Experimental Study on Intra-Cavity Frequency-Doubling at 532 nm in an Yb-Doped Fiber Laser

An Hongbo[1]　Niu Lihong[1]　Su Binghua[2,3]　Xue Junwen[3]　Tan Yu[2]

[1] *College of Optoelectronics Engineering, Shenzhen University, Shenzhen, Guangdong* 518060, *China*
[2] *School of Optoelectronics, Beijing Institute of Technology, Beijing* 100081, *China*
[3] *Information School, Zhuhai Campus, Beijing Institute of Technology, Zhuhai, Guangdong* 519085, *China*

Abstract A structure of intra-cavity frequency doubling in a continuous-wave (CW) Yb-doped double-clad fiber laser is proposed. High conversion efficiency green laser can be obtained in theory due to the high pump power density in the cavity. Advances in compact structure of double-clad fiber laser also allow for the availability of laser integration. In this work, the optimized efficiency is achieved when the waist is located at the edge of MgO∶PPLN and the Rayleigh length is equal to twice the length of the crystal, and the lens′ location in the system was calculated. 10.5 mW green laser is obtained, and the second harmonic generation (SHG) efficiency of the system is 0.35%. Laser oscillation in the cavity is verified and it is indicated that the structure can achieve effective CW green output.

Key words fiber laser; frequency doubling; intra-cavity; 532 nm laser

中图分类号 TN248.1　　**文献标识码** A　　**doi**: 10.3788/LOP49.071403

掺镱双包层光纤激光器内腔倍频绿光实验研究

安宏波[1]　牛丽红[1]　苏秉华[2,3]　薛竣文[3]　谭　羽[2]

[1]深圳大学光电工程学院，广东 深圳 518060；[2]北京理工大学光电学院，北京 100081
[3]北京理工大学珠海学院信息学院，广东 珠海 519085

摘要 提出了一种内腔形式的双包层光纤激光器倍频绿光的结构，利用腔内极高的抽运光功率密度，理论上能获得高转换效率的倍频绿光输出，结合双包层光纤激光器结构紧凑的优点，容易实现激光器一体化。根据高斯光束透镜变换定律计算了透镜与系统的相对位置，当高斯光束聚焦参数等于倍频晶体长度两倍且束腰处于晶体输出端面时，系统处于最佳聚焦。实验输出 10.5 mW 绿光，系统倍频效率为 0.35%。验证了激光在腔内形成振荡，表明该结构能实现高效的连续绿光输出。

关键词 光纤激光器；倍频；内腔；532 nm 激光

OCIS codes 140.3515；190.4370；140.3510；140.7300

1 Introduction

Recently, high-power continuous-wave (CW) green sources are of great interest for a variety of scientific and technological applications in astronomy, medicine, laser displays, communication, military and forensic testing[1,2]. The technology of generating 532nm green laser by double-clad fiber laser, with the advantages of high output power, high electro-optical conversion efficiency, good heat dissipation, good beam quality and compact structure, is gaining growing concern [3~6]. Currently the major concern is the external cavity frequency doubling using quasi-phase matching, however, the harmonic conversion efficiency is not ideal. The optical power density in the internal cavity is relatively high, so putting the crystal into the cavity can improve the overall system efficiency using its high

---

收稿日期：2012-01-16；**收到修改稿日期**：2012-02-23；**网络出版日期**：2012-05-22

基金项目：北京理工大学珠海学院青年教师科研发展基金(ky－2010－0016)资助课题。

作者简介：安宏波(1986－)，男，硕士研究生，主要从事光纤激光器关键技术方面的研究。
E-mail：anhongbo@email.szu.edu.cn

导师简介：牛丽红(1963－)，女，教授，主要从事光电成像技术、变像管高速摄影技术以及光电信息处理等方面的研究。
E-mail：niulh@szu.edu.cn(通信联系人)

pump power density. It is easy to implement laser integration with the compact structure of double-clad fiber laser. It is an effective method to obtain 532 nm green output that can overcome the lack of conversion efficiency in external cavity. For this consideration, an intra-cavity second harmonic generation (SHG) structure in a CW Yb-doped double-clad fiber laser based on MgO:PPLN is proposed in this paper.

