

NbN hot electron bolometer mixer at 5.3 THz

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ABSTRACT

We report the sensitivity of a superconducting NbN hot electron bolometer mixer integrated with a tight spiral antenna at 5.3 THz. Using a measurement setup with black body calibration sources and a beam splitter in vacuo, and an antireflection coated Si lens, we obtained a double sideband receiver noise temperature of 1150 K, which is 4.5 times $h\nu/k_B$ (quantum limit). Our experimental results in combination with an antenna-to-bolometer coupling simulation suggest that HEB mixer can work well at least up to 6 THz, suitable for next generation of high-resolution spectroscopic of the neutral atomic oxygen (OI) line at 4.7 THz.

Keywords: THz superconducting mixer, THz antenna, beam patterns, receiver noise temperature

1. INTRODUCTION

Superconducting hot-electron bolometer (HEB) mixers are so far the most sensitive heterodyne detectors at THz frequencies above 1.5 THz, and have been successfully used to detect spectral lines up to 2 THz from ground based [1-3] and space [4] telescopes. The HEB mixers become the detector of choice in the upper THz frequency range (3-6 THz) for high-resolution spectroscopic observations for astronomy. One example is the fine-structure line of neutral atomic oxygen OI ($^3P_1-^3P_2$) at 4.7448 THz, which is a major coolant of dense interstellar medium and is a vital tool for probing the physical conditions of massive young stars [5]. The OI line has been recorded by a Schottky heterodyne receiver flying on the Kuiper Airborne Observatory [6]. However, the sensitivity of the receiver used was very poor and was 75000 K at 4.7 THz. The sensitivity of a receiver, i.e. T_{rec}^{DSB} , is a crucial parameter that defines the minimal detectable line intensity and also the observation time.

The aim of this paper is to demonstrate experimentally the ultimate sensitivity of an NbN HEB mixer at the high-end of the THz frequency range. Here we use a similar HEB mixer and measurement setup as reported earlier for a measurement at 4.3 THz [7]. However, we extend the LO frequency to 5.25 THz. We report an extremely low T_{rec}^{DSB} at 5.25 THz. In addition, the coupling efficiency between spiral antenna and bolometer is simulated.

2. HEB DEVICE AND MEASUREMENT SETUP

The HEB mixer used consists of a 2 μm wide, 0.2 μm long, and 5.5 nm thick NbN bridge on a highly resistive Si substrate. The NbN thin film was produced by a group at Moscow State Pedagogical University (MSPU), Russia. The details of the NbN film can be found in Ref. 8. The bridge is connected to the antenna by Nb (10 nm)/Au (50 nm) superconducting bilayer contact pads [8]. Prior to deposition of the contact pads, Ar RF (radio frequency) sputter etching is applied to clean the surface of the NbN, eliminating contact resistance between NbN and contact pads [9]. Such contact structures allow RF and DC power to be dissipated only in the NbN bridge, thus there is no RF loss and no additional noise contribution due to the contact interface. The antenna is an on-chip self-complementary spiral antenna that is made of a 170 nm thick Au layer. It has a tight winding design with an inner diameter of 6.6 μm close to the NbN

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bridge (Fig.1a). The HEB has a low-temperature normal-state resistance (R_N) of 83Ω , a critical temperature of 9.3 K , and a critical current of $210 \mu\text{A}$ at 4.2 K .

We apply a similar measurement setup as described in Ref. 7 except for a different heat filter [10]. Furthermore, we do not use the bandpass filter. The HEB chip is glued to the backside of Si elliptical lenses [11] without and with an antireflection coating, mounted in a mixer unit that is placed in a 4.2-K liquid helium cryostat. As calibration sources, a blackbody at 295 K is used as the hot load and another one at 77 K as the cold load. The two loads can be selected by rotating a mirror. The radiation from the hot/cold load is combined with that from the LO by a $3\text{-}\mu\text{m}$ Mylar beam splitter. Before reaching the HEB, the radiation passes through the heat filter at 4.2 K that blocks infrared radiation. There is no window on the cryostat and all these components are in the same vacuum unit [12]. Therefore the radiation does not suffer from absorption due to water in the air and due to the window.

