Research on the characteristics of the Q-switched ytterbium-doped fiber lasers

Lin xiang, Yuan xiuhua, Xiong jie, Zhao ming

Huazhong University of Science and Technology, Wuhan National Lab for Optoelectronics, Hubei Wuhan 430074

E-mail: yuanxh@mail.hust.edu.cn

Abstract. Fiber lasers with pulse duration and repetition tuned have great application in space probe. On the basis of typical Q-switched ytterbium-doped double-clad fiber lasers under forward pump, the ion population and propagation equations for both pumping and signal light are presented, and the steady-state solution of inversion ion population, pumping power distribution and signal power distribution due to ASE are studied by the traveling-wave method. Moreover, the effects of fiber-laser parameters such as Yb-doped fiber length, pump power and fiber core diameter on pulse characteristics are analyzed.

1. Introduction
Lasers have great application in space exploration owing to their high angle, long distance, high velocity solution, wide speed range and excellent anti-interference ability, etc. The common lasers used in this area are mostly Nd:YAG lasers and CO\textsubscript{2} gas lasers, which are bulky and heavy, sensitive to vibration and temperature changes. In addition, the attached cooling devices increase the size and quality of the lasers. In the past two decades, the rare earth doped fiber lasers have undergone intense research due to their small size, reliability and high efficiency\textsuperscript{[1-3]}. Fiber lasers in advantage of double-clad ytterbium-doped structures have been extensively studied\textsuperscript{[4,5]}. The most appropriate laser source for space debris detection requires low output pulse repetition rate and pulse duration tunable properties. The pulse repetition frequency generally decided by the processing capacity of the system and the detection range. Moreover, the influence of the atmosphere should be considered. Therefore, studying the output characteristics of the fiber laser has further significance for space exploration.

2. Model
A typical end-pumped Q-switched fiber laser is shown in Fig 1, the pump output power and the signal output separate through the beam splitter(SP) in the left. Acousto-optic Q switch(AOQS) is in the right. The left mirror M1 is cut fiber facet with a reflection about 4% in the signal frequency. Suppose the Yb-doped fiber is much longer than the other fiber. The modulation of the right mirror reflection R2 is achieved by the AOQS. R2 is zero when the switch off while 0.45 when the switch on. Suppose all the mirrors are transparent for the pump light. Fig 2 shows the energy lever diagram of ytterbium ions.
When analyzing the process of the laser generation it is necessary to derive the value of the pump power $P_p(x)$, the right-moving signal power $P_s^+(x)$, the left-moving signal power $P_s^-(x)$ and the ion population inversion. The upper level ion population $N_2(x)$ and the lower level ion population $N_1(x)$ satisfy the equation $N_2(x)+N_1(x)=N$, where $N$ is the total ion population. Those can be derived from the following steady-state equations\(^6\):

\[ \frac{P_p(x)\sigma_{ap}\Gamma_p}{h\cdot v_p\cdot A} + \frac{(P_s^+(x) + P_s^+(x))\sigma_{as}\Gamma_p}{h\cdot v_s\cdot A} \right] N_1(x) - \frac{P_p(x)\sigma_{ap}\Gamma_p}{h\cdot v_p\cdot A} + \frac{(P_s^+(x) + P_s^+(x))\sigma_{es}\Gamma_p}{h\cdot v_s\cdot A} + \frac{1}{\tau} = 0 \]  

(1)

\[ \frac{dP_p(x)}{dx} = -\Gamma_p\{\sigma_{sp}\cdot N_2(x) - \sigma_{ap}\cdot N_1(x)\} P_p(x) - \alpha_p P_p(x) \]  

(2)

\[ \pm \frac{dP_s^\pm(x)}{dz} = \Gamma_s (\sigma_{es}\cdot N_2(x) - \sigma_{as}\cdot N_1(x)) \cdot P_s^\pm(x) + \]  

(3)

\[ \Gamma_s \cdot N_2(x)\sigma_{es} \cdot 2n_m h c^2 \Delta \lambda_s / \lambda_s^3 - \alpha_s P_s^\pm(x) \]

In the above equations, $\sigma_{ap}$, $\sigma_{sp}$ are pump power absorption and emission cross section, respectively; $\sigma_{as}$, $\sigma_{es}$ are signal power absorption and emission cross section, respectively; $\Gamma_p$, $\Gamma_s$ are the pump power and the signal power filling factors, respectively; $A$ is the core area; $h$ is Planck’s
constant; $\tau$ is the upper level ion lifetime; $h\nu p$ is the pump power photon energy; $\alpha_p$, $\alpha_s$ are the pump and signal loss factors, respectively. In order to effectively derive the approximate analytical solutions, it is necessary to make some simplification. Suppose that pump power is uniformly distributed in the cross section, $\Gamma p$ can be expressed as $\Gamma p = A / A_i$, $A_i$ is the inner cladding cross section area. Take the boundary conditions as follow into account:

$$P s^+ (0) = R 1 \times P s^- (0)$$  

(4)

$$P s^- (L) = R 2 \times P s^+ (L)$$  

(5)

$$P p (0) = W_0$$  

(6)

Where $W_0$ is the end pump power, $L$ is the fiber length. When the Q switch is on, $R2$ becomes 0.45 from 0 in about 300 nanoseconds.

