Applied Physics B (2021) 127:94
https://doi.org/10.1007/s00340-021-07641-6

Applied Physics B
Lasers and Optics

Pure single line oscillation of HF lasers in fine atmospheric window

Yuanhu Wang[1] · Liucheng Li[1] · Liping Duo[1] · Yuqi Jin[1] · Guofu Li[1] · Shukai Tang[1] · Shuqin Jia[1] · Haijun Yu[1] · Zengqiang Wang[1] · Jian Wang[1] · Jing Cao[1]

Received: 17 December 2020 / Accepted: 24 May 2021 / Published online: 3 June 2021

Abstract

The pure $P_2(8)$ line radiation of chemical hydrogen fluoride (HF) laser which can be weakly absorbed by atmosphere was generated using an absorbed module in a line-selected cavity. A numerical model of laser gain was investigated to predict and optimize the laser performance. An experimental verification was carried out in a compact continue wave (cw) tunable chemical HF laser device. It is found that $P_1(11)$ line can be suppressed by fundamental HF particles generated by combustion reaction, meanwhile the proportion of $P_2(8)$ line can be increased close to 100% from original 38%. The absorbance as well as output power of $P_2(8)$ line can also be influenced by concentration of absorbing media.

1 Introduction

A narrow spectral bandwidth laser operating at the mid-infrared wavelength regions has a variety of applications including molecular spectroscopy, remote sensing of the environment, medical diagnostics, laser radar, free space communication, etc. [1, 2]. A number of methods to produce mid-infrared laser radiation have been developed, such as HF/DF laser, optical parametric oscillator (OPO), quantum cascade laser (QCL), second harmonics generation (SHG) CO_2 laser, first-overtone CO laser, Cr and Fe-doped II–VI chalcogenides solid laser [3]. Among these methods, HF laser is so far considered as the highest output power laser system [4]. Conventionally, multiline laser emission is obtained due to ro-vibrational transitions of HF molecules. Most of these laser lines will be strongly absorbed by atmosphere because of moisture. However, several spectral lines with specific ro-vibrational energy levels of HF laser have fine atmospheric transmission, especially $P_2(8)$ line that has been demonstrated without obvious optical losses and thermal blooming effects even through long distance transportation in air [5]. In general, a configuration with a blazed grating as the rear mirror of the laser cavity is usually used to select and control the spectrum of such specific radiation [6, 7]. However, it is still difficult to obtain pure $P_2(8)$ line because of the $P_1(11)$ line oscillates simultaneously. It is because that the gain coefficients of these two lines are so similar, meanwhile the wavelength difference between them is so less that it cannot be finely differentiated by a diffraction grating in the cavity. However, in the case that high temporal or spatial coherence is desirable for the laser radiation, it is necessary to enhance its monochromaticity [8]. Some techniques have been provided to generate narrow linewidth laser such as using an etalon, interferometers, and injection locking [9]. These techniques are inapplicable to high-power laser because of low power threshold of optical selection components or cavity-mode match. An Integral Master Oscillator Power Amplifier (IMOPA) concept was proposed to achieve line-selected laser for high-power HF laser [10], however, output of $P_2(8)$ pure line laser has not been experimentally verified.

In this paper we present a hybrid cavity to obtain pure $P_2(8)$ line output in a cw HF laser system. An unstable laser cavity was employed to preliminarily select the lines, which constituted a grating in the Littrow arrangement and a convex mirror. An absorption section that generated ground state HF molecules had been set close to the gain section in the cavity to suppress oscillation of $P_1(11)$ line. The characteristics, which has high efficiency of absorbing medium and needs no additional optical components, can make high-power single line laser operate in fine atmospheric window of a HF laser in more feasible way. A numerical model was developed to describe gain variations of both lines when laser operated with or without the absorption section.

✉ Yuanhu Wang
wyh@dicp.ac.cn

[1] Key Laboratory of Chemical Lasers, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, People's Republic of China

Experimental verification was also presented to demonstrate that output power of $P_2(8)$ single line was depended on the characteristics of the gas ejected from the absorption section.

