Proof-of-concept experiment on a novel microwave circulator based on frequency converters

Sho Masui[1, 2], Hideo Ogawa[1], Toshikazu Onishi[1], Kazumasa Makise, Takafumi Kojima[2], and Yoshinori Uzawa[2]

Development of a scalable integrated circuit toward a large format array is one of the major challenges in the superconducting electronics for applications such as radio astronomy and superconducting quantum computer. One of the critical components in the superconducting circuit that limit the realization of the large-scale system is a non-reciprocal cryogenic circulator based on a ferrite. In a receiver frontend of a radio telescope, it is used between a superconductor-insulator-superconductor (SIS) mixer and cryogenic low-noise amplifier to mitigate the multiple reflection and provides the ideal condition in order for the cryogenic active components to be independently operated in the system. Performance of the microwave ferrite-based circulators (isolators) reported in recent has greatly improved and shows acceptable low insertion loss over multi-octave bandwidths [1]. On the other hand, this conventional circulator is in principle physically large compared to scale of the superconducting millimeter/microwave integrated circuits. This makes it difficult to minimize physical size of the receiver frontend, and therefore, provides limitation of the number of pixels in multibeam heterodyne receivers.

To break through this limitation, we are developing a novel circulator that could be fully integrated on a superconducting planar circuit [2]. The circulator can be configured by using two identical 90-degree hybrid couplers and a gyrator inserted between them. A gyrator is a non-reciprocal device that has a 180-degree differential phase shift between waves propagating through it in opposite directions. It can be realized by employing two mixers as frequency up and down converters, and phase shifters (Fig. 1 (a)). In addition, if the SIS-based frequency converters can be used as the mixing element in the circuit, which is equivalent to a superconducting microwave amplifier being developed at the NAOJ [3, 4], the circulator with a possible gain or an unidirectional low-noise amplifier can be realized. Before designing and fabricating the on-chip circulator, we conducted a proof-of-principle experiment using commercial microwave components to clarify the design issues. As shown in Fig. 1 (b), the circulator in this experiment is consisted of two 90-degree hybrid couplers and two sets of frequency up and down converters: one set for the gyrator with the 90-degree phase shifter, and the other for compensation of the conversion loss in the gyrator. By combining them, an input signal from Port 1 can be propagated to Port 2, and an input signal from Port 2 can be propagated to Port 3. In this experiment, input/output frequencies are 200-500 MHz as the base band, and the local oscillator (LO) frequency is set to 2.0 GHz. This corresponds to the lower sideband: 1.5-1.8 GHz and upper sideband: 2.2-2.5 GHz in up-converted frequency bands. For the phase shifters used in the up-converted band, we adopted coaxial cables and adapters to achieve 90 degrees at around 2.0 GHz, since we could not obtain wideband characteristics with commercially available ones. The measurement results of the *S*-parameters for the gyrator composed of the above phase shifter and two commercial mixers are shown in Fig. 2. As a result, the phase difference between S_{21} and S_{12} is 180 degrees, indicating that it is operating as a gyrator. Regarding the characteristics as a circulator, although the phase shifters have frequency dependences, a typical isolation of 10 dB and

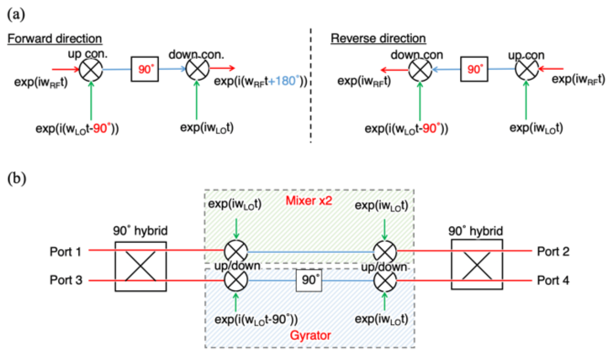

Fig. 1. (a) the schematic diagrams of a gyrator about forward direction and reverse direction. (b) the schematic diagram of circulator.

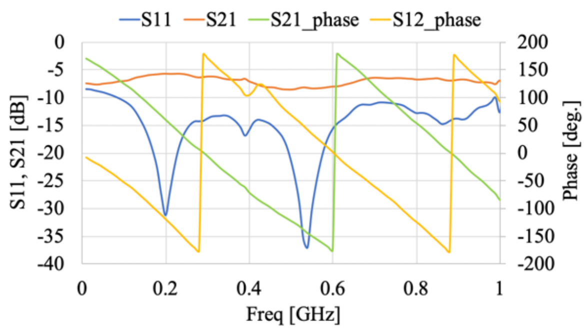

Fig. 2. The measurement results of *S*-parameter for the gyrator.

[1]Graduate School of Science, Osaka Prefecture University, Sakai, Osaka 599-8531 Japan; [2]Advanced Technology Center, National Astronomical Observatory of Japan (NAOJ), Mitaka, Tokyo 181-8588, Japan

NOTES:

the best isolation of 25 dB were successfully obtained in the base band.

In this symposium, we will report on the experimental results and the technical challenges in the circulator or isolator design. Besides, we plan to evaluate the gyrator using two SIS mixers as the frequency up and down converters, and we will present the progress of these measurements.

ACKNOWLEDGEMENTS

This work was supported in part by JST [Moonshot R&D] Grant Number [JPMJMS2067] and JSPS KAKENHI Grant Numbers JP18H03881 and JP19H02205.

REFERENCES

[1] L. Zeng, C. E. Tong, R. Blundell, P. K. Grimes and S. N. Paine, "A Low-Loss Edge-Mode Isolator with Improved Bandwidth for Cryogenic Operation," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 5, pp. 2154-2160, May 2018.

[2] B. Abdo, M. Brink, and J. M. Chow, “Gyrator Operation Using Josephson Mixers”, *Physical Review Applied*, Sep. 2017.

[3] T. Kojima, Y. Uzawa, and W. Shan, “Microwave amplification based on quasiparticle SIS up and down frequency converters”, *AIP Advances*, Feb. 2018.

[4] Y. Uzawa, T. Kojima, Y. Kozuki, Y. Fujii, A. Miyachi, T. Tamura, S. Ezaki, and W. Shan, “An SIS-mixer-based amplifier for multi-pixel heterodyne receivers”, *Proc. SPIE*, Dec. 2020.

NOTES: