Development of a New Multi-Beam Array 2SB Receiver in 100 GHz Band for the NRO 45-m Radio Telescope

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***Abstract*— We have developed a new multi-beam array receiver in 100-GHz band for the 45-m millimeter wave telescope located at Nobeyama Radio Observatory, Japan. This receiver has four (=2×2) beams and uses a ortho-mode transducer and two sideband-separating (2SB) mixers, both of which are based on the waveguide type for each beam. This new receiver is named "FOREST" (FOur-beam REceiver System for the 45-m Telescope). The RF range is 80-116 GHz and the IF ranges are 4.0-8.0 GHz for LSB and 4.0-12.0 GHz for USB. We have also developed new optics for the receiver and new IF chains for the 16 IF signals obtained by the receiver system. The SSB receiver noise temperature with 4.0-8.0 GHz IF are measured to be lower than approximately 50 K over the RF range of 80-116 GHz. The new receiver system has been installed in the telescope, and we successfully detected the ^{12}CO (*J*=1-0) lines toward IRC+10216 in May 2011. These are the first astronomical observations with the waveguide-type dual-polarization sideband-separating multi-beam array receiver system in 100-GHz band.**

***Index Terms*—Radio Astronomy, Receivers, Superconducting microwave devices**

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

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 telescope in the world. The 45-m telescope is equipped with low-noise high electron mobility transistor (HEMT) amplifier and superconductor-insulator-superconductor (SIS) receivers covering the observing frequency range of 20 to 116 GHz, along with powerful spectral-line and continuum back-ends. Scientific outcomes from this instrument include discoveries of a super-massive black hole [1][2] as well as finding of a number of interstellar molecules [3][4], and cover a wide range of research fields, such as formation of stars and planetary systems, the structure and activity of galaxies, and interstellar chemistry. Thus, the 45-m telescope is one of the most important millimeter wave single dish telescope in the ALMA era. The 45-m telescope has undergone a major upgrade, with an installation of three new 100-GHz band receivers [5][6], an intermediate frequency (IF) transmission system, an Analogue-to-Digital Converter (ADC) with a sampling rate of 4 GHz, and a new 32 GHz wide spectrometer [7]. These instruments are called "new observation system".

The 100-GHz band SIS receivers are the most important ones for this telescope, because they cover the highest frequency range of this telescope and also there are fundamental transitions of carbon-monoxide (CO) line in this band. Two type SIS receivers in 100-GHz band are operated in the old observation system. One is S80/S100, which is single-beam, one-polarization, and single-sideband (SSB) operation mode. Another one is BEARS (SIS 25-BEam Array Receiver System). This receiver is 25 multi-beam, one-polarization, and double-sideband (DSB) operation mode [8][9]. However, both of the receivers were developed more than 10 years ago, thus the

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receiver noise temperatures are higher than the other receivers in 100 GHz band in the world. Therefore, we are developing three type new sideband separating (2SB) SIS receivers in new observation system. The single-beam receiver named T100 [5], the 2-beam receiver named TZ [6], and new multi-beam array receiver named FOREST. In the present paper, we describe the new multi-beam array receiver and demonstrate its performance.

II. OPTICS

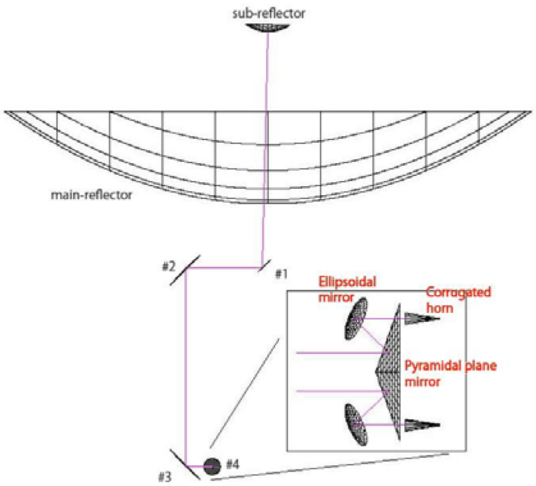

Fig. 2. Optical design of the 45-m telescope.

A. Optical Design

We have designed the receiver optics adapted the antenna optics. We used the method of both Gaussian optics and physical optics to design the receiver optics such as an ellipsoidal mirror and a corrugated feed horn. Fig.2 shows the design of the receiver optics. This receiver has four (=2x2) beams, which has 44″ of beam separation. The radio frequency (RF) signal is split to four-way by the plane mirror shaped pyramidal structure at the center and is focused by the ellipsoidal mirror to each horn.

