A 0.2–0.5 THz single-band heterodyne receiver based on a photonic local oscillator and a superconductor-insulator-superconductor mixer

Satoshi Kohjiro,[1,a)] Kenichi Kikuchi,[1] Masaaki Maezawa,[1] Tomofumi Furuta,[2] Atsushi Wakatsuki,[2] Hiroshi Ito,[2,b)] Naofumi Shimizu,[3] Tadao Nagatsuma,[3,c)] and Yuichi Kado[3]

[1]*National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan*
[2]*NTT Photonics Laboratories, NTT Corporation, 3-1 Morinomiya, Atsugi, Kanagawa 243-0198, Japan*
[3]*NTT Microsystem Integration Laboratories, NTT Corporation, 3-1 Morinomiya, Atsugi, Kanagawa 243-0198, Japan*

(Received 18 June 2008; accepted 6 August 2008; published online 4 September 2008)

We have demonstrated that a superconductor-insulator-superconductor (SIS) mixer pumped by a photonic local oscillator (LO) covers the whole frequency range of 0.2–0.5 THz. In the bandwidth of 74% of the center frequency, this single-band receiver exhibits noise temperature of $T_{RX} \leq 20hf/k_B$, where h is Planck's constant, f is the frequency, and k_B is Boltzmann's constant. Resultant T_{RX} is almost equal to T_{RX} of the identical SIS mixer pumped by three conventional frequency-multiplier-based LOs which share the 0.2–0.5 THz band. This technique will contribute to simple, wide-band, and low-noise heterodyne receivers in the terahertz region. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2976311]

Heterodyne spectroscopy is popular for accurate measurement of frequency and power in microwave and millimeter-wave regions. The extension of this technique to the terahertz range[1] requires a low-noise mixer pumped optimally by a local oscillator (LO) with high signal purity. Wide radio frequency (rf) band mixers and widely tunable LOs can decrease the number of frequency bands, which simplifies the receiver system and decreases its volume and cost. Our objective is development of general measuring instruments such as a portable terahertz spectrum analyzer for laboratory use and remote sensors of air-polluting or toxic gases. Though Schottky-barrier-diode (SBD) mixers[2–4] and frequency-multiplier-based LOs (Refs. 2, 5, and 6) look suitable for such application, their relative bandwidth (RBW), i.e., the bandwidth normalized by its center frequency, is less than 40%.[2] In addition, typical receiver noise temperature of SBD mixers operating at room temperature is $T_{RX} \approx 100hf/k_B$ even at the frequency point of best performance,[3,4] where h is Planck's constant, f is the frequency, and k_B is Boltzmann's constant. This value is roughly five times as large as the background noise in the above-mentioned applications. A superconductor-insulator-superconductor (SIS) mixer[7–10] pumped by a photonic local oscillator[11] (Ph-LO) is a candidate for both RBW > 60% and $T_{RX} \leq 20hf/k_B$. Though several authors reported low T_{RX} of a SIS mixer pumped by a Ph-LO,[12–14] RBW > 15% has not been reported yet. In this paper, we first report T_{RX} measurement with RBW = 88% and show $T_{RX} \leq 20hf/k_B$ in RBW = 74%.

A quasioptical mixer we developed for RBW > 60% consists of a distributed array of eight SIS junctions (DJA), a twin-slot antenna (TSA), and a three-stage transformer, as shown in the inset of Fig. 1(a). Eight SIS junctions implemented in a superconducting microstrip line provide seven resonant frequencies, at which junction capacitances are tuned out by microstrip inductances. Close positioning of these resonant frequencies is a way of developing wide-band SIS mixers.[15] A drawback of DJA, whose input resistance R_{DJA} is less than 10% of the radiation resistance R_{rad} of self-complementary antennas, is overcome by adopting a TSA operating around its full-wavelength resonance, yielding $R_{DJA} \approx 0.5R_{rad}$. Details of design, fabrication, and characterization of the mixer chip are described elsewhere.[16] The chip was cooled at 4.2 K in a liquid helium cryostat after it was glued on a silicon elliptical lens with 5 mm radius and an epoxy antireflection coating whose designed center frequency was 350 GHz. To evaluate rf transmission from the TSA to the DJA, the current responsivity of a voltage-biased DJA was measured by Fourier transform spectroscopy (FTS) prior to the heterodyne measurement.

