scientific viewpoint, the J = 1--0 emission line of carbon monoxide (CO) in this frequency band is a principal probe for studies of interstellar molecular gas. The SIS-80 (hearafter, S80) and SIS-100 (hearafter, S100) single-beam receivers, which cover radio frequency (RF) bands of 72--115 GHz and 77--115 GHz respectively, are installed in the 45-m telescope. However, as the receiver noise temperature decreases throughout the world (e.g., [3]-[5]), the performances of S80 and S100 have relatively worsened since their installation. Moreover, the most important cause of a high noise temperature is that these receivers use a wire grid for the separation of polarizations and a Martin-Puplett interferometer as an image rejection filter for the separation of sidebands. The loss with the quasi-optics results in a degradation of the system noise temperature. These quasi-optics are too sensitive for their optical alignment, and thus misalignment becomes another cause of degradation. The single side-band (SSB) receiver noise temperatures, including the quasi-optics are 150--300 K for both receivers. To solve these problems, we began the development of a new receiver system, which uses a waveguide-type ortho-mode transducer (OMT) and two sideband-separating (2SB) SIS mixers. To date, the simultaneous detection of molecular emission lines with a

Fig.1 Photograph of the 45-m telescope at NRO.

waveguide-type 2SB receiver has been performed by a few groups toward a limited number of observations (e.g., [6], [7]), suggesting that the 2SB receiver systems are more efficient compared to the other SSB receivers (e.g., [8]). As a result, we can reduce the number of the optical elements and the composition becomes simple. In addition, it is also noteworthy that through the simultaneous detection of two polarizations and two sidebands using a single optical horn, we can better determine the line-intensity ratios of among molecular lines without being contaminated by errors in pointing.

We developed a new 2SB receiver system in the 100-GHz band for the 45-m telescope. Over the RF range of 80--120 GHz, the SSB receiver noise temperature of the mixer is obtained to be lower than 100 K for the 4.0--8.0 GHz intermediate frequency (IF) band. The image rejection ratios (IRRs) are greater than 10 dB over the same range. It is confirmed that the typical SSB receiver noise temperature of the new system is approximately half that of the previous systems of S80 and S100. The IF bandwidth of the new receiver system is 4 GHz for each IF output, while those of previous receivers are 600 MHz. We can detect 16 GHz in total. Using the newly developed 100-GHz band SIS receiver system for 45-m telescope, we observed the ^{12}CO, ^{13}CO, $C^{18}O$ and the other emission lines simultaneously toward the Sagittarius B2 region in order to confirm the performance of the receiver system. This is the first astronomical observation using a waveguide-type dual-polarization sideband-separating SIS receiver system in the 100-GHz band [9].

II. RECEIVER

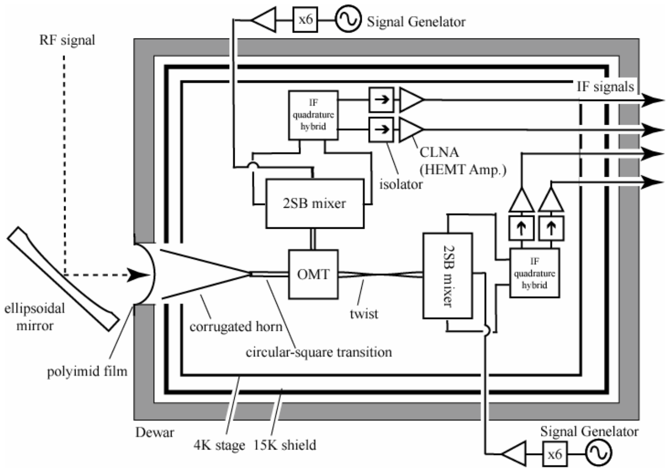
A. *Receiver configuration*

The specifications of the receiver system are summarized in table 1 and a block diagram of the receiver system is shown in Fig.2. The operation frequency range is from 72 to 128 GHz, which is limited by the frequency range of the local oscillator (LO) chain. The IF frequency range of 4.0--8.0 GHz with the bandwidth of 4.0 GHz is adopted. This receiver is composed of an OMT and two 2SB mixers, which are both based on a waveguide technique. The 2SB mixers are hereafter referred to as mixer-A and mixer-B. The photograph of the receiver in the dewar is shown in Fig.3.

