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Effective methods to improve pulse energy of Q-switched fiber laser

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The Q-switched fiber lasers are very attractive sources in many applications such as military affairs, surgical operation, laser machining, laser marking, nonlinear frequency conversion, range finding, remote sensing and optical time domain reflectometer. To improve the pulse energy of Q-switched fiber laser is what we pursue. In this paper, certain effective methods to improve the pulse energy are presented, with their theoretical basis clarified, which may be helpful to the design of the kindred Q-switched fiber lasers.

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1. Introduction

The Q-switched fiber lasers have many merits, which include high peak power, high pulse energy, high conversion efficiency, excellent beam quality, simple cavity construction, small volume, low cost and fiber-coupled output etc [1-4]. They are very attractive sources because of their wide applications such as military affairs, surgical operation, laser machining, laser marking, nonlinear frequency conversion, range finding, remote sensing and optical time domain reflectometer [1-2]. Recently, the Q-switched double-clad fiber lasers with high pulse energy are preferred thanks to their nice character [5,6]. To improve the pulse energy of Q-switched fiber laser is the goal that we pursue. In this paper, on the base of accurate calculation, we put forward some effective methods that can be used to improve the pulse energy of Q-switched fiber laser, with the related theoretical basis clarified. At the same time, the negative consequences of these methods are to some extent illustrated. In what follows, we will demonstrate the methods of improving the pulse energy through an example of an Yb^{3+}-doped Q-switched double-clad fiber laser pumped by a diode-laser. The analysis in this paper, which is the continuity of our earlier works [7-8], may be helpful to the design of kindred fiber lasers, as is expected.

2. Basic theory

As shown by Gaeta [9], if the relaxation oscillation was neglected, the pulse energy of Q-switched fiber lasers is described as

$$E = h\nu_s \cdot \frac{T}{\delta} \cdot \left(n_{in} - n_f\right) \ . \tag{1}$$

$h\nu_s$ is the signal photon energy. T is the output transmittance. δ is the high-Q-cavity round-trip loss. n_{in} is the initial particle inversion at the beginning of the Q-switched pulse. n_f is the final particle inversion remaining at the end of the Q-switched pulse. The relation between n_{in} and n_f can be described as

$$n_f / n_{in} = 1 + (n_t / n_{in}) \cdot \ln(n_f / n_{in}) \ , \tag{2}$$

where n_t is the particle inversion at threshold, which is equal to the inversion required to reach threshold in the CW case with the cavity loss equal to the loss of high-Q value cavity. Equation (2) may be the means of solving n_f when n_{in} and n_t are given.

In addition, the theoretical formulas of n_t and n_{in} are respectively described as

$$n_t = \frac{\delta}{2\sigma}\frac{A}{F_1}, \ \ n_{in} = \left(\frac{\tau_s}{h\nu_p}\right) P_{abs} \ .$$

σ is the stimulated emission cross section. $A = \pi d^2 / 4$ is the cross-section area of the fiber core, in which d is the fiber core diameter. F_1 is a dimensionless overlap coefficient introduced in the analysis of CW fiber laser [10], which describes the overlap between the signal mode and the pump mode. τ_s is the lifetime of the upper laser state. $h\nu_p$ is the pump photon energy. $P_{abs} = \left(1 - \exp(-\alpha_a L)\right) P_{in}$ is the amount of pump power absorbed by the laser medium, in which P_{in} is the pump power coupled into the fiber; α_a, the effective absorption coefficient at the pump wavelength. Besides, δ can be $\delta = 2\alpha_s L - \ln(1-T)$, in which L is the length of the fiber; α_s, the loss coefficient at the signal wavelength. The constants used in calculations are as follows [7-8], λ_p = 975 nm, σ = 3.5 × 10^{-24}m^2, τ_s = 770 μs, α_a = 0.691 m^{-1}, α_s = 0.0092 m^{-1}.

n_{in} and n_t can be determined by the pump power and the initial constants, but n_f can only be worked out via equation (2). Apparently, it is a key to solve equation (2) accurately, but to obtain the analytic solution of equation (2) is difficult. It is necessary to obtain the numerical solution by using the computer. Subsequently, we will adopt a new idea to solve equation (2) in order to reduce the calculation time. Now, we define the energy utility ratio $\mu = 1 - n_f / n_{in}$. The law that μ depends on n_{in} / n_t is shown in Fig. 1. According to Fig. 1: the greater n_{in} / n_t is, the higher μ will become. When n_{in} / n_t is 6.0, the energy utility μ is about 99.7%, that is to say, n_f / n_{in} is about 0.3, which can be regarded as zero. From the above analysis, it only needs to obtain the numerical solution under the condition that $1.0 < n_{in} / n_t < 6.0$. In other cases, for example, when $n_{in} / n_t \geq 6.0$, we can regard $n_f = 0$ as the solution of equation (2), and the situation that $n_{in} / n_t \leq 1.0$ does not conform to reality.

