# 980 nm Yb-doped single-mode fiber laser and its frequency doubling with BIBO

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## ABSTRACT

In this paper, a single-mode 980nm Yb-doped fiber laser was studied carefully in theory and experiment. Based on the theoretical research, we chose an appropriate fiber length of 36.5 cm. In the experiment, by adopting two 0° fiber ends as cavity mirrors, the Yb-doped fiber laser generated a total output power of 1.32 W at 980 nm with the slope efficiency of 75.3%.Through frequency doubling with BIBO crystal, a total output power of 15 mW at 490.8 nm was obtained. Simultaneously, we produced a 980nm Yb-doped single-mode pulse fiber laser pumped by an acousto-optics Q-switched Nd:YAG laser. The pulse fiber laser generated a total average power of 100 mW at 980 nm when the laser pulse was 10 ns at repetition frequency of 16 kHz.

Keywords: fiber laser, CW, Q-switched, 980 nm, frequency doubling

## 1. INTRODUCTION

As higher and higher output power of erbium-doped fiber laser amplifiers are demanded, the high-power high-quality quasi-three-level Yb-doped fiber laser at 980nm which is an important pump source of erbium-doped fiber amplifier becomes one of hot research areas in the field of fiber laser [1]. Besides, frequency doubling laser at 980nm can obtain the blue laser at 490nm [2-4] as the window-band of seawater, which has important applications in communication, atmosphere and underwater exploration of marine resources. It makes the quasi-three-level fiber laser a promising alternative at 980nm and a kind of substitutes for Ar-ion lasers. There are some reports on the research of single-mode Yb-doped fiber lasers at 980nm. 0.65 W of single-mode output at 980 nm from all-fiber laser pumped by a 1.1 W 946 nm Nd:YAG laser was obtained by L. A. Zenteno et al. [5]. A single-mode fiber laser with 2 W CW output at 978 nm pumped by 914 nm Nd:YVO4 laser was produced. By frequency doubling with PPLN, an output power of 83 mW at 489 nm was achieved by A. Bouchier et al. in 2005 [2]. A 980 nm fiber laser using an Yb:Al-doped depressed-clad hollow optical fiber yielded 7.5 W of output power with a relatively bad beam quality ($M^2 \sim 2.7$) [6]. Recently, F. Röser and Johan Boullet reported that the output laser around 980nm emitted up to 94W by adopting rod-type photo crystal fiber [7,8]. A Q-switched 980 nm Yb-doped fiber laser with 250 mW of average output power for repetition rates between 0.2 and 0.65 MHz was presented by S.A.Alam in 2002 [9].

In this paper, we reported on a 980nm CW single-mode fiber laser and a Q-switched 980 nm single-mode fiber laser which were both optimized by choosing a reasonable fiber length. The CW Yb-doped fiber laser emitted 1.32W at 980nm and the Q-switched Yb-doped fiber laser generated an average power of 100mW when the FWHM of the laser pulse was 10 ns at pulse repetition frequency of 16 kHz. A new bulky nonlinear crystal BIBO was utilized to obtain the blue light around 490nm by frequency doubling the 980nm laser. To the best of our knowledge, it was the first time for the CW 980 nm single-mode Yb-doped fiber laser pumped by a 946 nm Nd:YAG laser to produce a power beyond 1 W with a high slope efficiency and for the Q-switched 980 single-mode Yb-doped fiber laser to reach a peak power of 621W. A new bulky nonlinear crystal BIBO was also for the first time applied for frequency doubling the 980 nm single-mode laser.

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## 2. CW 980 NM FIBER LASER

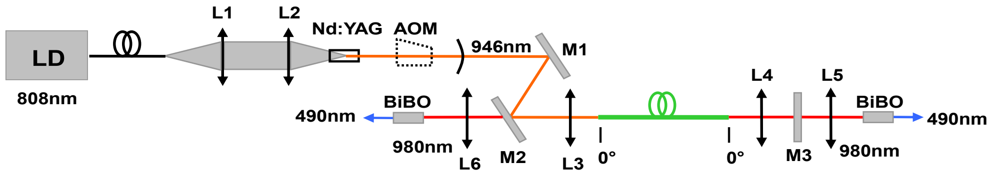


Fig. 1. Experimental set-up of the CW 980 nm single-mode Yb-doped fiber laser (without the AOM) and Q-switched 980 nm single-mode Yb-doped fiber laser (with the AOM)

The experimental set-up was shown in the Figure 1 (without the AOM). The pump source of the fiber laser was the home-made 946nm Nd:YAG laser pumped by a laser diode at 808nm. The Nd:YAG laser emitted a maximum CW output power of 4.23W at 946nm with a slope efficiency of 18.8% for a 23.4W incident pump power at 808nm and the beam profile was nearly diffraction-limited.