2 Theory

The spatial distribution of gain coefficient in some point can be relative predicted by a HF laser gain model. A computational fluid dynamical codes which can integrate the complex fluid properties with the myriad chemical reactions is employed to investigate the details of the laser performance. Four processes are assumed to contribute to alteration of the gain of HF laser: (1) combustion process producing atomic fluorine by D_2 reacted with NF_3 (by H_2 reacted with NF_3 for absorption section); (2) chemical reactions forming HF molecules; (3) vibrational relaxation and *V*–*V* energy transfer (including HF molecules themselves and with other atoms or molecules); and (4) rotational relaxation process.

Numerical simulations of the mixed flow output from the combustion chamber, the subtransonic flow in the supersonic nozzle, and the chemical reactions in the gain generator were investigated. The numerical model includes the conserved forms of compressible three dimensional Navier–Stokes equations, energy equations and the transport equations of each component.

The small signal gain of a HF laser induced by stimulated transition of populations from an upper u to a lower l state is given by [11]:

$$g = \frac{c^2 A}{8\pi\nu^2} g(\nu)\left[N_{\mathrm{u}} - \frac{g_{\mathrm{u}}}{g_{\mathrm{l}}} N_{\mathrm{l}}\right],$$

where A is the Einstein emission coefficient, ν is the frequency, $g(\nu)$ is the spectroscopic line shape, N_{u}, N_{l}, g_{u} and g_{l} are the number densities and degeneracies for the upper and lower states, respectively. A can be calculated from first principles with an accurate potential energy surface and a suitable dipole moment function [12], in this paper, they are based on the values found in Refs. [5, 12].

The distribution of calculated small signal gain coefficients of $P_1(11)$ line and $P_2(8)$ line at the exit of nozzle are shown in Fig. 1, where x and y along are perpendicular to the direction of flow respectively. The laser is perpendicular to the plane consisted of x and y. The alpha value which is defined as $\alpha = 1.5\left[NF_3\right]/\left[D_2\right]$ in the combustion chamber of the generator of atomic fluorine was set to 1.5, where $[NF_3]$ and $[D_2]$ represent the concentrations of NF_3 and D_2 molecules, respectively. The simulated value of average gain coefficient is 3.9% for $P_1(11)$ line and 5.7% for 2P(8) line at about 20 mm from the exit of nozzle. When the absorption section was added to the gain section, the simulated values are decreased for both lines, as shown in Fig. 2. Figure 3 shows absorption coefficients of both lines with changing of α of absorption section. Simulated values indicate that the absorption coefficients of $P_1(11)$ line is nearly an order of magnitude greater than $P_2(8)$ line when α is less than 1.8. As α further increased, absorption of both lines rise rapidly due to appearance of thermal resistance effects.

3 Experimental setup

A distribution feedback tunable diode(DFB) laser (2.9 µm, 2mW, Nanoplus) was used to obtain the absorption spectra of HF molecules in the absorption section, as shown in Fig. 4. The wavelength of the diode laser swept periodically by changing its current. The sweeping range of the diode laser was about 1.8 nm, which covered the spectral region of $P_1(11)$ and $P_2(8)$ lines of HF molecules. Both ends of absorption section was sealed by the laser-head sapphire Brewster windows to enhance the transmittance of diode laser. The output beam of the tunable diode laser went through the absorption region and the transmitting beam was focused

