Generating 0.42 THz radiation from a second harmonic gyrotron

FU WenJie *, YAN Yang, LI XiaoYun, YUAN XueSong & LIU ShengGang

Terahertz Research Center, School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China

Received March 20, 2011 ; accepted August 4, 2011

Gyrotrons are high powered coherent electromagnetic radiation sources, and are considered to be available powerful sources that have the potential to bridge the so-called terahertz gap. In the University of Electronic Science and Technology of China, a second harmonic gyrotron has been designed, manufactured, and tested. The gyrotron generated radiation at a 0.423 THz frequency in 5 μs pulses with an 8.1 Tesla magnetic field, with a power per pulse of about 4.4 kW. To date this is the highest frequency recorded for vacuum electronic devices in China. The gyrotron design, operation and measurements are presented.

terahertz, gyrotron, second harmonic

Terahertz (THz) waves, electromagnetic radiation between far infrared and millimeter wavelengths, have very important academic and application values. The characteristics of THz waves are used in a large and increasing number of applications. These applications include fundamental scientific research (physics, chemistry, etc.), many interdisciplinary fields (biophysics, etc.), radar, communication, material processing, and medical diagnostics and therapy. However, because there is a lack of reliable sources and detectors of terahertz radiation, most applications are still experimental. Consequently, current investigations on terahertz waves are concentrated on sources (electronics sources and optical sources), detectors, transmission, and applications [1,2].

In China, terahertz waves have become an active research area over the last 10 years [3,4]. Important achievements have been made, such as the THz vacuum electronic devices developed in the University of Electronic Science and Technology of China [5,6], the THz quantum cascade lasers (QCL) developed in the Shanghai Institute of Microsystem and Information Technology [7,8], the THz superconducting detector in the Nanjing University [9,10], the THz optical sources research carried out in Tianjin University [11] and Nankai University [12], the THz time-domain spectroscopy methodology and related application researches carried out in the Capital Normal University [13,14], the THz-material interaction carried out in the Shanghai Jiao Tong University and Institute of Physics, Chinese Academy of Sciences [15], and so on [16–18].

In this paper, we report on initial experiments on a second harmonic gyrotron developed at the University of Electronic Science and Technology of China (UESTC), which generated radiation at a frequency of 0.423 THz in 5 μs pulses, with a power per pulse of about 4.4 kW. To date this is the highest frequency recorded for vacuum electronic devices in China.

Gyrotrons are fast-wave vacuum electronic devices, based on the interaction of electronics gyrating in external magnetic fields with fast waves. There is no need for the slow-wave circuits used extensively in traditional vacuum electronic devices. Gyrotrons can have physical dimensions much larger than the operating wavelength, so they have higher output power and higher efficiency than traditional vacuum electronics devices [19]. Therefore, they are considered to be available powerful sources that have the potential to bridge the so-called terahertz gap. Only four institutes have developed gyrotron generated frequencies above 0.3 THz at output powers over 1 kW: the University of Sydney in Australia [20], Fukui University in Japan [21],...
One limiting factor in the development of high frequency gyrotrons is magnetic field technology. The gyrotron radiation frequency $f_0$ is related to the cyclotron frequency $f_c$ and the magnetic field $B$ according to [24]:

$$f_0 \approx sf_c = s \frac{eB}{2\pi m_e \gamma},$$

where $e$ is the charge of an electron, $m_e$ is the mass of an electron, $\gamma$ is the relativistic mass factor, and $s$ is the harmonic number. According to eq. (1), when operating the gyrotron at fundamental frequency, to generate 0.3 THz radiation, an 11 Tesla magnet is required. Hence with increasing operating frequency, the cost of the magnet will be too expensive. Operating at harmonics can reduce the necessary magnetic field $s$ times. However, mode competition is more severe for harmonic frequency interaction than for fundamental frequency interaction. Consequently, an appropriate design is important for a harmonic gyrotron.

Based on a previous 0.22 THz oscillator built at UESTC [5,6], a 0.42 THz second harmonic gyrotron has been designed, constructed and tested using an 8 Tesla superconducting magnet. The schematic is shown in Figure 1. Its components include a conventional taped cylindrical cavity (2.2 mm radius and 10 mm length) and a triode-type magnetron injection gun. The axis of the gyrotron lies along the vertical bore of an 8 Tesla superconducting magnet. A TE$_{26}$ mode has been selected as the operation mode. There are two competing second harmonic modes, the TE$_{06}$, and TE$_{74}$, and one competing fundamental mode, the TE$_{23}$. The interaction cavity was optimized for the TE$_{26}$ mode using a cold cavity simulation code, and the corresponding resonance frequency is 0.423 THz. Figure 2 shows the starting currents for the respective modes as a function of beam voltage, when $B_0=8.1$ Tesla.

