A 0.2-0.5 THz Heterodyne Receiver Based on a Photonic Local Oscillator and a Superconductor-Insulator-Superconductor Mixer

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***Abstract*—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 the noise temperature of $T_{RX} \leq 20hf/k_B$, where h is Planck's constant, f the frequency, and k_B Boltzmann constant. Resultant T_{RX} is almost equal to T_{RX} of the identical SIS mixer pumped by three conventional multiplier-based LOs which share 0.2-0.5 THz band. This technique will contribute to simple, wide-band, and low-noise heterodyne receivers in the terahertz region.**

I. Introduction

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 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. Though commercial Schottky-barrier-diode (SBD) harmonic mixers (HMs) and frequency-multiplier-based LOs are popular, their relative bandwidth (RBW), i.e., the bandwidth normalized by its center frequency, is less than 40 %.[1] In addition, typical receiver noise temperature T_{RX} of SBD-HMs is 5-10 times as large as 300-K radiation which is a background noise for passive spectroscopy. A superconductor-insulator-superconductor (SIS) mixer pumped by a photonic local oscillator (Ph-LO) is a candidate for both RBW>60 % and $T_{RX} \leq 300$ K. Though several authors reported low T_{RX} of a SIS mixer pumped by a Ph-LO so far,[2-4] 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 %, where h is Planck's constant, f the frequency, and k_B Boltzmann's constant.

II. Experimental Setup

A quasi-optical mixer we developed for RBW>60 % consists of a distributed array of 8 SIS junctions, a twin-slot antenna, and a 3-stage transformer.[5] The chip was cooled at 4.2 K in a cryostat. To evaluate RF transmission from the antenna to the junctions, the current responsivity of voltage-biased SIS junctions was measured by Fourier transform spectroscopy (FTS) prior to the heterodyne measurement.

A photonic local oscillator (Ph-LO) is based on two-mode beating of optical signal using an uni-traveling-carrier photodiode (UTC-PD)[6,7] and two wavelength-tunable laser-diodes operating around 1.55 µm. 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.[8] This matching circuit suppresses higher-order modes in WR-3 output waveguides as well as maximizing the coupling efficiency of its fundamental mode. The output power of $P_{Ph} \approx 400$ µW at 350 GHz and $P_{Ph} \approx 50$ µW at 500 GHz were experimentally obtained in a form of direct connection with a power meter to its output port. 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.[9]

Quasioptics for the wide-band coupling between LO and mixer were designed based on the theory of Gaussian beam propagation [10] and constructed as shown in Fig. 1.

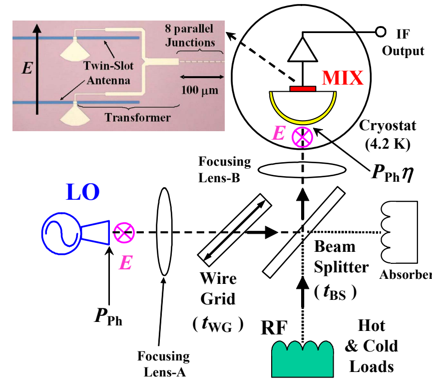

Fig. 1. Experimental setup for the receiver noise temperature measurement. The inset shows the central part of the mixer chip.

III. Results And Discussions

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 (295 K) antenna load to the cold (77 K) ones. For a single-ended mixer adopted in this experiment, the sideband noise of LO is also down-converted 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 amount of noise. Figure 2 shows T_{RX}-f characteristics with two kinds of LO. One is Ph-LO with 16-µm (squares) or 25-µm (diamonds) thick beam splitter (BS). The LO-mixer coupling of the latter is about