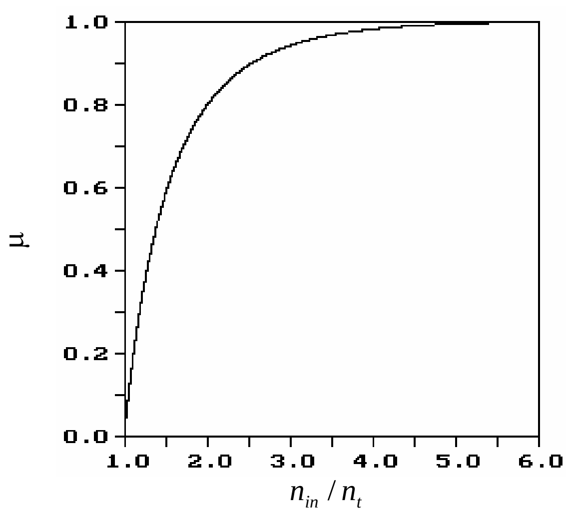

Fig. 1. Energy utility ratio as a function of initial particle inversion.

Next, we will design a program by using C language to solve equation (2). At the same time, using equation (1), we will discuss the characteristic that the pulse energy depends on the pump power, the fiber core diameter, the fiber length, the output transmittance and the fiber inherent loss on the basis of the above theories. Amid the discussions, under any circumstances that n_f is needed, we will never forget to solve equation (2) by adopting the above scheme. Meanwhile, the methods of improving the pulse energy are presented.

3. Methods to improve pulse energy

3.1. Enhancing pump power

The pump power is one of the factors that influence the pulse energy. Fig. 2 shows that the pump power influences the pulse energy. As is shown in Fig. 2, the pulse energy will increase linearly with the enhancement of the pump power. Perhaps this is a general law for all the Q-switched lasers. Moreover, with the enhancement of the pump power, as we expect, the peak power will also increase, and the pulse width narrows. The values of some constants used in this section are as follows, d = 20 μm, L = 6.0 m, T = 40%, α_s = 0.0092 m^{-1}.

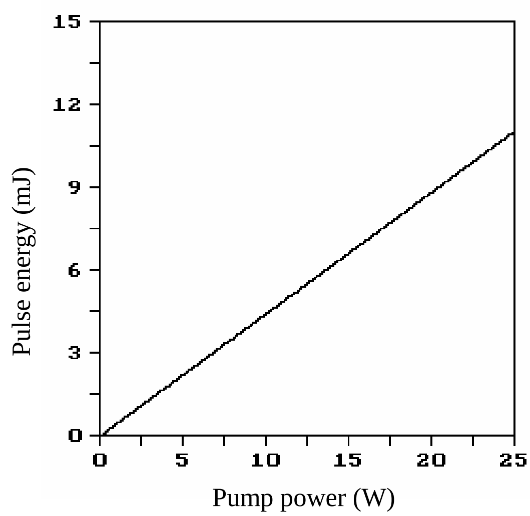

Fig. 2. Pulse energy as a function of pump power.

3.2. Decreasing fiber core diameter

The fiber core diameter is another factor that influences the pulse energy. The close relation between the pulse energy and the fiber core diameter is shown in Fig. 3: the pulse energy will increase slightly in case of decreasing the fiber core diameter (from 30 μm to 10 μm) because the particle inversion at threshold decreases. Although decreasing the fiber core diameter makes the pulse energy higher, the signal power density will increase obviously. Therefore, the fiber core diameter should not be too thin so that it cannot endure the intensity of signal power when the pulse energy has satisfied the requirement. The values of some constants used here are as follows,

P_{in} = 6.0 W, L = 6.0 m, T = 40%, α_s = 0.0092 m^{-1}.

