Generating 0.42 THz radiation from a second harmonic gyrotron

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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 μ s 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

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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 μ s 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],

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the Institute of Applied Physics (IAP) of the Russian Academy of Sciences (RAS) in Russia [22], and the Massachusetts Institute of Technology in the United States [23].

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]:

$$f_0 \approx s f_c = s \frac{eB}{2\pi m_e \gamma}, \quad (1)$$

where e is the charge of an electron, m_e is the mass of an electron, γ 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. In Figure 2, the straight line is the current voltage characteristic of the electron gun. In an attempt to overcome mode competition, the operating point has been set at 40 kV.

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

Figure 1 Cross-sectional schematic of the cylindrically symmetric second harmonic gyrotron.

Figure 2 Starting currents, as a function of beam voltage, for a uniform 2.2 mm radius, 10 mm long cylinder waveguide, when $B_0=8.1$ Tesla.

Figure 3 Block diagram of the measurement section of the experimental setup.

detector to measure the pulse width of the second harmonic output. The f_{osc} was generated by an Agilent 8257D PSG Analog Signal Generator, and the f_{if} was detected by a Tektronix TDS 6604 Oscilloscope.

The initial experiments were performed using voltage pulses with durations of approximately 5 μ 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 μ 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 μ s, where the IF signals were smaller and less stable. By varying the f_{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.

Figure 4 Oscilloscope beam voltage (a), collector current (b) and IF signal (c) of the second harmonic operation for the main magnetic field of 8.1 Tesla.

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 μ s 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.

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- 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 Inf 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, Marceau 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, Tsuchiya H, Watanabe O. Int J Infrared Millim Wave, 2006, 27: 319–331
- 22 Glyavin M Y, Luchinin A G, Golubiatnikov 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

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