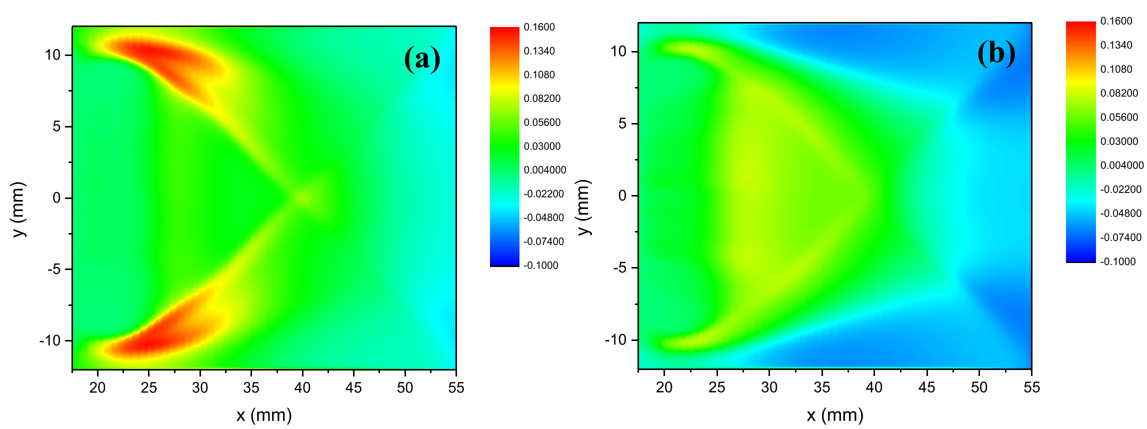


Fig. 1 Calculated small signal gain of HF laser with $\alpha(\alpha = 1.5\left[NF_3\right]/\left[D_2\right])$ set to 1.5 without absorption section: **a** $P_1(11)$ line; **b** $P_2(8)$ line

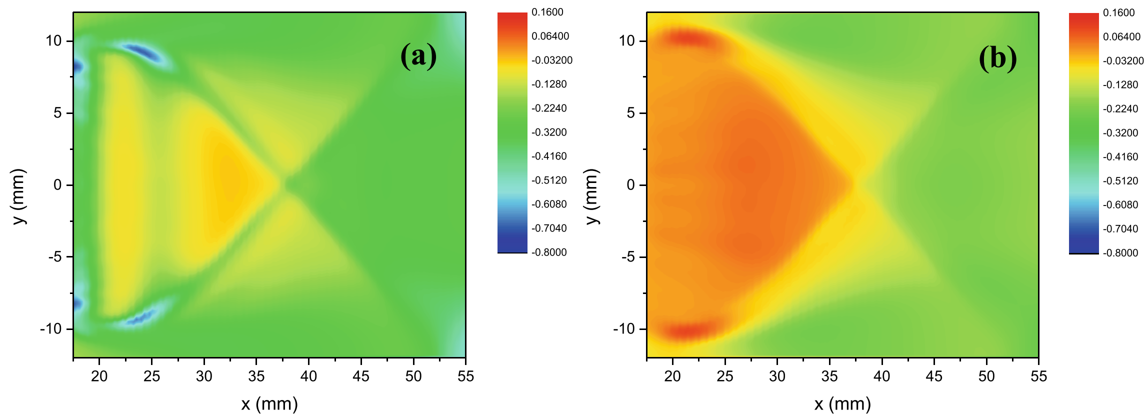


Fig. 2 Calculated small signal gain of HF laser with α of absorption section (α=1.5[NF_3]/[H_2]) set to 1.64: **a** $P_1(11)$ line; **b** $P_2(8)$ line

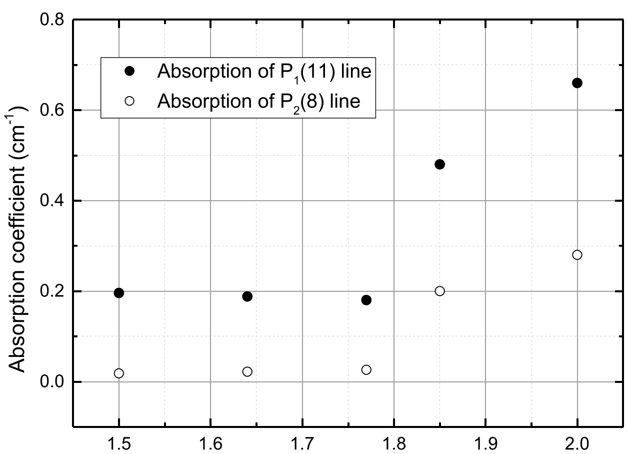


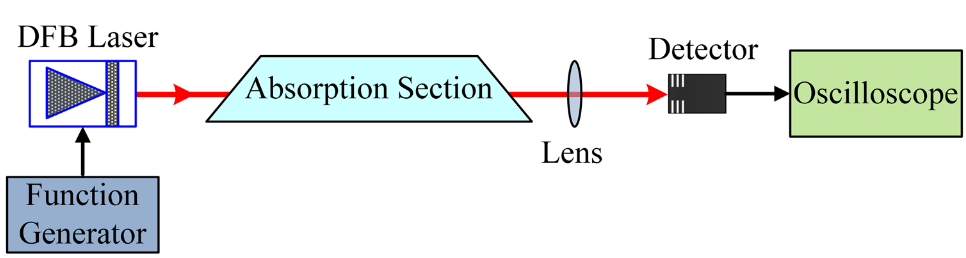
Fig. 3 Calculated absorption coefficients of both lines with changing of α of absorption section