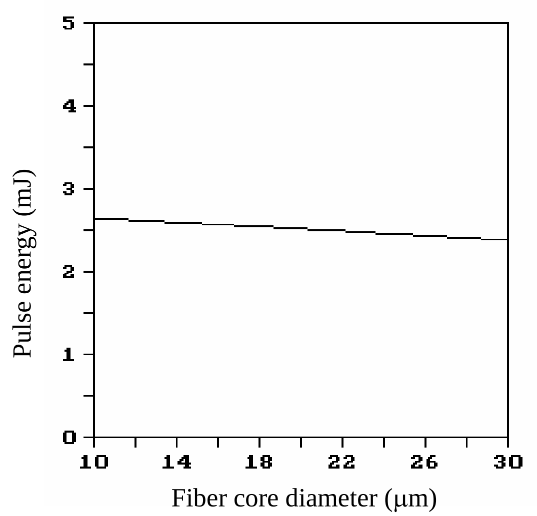

Fig. 3. Pulse energy as a function of fiber core diameter.

3.3. Calculating the optimal fiber length

Because of the inherent loss of the fiber, the pulse energy depends on the pump absorption and the signal loss. So there is an optimal fiber length which makes the pulse energy maximum when the pump power is definite. In this case, in order to obtain the highest pulse energy, the fiber length should be appropriate. Fig. 4 shows the law that the fiber length influences the pulse energy. From Fig. 4, the pulse energy reaches a peak at an optimal fiber length of about 4 m. The values of some constants used in this section are as follows, P_{in} = 6.0 W, d = 20 μm, T= 40%, α_s = 0.0092 m^{-1}.

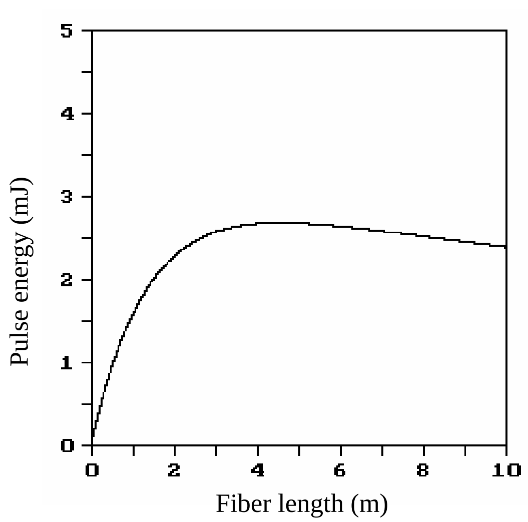

Fig. 4. Pulse energy as a function of fiber length.

3.4. Ascertaining the suitable output transmittance

The output transmittance, which can be looked on as a part of the cavity round-trip loss, is also an important factor that influences the pulse energy. As Fig. 5 shows, just as calculating the suitable fiber length described in section 3.3, the output transmittance should be also appropriate. If the output transmittance is too small, the pulse energy can not be released in time. If the output transmittance is too large, the signal feedback will be relatively lower. That is to say, the output transmittance has an optimal value which makes the pulse energy highest. But the optimal output transmittance probably makes the pulse width and the signal linewidth not well. Note that the greater the output transmittance is, the narrower the pulse width will be. In this sense we think that it is inappropriate to select the too small output transmittance. On the other hand, too large output transmittance will lead to the wider signal linewidth. Probably an eclectic scheme should be taken into account. The values of some constants used in this section are as follows, P_{in} =6.0 W, d =20 μm, L = 6.0 m, α_s = 0.0092 m^{-1}.

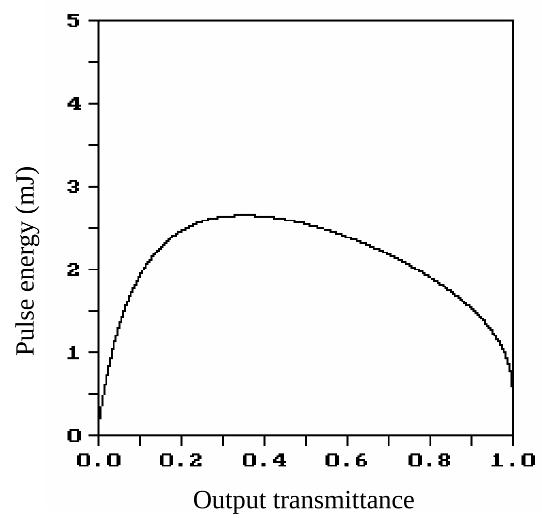

Fig. 5. Pulse energy as a function of output transmittance.