2 Frequency doubling experiment

2.1 Experimental setup

The periodically poled MgO:PPLN was proposed in order to overcome these problems: this crystal presents larger nonlinear susceptibilities, higher resistance against photorefractive damage and shorter wavelength transparency compared with PPLN. The 2 mm long, 0.5 mm thick and 2.2 mm wide crystal contains a single grating with period of $\Lambda = 6.96$ μm. Its input face M1 is anti-reflection (AR)-coated ($R<0.5\%$) at 1064 nm and 532 nm, the M2 as output face is AR-coated ($R>99.8\%$) at 1064 nm and has high transmission ($T>99.5\%$) at 532 nm. It is housed in an oven with a temperature stability of ±0.1 ℃. The optimal theoretical SHG temperature is 32 ℃ when pumped at 1064 nm as shown in Fig.1.

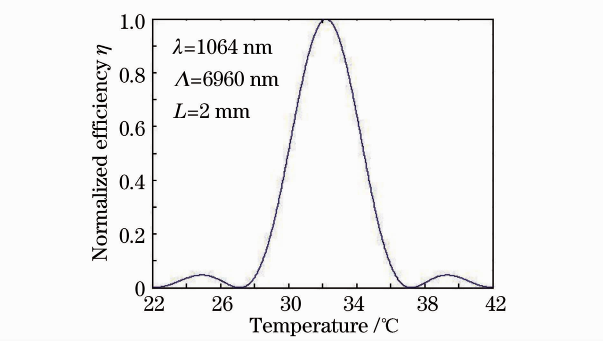

Fig.1 Dependence of conversion efficiency on the temperature of crystal

The experimental setup consists of pump laser diode array (LDA), fiber coupler, fiber grating and SHG device. As a laser source, the Yb-doped fiber laser pumped by LDA was chosen to generate 1064 nm laser. The fiber length was 15 m, and fiber Bragg grating (FBG) was used to select the fiber laser's operating wavelength and to narrow the emission bandwidth so that it was less than the phase matching bandwidth for the nonlinear crystal[7]. To achieve intra-cavity frequency doubling, we removed the output Bragg grating. The schematic of the experiment setup is shown in Fig.2. The Fabry-Perot (F-P) cavity was formed by the input Bragg grating in the Yb-doped fiber and the MgO:PPLN crystal output face M2. Taking into account the power density in cavity and the acceptance angle of crystal, the diverging light emerging from the fiber end was collimated using a Rayleigh lens L1 and refocused to the crystal by L2. And the polarization beam splitter (PBS) as the polarizer was used to output horizontally polarized 1064 nm laser.

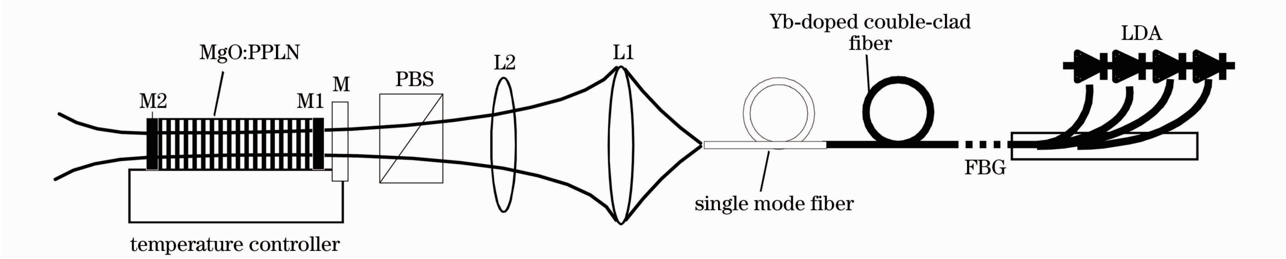

Fig.2 Schematic of intra-cavity frequency doubling in fiber laser

The filter, M, ($R>99\%$ at 532 nm, $T>95\%$ at 1064 nm), reflected 532nm to avoid it entering the fiber. The fiber end near L1 was cleaved at 0 ℃ from perpendicularity with the cavity axis to increase the back reflection into the fiber to fully pump the doped fiber and thus enhance the fundamental power[8].

2.2 Focus computations

Gaussian laser beam is focused by Rayleigh lens as shown in Fig.3.