By using an OMT, it is possible to receive signals in the dual linear polarizations independently and simultaneously. The OMT adopted herein was developed at the Australia Telescope National Facility (ATNF), Commonwealth Scientific and Industrial Research Organization (CSIRO), and consists of a square to double ridged guide transition followed by a junction of two side arms with the central guide [10]. The measurement of the OMT performance by ATNF has revealed a return loss of > 20 dB from 71 to 118 GHz and an insertion loss at room temperature of < 0.16 dB for both polarizations.

The detailed structure of a split-block waveguide unit for our 2SB mixer is described in [11]. The basic design of the present sideband-separating SIS mixer is similar to that described in [12]. The split-block waveguide unit contains an

Fig.2 Block diagram of the dual-polarization sideband-separating receiver



system. Two orthogonal polarizations of the RF signal into a single horn are separated by an OMT, and two sidebands of each polarization are separated by two 2SB mixers. Thus, we can obtain four IF signals independently and simultaneously.

RF quadrature hybrid, two LO directional couplers, an LO power divider, and 4 K cold image terminations. We also integrated two double side-band (DSB) mixers on the single split-block waveguide unit through the waveguide taper transformers. The RF and LO signals are fed to the feed point through a linearly tapered waveguide impedance transformer, which uses a full height to 1/5 reduced height waveguide for the waveguide-to-stripline transition of the SIS mixer. The linearly tapered waveguide impedance transformer was designed using a lumped-gap-source port provided by HFSS^{TM} [11]. The SIS junctions adopted herein were developed at the NRO. A six-series array was composed of Nb/AlO$_x$/Nb junctions with a normal state resistance of approximately 80--90 Ω, and each junction area was

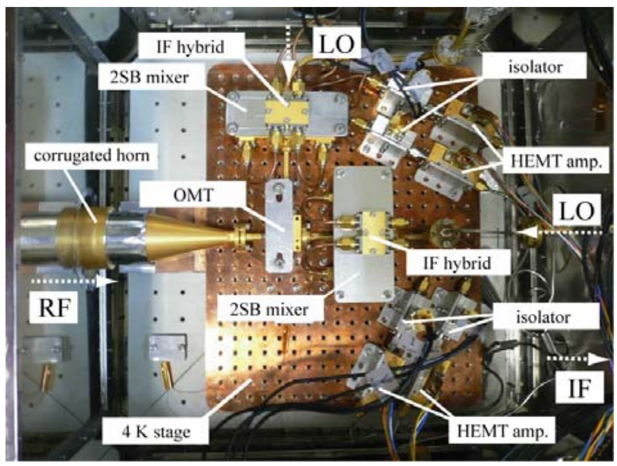


Fig.3 Photograph of the 4 K cooled stage in the receiver dewar. The RF signal is fed into the OMT located in the middle of the figure from the lower side using a detachable corrugated horn. The LO signals are fed from the upper side for the 2SB mixer located above the OMT and from the left side for the other 2SB mixer