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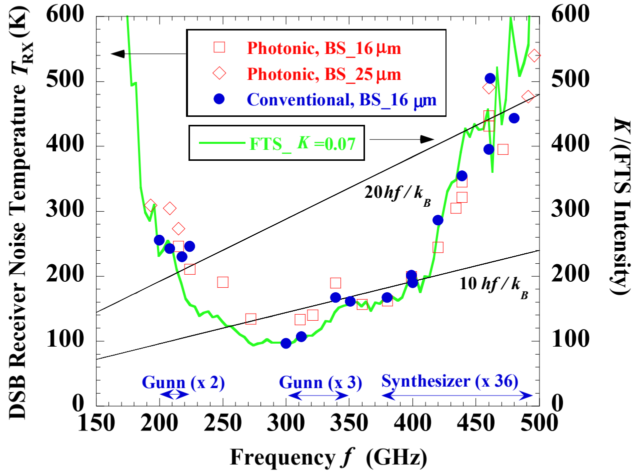

Fig. 2. Uncorrected DSB receiver noise temperature vs. frequency. The SIS mixer is pumped either by a Ph-LO or 3 multiplier-based LOs (filled circles) driven by a microwave synthesizer or Gunn diodes with different bands (arrows; ×2, ×3, and ×36 denote each harmonic number). For Ph-LO, 2 thickness of beam splitter (BS) is adopted, in which the LO-mixer coupling of 25-µm-thick BS (diamonds) is about 2 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).

2 times as larger as that of the former instead of sacrificing the RF coupling of the mixer. The other is commercial multiplier-based CW oscillators driven by a microwave synthesizer or Gunn diodes (filled circles). As shown in Fig. 2, T_{RX}-f characteristics of both LOs agree quantitatively with the inverse of the FTS responsivity with a fitting coefficient of K=0.07 (green solid line). This indicates T_{RX} of Ph-LO is almost equal to T_{RX} of conventional LOs, exhibiting that the Ph-LO does not produce the remarkable additional noise in comparison with the conventional multiplier-based LOs. Origin of slightly higher T_{RX} of the Ph-LO at particular frequency points such as 312, 339, and 460 GHz is now under the investigation. It may be related to the dynamics of the source lasers, since 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 of T_{RX} at these frequency points. Figure 2 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 band cover a part of this band (arrows). $T_{RX}\leq 20hf/k_B$ is achieved in RBW=74 %.

Pumping power of this wide-band and low-noise operation of SIS mixer was roughly estimated from the frequency dependent P_{Ph}.[8] The coupling coefficient between LO and mixer η is given by $\eta=\zeta\times(1-t_{BS})\times t_{WG}$, where t_{BS} is the BS's transmission, t_{WG} the transmission of a wire grid, and ζ 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}, theoretical values of t_{BS} and t_{WG}, and assuming the ideal coupling of ζ=1, $0.7\leq P_{Ph}\eta\leq 5$ µW is calculated and shown in Fig. 3. Resultant $P_{Ph}\eta$ is 2-3 orders of magnitude lower than the typical LO-power requirement P_{LO} for SBD operating at the room temperature, i.e., $P_{LO}\geq$0.5 mW

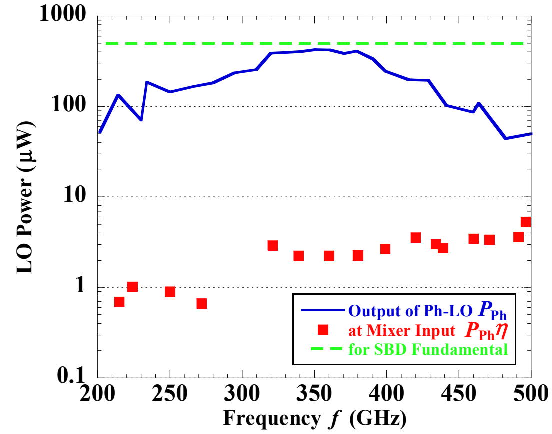

Fig. 3. Frequency dependence of the output power of the photonic LO P_{Ph} (solid line) and the maximum pumping power at the mixer input $P_{Ph}\eta$ (filled square) calculated from t_{WG} and t_{BS}. The dashed line denotes the reported LO power requirement for a SBD fundamental mixer at room temperature.

for the fundamental mixing and $P_{LO}\geq$2 mW for the 2nd harmonic one.[1] The combination of the SIS mixer with such small P_{LO} and the Ph-LO with 50-400 µW output realizes the wide-band and low-T_{RX} heterodyne detection.

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

Acknowledgment

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