The LO is an optically pumped Far Infrared (FIR) ring gas laser, operated at a frequency of 5.2456 THz using CH_3OD gas, which is pumped by the $9\text{R}08 \text{ CO}_2$ line. We choose this frequency because it provides enough power in the frequency range of interest. The LO power coupled to the mixer is regulated by rotating a wire grid in front of the gas laser

The IF signal, resulting from the mixing of the LO and the hot/cold load signal, first passes through a bias-T, a

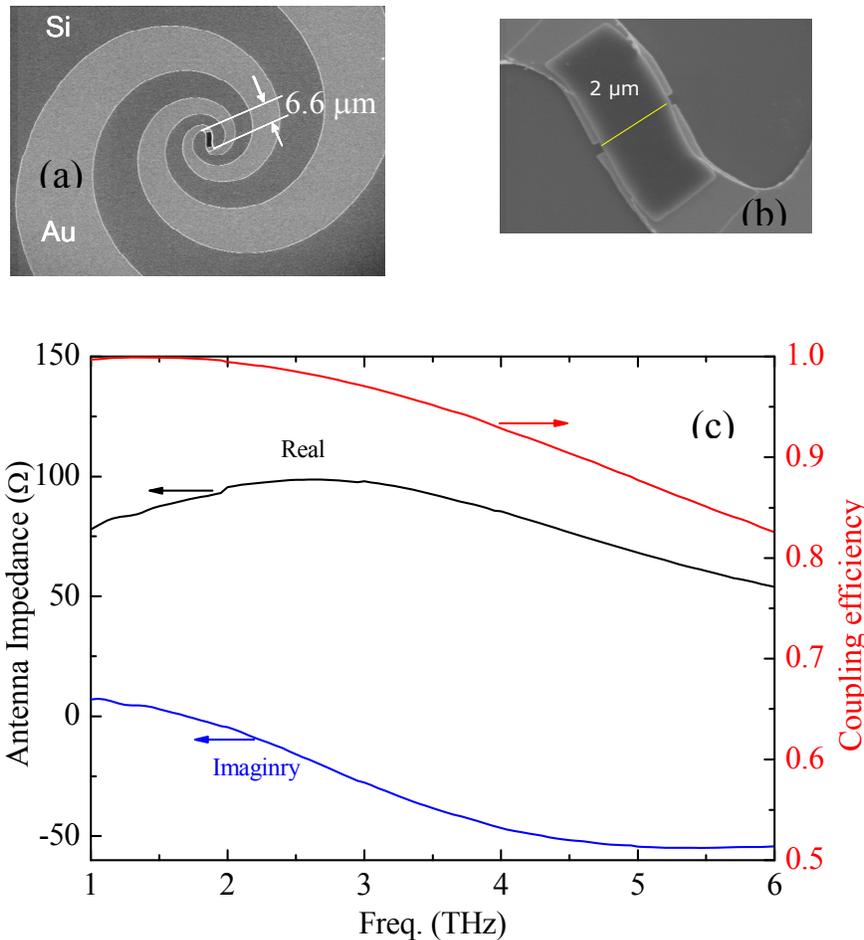


Fig. 1 Measured receiver output powers at the optimum bias voltage of 0.6 mV (dots) and the polynomial fit (lines) responding to the hot and cold load as a function of bias current of the HEB, which is varied by changing the LO power (left axis). One set of data are measured using uncoated lens and another set of data (2 dB positive offset for clarity) are measured using a coated lens. The resulted DSB receiver noise temperature curves are also shown as a function of bias current of the HEB (right axis).

circulator, and then a cryogenic low noise amplifier (Berkshire 1.3-1.7 GHz) operated at 4.2 K, followed by room-temperature amplifiers. This signal is filtered at 1.5 GHz within a band of 80 MHz. Between each two components in the IF chain, an attenuator is added to avoid standing waves. The entire IF chain has a gain of about 80 dB and a noise temperature of 7 K.