A Ph-LO is based on two-mode beating of the optical signal using a unitraveling-carrier photodiode[17–20] (UTC-PD) and two wavelength tunable laser diodes operating around 1.55 μm. The UTC-PD provides large bandwidth and large saturation power simultaneously since only electrons are the active carriers traveling through the junction depletion region.[17] The output frequency band of developed UTC-PD modules with rectangular waveguides has been increased from 75–110 to 220–325 GHz.[18–20] For 0.2–0.5 THz operation in this work, a new module was developed by the optimization of the matching circuit between the photodiode and the output waveguide.[21] This matching circuit suppresses higher-order modes in WR-3 output waveguides and also maximizes the coupling efficiency of its fundamental mode. The output powers of $P_{Ph} \approx 400$ μW at 350 GHz and $P_{Ph} \approx 50$ μW at 500 GHz were experimentally obtained in the form of direct connection with a power meter to its output port.[21] The oscillation linewidth of the present Ph-LO, $\delta f \sim 10$ MHz, is dominated by the mutual frequency stability of two laser sources. We believe $\delta f \ll 1$ kHz will be achieved in the future by extending an advanced technique proven at around 0.3 THz (Ref. 22) to 0.2–0.5 THz.

a)Electronic mail: s-kohjiro@aist.go.jp.
b)Present address: Kitasato University, Sagamihara, Kanagawa 228-8555, Japan.
c)Present address: Osaka University, Toyonaka, Osaka 560-8531, Japan.

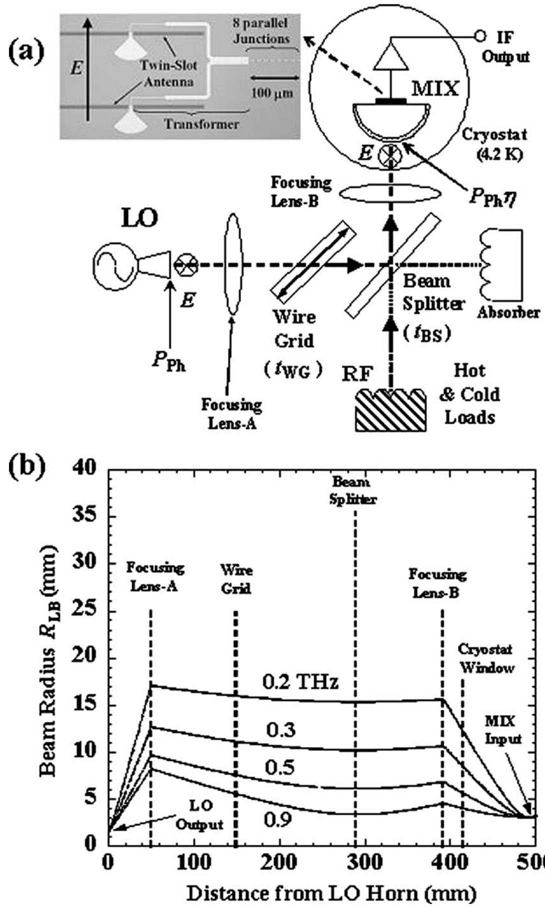

FIG. 1. (a) Experimental setup for the receiver noise temperature measurement. The inset shows the central part of the mixer chip. E denotes the electric field of the LO signal, P_{Ph} and $P_{\mathrm{Ph}}\eta$ are the LO powers, and t_{WG} and t_{BS} are the transmissions (see text). (b) Calculated beam radius vs the distance from the LO horn antenna along the path of LO signal shown in (a). Dotted vertical lines denote the position and the aperture radius of optical components.

Figure 1(a) shows the experimental setup for the receiver noise temperature measurement. The rf signal is thermal radiation from hot (295 K) and cold (77 K) antenna loads, which transmits through a Mylar beam splitter (BS) with a thickness of 16 or 25 μm. A linearly polarized LO signal from a horn antenna transmits through a one-dimensional wire grid (WG) and its portion (<12%) reflects at the surface of the BS. The direction of the electric field (E-field) of the LO beam is fixed as perpendicular to the long side of slots used for TSA in the mixer chip. The LO power coupled to the mixer was adjusted by the angle between the wire and the E-field, which determines the transmission of the WG t_{WG}. Quasioptics for the wide-band coupling between LO and mixer were designed based on the theory of Gaussian beam propagation.[23] Figure 1(b) shows the calculated beam radius R_{LB} versus the distance from the LO horn antenna at 0.2, 0.3, 0.5, and 0.9 THz. In general, R_{LB} depends on the frequency and distance from the source. The requirement of our optics is as follows. First, R_{LB} should be independent of the frequency at the mixer input to keep a high coupling efficiency in a wide rf band. Next, the ratio of LO power density at the aperture edge of all optical components to that on the axis should be less than −17 dB above 200 GHz. To satisfy these conditions, the position of two Teflon lenses was optimized both at the LO output (focusing lens-A) and in front of the cryostat window (focusing lens-B). As the result of optimization, the calculated R_{LB} at the substrate lens is independent of the frequency between 0.2 and 0.9 THz, as shown in Fig. 1(b).