### 3. Simulations and analysis

According to the mathematical model mentioned above, we use iterative algorithm to simulate the output characteristics of Q-switched fiber laser. Moreover, the laser structure and parameters’ influence on the output are analyzed. The related parameters are shown in Table 1. The initial steady state value of the inversion population, pump power and signal power are shown in Figure 3.

#### Table 1. The parameter used in the simulation

| Parameter | value |
|-----------|-------|
| $\sigma_{ap}$ | $3 \times 10^{-21} \text{cm}^2$ |
| $\sigma_{as}$ | $1.4 \times 10^{-23} \text{cm}^2$ |
| $n$ | 1.45 |
| $\Gamma s$ | 0.75 |
| $\tau$ | 1ms |
| $R$ | $8 \mu\text{m}$ |
| $N$ | $4 \times 10^{19} \text{cm}^{-3}$ |
| $\sigma_{es}$ | $2.5 \times 10^{-21} \text{cm}^2$ |
| $\lambda s$ | 940nm |
| $\lambda p$ | 1080nm |
| $L$ | 5 m |
| $W_0$ | 5W |
| $Rcl$ | 200$\mu\text{m}$ |
| $\alpha_s$ | $5 \times 10^{-5} \text{cm}^{-1}$ |

It is seen that in Fig.3(a) the inversion populations distribute nearly uniform when the pump power are 15W and 25W, whereas in the 35W case it has a dramatic decline at the right end. The reason for those can be seen in Fig.3(c), which indicates the spontaneous emission noise is extremely high at the right end. From Fig.3(b) it is obvious that the pump powers are not completely absorbed by the fiber laser.

Take it into consideration that the laser operates in a single transverse mode, when the Q switch process starts, Fig.4 shows the variation of the pulse duration and energy with pump power. It is seen
that the pulse energy changes linear with the pump power; whereas the variation relationship between the pulse duration and pump power is more complicated, when the pump power is larger than the threshold, the pulse duration increased due to the fluorescence, and pump power increased, the net cavity gain coefficient becomes larger and larger, the raise of photon and the decrease of the inversion populations are much faster, the front and rear of the pulse contract ,making the pulse duration reduced and eventually to be a constant that is the photon lifetime of the cavity.

Figure 3 Steady-state solution of a fiber laser at three pump power levels at switch off
Figure 4. Pulse duration versus pump power

Figure 5. Pulse duration versus Yb-doped fiber length
Fig 5 shows the influence of the fiber length on the output pulse. The distribution of the pump power becomes uneven because the different distance from the pump source as the fiber length increases. So the pulses generate at times along the different position in the Yb-doped fiber, resulting in the multiple pulse overlap, and at last broaden. The pulse energy are decided by the absorption of the pump and signal power, as a result there is an optimal length, making the maximum output pulse energy.

Fig 6 illustrates the pulse duration and energy vary with the core diameter. As the core diameter increases, the uniform distribution of the pump power spoils and broaden the duration. The higher the absorption efficiency of the core, the greater signal power loss in the fiber core, so the variation of the pulse energy depends on the interaction of both.

![Figure 6. Pulse width versus core diameter of fiber](image)

4. Conclusion
The improvement of output characteristics of the Q-switched fiber laser mainly focus on the pulse duration and energy. Output pulse characteristics relate with the initial parameters once the fiber laser running at its best, therefore the choice of parameters is completely crucial. Increasing pump power, reducing the rare-earth doped fiber length and decreasing the fiber core diameter are beneficial for short pulse duration. Unfortunately, those above are negative for improving the pulse energy. Therefore, it should be integrated to measure the impact of each parameter to determine the whole system.

Reference
[1] J.Kirchhof, T.Sandrock, A.Harschak. 1.3kW Yb-doped fiber laser with excellent beam quality. CLEO,2004,CPDD2
[2] Gapontsev ,V Gapontsev D,Platonav N,et al. 2kW CW ytterbium fiber laser with record diffraction-limited brightness. CLEO. 2005, 508
[3] DingWei Huang,WenFung Liu,Yang C.C.Q-switched all-fiber laser with an acoustically
modulated fiber attenuator. IEEE Photonics Technology

[4] Letters,2000,12(9):1153-1155

[5] H.M.Pask,J.L.Archambault,D.C.Hanna,et al . Operation of cladding-pumped Yb3+-doped silica fiber lasers in the 1um region. Electron. Lett. 1994,30,11:863-864

[6] H. Po, J. D. Cao, B. M. Laliberte, R. A. Minns, R. F. Robinson, B. H. Rockney, R. R. Tricca, and Y. H. Zhang, “High power neodymium-doped single transverse mode fibre laser,” Electron Lett. 29, 1500-1501

[7] Yanming Huo, Robert T. Brown, George G. King, et al. Kinetic modeling of Q-switched high-power ytterbium-doped fiber lasers. APPLIED OPTICS, Vol. 43, No. 6:1404-1411