Fig.3 shows the antenna beam radiation. Aperture efficiency is calculated about 0.76 at 100 GHz without surface error, ohmic loss, blocking in this calculation.

B. Corrugated Horn

Corrugated horns are commonly used with reflector antenna systems. Because corrugated horns can reduce the edge diffraction, improved pattern symmetry and reduced cross-polarization can be obtained [10]. Such improved performance was needed for a horn that is to be used over a wide range of the RF frequency. We repeatedly calculated the appropriate corrugation pattern from the basic design. As a result, we obtained a return loss lower than -25 dB, a maximum cross-polarization level lower than -25 dB, and good similarity between the calculated beam profiles of the E-plane and H-plane. We fabricated the horn using the direct-dig method, rather than the electro-forming method [11].

III. RECEIVER

A. Receiver Configuration

The 3D CAD image of the receiver system is shown in Fig.4. This receiver is composed of an ortho-mode transducer (OMT) and two 2SB mixers, which are both based on a waveguide technique [12], and an IF quadrature hybrid in each beam. The RF signal is down converted to 6 GHz band using 2SB mixers. We can obtain 16 IF signals independently and simultaneously. The IF band width of USB and LSB are 8 GHz (4-12 GHz) and 4 GHz (4-8 GHz), respectively. The SIS junctions adopted herein were developed at the Advanced Technology Center (ATC) of NAOJ. A four-series array was composed of Nb/AlOx/Nb junctions. The reason for using the series junction is that a wider bandwidth of RF frequency can be achieved. Moreover, the series junction barely saturates and the intensity can be calibrated with high accuracy [13]. We designed new

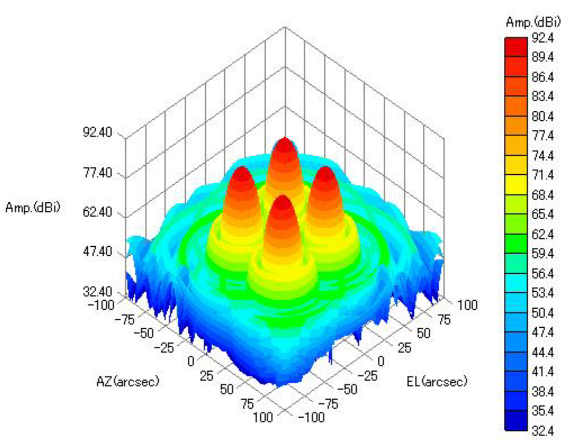

Fig. 3. Four beam antenna radiation.

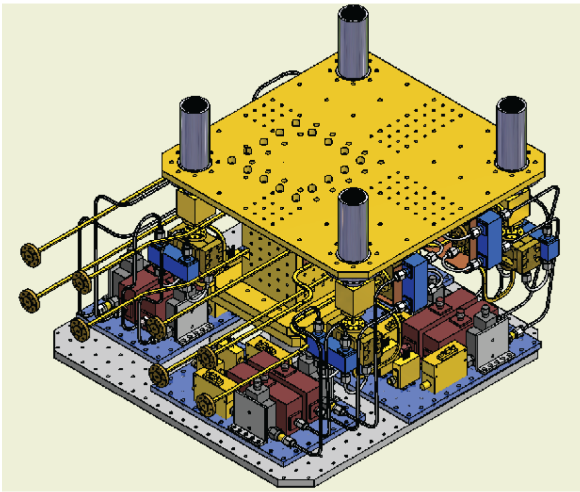

Fig. 4. CAD image of the receiver components.

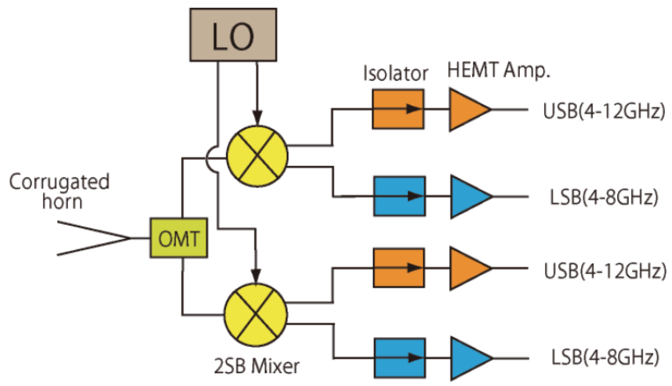

Fig. 5. Block diagram of 1-beam components.

wave-guide type OMT with wide frequency band. The OMT consists of a square to smooth taper double-ridge transition guide followed by a Bφifot type junction of two side arms with central guide [14].