The single-mode Yb-doped fiber used in the experiment had a core diameter of 6μm and an absorption coefficient of about 30dB/m for pump light at 946nm. Two fiber ends were ground at 0° angle with 4% Fresnel reflection. As shown in Figure 1, two parallel fiber ends played the role of cavity mirrors and the 980nm laser beam emitted from both ends. The laser was obtained behind the mirror M2 and M3 which were used to filter the residual pump light.

There are two problems that must be resolved for the Yb-doped fiber laser operating at 980 nm. First, it is easier to operate at the four-level transmissions around 1030nm owing to the low threshold and small re-absorption effect. Second, the serious re-absorption effect at 980 nm should be avoided. So selecting an appropriate fiber length is essential for the quasi-three-level Yb-doped fiber laser at 980nm.

The laser gain at 980nm can be obtained by numerically simulating the transcendental equation [10] below:

$$P_p^{in} - P_p^{in}\left(\frac{G_{980}}{G_{max}}\right)^q = P_s^{CS}(\alpha_s L - \ln G_{980}) + P_s^{in}(G_{980} - 1). \tag{1}$$

The relationship between the undesired gain at 1030nm and the laser gain at 980nm in Yb-doped single-mode fiber is deduced [8] $G_{1030} = 0.14G_{980} + 1.1\alpha_p$ where $G_{max}$ accounts for the maximum gain $G_{max} = \exp[(\alpha_p/q\text{-}\alpha_s)\cdot L]$ in which q is the saturation power ratio $q = P_s^{CS}/P_p^{IS}$. $P_p^{in}$ ($P_s^{in}$) is the incident pump (laser) power in the laser cavity and $\alpha_s$ ($\alpha_p$) is the laser (pump) absorption coefficient. $P_s^{IS}$ and $P_s^{CS}$ are the laser intrinsic-saturation power and cross-saturation power respectively. Suppressing the four-level transmissions demands that the unwanted gain at 1030nm less than the laser gain at 980nm.

Based on the rate equations and optics propagation theory in fiber laser [10], the expression of the optimal fiber length for our experiment is derived below by differentiating the laser power with respect to the fiber length:

$$L_{opt} = \frac{1}{\alpha_s q - \alpha_p}\ln\left\{\frac{T_2^2 R_{2p} - 1 + \left[\left(T_2^2 R_{2p} - 1\right)^2 - \dfrac{8T_2^2 R_{2p} P_s^{CS}\alpha_s}{(\alpha_s q - \alpha_p)\cdot P_p^{in}}\right]^{1/2}}{4T_2^2 R_{2p}(TR_s)^{-q}}\right\}. \tag{2}$$

Where the intra-cavity transmissions coefficient are $T_1$, $T_2$ and $T = T_1 \cdot T_2$. $R_{1s}$ ($R_{1p}$) and $R_{2s}$ ($R_{2p}$) are the reflectivity of two cavity mirrors at the laser (pump) wavelength and $R_s^2 = R_{1s}\cdot R_{2s}$.

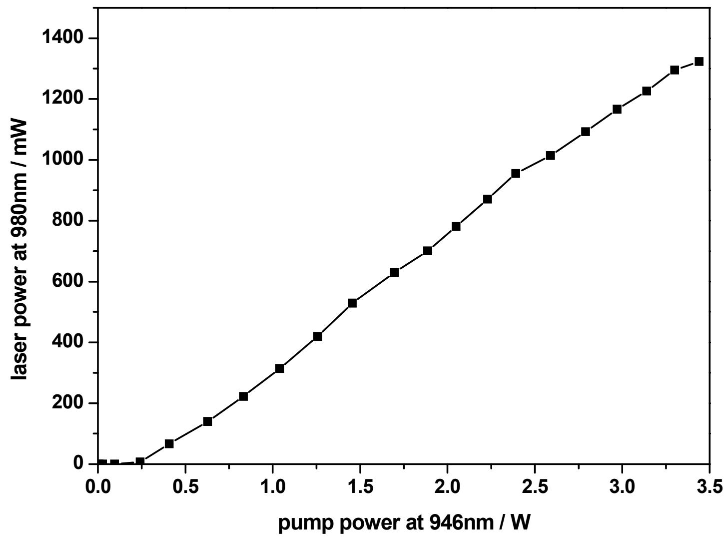


Fig. 2. Output power of the CW 980 nm single-mode Yb-doped fiber laser versus the 946 nm pump power

In the experiment, we chose an appropriate fiber length of 36.5 cm according to the theoretical research. The maximum output power behind the mirror M2 and mirror M3 were 642mW and 681mW respectively. The threshold pump power was 68 mW with the slope efficiency of 75.3%. The beam profile was nearly diffraction-limited with $M^2 \sim 1.1$. The laser power at 980 nm rose almost linearly with the pump power increasing. When the pump power was 3.44 W with the incident power of 2 W into the fiber, the total output power achieved 1.32 W as shown in Figure 2. The laser wavelength ranged from 978 nm to 982 nm with the laser linewidth about 4 nm as shown in Figure 3.

