Terahertz coherent transition radiation based on an ultrashort electron bunching beam*

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The experimental result of terahertz (THz) coherent transition radiation generated from an ultrashort electron bunching beam is reported. During this experiment, the window for THz transmission from ultrahigh vacuum to free air is tested. The compact measurement system which can simultaneously test the THz wave power and frequency is built and proofed. With the help of improved Martin–Puplett interferometer and Kramers–Krong transform, the longitudinal bunch length is measured. The results show that the peak power of THz radiation wave is more than 80 kW, and its radiation frequency is from 0.1 THz to 1.5 THz.

Keywords: coherent transition radiation, ultrashort electron bunching beam, Martin–Puplett interferometer, compact measurement system

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1. Introduction

Recently, the THz radiation wave with a frequency of from 0.1 THz to 10 THz has attracted a great deal of attentions because of its varied applications to far-infrared spectroscopy, medical and industrial imaging, biomedical research and materials science.[1−3] Various schemes for generating THz waves have been employed, such as quantum cascade lasers (QCLs),[4] ultrafast laser pulses[5] and vacuum electron devices.[6] Among the varied generations of THz wave, the transition radiation (TR) being one of the THz sources has a unique performance for its broadband.

TR[7,8] is produced by relativistic charged particles when they cross the interface of two media of different dielectric constants. For almost two decades, coherent transition radiation (CTR) in the far-infrared regime has been established as a tool for longitudinal electron beam diagnosis. The first observation of CTR was reported in the early 1990s.[9,10] A particularly interesting application was the reconstruction of a longitudinally asymmetric electron bunch shape by measuring the far-infrared CTR spectrum with a polarizing Michelson spectrometer and determining the phase of the bunch form factor with the help of the Kramers–Krong (KK) dispersion relation. The use of far-infrared CTR for longitudinal bunch shape analysis was investigated in Refs. [11] and [12]. To analyse the characteristics of TR, some theories[13−15] have been developed, such as wakefield theory, vector electromagnetic theory and image methods. Moreover, some methods have been used to generate the THz TR. Nikoghosyanac *et al.*[16] observed the transition radiation generated by short optical pulses crossing the boundary between linear and non-linear materials. Leemans *et al.*[17] and Plateau *et al.*[18] have applied the laser to driving the plasma for the generation of THz CTR. Hemsing and Rosenzweig[19] presented a novel method of generating the CTR with a helical microbunched beam. Recently, it was reported that the ultrabroadband THz source based on CTR[20] was obtained, the radiation frequency is from 5 THz to 100 THz and its radiation energy is in the order of 10 μJ. In the present paper, observation of THz CTR generated from an ultrashort electron bunching beam is reported and the

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power and frequency of THz radiation wave are measured. Moreover, the root mean square (RMS) bunch length is measured by the hand-made Martin–Puplett interferometer (MPI) with KK dispersion relation.

This paper is organized as follows: The key elements are studied in Section 2, the experiment setup is described in Section 3, the experiment results and some outlooks are given in Section 4.

2. Key components in the experiment

2.1. THz transmission window

For obtaining a THz high transmission, the choices of window material characteristics are key components. Commonly, the conventional window materials for THz applications are low-density polyethylene (LDPE), z-cut single crystal quartz (SCQ) and sapphire, but by far the best choice is grown by chemical vapor deposition (CVD) diamond. Among these materials, the diamond is the most expensive one. Considering the costs and conveniences, we think the z-cut SCQ is prior to be used.

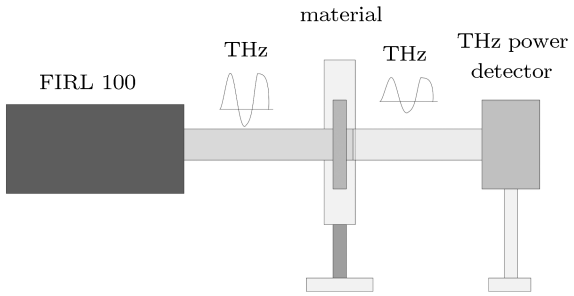


Fig. 1. Transmission material setup.