From the transformation theory of Gaussian beam by a thin lens, the focused waist location and waist radius are

$$L_2 = \frac{(L_1^2 + b^2 - fL_1)f}{(f - L_1)^2 + b^2}, \quad (1)$$

$$\omega'_0 = \frac{f^2\omega_0^2}{(f - L_1)^2 + b^2}, \quad (2)$$

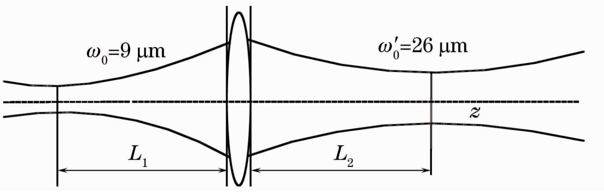

Fig.3 Gaussian beam focused by lens

where f is the focal length of the lens, $b = 2z_f = 2\pi\omega_0^2/\lambda$ is the confocal parameter, λ is the fundamental wavelength, $\omega_0 = 9\ \mu\text{m}$ is the Gaussian beam waist before focused, i.e., the fiber core diameter, ω'_0 is the Gaussian beam waist after focused, L_1 and L_2 are the distances of ω_0 position to the front convex of lens and ω'_0 position to the last convex of lens, respectively.

In order to increase the SHG efficiency, it is expected to get the best focus, there is a Boyd-Kleinman focusing factor $h = l/(2z_f)$[9], where $l = 2$ mm is the crystal length. The best focus factor is $h \approx 1$ usually, that is, the optimized efficiency would be achieved when the Gaussian beam Rayleigh length b is equal to the MgO:PPLN length l. For the unfolded structure, focusing optics are needed to convert Gaussian beam of fiber output to a beam with the waist located at the edge of MgO:PPLN and Rayleigh length equal to twice its length. According to Eqs. (1), (2), $\omega'_0 = 26\ \mu\text{m}$. Lenses with focal length, of 10 mm and 15 mm were used for focusing the Gaussian beam, respectively. The lens' location in the system is shown in Table 1.

Table 1 Lens' location in the system (unit: mm)

Focal length f	L_1	L_2
10	14.9	22
15	20.35	60

3 Results and analysis

Parallelly pumped by two 2 W 915 nm LDs, the laser was oscillated and amplified in the F-P cavity formed by the input Bragg grating and M2. Fundamental wave that passed MgO:PPLN but has not converted to 532 nm light was reflected into MgO:PPLN by M2 to generated second harmonic, then all the green light was reflected by the filter M and outputted. In theory, high conversion efficiency green output can be obtained. Before SHG experiments, a 1064 nm output mirror ($T = 20\%$, $R = 80\%$) was butted to the output end of the fiber instead of the crystal, then the fundamental wave was reflected into the fiber and intra-cavity oscillation was formed.

Figure 4 shows the output power with/without output mirror as a function of the fundamental power. The output power with output mirror is much higher than that without output mirror, and it can be judged that laser oscillates in the doped fiber. Thus the feasibility of the structure is verified. After putting the lens and crystal into the cavity, the 10.5 mW green light is obtained when the pump power is 3 W and the SHG efficiency of the system is 0.35%. The output green power versus pump power is shown in Fig.5.

