

High energy optically pumped NH_3 terahertz laser with simple cavity

Liang Miao (苗亮), Duluo Zuo (左都罗), Zhixian Jiu (纠智先), Zuhai Cheng (程祖海)*, Chunchao Qi (祁春超), and Junzhu Wu (吴君竹)

Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

*E-mail: chengzuhai@mail.hust.edu.cn

Received August 25, 2009

A high energy pulsed terahertz (THz) laser is studied experimentally. The laser cavity simply consists of a quartz glass waveguide, a coated GaAs input window, and a crystal quartz output window. NH_3 is filled in the cavity as gain medium, and pumped by an 8-J line-tunable transversely excited atmospheric (TEA) CO_2 laser. When 9R(16) transition acts as the pump line, 55.6-mJ THz radiation ($90\ \mu\text{m}$) is obtained at 730-Pa NH_3 pressure. The corresponding conversion efficiency is 13.54%. Energy and optimal pressure of amplified spontaneous emission and laser oscillation are compared.

OCIS codes: 140.3070, 140.4130, 140.6630.

doi: 10.3788/COL20100804.0411.

Terahertz (THz) radiation ($30\ \mu\text{m}$ – $3\ \text{mm}$) has great applications in many fields, such as imaging^[1], safety inspection, and spectroscopy. However, THz radiation sources have not been well developed because of their low efficiency. Among all the ways of producing THz radiation, optically pumped THz lasers are known to be very efficient and practical. Since the first optically pumped THz laser was invented by Chang *et al.* in 1970^[2], NH_3 has been proven to be a source of many strong THz laser transitions^[3]. When NH_3 is pumped by 9R(16) transition of a transversely excited atmospheric (TEA) CO_2 laser, very intense THz radiation at $90\ \mu\text{m}$ is emitted. Many kinds of THz laser cavity have been used to produce THz radiation^[3–7]. Mirrorless THz laser cavities with NaCl or teflon windows are inefficient^[3,5]. And cavities with metal meshes mirrors are difficult in manufacturing and collimating in spite of their high efficiency^[4,7]. In this letter, a simple efficient NH_3 THz laser cavity is designed, from which 55.6-mJ THz radiation is extracted under 8-J pump energy.

The experimental setup is shown schematically in Fig. 1. The NH_3 THz laser was pumped by a TEA CO_2 laser operating on 9R(16) transition ($9.29\ \mu\text{m}$). The TEA CO_2 laser was home-made with about 8-J output energy on the pump transition. Line tuning of the pump laser was realized by replacing the rear reflector by a 150-groove/mm Littrow-mounted blazed grating. Pulse width was shortened to about 300 ns (full width at 10% maximum) by adjusting the pressure ratio of the working gas to $\text{CO}_2:\text{N}_2:\text{He} = 3:1:6$ to suppress the N_2 tail. The final pump intensity was 2.8–3.6 MW/cm^2 . Temporal structure of the pump pulse is shown in Fig. 2. The pump laser was focused into the THz laser cavity by two gold-coated silicon reflectors and a GaAs lens with 2-m focal length. The lens was set 1 m away from the input window. Its focal length was long enough so that the spot diameter of the pump laser did not change too much in the cavity.

The THz laser cavity was composed of a 2-m-long,

50-mm-inner-diameter quartz glass waveguide, a 6-mm-thick antireflection-coated GaAs, and a 4-mm-thick optically polished Z-cut crystal quartz (SiO_2). GaAs was the input coupling window of the pump laser, and SiO_2 was the output coupler of THz radiation. SiO_2 was opaque to CO_2 laser and transparent to THz radiation^[8,9], which insured the detector only receiving the latter.

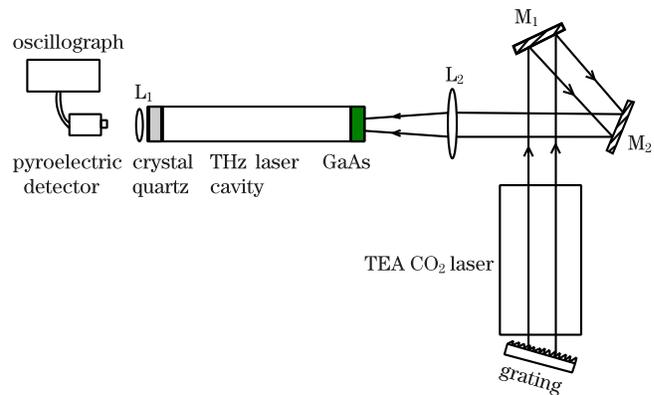


Fig. 1. Optically pumped NH_3 THz Laser. M_1 , M_2 : gold-coated silicon mirrors; L_1 : GaAs lens (2-m focal length); L_2 : tsurupica lens (18-cm focal length).