In the present test experiment, two kinds of material including SCQ and sapphire are tested and the test system is shown in Fig. 1. The THz wave is produced by a far infrared laser of model 100 (FIRL100) and detected by a THz wave power detector. In this test system, the FIRL100 can generate a THz wave with frequency of from 0.245 THz to 7.5 THz and with maximum output power of 150 mW. During the present experiment, the operation frequency of 2.52 THz is used. The SCQs with thicknesses of 1.5 mm and 2.5 mm are tested. Similarly, the sapphire plates with thicknesses of 1 mm and 2 mm are tested. Because the path of THz wave is very short, the attenuation can be neglected. The penetration ratio of test material is given as follows:

$$P(\%) = \frac{P_1}{P_2} \times 100\%, \tag{1}$$

where P_1 and P_2 are the test powers of the THz detector when the material is and is not placed in the path, respectively. The results are listed in Table 1, in which Z_i and S_i $(i = 1, 2)$ represent the different z-cut SCQ and sapphire plate, respectively.

Table 1. Test of THz wave transmission penetration at 2.52 THz.

Material	Thickness/mm	P_1/mW	P_2/mW
Z_1	1.5	90	119
Z_2	2.5	85	118
S_1	1	28	123
S_2	2	21	126

2.2. THz compact measurement system

As is well known, the tests of THz wave power and frequency are of key importance to know the performances of THz source. In this experiment, the THz wave power is detected by a detector of Golay cell made by QMC Limited Inc. and the THz wave frequency is tested with the help of hand-made MPI. However, it is a very interesting test if the power and frequency of THz wave can be simultaneously detected.

To achieve this aim, a compact system for measuring THz wave power and frequency is presented and built, which is based on the THz wave passing path and polarization. The scheme is configured in Fig. 2(a) and the compact system is constructed as shown in Fig. 2(b).When THz wave enters the measurement system, the converged THz wave is translated into a parallel line by off-axis parabolic mirror (OAP) named OAP 1# and its effective focus length (EFL) is 190.5 mm. Then the THz wave is reflected to polarizer by a plane mirror coated with gold. Through the polarizer with diameter of 15 μm and spacing of 60 μm, one half of THz wave is reflected to detector 1# as power signal collected by the OAP2# and plate mirror (7) and the other transmission part is measured for THz frequency by an improved MPI reported in Ref. [21], which is obtained by detector 2#. The wave formations simultaneously obtained by the compact system are displayed in Fig. 3, signal (1) is for power obtained by detector 1# and signal (2) is for frequency obtained by detector 2#.

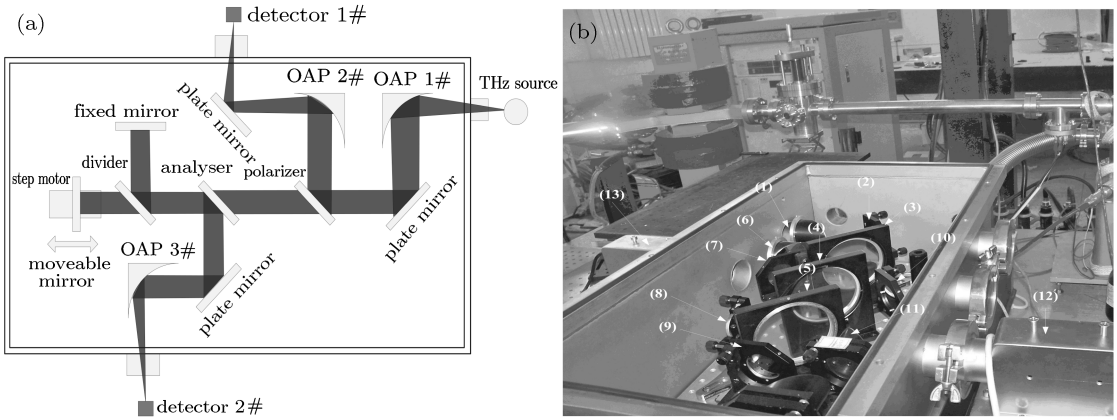


Fig. 2. THz measurement setup. (a) Schematic diagram, (b) experimental setup: (1) OAP 1# with EFL being 190.5 mm, (2) plane mirror, (3) polarizer, (4) analyser, (5) beam splitter divider, (6) OAP 2#, with EFL being 190.5 mm, (7) plane mirror, (8) fixed plane mirror, (9) moveable mirror, (10) plane mirror, (11) OAP 3# with EFL being 152.4 mm, (12) detector 2#, (13) detector 1#.

