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Study on the performance improvement of high power gas terahertz laser by optimizing L-shaped cavity

Lijie Geng*, Zhifeng Zhang, Ruiliang Zhang, Yusheng Zhai*, Yuan Luo, Yuling Su

School of Physics & Electronic Engineering, Zhengzhou University of Light Industry, Zhengzhou 450002, Henan, China

HIGHLIGHTS

- A high efficient, high power gas THz laser based on L-shaped cavity is present.
- THz output performance was investigated both in theory and experiment.
- The optimum output coupling is 0.8 and the optimum gas pressure is 500 Pa.
- The maximum THz pulse energy is 8.4 mJ under the pumping energy of 1.6 J.

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ABSTRACT

A high power gas terahertz laser based on L-shaped cavity was demonstrated. We, for the first time, investigated the output performances of D_2O gas 385 μm THz laser by optimizing the output coupler transmittance of the L-shaped cavity both in theory and experiment. Under the pump energy of 1.6 J, the optimum output coupler transmittance was about 0.78 and the optimum gas pressure was about 500 Pa. Up to 8.4 mJ pulse energy at 385 μm was achieved at output coupler transmittance of 0.8, corresponding to a photon conversion efficiency of 43.7%. Pulse width of 120 ns, and beam quality factor M^2 of 1.58 were obtained at the highest output energy. In addition, the experimental results are in agreement with the theoretical simulation results.

1. Introduction

Optically pumped gas THz laser (OPGTL) technology is one of promising ways to generate coherent THz radiation, and can be widely used, such as THz imaging [1–3], digital holography [4,5], THz radar [6,7], Optical measurement [8], and atmosphere remote sensing [9]. In the past decades, improving photon conversion efficiency (PCE) and thus enhancing THz output energy have attracted many scientists. Many experimental studies have been reported to improve the output performance of OPGTL with different kinds of THz cavity configurations, such as unstable cavity [10], metal mesh oscillator [11,12], hole-coupled mirror oscillator [13,14] and intracavity-pumping configuration [15]. Using complicated intracavity-pumping configuration, the PCE of 47% at 151.5 μm has been obtained from NH_3 medium, and this PCE is the highest for OPGTL [15]. In order to achieve high efficient, high-power THz laser output, we proposed a novel high-efficient and compact cavity oscillator [16], and the PCE of 44% at 385 μm output was the highest efficiency for D_2O gas THz laser to the best of our knowledge.

In order to achieve high efficiency, high power and stable THz sources, it is necessary to study the influence of the output coupler, pump energy, and gas pressure on the THz output performance. Unfortunately, as a note, the coating technology for THz wave band is not yet mature. Therefore, it is difficult to achieve a specific transmissivity or reflectivity at THz frequencies [12,17,18]. Furthermore, there is little work reported about THz output energy/power influenced by the transmittance of output coupler for high efficiency, high power OPGTL. Therefore, the main objective of this work was to research the output performance of OPGTL influenced by different transmittance of the output coupler.

In this paper, we present a high efficiency, high power and good beam quality OPGTL operating at 385 μm based on L-shaped THz laser cavity at room temperature. The output THz energy was studied at different gas pressure and pump energy under different output couplers both in theory and experiment. The optimum output coupler transmittance and the optimum gas pressure of the THz laser were investigated at different pump energy. Three output couplers with transmittance of 0.38, 0.54 and 0.8 were used, and the maximum

* Corresponding authors.
E-mail addresses: genglijie1984@163.com (L. Geng), hf_sy@sohu.com (Y. Zhai).

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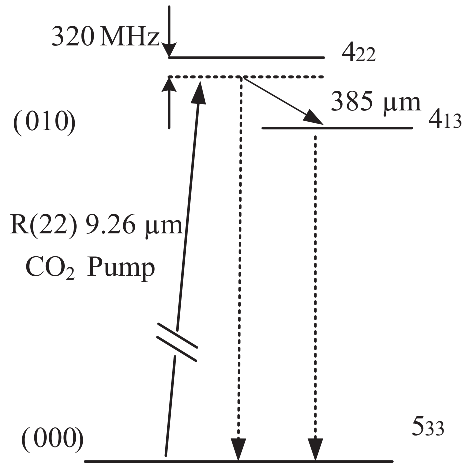

Fig. 1. Schematic diagram of the D_2O molecule energy diagram.

output energy of about 3.39 mJ, 5.3 mJ and 8.4 mJ were obtained, respectively. The corresponding photon conversion efficiency are about 43.7%, 27.8% and 17.3%. The theoretical simulation results are in agreement with the experimental results.

2. Theoretical model

For D_2O gas THz laser pumped by a TEA CO_2 laser, a three-level-system approximation treatment is reasonable alternative, and the energy-level structure and the transition processes are given in Fig. 1. When the D_2O molecules were pumped by a CO_2 laser line with wavelength of 9.26 μm, the absorption from the 5_{33} rotational level in the (0 0 0) ground vibrational state to the 4_{22} level of the excited (0 1 0) vibrational state has been occurred. Two photon Raman process as well as the usual two-step laser process of 385 μm lasing transition occurred from level 4_{22} to level 4_{13} in the excited (0 1 0) vibrational state [19].