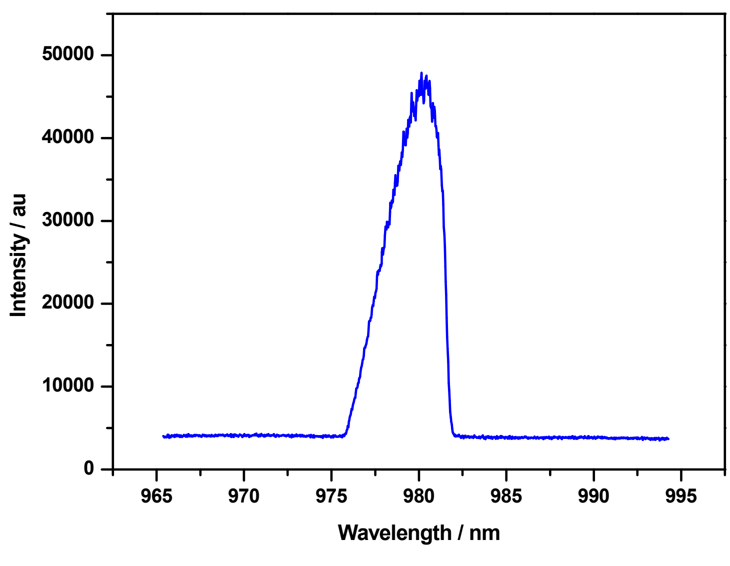


Fig. 3. Spectrogram of the CW 980 nm single-mode Yb-doped fiber laser

## 3. Q-SWITCHED 980 NM FIBER LASER

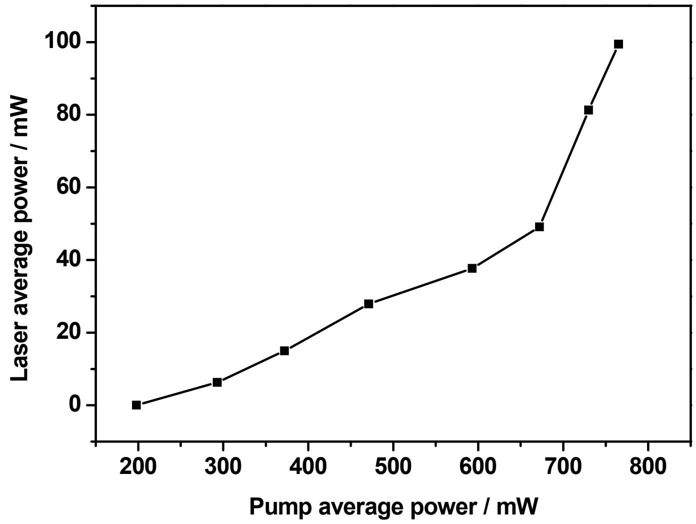


Fig. 4. Output power of the 980 nm Q-switched single-mode Yb-doped fiber laser versus the 946 nm pump power

We added an acousto-optics Q-switched in the cavity of 946 nm Nd:YAG pump laser as shown in Figure 1. The 946 nm pump laser generated an average power of 765mW and the pump coupling efficiency is 42%. The FWHM of the 946 nm pulse laser was 200 ns at pulse repetition frequency of 16 kHz. The cavity configuration was the same as the CW 980 nm fiber laser. The fiber laser generated a total average power of 100 mW at 980 nm at pulse repetition frequency of 16 kHz with the slope efficiency of 38%. The peak power was about 621W with the laser pulse of 10 ns as shown in Figure 5. The laser power at 980nm from each fiber end was almost equal. The linewidth of the laser at 980 nm was 4 nm arranging from 977 nm to 981 nm as shown in Figure 6.