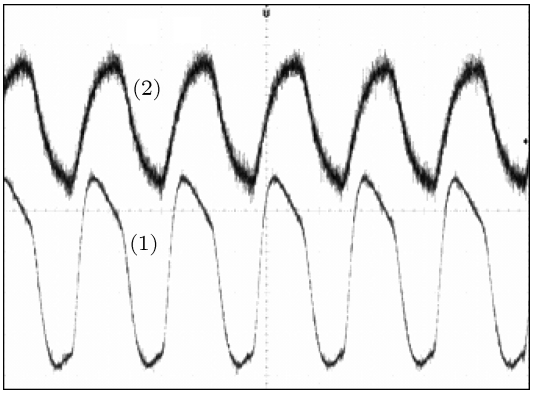


Fig. 3. Test signal.

Through the compact system, the measured THz wave frequency is 2.43 THz, which is less than 5%, compared with the theoretical value. The detected power obtained by detector 1# is consistent with the power at entrance of compact system considering the constructer and attenuation. The results show that the compact system can simultaneously detect the power and frequency.

2.3. Selection of target

As the THz radiation intensity is remarkably affected by the size of target and material characteristic, the selection of target is very important, which is studied before this experiment. First, we use the titanium foil as the target material, as shown in Fig. 4(a), because it is hardly oxidised. However, it has some drapes when assembled to a thickness of only 50 μm. On the other hand, the radius of titanium foil is 10 mm, which will affect the collection of THz wave radiation. Based on this analysis, this scheme is abolished. As the second scheme, an aluminum foil with a thickness of 1.0 mm is used. Considering the radiation direction, the radius of 15 mm is employed, as shown in Fig. 4(b).

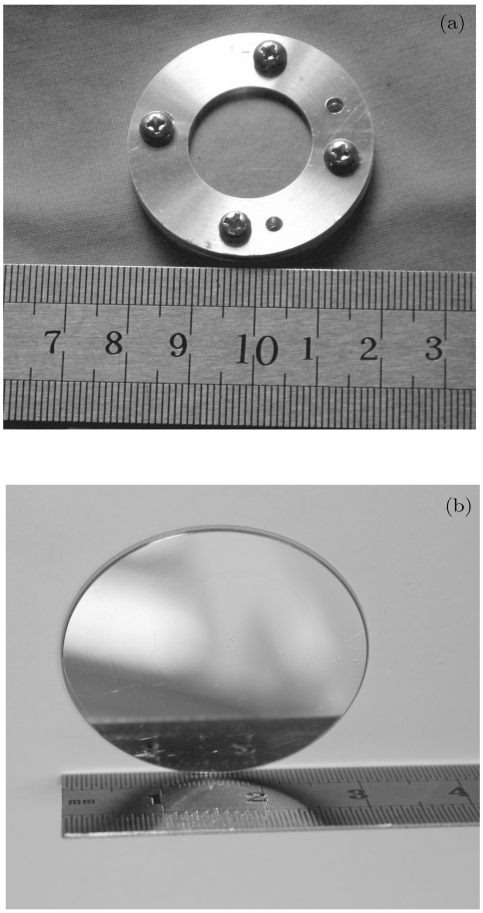


Fig. 4. Interaction target: (a) titanium, (b) aluminum.

3. Descriptions of THz experimental setup

A THz CTR experiment system was built at the Tsinghua Thomson scattering X-ray source facility and its schematic diagram is shown in Fig. 5. An S-band 1.6 cell photocathode RF gun served as the electron bunching beam source. A UV laser pulse illuminates the centre of the photocathode with a nearly normal incidence. The photoelectric-emitted electron pulse is rapidly accelerated to relativistic energy with a few mega-electronvolts (MeV) by the high amplitude electric field in the RF gun and its intensity is about 65 MeV/m. After the gun, a solenoid is used to control the electron spot size. The charge escaping from the photocathode is measured with an integrate current transform (ICT), the scale of charge in present UV laser energy is from 0.1 nC to 0.5 nC and the peak current can be obtained through the bunch length.