on an InSb detector (J10D, Judson) which was cooled by liquid nitrogen. A digital oscilloscope (625Zi, LeCroy) was used to record the voltage signal of the detector as a function of time. The transmission spectra were obtained by comparing the absorption and non-absorption traces. It could be inferred that the absorbance of the high J lines of HF molecules would be very low at room temperature as a consequence of Boltzmann's equilibrium law. To get large absorbance of high J lines of HF molecules, the experiment had been performed on a configuration using a generator of atomic fluorine and a supersonic nozzle array, as shown in Fig. 5. NF_3 and H_2 was injected to the combustor, respectively, and reacted with each other to produce high temperature ground state HF molecules. The supersonic nozzle array consisted of alternative F main nozzle and H_2 secondary nozzle units. The combustion products flowed through the supersonic nozzle array and entered the absorption region. The pressure of the combustor mixing gases is about 1 bar.

Further experiment was carried out to investigate the behavior of laser output from the HF laser using hybrid section, as shown in Fig. 6. The geometry of generator of atomic fluorine and nozzle that generated the gain region was similar to what was described in absorption section. NF_3 reacted with D_2 to produce atomic fluorine in the combustor. Then the gas containing atomic fluorine was expanded and accelerated by the supersonic nozzle array and entered the gain region, in which F reacted with H_2 to form excited HF molecules. Turbulators were set in each nozzle unit to enhance the mixing of reaction gas. The parameters of reagents in the experiment were in accordance with the data used in calculation previously.

A diffraction grating of 500 grooves/mm, which was placed at a Littrow angle, was employed to yield the two lines of the laser. A diffraction efficiency of over 96% was measured at $P_2(8)$ wavelength when the polarization of the laser was parallel with the direction of grooves. A 42 m radius convex mirror was used to combine with the grating to form a nonconfocal unstable resonator. The convex mirror

Fig. 4 Schematic diagram of absorbance of two lines output from a swept DFB laser by the absorption section