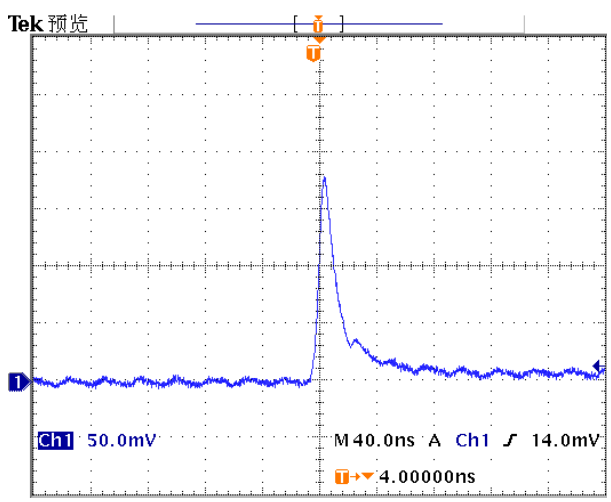


Fig. 5. Temporal behavior of the 980nm pulse laser

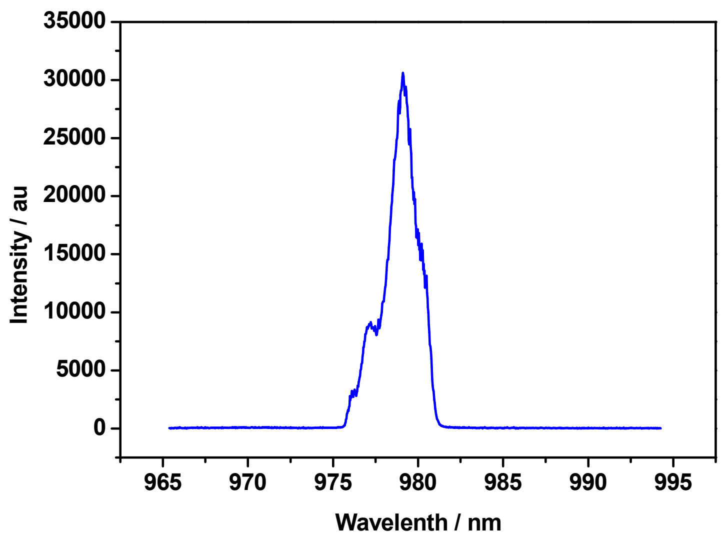


Fig. 6. Spectrogram of the Q-switched 980 nm single-mode Yb-doped fiber laser

# 4. FREQUENCY DOUBLING WITH BIBO

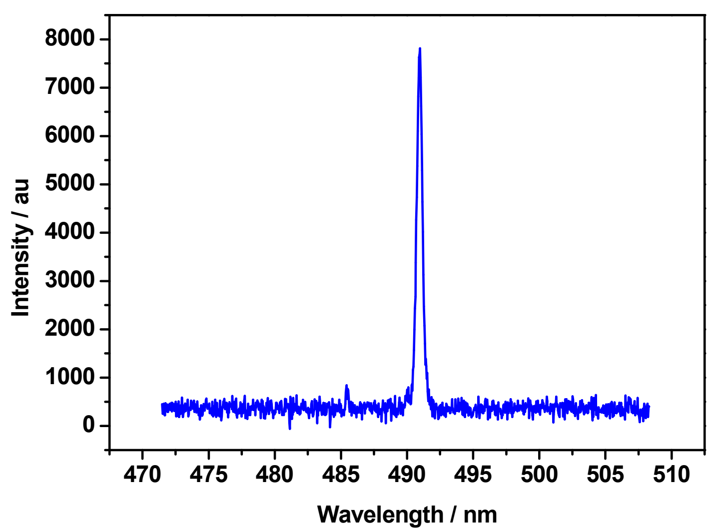


Fig. 7. Spectrogram of blue-green laser obtained by frequency doubling 980nm laser with BIBO

Two 3×3×10mm BIBO crystals were used for frequency doubling the 980nm laser emitting from two fiber sides respectively. BIBO is a sort of novel crystals and its nonlinear optical coefficient ($d_{eff} = 3.24$) is about four times higher than LBO and about 1.6 times higher than BBO. Its walk-off angle, angular and spectral acceptance bandwidths are all appropriate to the experiment. Correspondingly, we chose BIBO crystal for frequency doubling the single-mode laser at 980nm in the experiment. In the CW Yb-doped fiber laser, a total 15mW output power at 490.8nm was finally achieved. Through frequency doubling with BIBO crystals, a blue-green laser source at 490.8 nm was obtained with the linewidth of 0.5 nm as show in Figure

7.

## 5. CONCLUSION

In conclusion, we have demonstrated a CW 980nm single-mode Yb-doped fiber laser and a pulse 980nm single-mode Yb-doped fiber laser with the CW and Q-switched 946 nm Nd:YAG pump laser respectively. The CW Yb-doped fiber laser emitted 1.32W at 980nm and a total 15mW output power at 490.8nm was achieved by frequency doubling with BIBO crystals. The Q-switched Yb-doped fiber laser generates an average power of 100mW with the peak power of 621W. Based on our experiments, it can be concluded that the 980nm Yb-doped fiber laser would be a promising source to obtain the blue-green light.

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