The block diagram of 1-beam components is shown in Fig.5. We can obtain 4 IF signals independently and simul- taneously. The IF frequency ranges are 4-8 GHz for LSB and 4-12 GHz for USB. Thus, we can observe ^{12}CO (J=1-0), ^{13}CO (J=1-0) and C^{18}O (J=1-0) lines simultaneously.

B. Receiver Performance

The noise temperature of the 2SB receiver was measured by a standard Y-factor method. The DSB receiver noise temperatures were including the noise contribution from the vacuum window, the feed horn, and the IF amplifier chain approximately 20~30 K over the LO frequency range of 80-115 GHz, which corresponds to 4-5 hf / k. The SSB receiver noise temperatures of each sideband were measured to be lower than approximately 50 K over the RF frequency range of 85-115 GHz (Fig.6).

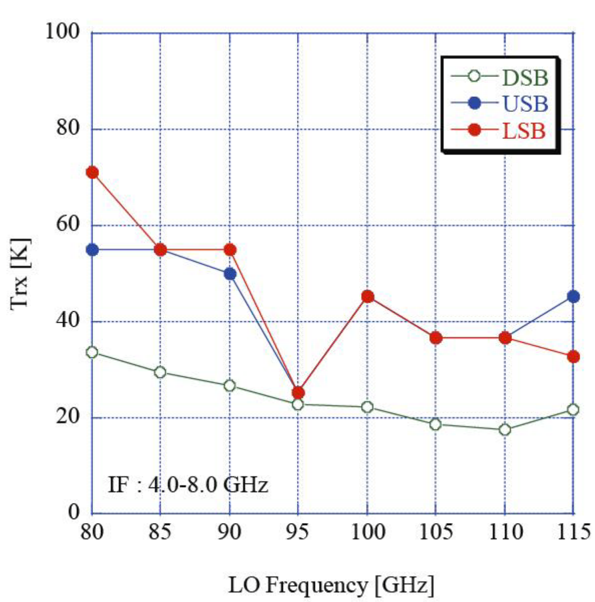

Fig. 6. Receiver noise temperatures of DSB and 2SB (SSB) mode.

IV. INSTALL & TEST OBSERVATIONS

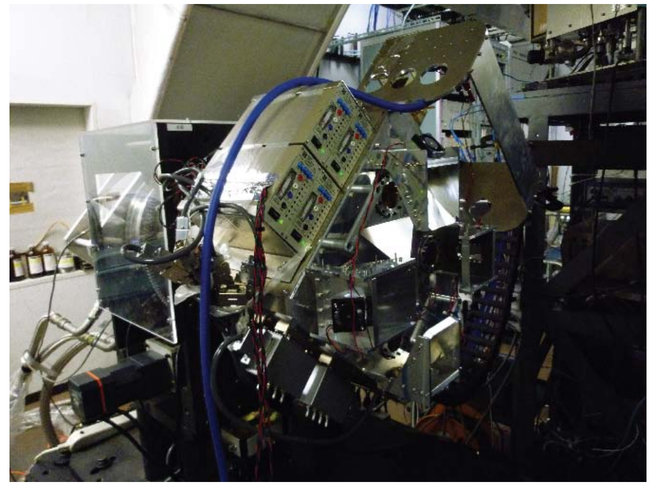

Fig. 7. Photograph of the receiver system in the receiver cabin of the telescope.

We have installed the receiver in the 45-m telescope on May 6, 2011 (Fig.7). The SSB receiver noise temperatures, including the receiver optics, were measured to be about 50-100 K for all 2SB mixers. The beam pattern of the antenna is obtained from the resultant map of the Saturn (Fig.8). The elongated feature in three directions is the effect of sub- reflector stays.

The first astronomical signal was obtained ^{12}CO (J=1-0) spectra at 115.271 GHz from the IRC+10216 on May 19, 2011.