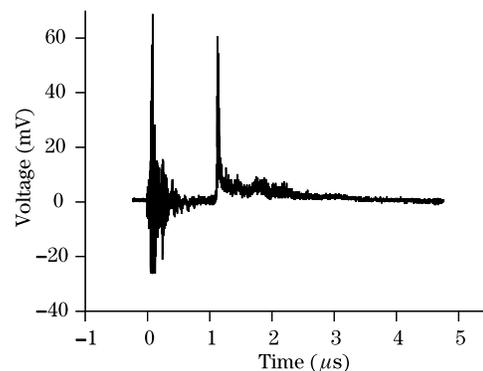


Fig. 2. Temporal structure of pump pulses.

Close to the SiO₂ window was an optically polished tsurupica lens of 180-mm focal length (Microtech Instruments, USA). It was highly transparent to THz radiation and opaque to CO₂ laser. For detection of focused THz radiation, two different pyroelectric detectors were used. One (SPJ-A-8-OB, Spectrum Detector, USA) was of high response to measure THz pulse energy. It bore 0.6 V/mJ responsivity, a 7.8-mm-diameter aperture, and a 500- μ s time constant. The other (P3-01, Molelectron Detector, USA) was of high speed to measure temporal structure of THz pulses. At last, THz pulse energy and waveform signals were shown on an oscillograph (DSO7034A, Agilent Technology, USA) with a 350-MHz bandwidth.

Experiments have been carried out in two ways: amplified spontaneous emission (ASE) and laser oscillation. In the way of ASE, the THz laser windows are inclined with the cavity axis. When the pump laser enters the cavity from the GaAs window, THz radiation is amplified along the cavity axis from weak spontaneous emission. At the SiO₂ window, the THz radiation is strong enough to be extracted from the cavity under high pump power, suitable cavity length and gas pressure. When 9R(16) transition is used as the pump line, the most intense THz radiation of ASE is 16.9 mJ at 1130 Pa. The result is quite consistent with Gross' work^[3].

In order to analyze the characteristics of THz laser oscillation, properties of GaAs and SiO₂ must be discussed first. In case of normal incidence at material surface, single-side reflectivity R_0 is given by

$$R_0 = \left(\frac{n-1}{n+1} \right)^2, \quad (1)$$

where n is the refractive index of the material. Two-side reflectivity R ignoring absorption increases to^[10]

$$R = 2R_0 - R_0^2. \quad (2)$$

The refractive index of SiO₂ is 2.1 in THz range^[8,9], and that of GaAs is near 3.6^[10,11]. As mentioned above, SiO₂ is transparent to THz radiation, so optically polished SiO₂ bears 23.6% reflectivity (two-side). Though GaAs is semitransparent to THz radiation in short wavelengths^[10,11], its reflectivity is still more than 32% (single-side). In conclusion, both windows show relatively high reflection and low absorption for THz radiation. When both windows are adjusted to be perpendicular to the cavity axis, they form a resonant cavity together with the quartz glass waveguide. Under this condition, THz laser oscillates in the resonant cavity, and THz pulse energy increases by a factor of 3.3 compared with the ASE. Temporal structure and energy record of the THz laser are shown in Figs. 3 and 4.

The responsivity of the energy measuring detector is 600 V/J with energy range from 3 μ J to 30 mJ. When NH₃ is near the optimal pressure, THz-laser energy is above 30 mJ. So the result in Fig. 3 is taken with a 2-mm-thick SiO₂ for attenuation in front of the detector. Since transmissivity of the 2-mm-thick SiO₂ for 90- μ m radiation is measured to be 48%, the maximum THz energy shown in Fig. 3 denotes 55.6 mJ, and the optimal NH₃ pressure is 730 Pa. Energy conversion efficiency in

quantum limit^[4] is given by

$$E = \frac{1}{2} \frac{\lambda_P}{\lambda_T}, \quad (3)$$

where λ_P is the pump wavelength and λ_T is the THz laser wavelength. In the experiment, the quantum efficiency is 5.17%. For the 8-J pump energy of 9R(16) transition, the maximum THz energy is 55.6 mJ. So the corresponding photon conversion efficiency is 13.54%.