3.5. Selecting fiber with less inherent loss

The inherent loss, which can be part of the cavity round-trip loss, is expressed as $2\alpha_s L$. The influence of the inherent loss on the pulse energy is similar to that of the output transmittance. Fig. 6 indicates that the pulse energy will enhance significantly with the drop of the inherent cavity loss. Of course, the smaller the inherent loss is, the wider the pulse width will be. In some circumstances, selecting fiber with less inherent loss at the cost of widening the pulse width is possibly worthy. The values of some constants used here are as follows, P_{in} =6.0 W, d =20 μm, L = 6.0 m, T = 40%.

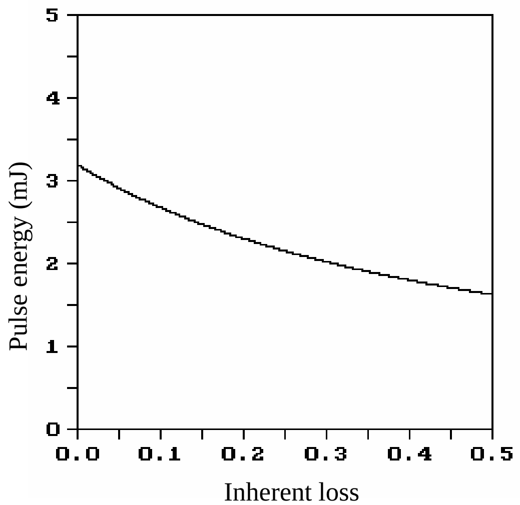

Fig. 6. Pulse energy as a function of inherent loss.

4. Conclusions

In conclusion, certain effective methods to improve the pulse energy are introduced, with their theoretical basis clarified, which may be helpful to the design of the kindred Q-switched fiber lasers. Generally, it is necessary to adopt the above methods simultaneously to improve the pulse energy. But sometimes the optimal determination of the pulse energy cannot make the other output performances optimum. In order to optimize a Q-switched fiber laser, an eclectic consideration is perhaps required when we improve the pulse width intentionally. On all accounts, to improve pulse energy is merely one aspect of designing a Q-switched fiber laser, and to improve the peak power and to narrow the pulse width and so on are also the goals we pursue. The key point of designing a Q-switched fiber laser is to consider all the aspects comprehensively, in which to improve the pulse energy is always an important issue.

References

[1] Y. X. Fan, F. Y. Lu, S. L. Hu, K. C. Lu, H. J. Wang, X. Y. Dong, G. Y. Zhang, IEEE Photonics Technology Letters **15**(5), 652 (2003).
[2] Y. Wang, A. Martinez-Rios, H. Po, Optics Communications **224**, 113 (2003).
[3] D. Savastru, S. Miclos, R. Savastru, J. Optoelectron. Adv. Mater. **7**(4), 1909 (2005).
[4] X. Yu, P. Shum, J. Optoelectron. Adv. Mater. **7**(6), 3185 (2005).
[5] A. Piper, A. Malinowski, K. Furusawa, D. J. Richardson, Electronics Letters **40**(15), 928 (2004).
[6] C. C. Renaud, R. J. Selvas-Aguilar, J. Nilsson, P. W. Turner, A. B. Grudinin, IEEE Photonics Technology Letters **11**(8), 976 (1999).
[7] L. J. Shang, J. P. Ning, G. F. Fan, Z. Q. Chen, Q. Han, H. Y. Zhang, J. Optoelectron. Adv. Mater. **8**(1), 359 (2006).
[8] L. J. Shang, J. P. Ning, G. F. Fan, Z. Q. Chen, Q. Han, H. Y. Zhang, J. Optoelectron. Adv. Mater. **8**(2), 851 (2006).
[9] C. J. Gaeta, M. J. F. Digonnet, H. J. Shaw, Journal of Lightwave Technology **LT-5**(12), 1645 (1987).
[10] M. J. F. Digonnet, C. J. Gaeta, Applied Optics **24**(3), 333 (1985).

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