3. SIMULATION OF THE IMPEDANCE OF THE ANTENNA AND COUPLING

To predict the impedance of the antenna and further calculate the coupling efficiency of the radiation power from the antenna to the HEB at the upper THz frequencies, we model the antenna using a three-dimensional electromagnetic field simulator HFSS [13] based on finite element method. We assume that an RF signal is excited at the slit between two contact pads of the HEB, which is called a lumped gap source. The Si substrate with a refractive index $n_{si}=3.42$ is set to be much thicker than the wavelength (λ) of the radiation and is treated as a half infinite space. The Au antenna layer is set to be a perfect conductor, which should be a good approximation since its electric conductivity is very high ($\sim 10^7$ S/m). All the surfaces are taken as radiation boundaries. To perform the simulation, the whole structure is first divided into many small elements, which are smaller than 0.05λ . For the regions where the electromagnetic field varies significantly it will be further automatically divided into even smaller elements to achieve accurate field and current distribution. The scattering parameters are then extracted from the electromagnetic field distribution. From the complex reflection coefficient (S_{11}) and its characteristic impedance (Z_0), the input impedance ($Z_{antenna}$) of the spiral antenna can be given as [14]:

$$Z_{antenna} = R_{antenna} + iX_{antenna} = Z_0 \frac{1+S_{11}}{1-S_{11}} \tag{1}$$

Fig. 1c shows the simulated $Z_{antenna}$ of the spiral antenna as a function of frequency between 1 and 6 THz. At lower frequencies the impedance is real and has a value close to 75 Ω , as expected for an equiangular spiral antenna [15]. However, with increasing the frequency the reactive part appears and increases to -50 Ω at around 5 THz. The reactance

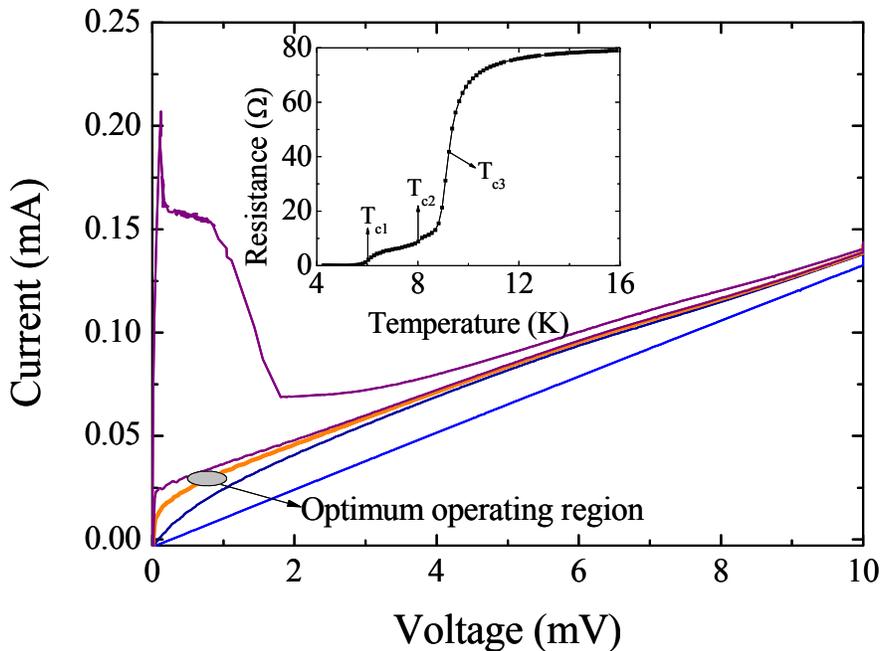


Fig. 2 A set of current-voltage curves of the NbN HEB mixer at 4.2 K and at different LO power, where the optimum operating region is indicated. The inset shows the DC resistance versus temperature of a very similar HEB, which was measured in the low current limit.

can be explained by a parasitic effect that is due to the presence of a transition structure, namely the contact-pad structure between the HEB and the two arms of the spiral (see Fig.1b) [16].

Given that our HEB impedance (R_{HEB}) is constant [17], equal to R_N , the coupling efficiency η can be calculated based on the impedance match:

$$\eta = \frac{4R_{HEB}R_{antenna}}{|R_{HEB} + Z_{antenna}|^2} \quad (2)$$

The calculated η is also given in Fig. 1c. We find that η is nearly 100 % at the frequencies below 3 THz, while above this value it decreases gradually with increasing frequency. Even at the highest frequency of 6 THz, it is still more than 80 %, suggesting that our particular spiral antenna with the tight winding design can work well up to at least 6 THz and even beyond this frequency.