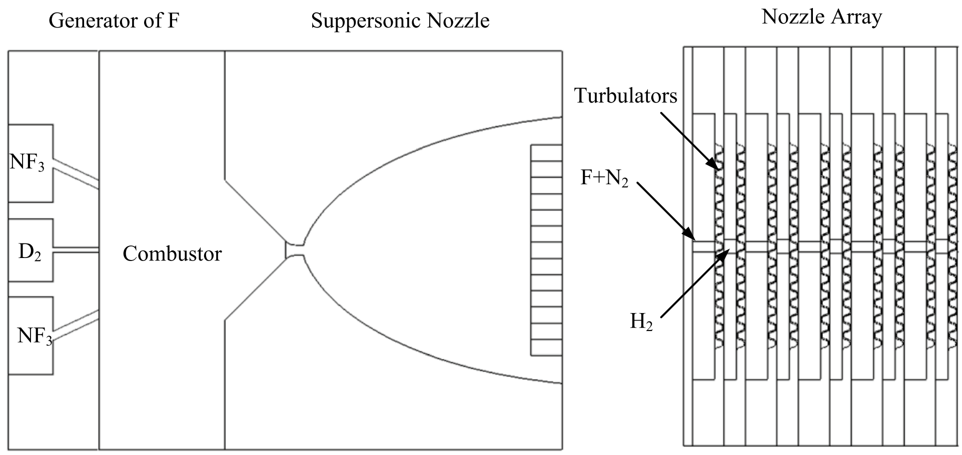


Fig. 5 Schematic diagram of structures of F generator and nozzle

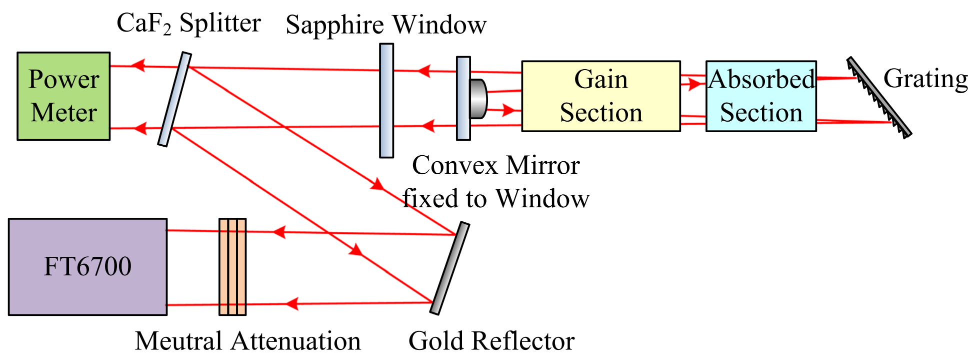


Fig. 6 Schematic diagram of the experimental setup for obtaining $P_2(8)$ single line oscillation

was fixed to a sapphire window so that the laser could output from the edge of the mirror. The length of the cavity is 3 m, and the magnification is 1.7. All the optical elements were set in the vacuum chamber that was connected to the nozzle. The laser output from the chamber through a window on it ultimately. The output power of the laser was measured with a power meter (PM5K, coherent), and the wavelength was monitored with a Nicolet 6700 spectrometers (resolution in experiment was 0.25 cm^{-1}).

4 Results and discussion

4.1 Characteristic of absorption section

Figure 7 shows the typical transmission spectra of the HF molecules emitting from the combustor of the absorption section. As seen in Fig. 7a, a notable absorption of $P_2(8)$ line was observed in the absorption section which implied the survival of vibrational excited state HF molecules in spite of frequently collisional deactivation of excited state combustion products. By controlling the deactivation process of excited HF molecules, the absorption of $P_2(8)$ line could be suppressed at a negligible level as shown in Fig. 7b.

It was found experimentally that $P_1(11)$ line absorbance was also suppressed while the $P_2(8)$ line absorbance was suppressed. Fortunately, the HF $P_2(8)$ line absorbance was suppressed more than $P_1(11)$ line. Figure 8 shows the ratio of $P_1(11)$ line absorbance to $P_2(8)$ line absorbance as a function of the α value. From Fig. 8, it was found that the ratio of the $P_1(11)$ line absorbance to the HF $P_2(8)$ line absorbance is strongly relevant to the α value. When the α value is smaller than 1.0, the absorbance ratio remains almost constant. On the other hand, when the α value is larger than 1.0, the absorbance ratio increases dramatically with the α value. It can be known that the gas temperature in the combustor decreases and the concentration of atomic fluorine increases with the α value when the α value is larger than 1.0. That means the combustion plays an important role in producing HF particles for absorption, and the combustion products contain not only ground state but also excited state particles that was not considered previously.

4.2 Pure single line oscillation in HF laser

When the laser cavity consisted of only gain section and optical components, output spectra typically contained $P_2(8)$ and $P_1(11)$ lines. The power was 1 kW when the α was set to 1.56, and $P_2(8)$ line accounted for one thirds of the total power approximately, as shown in Fig. 9a. $P_1(11)$ line was depressed obviously due to presence of fundamental HF particles as the absorption section operated, as shown