The measurement system is shown in Figure 3. The frequency of the second harmonic output was measured by a 14th harmonic mixer with a corresponding frequency range of 0.4–0.5 THz. The mixer was also used as an RF detector to measure the pulse width of the second harmonic output. The $f_{\text{osc}}$ was generated by an Agilent 8257D PSG Analog Signal Generator, and the $f_{\text{if}}$ was detected by a Tektronix TDS 6604 Oscilloscope.

The initial experiments were performed using voltage pulses with durations of approximately 5 $\mu$s for the main magnetic field of 8.1 Tesla. For the experiment, Figure 4 shows an example of typical oscilloscope traces of the electron beam voltage, collector current and intermediate frequency (IF) signal from the mixer. The beam voltage and collector current were measured through a resistor voltage divider and Rogowsky coils, respectively. The noise and distortions on the pulse shape are due to power supply ripple.

Within the positive and negative edges of the pulse, no second harmonic IF signal was detected. Within the middle section of the pulse, the second harmonic IF signal was detected. Within the first 2 $\mu$s, the power supply ripple and noise and distortions of the beam current relative to the pulse shape were larger than within the last 3 $\mu$s, where the IF signals were smaller and less stable. By varying the $f_{\text{osc}}$ frequency, the output frequency was confirmed to be 0.423 THz, which agrees with the design. The experimental results also show the second harmonic operation is strongly dependent on the beam voltage.
The power is measured by a modified calorimeter which is described in [5]. Because there was no calibrated 0.42 THz source available, the sensitivity of the calorimeter at 0.22 THz was used to scale the output power. For a single pulse, the scaled output power was about 4.4 kW for the initial experiment.

In the University of Electronic Science and Technology of China, a second harmonic gyrotron was designed, manufactured, and tested. Using an 8.1 Tesla magnetic field, the gyrotron generated radiation at a 0.423 THz frequency in 5 μs pulses, with a power per pulse of about 4.4 kW. To date this is the highest frequency recorded for vacuum electronic devices in China. Furthermore, higher frequency gyrotrons are in the planning stage.

This work was supported by the National Natural Science Foundation of China (60877058) and the National Basic Research Program of China (2007BCC310401).

1. Siegel P H. IEEE Trans Microwave Theory Tech, 2002, 50: 910–920
2. Mueller E R. Indu Phys, 2003, 27–29
3. Liu S G. Chinese Bais Sci, 2006, 8: 7–13
4. Liao F J. Acta Electron Sin, 2003, 31: 1361–1364
5. Yan Y, Liu S G, Li X Y, et al. Chinese Sci Bull, 2009, 54: 1495–1499
6. Fu W J, Yan Y, Li X Y, et al. Inter J Infr Mill Tera Wave, 2010, 31: 404–410
7. Chang J, Li H, Han Y J, et al. Acta Phys Sin, 2009, 58: 7083–7087
8. Tan Z Y, Guo X G, Cao J C, et al. Acta Phys Sin, 2010, 59: 2391–2395
9. Xu W W, Chen J, Kang L, et al. Sci China Technol Sci, 2010, 53: 1247–1251
10. Lu X H, He N, Kang L, et al. Chinese Sci Bull, 2009, 54: 3344–3346
11. Liu H, Xu D G, Yao J Q. Acta Phys Sin, 2008, 57: 5662–5669
12. Chen Y P, Morneau C, Liu W W, et al. Appl Phys Lett, 2008, 93: 231116
13. Zhou Q L, Shi Y L, Li T, et al. Sci China Ser G: Phys Mech Astron, 2009, 52: 1944–1948
14. Tian L, Zhou Q L, Jin B, et al. Sci China Ser G: Phys Mech Astron, 2009, 52: 1938–1943
15. Wang W M, Sheng Z M, Wu H C, et al. Chinese Phys C, 2009, 33: 142–145
16. Ge M, Zhao H W, Ji T, et al. Sci China Ser B: Chem, 2006, 49: 204–208
17. Ge M, Zhao H W, Wang W F, et al. Sci China Ser B: Chem, 2008, 51: 354–358
18. Qu Y G, Chen H, Qin X C, et al. Sci China Ser C: Life Sci, 2007, 50: 350–355
19. Chu K R. Rev Modern Phy, 2004, 76: 489–540
20. Hong K D, Brand G F, Idehara T. J Appl Phys, 1993, 74: 5250–5258
21. Idehara T, Tsachiya H, Watanabe O. Int J Infrared Millim Wave, 2006, 27: 319–331
22. Glyavin M Y, Luchinin A G, Goloubatinov G Y. Phy Rev Lett, 2008, 100: 015101
23. Hornstein M K, Bajaj V S, Griffin R G, et al. IEEE Trans Electron Devices, 2005, 52: 798–807
24. Liu S G. Relativistic Electronics (in Chinese). Beijing: Science Press, 1986

**Open Access** This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.