4. MEASUREMENT RESULTS

4.1 R-T curve and pumped I-V curves of the HEB mixer

The resistance of a similar HEB from the same fabrication run has been measured as a function of temperature. The result is shown in the inset of Fig. 2. It is featured by three superconducting transitions. The lowest transition T_{c1} of 6 K is associated with the Au/Nb/NbN contact structures; the middle transition T_{c2} of 8 K is associated with the NbN under Au (thick) antenna layer; and the highest transition T_{c3} of 9.3 K is due to the NbN bridge. The resistance above T_{c3} is about 83Ω , making a good impedance match possible with the spiral antenna. It is important to mention that in our case when the HEB is operated at the optimal biasing point, the contacts are in the superconducting state. More discussions of the superconducting transitions in such structures can be found elsewhere [9].

A typical set of I-V curves of the HEB with different LO power levels at 5.25 THz, recorded at 4 K, is shown in Fig. 2. With increasing LO power level, the superconductivity of the NbN bridge becomes gradually suppressed, showing a transition from the superconducting state to the normal one. The measured curves can be explained by a nonuniform

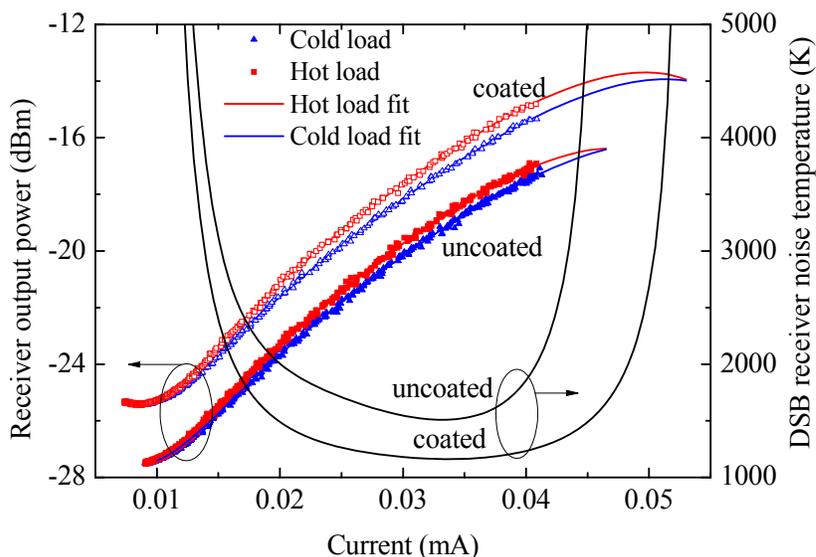


Fig. 3 Measured receiver output powers at the optimum bias voltage of 0.6 mV (dots) and the polynomial fit (lines) responding to the hot and cold load as a function of bias current of the HEB, which is varied by changing the LO power (left axis). One set of data are measured using uncoated lens and another set of data (2 dB positive offset for clarity) are measured using a coated lens. The resulted DSB receiver noise temperature curves are also shown as a function of bias current of the HEB (right axis).

distribution model for a HEB [18]. The optimum operating region, where the lowest T_{rec}^{DSB} can be obtained, is indicated in the I-V plot. This region is centered at a bias voltage of 0.6 mV and a current of 34 μ A. The optimum LO power in the HEB is about 150 nW, obtained by the isothermal technique and making use of the I-V curves at the high bias voltage region [19, 20]. The LO power required for a HEB is known to be proportional to the volume and the T_{c3} of the HEB.

Table I. Summary of the data at 5.25 THz: optical loss of the 3- μ m Mylar beam splitter at 300 K (L_{BS} , calculated), heat filter at 4 K (L_{filter} , measured), 20 cm air (L_{air} , calculated), HDPE window (L_{window} , measured), two Zitex layers (L_{Zitex} , measured), coated and uncoated Si lens at 4 K (L_{lens} , reflection loss calculated; absorption loss is negligible based on our measurements), and DSB receiver noise temperature (T_{rec}^{DSB} , measured). The table shows the data for four different setups: Air setup; Vacuum setup; Vacuum setup, but removed two Zitex layers; Vacuum setup, but removed two Zitex layers and used an anti-reflection coated Si lens.