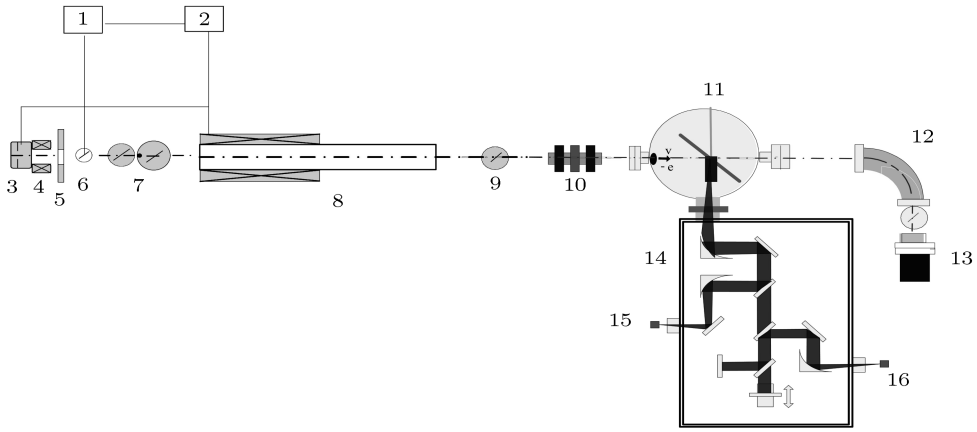


Fig. 5. Experimental system for THz CTR: 1 UV laser system, 2 RF system, 3 photocathode RF gun, 4 coil, 5 ICT, 6 chamber for incidence laser, 7 beam test chamber, 8 3-m traveling accelerating tube, 9 beam test chamber, 10 Q-magnet, 11 chamber for interaction beam-target, 12 dipole magnet, 13 dump, 14 THz compact system, 15 detector for THz power, 16 detector for THz frequency.

Table 2. Parameters of experiment.

Parameters	Value
Bunching beam length/ps	0.17–0.43
Accelerated energy/MeV	~ 15
Bunches beam charge/nC	0.2–0.5
Radius of target/mm	15
Thickness of target/mm	1.0
Material of target	aluminum
RF frequency/MHz	2856
RF repetition frequency/Hz	10

The RF photocathode and 3-m travel accelerating tube (TAT) are driven by a common 2856 MHz klystron with a repetition frequency of 10 Hz and there is a phase shifter which allows independent adjustments of the RF phase and the amplitude of each structure. During the running of bunching beam, the YAG screen is used to observe its positions as compared to the centre of beamline. The Q-magnet is used to measure bunching beam emittance exiting from the accelerating section. The bunching beam energy after the accelerating section can be obtained with the help of dipole. The radiation power and frequency of THz wave generated from the bunching beam with the interaction of foil is simultaneously measured by a compact system, in which the THz power is detected by Golay cell and its frequency is obtained by an improved MPI. The main parameters in the present experiment are listed in Table 2.

4. Experimental results

As mentioned above, the THz wave frequency is obtained by using the fast Fourier transform (FFT) of autocorrelation curve, which is produced by the compact measurement system. In the present experiment, each running distance of the step motor is 0.01 mm. The signal is detected by Golay cell of a model of OAD-7 manufactured by QMC instrument limited.

The typical THz signal generated by the CTR is detected as shown in Fig. 6 and the signal rising up time is about 20 ms, the amplitude is about 140 mV and its repetition frequency is 10 Hz, which is consis-

tent with the klystron RF repetition frequency. By running the step motor, we can obtain an autocorrelation curve as shown in Fig. 7. From this curve, one can see that the signal amplitude is close to zero when the optic path difference equals zero and that MPI is well interferential. Through the FFT of autocorrelation curve, the THz wave radiation spectrum is shown in Fig. 8. Obviously, its frequency varies from 0.1 THz to 1.5 THz and the centre frequency is about 0.8 THz. The obtained frequency spectrum does not strictly obey the single bunching beam radiation frequency, due to the effects of bunching beam size and the finite foil size in the vacuum chamber.