TABLE I

SPECIFICATIONS OF THE RECEIVER SYSTEM

Tuning range Mixer type Receiving mode Polarization Receiver noise temperature (DSB)	72--128 GHz SIS (Nb/AlO_x/Nb) six-series junction mounted on fixed-tuned waveguide-type 2SB mixer block SSB (2SB) operation dual linear polarization ~ 50 K (f_{LO} = 80--115 GHz)
mixer-A Receiver noise temperature (SSB) Image rejection ratio	 less than or similar 100 K (f_{RF} = 75--120 GHz) ~ 68 K (minimum value at f_{RF} = 90 GHz in the USB) LSB : 86.8 K (average value at f_{RF} = 75--106 GHz) USB : 88.2 K (average value at f_{RF} = 79--120 GHz) > 10 dB (f_{RF} = 80--123 GHz) LSB : 14.9 dB (average value at f_{RF} = 80--111 GHz) USB : 14.3 dB (average value at f_{RF} = 84--123 GHz)
mixer-B Receiver noise temperature (SSB) Image rejection ratio	 less than or similar 100 K (f_{RF} = 75--120 GHz) ~ 49 K (minimum value at f_{RF} = 95 GHz in the LSB) LSB : 74.5 K (average value at f_{RF} = 75--106 GHz) USB : 72.7 K (average value at f_{RF} = 79--120 GHz) > 10 dB (f_{RF} = 80--100 GHz) LSB : 13.4 dB (average value at f_{RF} = 80--100 GHz) USB : 12.2 dB (average value at f_{RF} = 84--110 GHz)
IF frequency band IF amplifier	4.0--8.0 GHz (4.0 GHz bandwidth) cooled low noise HEMT amplifier (typical noise temperature of 8 K and gain of + 30 dB)

1.9 x 1.9 μm^2. The reason for using the series junction is that a wider bandwidth of RF frequency can be achieved. In the present system, the required fractional bandwidth totals greater than or similar 40 %. The parallel connected twin junction (PCTJ) designed by [4] is not suited for this receiver because the designed RF frequency range is 90--115 GHz, which corresponds to a fractional bandwidth of only approximately 25 %. Moreover, the series junction barely saturates and the intensity can be calibrated with high accuracy [13]. The IF signals from the two DSB mixers are combined in a commercial quadrature hybrid, which made by Nihon Tsushinki Inc.

B. Receiver performance

Before installing the receiver system in the telescope, we evaluated its performance. The noise temperature of the 2SB SIS receiver was measured by a standard Y-factor method using hot (300 K) and cold (77 K) loads in the laboratory. The mixer was mounted on a 4 K cold stage in a dewar. The first-stage IF amplifier is a 4 K cooled HEMT at the 4.0--8.0 GHz band. The equivalent noise temperature and the gain of the HEMT amplifier associated with an isolator were approximately 8 K and +30 dB, respectively. The following-stage amplifiers work at room temperature.

The measured DSB receiver noise temperatures of the SIS mixers with 4.0--8.0 GHz IF by a power meter are approximately 50 K over the LO frequency range of 80--115 GHz. The SSB receiver noise temperature, including the noise contribution from the vacuum window, the feed horn, and the IF amplifier chain, were measured by a spectrum analyzer. For a certain LO frequency, the output spectra were smoothed to a resolution of 500 MHz and sampled at eight IF frequency points from 4.25 GHz to 7.75 GHz at intervals of

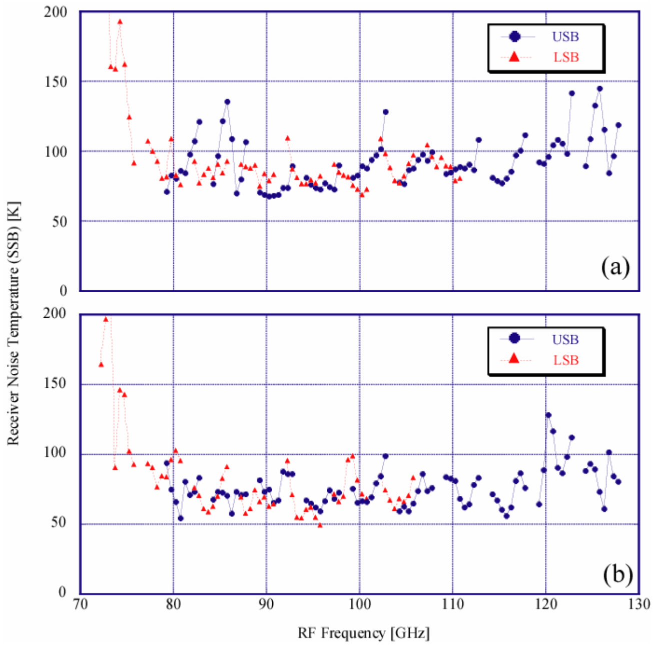


Fig.4 SSB receiver noise temperatures in the LSB and USB of (a) mixer-A and (b) mixer-B. These values are measured by 4.0--8.0 GHz IF and are shown as a function of RF frequency (see text).