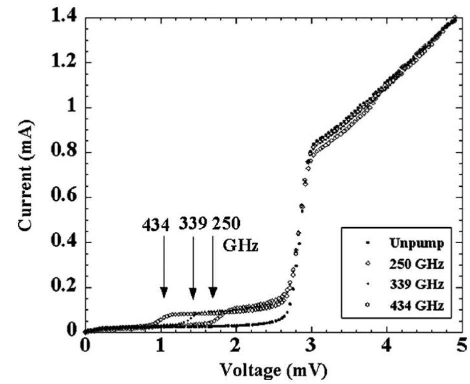

FIG. 2. Current-voltage characteristics of the SIS mixer pumped by the photonic LO. Arrows denote theoretical voltages of the first photon-assisted tunneling step corresponding to 250, 339, and 434 GHz.

Figure 2 shows unpumped and pumped current-voltage curves of the SIS mixer. Here, the Ph-LO frequency was set at 250, 339, and 434 GHz, and the LO-mixer coupling was adjusted so that T_{RX} was the minimum. The first photon-assisted tunneling steps are observed at the voltages of $V_{\mathrm{PAT}} \approx 1.7$, 1.4, and 1.0 mV for $f=250$, 339, and 434 GHz, respectively. These experimental values agree with theoretical ones[7] of $V_{\mathrm{PAT}}=V_G-hf/e=1.69$, 1.43, and 1.03 mV, where $V_G=2.83$ mV is the gap voltage of the SIS mixer. This suggests the following properties of the Ph-LO at 0.2–0.5 THz. First, the radiation frequency was equal to the prediction. Next, the radiation power was enough for the mixer operation with the lowest T_{RX} under the loss of our coupling optics.

The uncorrected double-sideband (DSB) receiver noise temperature T_{RX} was measured with a conventional Y-factor method, where T_{RX} is derived from the ratio of the intermediate frequency (IF) output power for the hot antenna load to the cold one. For the single-ended mixer adopted in this experiment, the sideband noise of LO is also downconverted to the IF output of the mixer and degrades T_{RX}. Thus, comparison of T_{RX} of an identical mixer pumped by two kinds of LO makes clear whether these two LOs produce different amounts of noise. Figure 3 shows T_{RX}-f characteristics with two kinds of LO. One is Ph-LO with 16-μm or 25-μm thick BS. The LO-mixer coupling of the latter is about 2 times as large as that of the former with sacrificing the rf coupling of the mixer. The other LO device is composed of commercial multiplier-based cw oscillators driven by a microwave synthesizer or Gunn diodes. As shown in Fig. 3, T_{RX}-f characteristics of both LOs agree quantitatively with the inverse of the FTS responsivity with a fitting coefficient of $K=0.07$. This indicates that T_{RX} of Ph-LO is almost equal to T_{RX} of conventional LOs, demonstrating that the Ph-LO does not produce remarkable additional noise in comparison with the conventional multiplier-based LOs. The origin of slightly higher T_{RX} for the Ph-LO at particular frequency points such as 312, 339, and 460 GHz is now under investigation. The origin may be related to the dynamics of the source lasers since the T_{RX} of Ph-LOs is found to be sensitive to the choice and conditions of the lasers. In this case, the optimization of source lasers will contribute to the reduction in T_{RX} at these