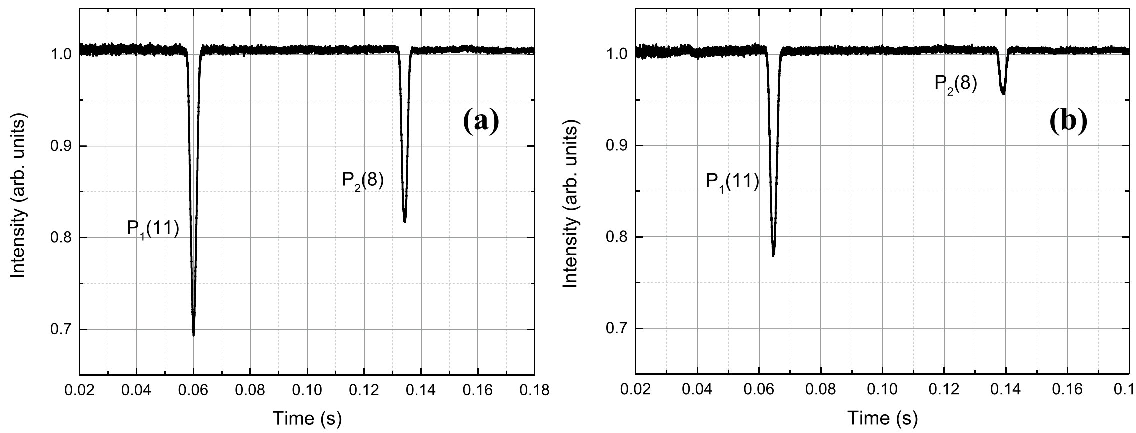


Fig. 7 Transmission spectra in the absorption section of the HF molecules emitting from the combustor: **a** $P_1(11)$ and $P_2(8)$ lines with notable absorption; **b** $P_2(8)$ line with negligible absorption

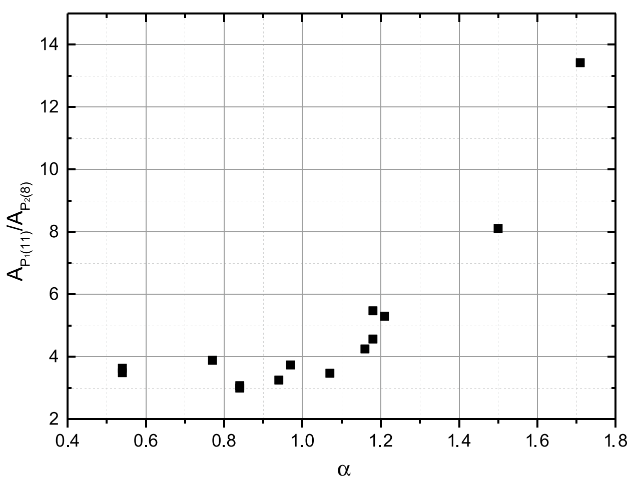


Fig. 8 The ratio of $P_1(11)$ line absorbance to $P_2(8)$ line absorbance as a function of α

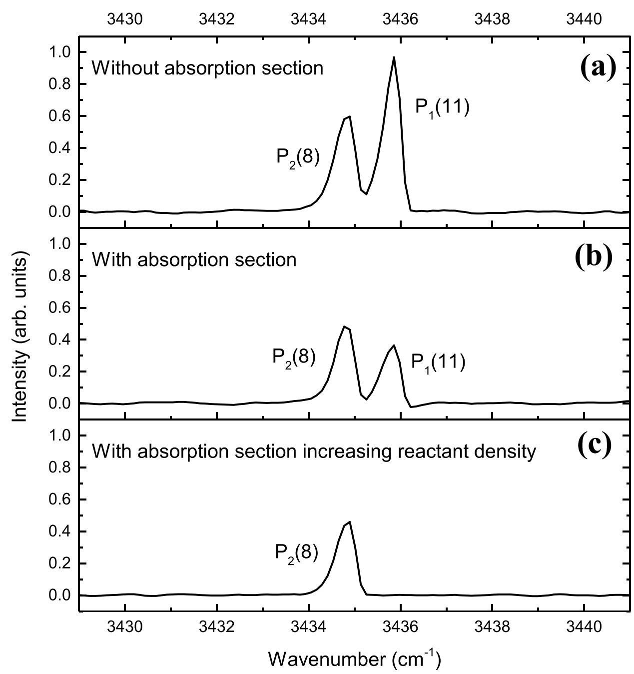


Fig. 9 Spectra of output laser using fundamental HF particles: **a** $P_1(11)$ and $P_2(8)$ lines without absorption; **b** $P_1(11)$ absorbed by fundamental HF; **c** output of single $P_2(8)$ line

in Fig. 9b. With the reactant density improved further in absorption section by increasing flow rate of reactants in its combustor, $P_1(11)$ line was suppressed completely. Figure 9c shows $P_2(8)$ single line spectra with flow rate of reactants in combustor of absorption section similar to gain section, and output power of $P_2(8)$ line has little changed.