0.5 GHz. We then swept the LO frequency from 80 GHz to 120 GHz by a step of 5 GHz to cover the RF frequency range from 72.25--127.75 GHz. Finally, the measured SSB receiver noise temperatures were corrected for the IRR, in order to obtain the SSB receiver noise temperature. Since the IRRs were measured with the different measurement system from the one used to measure the noise temperature, we assumed the IRRs to be 10 dB, that is nearly equal to the smallest value among the actual IRRs, for all the measured points. Therefore, it is to be noted that the actual SSB receiver noise temperature will be better than the values presented in this paper for most of the measured points. The SSB receiver noise temperatures were measured to be lower than approximately 100 K over the RF range of 75--120 GHz, and the minimum value of ~ 68 K for mixer-A in the upper side-band (USB) and ~ 49 K for mixer-B in the lower side-band (LSB) are achieved at approximately 90 GHz and 95 GHz, respectively. The mean value and standard deviation between the RF frequency range of 75--106 GHz in the LSB and 79--120 GHz in the USB are 87 ± 11 K and 88 ± 15 K, respectively, for mixer-A (Fig.4 (a)) and are 75 ± 14 K and 73 ± 10 K, respectively, for mixer-B (Fig.4 (b)).

The IRRs were evaluated by measuring the relative amplitudes of the IF responses in the USB and LSB when injecting a continuous wave signal [14] from a signal generator. The IRR measured in the IF range of 4.0--8.0 GHz IF was greater than 10 dB over the RF frequency range of 80--123 GHz for mixer-A (Fig.5 (a)). The mean value between the RF frequency range of 80--111 GHz in the LSB and 84--123 GHz in the USB were as high as 15 dB and 14 dB, respectively. The IRR of mixer-B was lower than 10 dB at f_{LO} greater than or similar 105 GHz (Fig.5 (b)). However, both the mean value between the RF frequency range of 80--100 GHz in the LSB and that between the RF frequency range of 84--110 GHz in the USB were about 12 dB.

Therefore, it is most desirable to use mixer-B for observation at lower RF frequency. We will replace by new one if we developed mixers with the better performance.

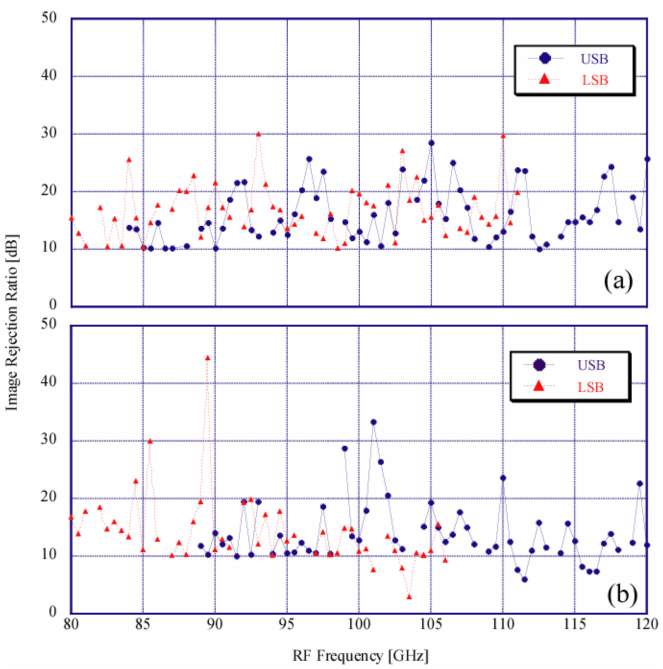


Fig.5 Image rejection ratio in the LSB and USB of (a) mixer-A and (b) mixer-B. These values are measured by 4.0-8.0 GHz IF and are shown as a function of RF frequency.