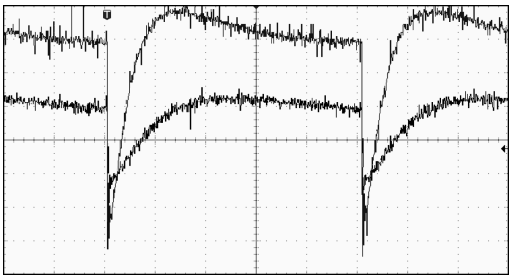


Fig. 6. Typical THz signal.

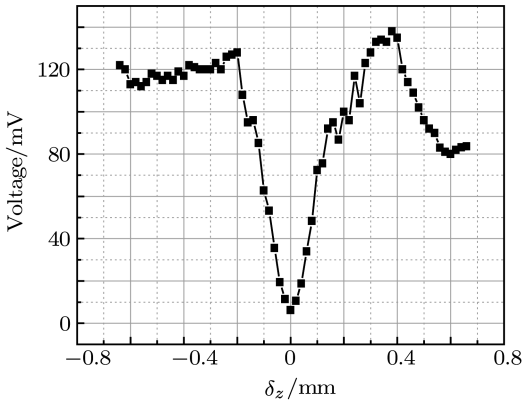


Fig. 7. Autocorrelation curve. δ_z is the optical difference path.

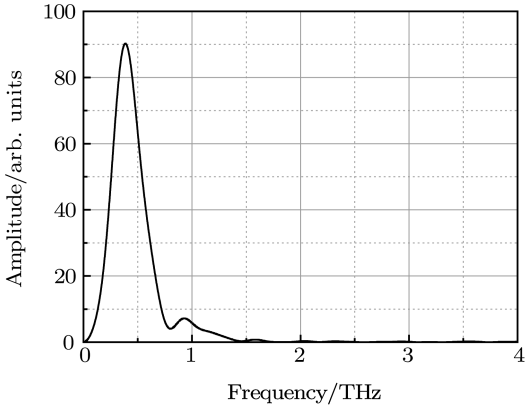


Fig. 8. FFT of autocorrelation curve.

Based on the autocorrelation curve and radiation spectrum, combining with the KK dispersion relationship, the bunch length is evaluated to be about 0.35 ps (RMS), as shown in Fig. 9. Through the bunch length, we can estimate the THz wave pulse length L_1 to be about 1.4 ps, the radiation energy $E_{\rm T}$ to be about 0.024 μJ, which is obtained by integration of power signal. Based on the z-cut SCQ with attenuation (A) of 20% and that the signal amplitude detected by detector 1# is only a quarter (1/4) of the signal that enters, the peak power of THz wave is

$$\hat{P} = \frac{E_{\rm T}}{(1-A)\times L_1 \times (1/4)}. \tag{2}$$

From Eq. (2), we obtain that the THz wave peak power is about 86 kW.

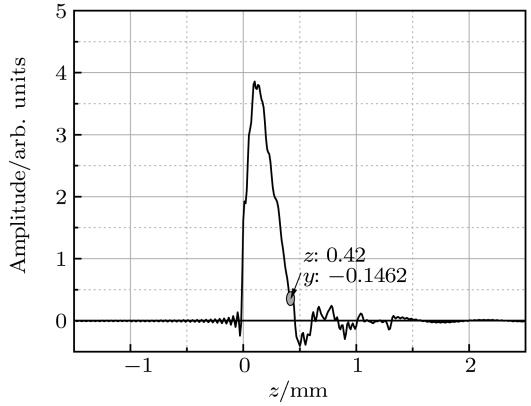


Fig. 9. Bunch profile.

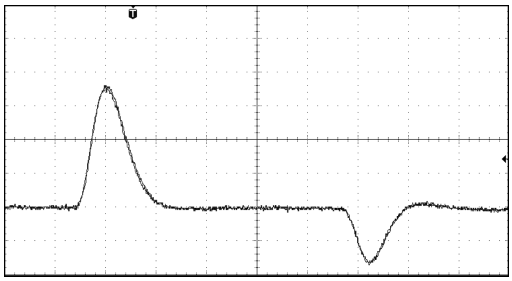


Fig. 10. Emitted charge.