For given pump energy and THz cavity length, there is an optimal pressure for the highest THz output. For this study, relations between THz energy and NH₃ pressure are given in Fig. 5. The relation between ASE energy and NH₃ pressure is measured without being focused by the tsurupica lens, so the maximum energy in this curve is lower than the real value. The optimal pressures of THz ASE and THz laser are about 1100 and 700 Pa, respectively.

Reflectance of the polished SiO₂ is near 80% at 9R(16) transition (9.29 μ m)^[12]. When THz cavity is operating in the ASE way, the SiO₂ and GaAs windows are both inclined with the cavity axis, so that the pump laser and THz radiation reflected by the two windows are mostly wasted. As a result, THz ASE is much weaker than THz laser. Meanwhile, there must be enough NH₃ to absorb the pump energy in a 2-m-long distance. However, the effective absorption distance of pump is almost doubled in the laser oscillation way, so the optimal NH₃ pressure is lower than that in the ASE way. The optimal pressure cannot be too low, because high pump power will result in pump saturation.

In conclusion, An optically pumped NH₃-THz laser with simple cavity is studied. A 2-m-long quartz glass

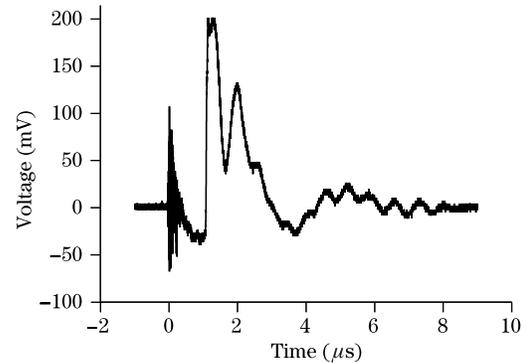


Fig. 3. Temporal structure of THz pulses.

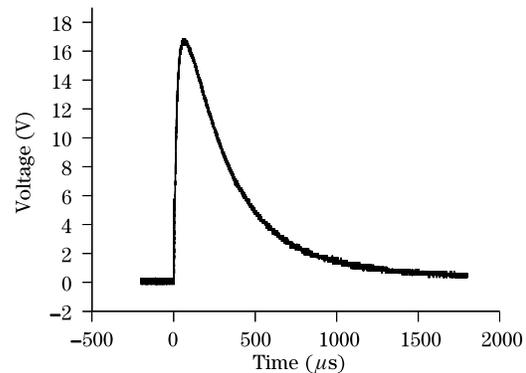


Fig. 4. Maximum THz laser energy.

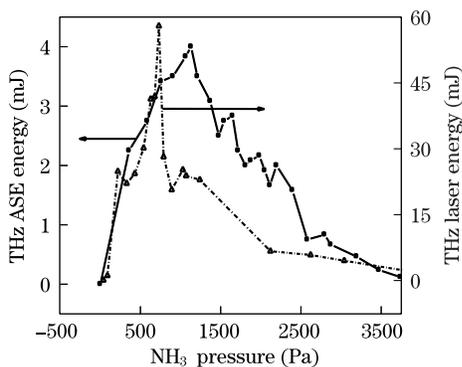


Fig. 5. THz energy versus NH_3 pressure.

tube forms a waveguide. Two common crystals, GaAs and SiO_2 , act as the pump input and THz output couplers, respectively. Experimental results indicate the configuration is efficient, and 55.6-mJ THz radiation at 90 μm is obtained using a 8-J line-tunable TEA CO_2 pump laser. The photon efficiency is 13.54%. THz laser oscillation is over two times more efficient than THz ASE and its optimal pressure is lower than the latter, too. Further work is in progress to improve the conversion efficiency, including narrowing the linewidth of the pump laser and optimizing the cavity structure.

This work was supported by the Creative Foundation of Wuhan National Laboratory for Optoelectronics under

Grant No. Z080007.

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