As reactants in absorption section were much more than the optimal quantity, output power of $P_2(8)$ line was also reduced even suppressed. It is because the $P_2(8)$ line had been absorbed by HF($v=1$) particles produced in that condition. Figure 10a shows $P_2(8)$ single line with α of absorption section set to 1.65. However, when the flow rate of reactants was risen to 1.6 times, power of $P_2(8)$ line was reduced to less than one half, as shown in Fig. 10b.

For a traditional HF laser, H_2 is usually forbidden to use as fuel to react with oxidizer in combustor (D_2 cannot be used for DF laser similarly) because the resulting massive HF($v=0$) particles will quench excited HF particles seriously. The principle also applies to DF laser, D_2 cannot be used as fuel either. In a hybrid laser, when H_2 is injected to nozzle exit region in absorption section as secondary fuel, HF($v=2$) particles produced from H_2 reacted with atomic fluorine will be deexcited by HF($v=0$) particles flowed from combustor and produce HF($v=1$) particles which will lead to reduce the efficiency of $P_2(8)$ line by absorption, as shown

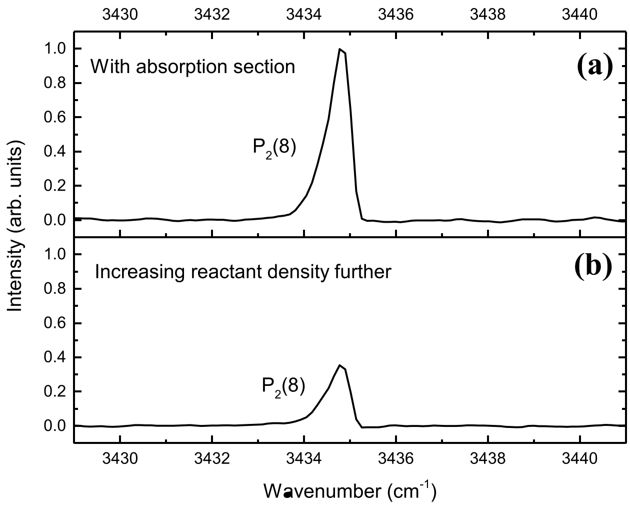


Fig. 10 Absorption of $P_2(8)$ line with increasing the flow rate of reactants. **a** Radiation of single $P_2(8)$ line; **b** decrease of $P_2(8)$ line as further improving absorption

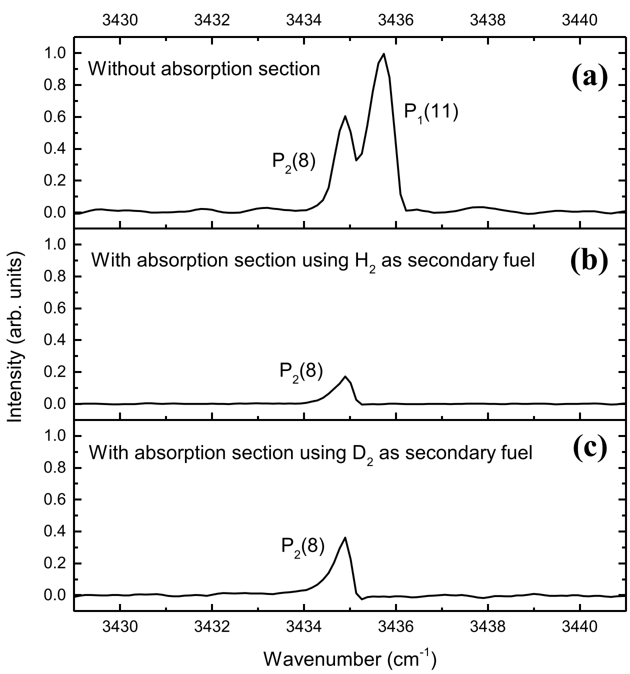


Fig. 11 Spectra of output laser using D_2 as secondary fuel instead of H_2 to react with F in absorption section. **a** $P_1(11)$ and $P_2(8)$ lines without absorption; **b** using H_2 as secondary fuel of absorption section; **c** using D_2 as secondary fuel of absorption section

in Fig. 11b. However, if D_2 is injected to mix with atomic fluorine instead of H_2, there is no significant effect on output of $P_2(8)$ line, as show in Fig. 11c. That means it is possible to obtain both a HF selected line and a DF selected line in a common laser cavity using two different gain sections and a dual-wavelength grating.