| | LBS (dB) | L_{heat} (dB) | L_{air} (dB) | L_{window} (dB) | L_{Zitex} (dB) | L_{lens} (dB) | T_{rec} (DSB)(K) |
|------------------------------|----------|-----------------|----------------|-------------------|------------------|-----------------|--------------------|
| Air setup | 0.71 | 0.81 | 0.5 | 1.2 | 2.1 | 1.5 | 3800 |
| Vacuum setup | 0.71 | 0.81 | | | 2.1 | 1.5 | 2600 |
| Vacuum setup Remove Zitex | 0.71 | 0.81 | | | | 1.5 | 1550 |
| Vacuum setup Coated lens | 0.71 | 0.81 | | | | 0.36 | 1150 |

4.2 Receiver noise temperature at 5.25 THz

By applying a different characterization method [7] we can measure directly T_{rec}^{DSB} , without suffering from both the direct detection and the instability of the gas laser. At the bias voltage of 0.6 mV we measure the receiver output power as a function of bias current, which is the result of varying LO power. Two such data sets are recorded, $P_{out,hot}(I)$ responding to the hot load and $P_{out,cold}(I)$ to the cold load. The Y factor can be obtained by $Y(I) = P_{out,hot}(I)/P_{out,cold}(I)$ at the same current using the fitted polynomial curves to the $P_{out,hot}(I)$ and $P_{out,cold}(I)$ data points. The calculated T_{rec}^{DSB} as a function of bias current is plotted in Fig. 3 and shows a broad minimum at a bias current of around 34 μ A and the lowest

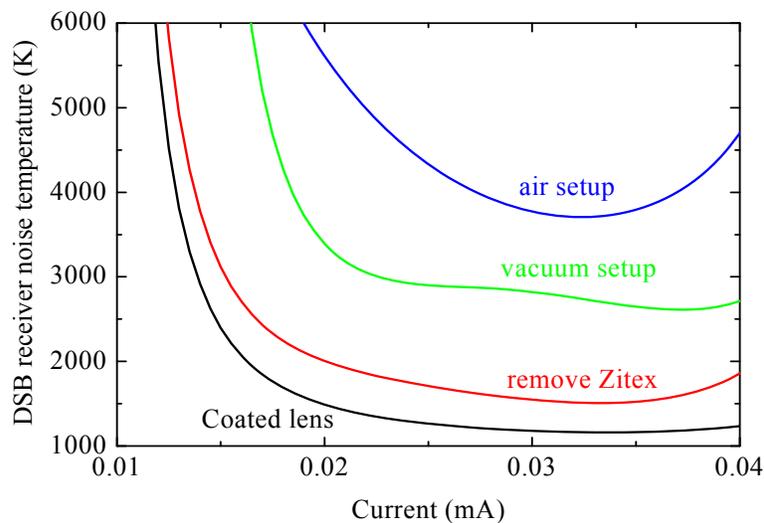


Fig. 4. Measured DSB receiver noise temperature at 5.25 THz, at the optimum bias voltage of 0.6 mV, as a function of bias current of the HEB, which is varied by changing the LO power. Four sets of data were taken in different cases of optical loss, which are defined in table I.

value of 1550 ± 50 K. As discussed in Ref. 7, a clear advantage of this method is that the T_{rec}^{DSB} can be determined precisely and is independent of LO power instability. This is because LO power is used as a variable. Any data point at any LO power is a useful contribution to the $P_{out}-I$ curve. In contrast to the standard manner, where the LO power is required to be fixed, here, it is used as a variable. Another advantage with this method is that the Y -factor and thus the T_{rec}^{DSB} are not influenced by the direct detection effect because $P_{out,hot}$ and $P_{out,cold}$ are taken at exactly the same bias point. We also measured the mixer conversion loss that is found to be about 8.8 dB.

Now we measure T_{rec}^{DSB} of the same HEB, but mounted on the coated Si lens. Again, we measure at the optimum bias voltage of 0.6 mV. The data are added in Fig. 3. For clarity, the receiver output power data as a function of current, responding to hot/cold loads, are offset positively by 2 dB. The lowest T_{rec}^{DSB} obtained is 1150 ± 40 K, which is about 23 % lower than the value (1550 K) measured previously using the uncoated lens. This difference is consistent with what is expected from using the anti-reflection coating. Table I summarizes the optical loss at 5.25 THz.