III. RESULTS

The receiver system was installed in the 45-m telescope in early December 2007. Fig.6 shows the receiver dewar in the receiver cabin. The SIS and HEMT amplifier biases, LO oscillators, and IF chains are placed around the dewar. The LO signals for each 2SB mixer of dual-polarization are independently generated by multiplying the output of the signal generators (~ 12--20 GHz) with 2 x 3 multipliers. Therefore, the four IF signals from two 2SB mixers can cover different regions of the RF frequency band. Hereafter, the polarization for mixer-A is referred to as pol-1, and the polarization for mixer-B is referred to as pol-2.

A. System noise temperature

The performance of the receiver may change when it is installed in the telescope because the environment of the receiver is different from that in the laboratory. Therefore, we installed the receiver system in the telescope and measured

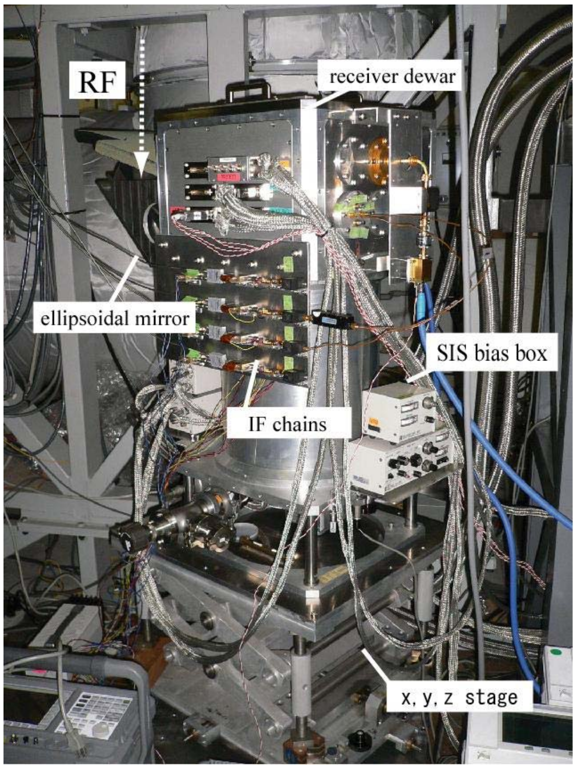


Fig.6 Photograph of the receiver system in the receiver cabin of the telescope.

the performance of the receiver system. Note that the noise temperatures in this subsection are not corrected for IRR. Even after correcting for IRR, the noise temperature increases only less than or similar 10 %. The SSB receiver noise temperature, including the ellipsoidal mirror before the horn, is measured by a standard Y-factor method to be

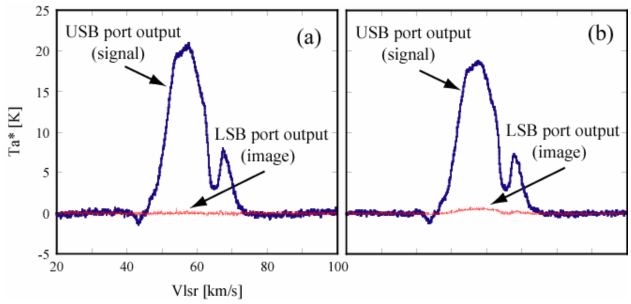


Fig.7 IF signal outputs of the USB and LSB ports obtained by observations toward W51. The signal of the ^{12}CO (J = 1--0) line in the USB port (bold line) leaks to the LSB port (thin line). The output of the 2SB mixer for pol-1 is shown in (a), and that for pol-2 is shown in (b). Note that the absorption at V_{lsr} ~ 45 km s^{-1} may be caused by the emission in the OFF position.

approximately 60 K in the USB at f_{LO} = 109 GHz (f_{RF} = 115 GHz) for both 2SB mixers. The SSB noise temperatures of the system, including the atmosphere, are approximately 180 K in the LSB at f_{LO} = 109 GHz (f_{RF} = 103 GHz) for pol-1 and at f_{LO} = 104 GHz (f_{RF} = 98 GHz) for pol-2 at an elevation of 80°. The system noise temperature, including the atmosphere, became approximately half of that of the previous receiver system (S100).