5 Conclusions

We have demonstrated a hybrid configuration to achieve pure $P_2(8)$ line weakly absorbed in the atmosphere of a cw HF laser operation. Single line oscillation has been theoretically predicted using a 3D HF gain model. Experimental verification was carried out using absorbance of a swept DFB laser and output of a hybrid laser, respectively. The results indicate that $P_1(11)$ line has been absorbed significantly by fundamental HF($v=0$) particles at high J level produced from combustion, and the efficiency of $P_2(8)$ line also has been affected by a little HF($v=1$) particles. The absorbance depends on mole ratio and concentration of reactant greatly: it was improved for $P_1(11)$ line while reduced for $P_2(8)$ line as α increased; When flow rate of reactants was increased, the absorbance of both lines grew rapidly. Output laser of pure $P_2(8)$ single line was obtained with little loss when reactant concentration of absorption section was similar to gain section but α was set to 1.6. D_2 as secondary fuel in the absorption has proved to be not an obvious impact on output of $P_2(8)$ line, which makes it be possible to obtain two selected lines weakly absorbed by atmosphere output simultaneously from a HF/DF dual-module laser.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Nos. 11704379, 21590803).

Declarations

Ethical statement The authors states that this manuscript has not be submitted to another journal for simultaneous consideration. The submitted work is original and have not been published elsewhere in any form or language. This work has not been split up into several parts to increase the quantity of submissions. All the data or results in this manuscript is presented honestly, and without falsification. There is not any plagiarism, cheating or other behaviors that are violations of academic ethics taken in the manuscript.

References

1. R. Stanley, S.D. Jackson, Y. Yao, Mid-infrared photonics. Nat. Photonics **6**, 407 (2012)
2. T. Gaijuan, X. Jijiang, Z. Laiming, G. Jin, Y. Guilong, S. Chunlei, C. Fei, Y. Xinxin, R. Peng, Recent progress in mid-infrared laser technology. Chin. Opt. **6**, 501 (2013)
3. S.B. Mirov, V.V. Fedorov, D. Martyshkin, I.S. Moskalev, M. Mirov, S. Vasilyev, Progress in mid-IR lasers based on Cr and Fe-doped II–VI chalcogenides. IEEE J. Sel. Top. Quantum Electron. **21**, 1601719 (2015)
4. J. Shwartz, G.T. Wilson, J.M. Avidor, Tactical high-energy laser. Proc. SPIE Int. Soc. Opt. Eng. **4632**, 10 (2002)

5. R.W.F. Gross, J.F. Bott, *Handbook of Chemical Lasers* (Wiley, New York, 1976).
6. I.A. Fedorov, Yu.P. Maksimov, N.E. Tret'yakov, A.L. Étsina, A.P. Zhevlakov, Selection of spectral lines of a CW chemical HF laser. Opt. Spectrosc. **94**, 114 (2003)
7. R.A. Chodzko, Multiple-selected-line unstable resonator. Appl. Opt. **13**, 2321 (1974)
8. I.A. Fedorov, Yu.P. Maksimov, A.P. Zhevlakov, Control of spectral lines weakly absorbed by atmosphere in continuous wave chemical HF lasers. Opt. Spectrosc. **110**, 630 (2011)
9. Y. Wang, Qu. Yanchen, W. Zhao, C. Jiao, Z. Liang, D. Ren, Single longitudinal mode oscillation from a multi-interferometric cavity. Appl. Opt. **48**, 1430 (2009)
10. B.R. Graves, W.A. Duncan, S.P. Patterson, Optical system design, modelling, and analysis of selected line HF and DF lasers. SPIE **2119**, 68 (1994)
11. J.J. Hinchen, R.H. Hobbs, Rotational population transfer in HF. J. Appl. Phys. **50**, 628 (1978)
12. G.C. Manke II., G.D. Hager, A review of recent experiments and calculations relevant to the kinetics of the HF laser. J. Phys. Chem. Ref. Data **30**, 713 (2001)