To make a comparison with the measured T_{rec}^{DSB} at 5.25 THz reported in Ref. 21, we also performed a noise measurement in a standard measurement setup in air, as shown in Fig. 4. In this case, we have the optical loss of 6.8 dB in total, contributed not only by the beam splitter, the heat filter, and uncoated Si lens (as given in Table I), but also by a window, two Zitex heat filters, and air. We measured a T_{rec}^{DSB} of 3800 K at 5.25 THz, which is about a factor of 2 better than the one reported in Ref. 21 where the total optical loss is 5.6 dB.

4.3 Direct detection

Fig. 5 shows the measured receiver output power, together with the DC current of the HEB, as a function of time over a period of 150 seconds, during which the hot and cold loads are manually switched after roughly every 5 seconds. The HEB in this case is mounted on the coated lens. The bias voltage is fixed at 0.8 mV and the LO power set at the optimal value. The periodic jumps of ≤ 0.3 dB in the output power between the hot and cold load should reflect directly how large the Y -factor is. However, the actual value is affected by the direct detection effect [22]. This effect is demonstrated

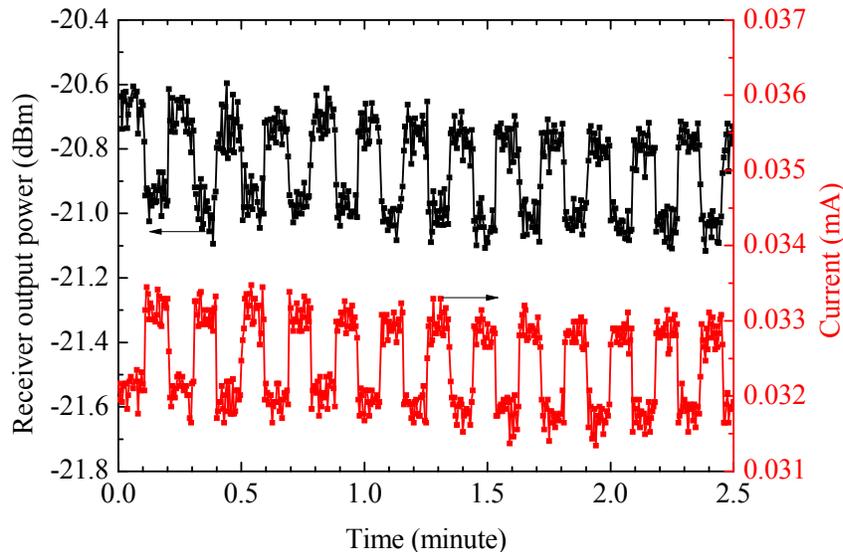


Fig. 4 Measured receiver output power (left axis) and bias current of the HEB (right axis) as functions of time over a period of 150 seconds, during which the hot and cold loads are manually switched after roughly every 5 seconds.

by the observed jumps in the current, which is about 1.2 μA in amplitude. In principle, the direct detection effect can be minimized or eliminated by using a narrow band antenna, such as a twin slot antenna, or reducing the blackbody radiation power, for example, by adding a narrow bandpass filter in front of the mixer [7, 20].

The absolute value of the bias current corresponding to either the hot or cold load varies less than 2 % during the measurement period in Fig. 6, which is low enough to measure the Y-factor under a fixed LO power. However, the variations can cause considerable fluctuations in T_{rec}^{DSB} and discussed in sub-section 4.2.

5. CONCLUSION

We have demonstrated a highly sensitive spiral antenna coupled NbN HEB mixer at 5.25 THz. We measured the lowest T_{rec}^{DSB} of 1150 K at 5.25 THz. Based on this and the newly measured T_{rec}^{DSB} at 4.3 THz (860 K) [23], we expect T_{rec}^{DSB} of 1000 K at 4.7 THz. It is worthwhile to note that this sensitivity at 4.7 THz is about 75 times better than a Schottky diode mixer at the same frequency [6]. Such a mixer together with recently developed THz quantum cascade lasers as LO should allow the construction of new receivers [24,25] for detecting OI line at 4.7 THz for future airborne and spaceborne telescopes. Much progress has been made on THz QCLs with regard to the operating frequency, temperature, output power, and phase locking [26], making them ready for applications.

6. ACKNOWLEDGEMENTS

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