B. Test observations

The first astronomical signal after the installation, ^{12}CO spectra at 115.271 GHz from the W51 giant molecular cloud, was obtained on December 11, 2007. The IRRs of the two 2SB mixers were estimated from these spectra, resulting in > 20 dB for pol-1 (Fig.7 (a)) and > 14 dB for pol-2 (Fig.7 (b)), respectively. These values are as good as those obtained in the laboratory. Moreover, we successfully observed the molecular lines toward the Sagittarius B2 region by using six digital spectrometers [15] with bandwidths of 512 MHz. Fig.8 shows an example of the results, which are obtained by a single pointing. We detected CH_3C_2H and H_2CS in the LSB and ^{12}CO in the USB, respectively, for pol-1, and CS in the LSB and SO_2, $C^{18}O$, HNCO, ^{13}CO and CH_3CN in the USB, respectively, for pol-2. Since four IF signals can be observed independently and simultaneously, we obtained these spectra by integrating the signal only for five minutes. This was the first astronomical observation using the waveguide-type dual-polarization sideband-separating SIS receiver system in the 100 GHz band.

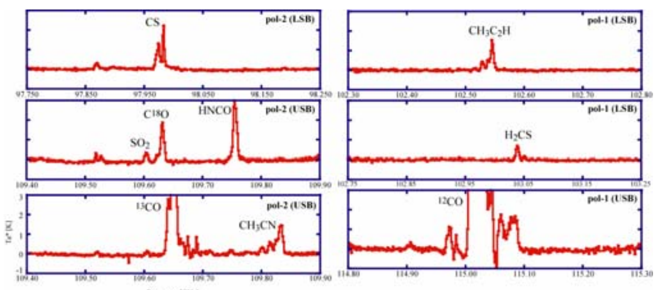


Fig.8 Results of the line survey toward Sgr B2. The four IF signals were obtained independently and simultaneously by a single pointing.

CONCLUSIONS

A waveguide-type dual-polarization sideband-separating SIS receiver system in the 100 GHz band was developed for and installed in the NRO 45-m telescope. This receiver system is composed of an ortho-mode transducer and two sideband-separating SIS mixers, both of which are based on the waveguide type. The four IF bands, 4.0--8.0 GHz, in each of the polarizations and sidebands can be observed simultaneously and separately. Over the RF frequency range of 80--120 GHz, the single-sideband receiver noise temperatures are 50--100 K and the image rejection ratios are greater than 10 dB. The new receiver system was installed in the 45-m telescope, and we successfully observed the ^{12}CO, ^{13}CO, $C^{18}O$ and the other emission lines simultaneously toward the Sagittarius B2 region. This is the first astronomical observation using a waveguide-type dual-polarization 2SB SIS receiver system in the 100 GHz band. The SSB noise temperatures of the system, including the atmosphere, are approximately 180 K in the LSB at f_{LO} = 109 GHz (f_{RF} = 103 GHz) for one polarization, and at f_{LO} = 104 GHz (f_{RF} = 98 GHz) for the other polarization at an elevation of 80°. The SSB system noise temperature became approximately half of that of the previous receiver system. The IRRs of the two 2SB mixers were calculated from the ^{12}CO (J = 1--0) spectra at 115.271 GHz in the USB from the W51 giant molecular cloud, resulting in > 20 dB for one polarization and > 14 dB for the other polarization.

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