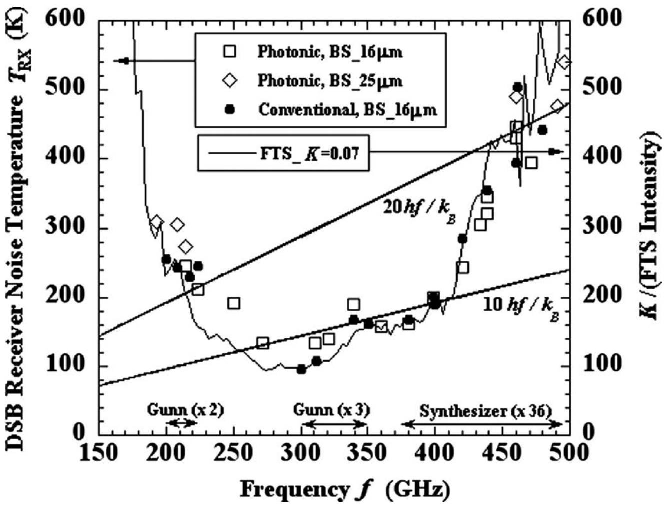

FIG. 3. Uncorrected DSB receiver noise temperature vs frequency. The SIS mixer is pumped either by a Ph-LO or three multiplier-based LOs (filled circles) driven by a microwave synthesizer or Gunn diodes with different bands (arrows; ×2, ×3, and ×36 denote each harmonic number). For Ph-LO, a two-thickness BS is adopted, in which the LO-mixer coupling of 25-μm-thick BS (diamonds) is about two times as large as that of 16-μm-thick BS (squares). The solid curve denotes the inverse of FTS responsivity with $K=0.07$ (right axis).

frequency points. Figure 3 indicates the clear difference of bandwidth between the Ph-LO and the conventional LOs. A Ph-LO covers 0.2–0.5 THz completely, while three conventional LOs with different frequency bands cover a part of this range. $T_{RX} \leqslant 20hf/k_B$ is achieved in RBW=74%. This bandwidth is dominated by that of the present SIS mixer.

The pumping power of this wideband and low-noise operating SIS mixer was roughly estimated from the frequency dependent P_{Ph}.[21] The coupling coefficient between LO and mixer η is given by $\eta=\zeta(1-t_{BS})t_{WG}$, where t_{BS} is the BS transmission, and ζ is the beam coupling efficiency in terms of other factors. The product of $P_{Ph}\eta$ is the pumping power at the mixer input. From the frequency dependent P_{Ph}, taking theoretical values of t_{BS} and t_{WG}, and assuming the ideal coupling of $\zeta=1$, $0.7 \leqslant P_{Ph}\eta \leqslant 5\ \mu$W is calculated[24] and shown in Fig. 4. Resultant $P_{Ph}\eta$ is two to three orders of magnitude lower than the typical LO power requirement P_{LO}

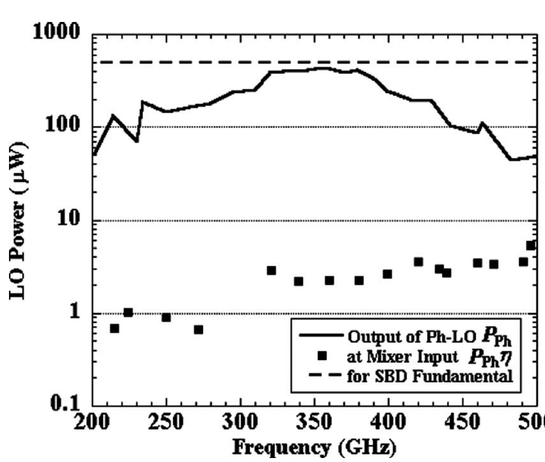

FIG. 4. Frequency dependence of the output power of the photonic LO P_{Ph} (solid line) and the maximum (Ref. 24) pumping power at the mixer input $P_{Ph}\eta$ (filled square) calculated from t_{WG} and t_{BS}. The dashed line denotes the reported LO power requirement for a SBD fundamental mixer at room temperature.

for SBD operating at room temperature, i.e., $P_{LO} \geqslant 0.5$ mW (Refs. 2 and 4) for the fundamental mixing and $P_{LO} \geqslant 2$ mW for the second harmonic one.[2,3] The combination of the SIS mixer with such small P_{LO} and the Ph-LO with 50–400 μW output achieves wide-band and low-T_{RX} heterodyne detection.

In summary, a low-noise and wide-band heterodyne detection is demonstrated with a quasioptical SIS mixer pumped by a UTC-PD-based Ph-LO. This combination of mixer and LO creates a single-band receiver which fully covers 0.2–0.5 THz and exhibits $T_{RX} \leqslant 20hf/k_B$ in RBW =74%.