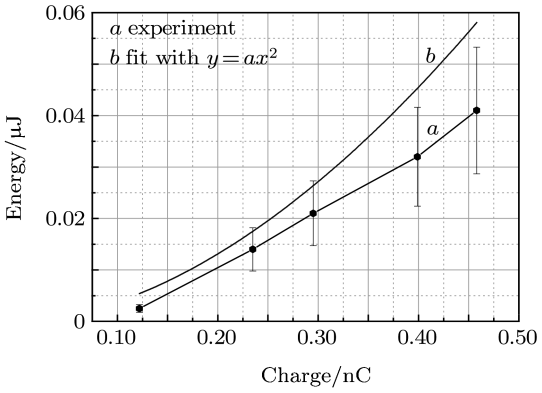


Fig. 11. Radiation energy versus charge.

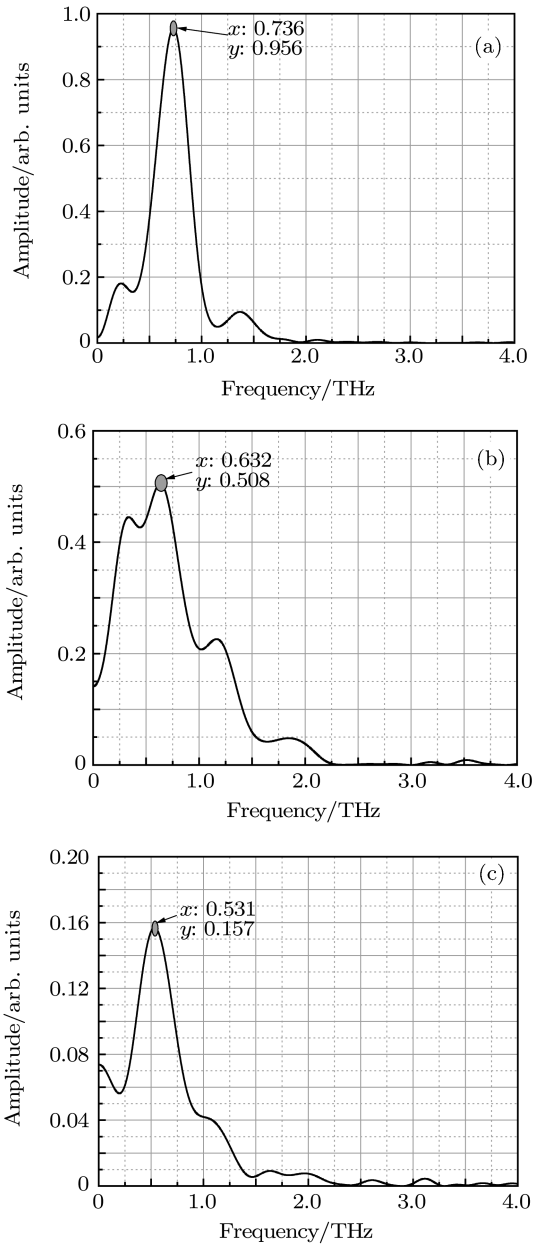


Fig. 12. FFT of autocorrelation curves: (a) 0.25 ps, (b) 0.3 ps and (c) 0.37 ps.

We change the laser energy and the emitted charge, which is detected by an ICT displayed in Fig. 10. The variation of energy with charge is displayed in Fig. 11. We can see that the radiated energy is proportional to the square of charge. Moreover, the influence of longitudinal length of bunching beam on THz wave frequency is found in this experiment and the result is shown in Fig. 12. This figure shows that the THz wave frequency will be reduced due to the increase of longitudinal length of bunching beam. From this demonstration, one can gain a higher THz wave power and frequency with increasing charge and decreasing longitudinal length of bunching beam, respectively.

5. Conclusions

In this paper, the THz CTR generated from the ultrashort electron bunching beam is demonstrated. To obtain a higher transmission of the THz wave, the materials of the window are tested. To simultaneously test the power and the frequency, a compact measuring system is presented and built and it is adjusted in the FIRL100. With the help of a compact test system, the THz wave power and frequency are obtained. The experimental results show that the THz wave frequency covers from 0.1 THz to 1.5 THz and its peak power is more than 80 kW. Moreover, the effect of the charges of the bunching beam on the THz frequency and radiation energy is studied.

The present experiment results are the preliminary performances, in future study we will aim to obtain a higher peak power and improve the THz wave spectrum, such as the train bunching, the compressor of bunching beam and the laser energy. Moreover, the measuring system is necessary to be optimized.

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