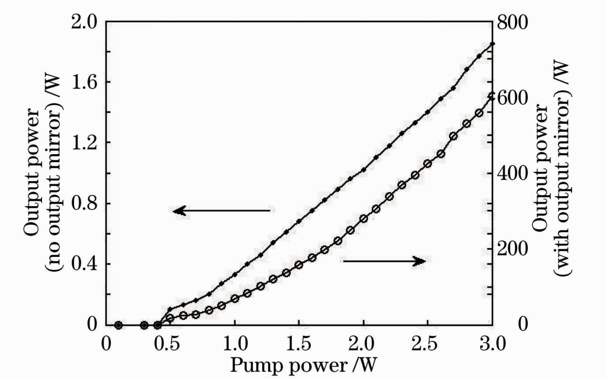

Fig.4 Output power versus pump power

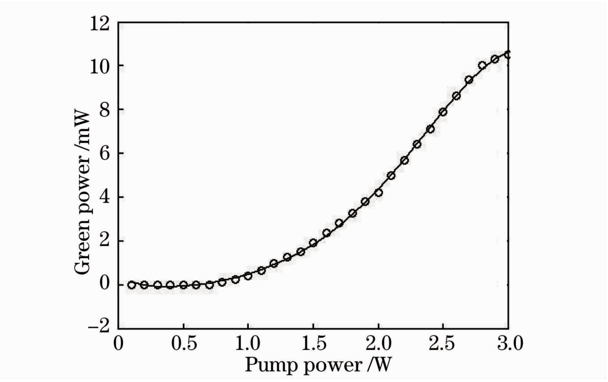

Fig.5 Output green power versus pump power

Structural instability is the main reason for the low output power of the green light. In the experiment, the F-P cavity was formed by the input Bragg grating and the crystal output face, the of all fiber structure was broken, so a great loss was brought to the resonator inevitably. And the core diameter of fiber was too fine to collect the laser reflected by the crystal output face M2, it required very high for the focusing of laser. Moreover, the fiber end polishing angle has a significant impact on laser oscillation in the fiber. To achieve laser oscillation in the cavity is very difficult due to the existence of all the above problems, but it can be judged that laser oscillates in the doped fiber from Fig.4, so we can be confident that high conversion efficiency green laser can be obtained by changing the related conditions.

4 Conclusions

A new structure of frequency doubling has been proposed. Due to the high pump power density of intra-cavity in the CW double-clad fiber laser, high conversion efficiency green laser can be obtained in theory. In the experiment, 10.5 mW green laser is obtained when the pump power is 3 W, and the SHG efficiency is 0.35%. In the next work, we will continue to increase the SHG efficiency by improving the structural stability, using different fiber with different output reflectivity to improve the fundamental power which oscillates in the Yb-doped fiber, and calculating the appropriate polishing angle of the fiber end.

Acknowledgement

We thank Dr. Cai Bo for his encouragement and helpful discussions.

References

1 He Jingliang, Hou Wei, Zhang Hengli *et al*.. Continuous wave output of 5.5 W at 532 nm by intracavity frequency doubling of a Nd∶YVO_4 laser[J]. *Chinese Physics*, 1998, **15**(6): 418～419

2 Xu Degang, Yao Jianquan, Guo Li *et al*.. 104 W laser diode-pumped intracavity frequency-doubled Nd∶YAG green light laser[J]. *Acta Optica Sinica*, 2004, **24**(7): 925～928
徐德刚, 姚建铨, 郭丽 等. 104 W 内腔倍频全固态 Nd∶YAG 激光激光器[J]. 光学学报, 2004, **24**(7): 925～928

3 G. K. Samanta, S. Chaitanya Kumar, Kavita Devi *et al*.. 55%-efficient, 13-W, single-pass SHG of a CW Yb-fiber laser in a double-crystal scheme[C]. CLEO, 2010, CWQ7

4 Zhu Xiaozheng, Zhou Jun, Lou Qihong *et al*.. Experimental investigation of quasi-CW frequency-doubling of broadband fiber laser in periodically poled lithium niobate[J]. *Acta Optica Sinica*, 2004, **24**(10): 1330～1334
朱晓峥, 周军, 楼祺洪 等. 宽带准连续光纤激光在周期极化铌酸锂中倍频特性的研究[J]. 光学学报, 2004, **24**(10): 1330～1334

5 S. V. Popov, J. R. Taylor, V. P. Gapontsev. 7 W average power second harmonic generation of quasi-CW Yb source in MgO-doped stoichiometric PPLT[C]. CLEO, 2005, CFL2

6 R. Cieslak, J. K. Sahu, W. A. Clarkson. Efficient intracavity frequency doubling of an Yb-doped fiber laser using an internal resonant enhancement cavity[C]. CLEO, 2010, CMW4

7 Tan Yu, Binghua Su, Hongbo An *et al*.. All-fiber laser with narrow line width at 1064 nm[C]. *Am. J. Eng. Technol. Res.*, 2011, **11**(12): 3357～3360

8 Chen Shuang, Wang Ling, Feng Ying. Effects of reflection if fiber end on characteristics of high power fiber amplifier[J]. *High Power Laser and Particle Beams*, 2008, **20**(12): 1997～2000
陈爽, 王珍, 冯莹. 光纤端面反射对高功率光纤放大器特性的影响.[J]. 强激光与粒子束, 2008, **20**(12): 1997～2000

9 G. D. Boyd, D. A. Kleinman. Parametric interaction of focused Gaussian light beams[J]. *IEEE J. Quantum Electronics*, 1968, **4**(5): 353