S.K. acknowledges J. Inatani, Y. Uzawa, and S. C. Shi for fruitful discussions on the receiver concept and the mixer design. S.K. also thanks T. Kawai for his homemade WGs, and Z. Wang, S. Saito, Y. Irimajiri, and M. Takeda for the evaluation of conventional LOs and related discussions. A. Shoji's continuous support and encouragement is appreciated. This work is supported in part by the National Institute of Information and Communications Technology, Japan.

[1] P. H. Siegel and R. J. Dengler, Int. J. Infrared Millim. Waves **27**, 465 (2006); **27**, 631 (2006).
[2] Available: http://www.virginiadiodes.com/
[3] N. R. Erikson, Proc. IEEE **80**, 1721 (1992).
[4] J. L. Hesler, W. R. Hall, T. W. Crowe, R. M. Weikle II, B. S. Deaver, Jr., R. F. Bradley, and S. K. Pan, IEEE Trans. Microwave Theory Tech. **45**, 653 (1997).
[5] A. V. Raisanen, Proc. IEEE **80**, 1842 (1992).
[6] I. Mehdi, Proc. SPIE **5498**, 103 (2004).
[7] J. R. Tucker and M. J. Feldman, Rev. Mod. Phys. **57**, 1055 (1985).
[8] J. Zmuidzinas and P. L. Richards, Proc. IEEE **92**, 1597 (2004).
[9] A. Karpov, D. Miller, F. Rice, J. A. Stern, B. Bumble, H. G. LeDuc, and J. Zmuidzinas, IEEE Trans. Appl. Supercond. **17**, 343 (2007).
[10] W. Shan, T. Noguchi, S. C. Shi, and Y. Sekimoto, IEEE Trans. Appl. Supercond. **15**, 503 (2005).
[11] E. R. Brown, F. W. Smith, and K. A. Mcintosh, J. Appl. Phys. **73**, 1480 (1993).
[12] S. Verghese, E. K. Duerr, A. McIntosh, S. M. Duffy, S. D. Calawa, C.-Y. E. Tong, R. Kimberk, and R. Blundell, IEEE Microw. Guid. Wave Lett. **9**, 245 (1999).
[13] A. Ueda, T. Noguchi, S. Asayama, H. Iwashita, Y. Sekimoto, M. Ishiguro, H. Ito, T. Nagatsuma, A. Hirata, and W. Shillue, Jpn. J. Appl. Phys., Part 2 **42**, L704 (2003).
[14] I. C. Mayorga, P. M. Pradas, M. Michael, M. Mikulics, A. Schmitz, P. van der Wal, C. Kaseman, R. Gusten, K. Jacobs, M. Marso, H. Luth, and P. Kordos, J. Appl. Phys. **100**, 043116 (2006).
[15] S. C. Shi, T. Noguchi, J. Inatani, Y. Irimajiri, and T. Saito, IEEE Trans. Appl. Supercond. **9**, 3777 (1999).
[16] S. Kohjiro, S. C. Shi, J. Inatani, M. Maezawa, Y. Uzawa, Z. Wang, and A. Shoji, IEEE Trans. Appl. Supercond. **17**, 355 (2007).
[17] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, and T. Furuta, in *Proc. OSA TOPS on Ultrafast Electronics and Optoelectronics* (Optical Society of America, Washington, D.C., 1997), Vol. 13, pp. 83–87.
[18] H. Ito, T. Ito, Y. Muramoto, T. Furuta, and T. Ishibashi, J. Lightwave Technol. **21**, 3456 (2003).
[19] T. Furuta, T. Ito, Y. Muramoto, H. Ito, M. Tokumitsu, and T. Ishibashi, Electron. Lett. **41**, 715 (2005).
[20] H. Ito, T. Furuta, Y. Muramoto, T. Ito, and T. Ishibashi, Electron. Lett. **42**, 1424 (2006).
[21] A. Wakatsuki, T. Furuta, Y. Muramoto, T. Yoshimatsu, and H. Ito (unpublished).
[22] H. J. Song, N. Shimizu, T. Furuta, K. Suizu, H. Ito, and T. Nagatsuma, "Broadband frequency-tunable sub-terahertz wave generation using an optical comb signal, AWGs, optical switches, and uni-traveling carrier photodiode for spectroscopic applications," J. Lightwave Technol. (to be published).
[23] P. F. Goldsmith, *Quasioptical Systems* (IEEE, New York, 1998).
[24] Because of the assumption of $\zeta=1$, the calculated $P_{Ph}\eta$ gives the maximum value of the real pumping power.