To model the THz output characteristics, a modified laser kinetics model based on semi-classical density matrix rate equation and time evolution equation of laser cavity-field intensity has been established by us [19]. There are many numerical methods for solving the laser kinetics model. A MATLAB computer program, based on the Runge-Kutta method, was used to solve these equations. The physical constants used in calculations are given in Table 1 [19], and some laser dimensions used in this work are also shown in Table 1.

Table 1
Physical constants used in the calculation [19].

Symbol (Parameter)	Values/Unit
λ (pump wavelength)	9.26 μm
T (operating temperature)	273 K
E_1 (Level 1)	267.53083 cm^{-1}
E_2 (Level 2)	1321.41375 cm^{-1}
E_3 (Level 3)	1347.39375 cm^{-1}
T_i (relaxation time)	8 ns·torr
μ_{13}	4.0×10^{-31} C·m
μ_{23}	6.1×10^{-30} C·m
L (Length of THz cavity)	120 cm
R_1 (Reflectance of M_1)	1.0
R_2 (Reflectance of M_2)	0.2/0.46/0.62
f_1	0.01791
f_2	0.00014
f_3	0.000125

f_i is the Boltzmann occupation factor of level *i*.
μ_{ij} is the dipole moment from level i to level j.

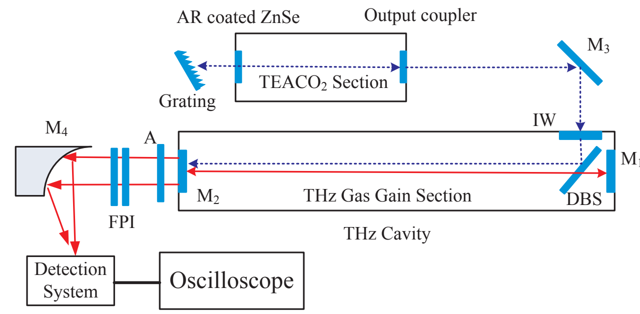

Fig. 2. Experimental setup of L-shaped cavity based on z-cut crystal quartz as DBS.

3. Experiment setup

The experimental configuration of OPGTL is shown in the Fig. 2. The schematic of the experimental apparatus consists of three main parts: the TEA CO_2 laser, the THz cavity, and the detection system. A tunable Multi-transverse mode TEA CO_2 laser, with emission wavelength of 9.26 μm is utilized as a pump source. The output coupler with transmittance of 0.54 at 9.26 μm was a plano-concave mirror (with radius of curvature of 15 m). The pulse energy and pulse shape of the pump laser are detected by Newport 818E-20-50L and HgCdTe detector with bandwidth of 100 MHz, respectively.

The L-shaped THz laser cavity consists of an input window (IW), a dichroic beam splitter (DBS), a mirror (M_1), and a THz output coupling mirror (M_2). The IW is a piece of AR-coated ZnSe with 99.5% transmittance at the pump wavelength of 9.26 μm. The flat 45° dichroic beam splitter (DBS) is high transmittance (about 75%) at 385 μm and high reflective (about 92.5%) in the wavelength range of 9.0 μm–11.0 μm. M_1 with curvatures of 20 m is high reflective (about 99.2%) at 385 μm. The THz Fabry-Perot cavity consists of a high reflective mirror (M_1) and an output coupler (M_2), and the total physical length of the resonator is about 120 cm. Considering the transmittance losses of the ZnSe input window and the reflective losses of the DBS, nearly 92% of the pump power was coupled input to THz cavity.

In this work, to study the THz output performances under different output couplers, a crystal quartz plate (4 mm thick), a high resistivity silicon plate (4 mm thick) and a Ge single crystal plate (3 mm thick) were used as the output coupler, respectively. And the corresponding transmittance at 385 μm THz laser are 0.8, 0.54 and 0.38, respectively.

The THz energy was fully coupled to the THz energy detector (SPJ-A-8-OB, Spectrum Detector) by off-axis parabolic mirror (M_4). A Schottky diode detector (VDI, Quasi-Optical Broadband Detector), with sub-ns response time at the frequency range from 0.1 THz to 1 THz radiation, was used to detect the profile of the THz pulse. Finally, all electrical signals were recorded by a Tektronix TDS3032C digital oscilloscope with a 300 MHz bandwidth.

4. Results and discussion

4.1. Simulation results and discussion

In the simulation, the pumping geometry and THz cavity was shown in Fig. 2. The total physical length of the resonator is about 120 cm, and the reflectance of M_1 is about 100%. The pump pulse with pulse width of 110 ns was simulated by a Gaussian function. The insertion loss of the dichroic beam splitter (DBS) is about 25%. The pump energy and the pump spot are about 1.6 J and 22 mm * 22 mm, respectively.

For gas THz laser, the output THz energy depends on the gas pressure. As one can see from Fig. 3, when the pump energy is 1.6 J, there is obviously an optimum gas pressure at which the THz energy is maximized. When the output coupler transmittance was 0.38, 0.54 and 0.8, the maximum output pulse energy of 8.4 mJ at 490 Pa, 6.4 mJ at 600 Pa