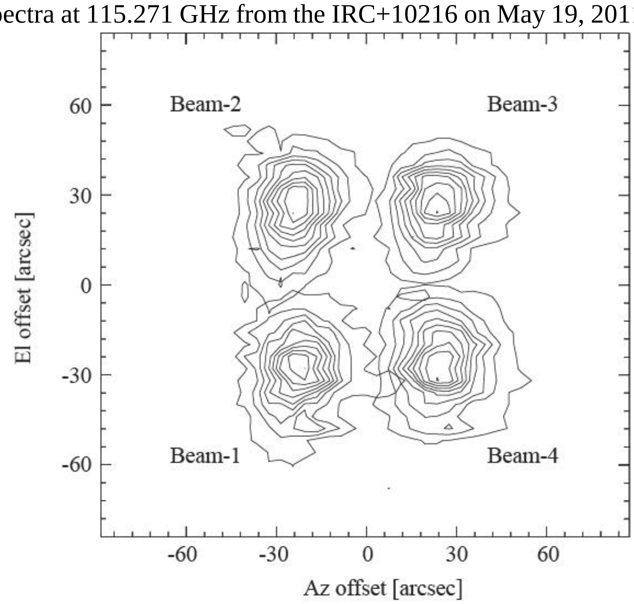

Fig. 8. Beam pattern.

These are the first astronomical observations with the waveguide-type dual-polarization sideband-separating multi-beam array receiver system in 100-GHz band (Fig.9). The system noise temperature, including the atmosphere, is about 300-400 K in 115 GHz. In our plan, we will start a scientific use with this new multi-beam array receiver from Dec. 2012.

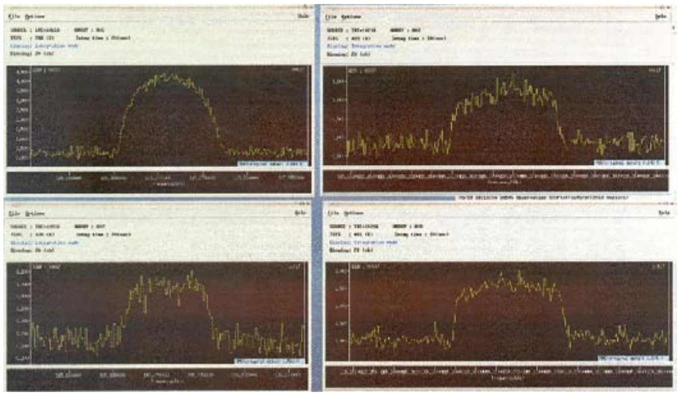

Fig. 9. First light spectrum in quick look images.

V. Conclusion

We have developed a new multi-beam waveguide-type dual-polarization sideband-separating SIS receiver system in 100 GHz band on the 45-m radio telescope at the Nobeyama Radio Observatory, Japan.

This receiver has four (=2×2) beams, with about 16″ of the HPBWs at 100 GHz. It has 44″ of beam separation and allows on-the-fly (OTF) mapping observation. The receiver of each beam is composed of an OMT and two 2SB mixers, both of which are based on a waveguide technique, and has four intermediate frequency bands of 4.0-8.0 GHz for LSB and 4.0-12.0 GHz for USB.

The SSB receiver noise temperatures of each sideband were measured to be lower than approximately 50 K over an RF frequency range of 85-115 GHz.

The new receiver system was installed in the telescope, and we successfully observed a ^{12}CO (J=1-0) emission line toward a IRC+10216 on May 19, 2011.

Acknowledgment

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References

[1] Nakai, N., Inoue, M., & Miyoshi, M. 1993, Nature, 361, 45
[2] Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
[3] Kawaguchi, K., Kasai, Y., Ishikawa, S., & Kaifu, N. 1995, PASJ, 47, 853
[4] Kaifu, N., et al. 2004, PASJ, 56, 69
[5] Nakajima, T., et al. 2008, PASJ, 60, 435
[6] Nakajima, T., et al. 2012, submitted to PASJ
[7] Kamazaki, T., et al. 2012, PASJ, 64, 29
[8] Sunada, K., Yamaguchi, C., Nakai, N., Sorai, K., Okumura, S., & Ukita, N. 2000, SPIE, 4015, 237
[9] Yamaguchi, C., Sunada, K., Iizuka, Y., Iwashita, H., & Noguchi, T. 2000, SPIE, 4015, 614
[10] Clarricoats, P. J. B., & Olver, A. D. 1984, Corrugated horns for microwave antennas (London: Peter Peregrinus Ltd)
[11] Kimura, K., Iwashita, H., Asayama, S., Sugimoto, M., Kikuchi, G., & Ogawa, H. 2008, Int. J. Infrared Millimeter Waves, 29, 713
[12] Asayama, S., Ogawa, H., Noguchi, T., Suzuki, K., Andoh, H., & Mizuno, A. 2004, Int. J. Infrared Millimeter Waves, 25, 107
[13] Kerr, A. R. 2002, ALMA Memo, 401
[14] Asayama, S., & Nakajima, T. submitted to J. Infrared Millim. Terahertz Waves