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Effective methods to narrow pulse width 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 narrow the pulse width of Q-switched fiber laser is what we pursue. In this paper, certain effective methods to narrow the pulse width 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 [1-5]. 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 narrow pulse width are preferred thanks to their nice character [2,3]. To narrow the pulse width 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 narrow the pulse width 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 narrowing the pulse width through an example of an Yb^{3+}-doped Q-switched double-clad fiber laser pumped by a diode-laser. The analysis in this paper may be helpful to the design of kindred fiber lasers, as is expected.

2. Basic theory

As Gaeta [6] holds, if the pulse was a triangular temporal shape, the pulse width of Q-switched fiber lasers is described as

$$\Delta t = \tau_c \frac{n_{in} - n_f}{n_t \ln \frac{n_t}{n_{in}} - (n_t - n_{in})} . \qquad (1)$$

$\tau_c = 2Ln / c\delta$ is the lifetime of the photons in the cavity, in which L is the length of the fiber; n, the refractive index of the active medium to signal light; c, the velocity of light in free space; T, the output transmittance; δ, the high-Q-cavity round-trip loss. 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. 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 theoretical formulas of n_t and n_{in} are respectively described as

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

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 [7], 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. $P_{abs} = (1 - \exp(-\alpha_a L))P_{in}$ 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 $\delta = 2\alpha_s L - \ln(1-T)$, and α_s is the loss coefficient at the signal wavelength. The constants used in calculations are as follows [8], $\lambda_p = 975nm$, $\sigma = 3.5\times10^{-24} m^2$, $\tau_s = 770\mu s$, $\alpha_a = 0.691 m^{-1}$, $n = 1.49$, $\alpha_s = 0.0092 m^{-1}$.

In addition, the relation among n_{in}, n_t and n_f can be described as

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

which may be the means of solving n_f when n_{in} and n_t are given.

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.

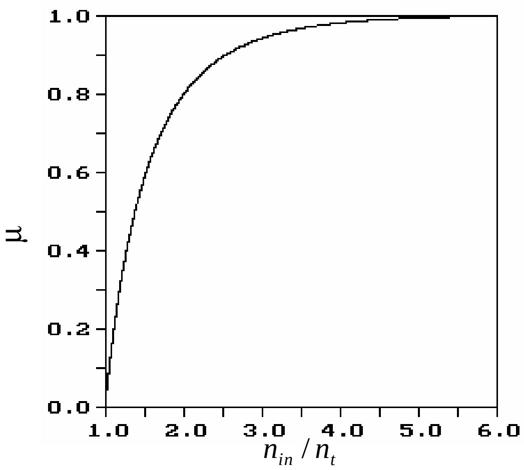

Fig. 1. Energy utility ratio as a function of initial particles inversion.

Next, we will design a program by using C language to solve equation (2). Using equation (1), we will discuss the characteristic that the pulse width 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 narrowing the pulse width are presented.

3. Methods to narrow pulse width

3.1. Enhancing pump power

The pump power is one of the factors that influence the pulse width. Fig. 2 shows that the pump power influences the pulse width. As is shown in Fig. 2, when the pump power is near the pumping threshold, due to the obvious fluorescent effect, the pulse width is wide. But with the enhancement of the pump power, the net gain coefficient increases, so the increase of photons and the decrease of inversion particles are both rapid. As a result, the time of establishing and extinguishing the pulse is shortened, so the pulse width narrows. According to the laser theory, the pulse width will tend toward a constant that is the lifetime of the photons in the cavity. 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}.

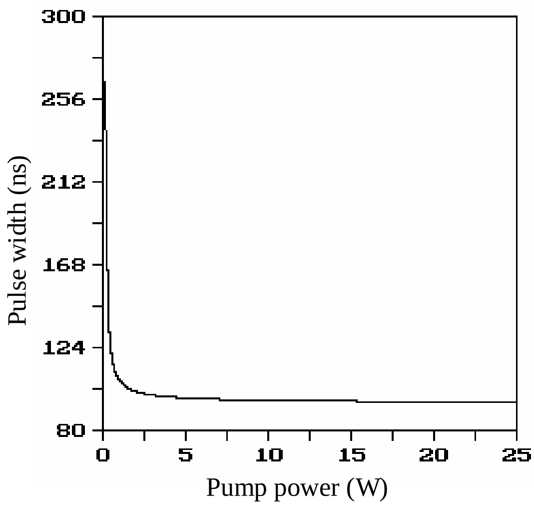

Fig. 2. Pulse width as a function of pump power.

3.2. Decreasing fiber core diameter

The fiber core diameter is another factor that influences the pulse width. The close relation between the pulse width and the fiber core diameter is shown in Fig. 3: the pulse width will narrow slightly in case of decreasing the fiber core diameter because the non-homogenization of the pump photon distribution decreases. Although decreasing the fiber core diameter makes the pulse width narrow, the signal power density will increase obviously. Therefore, the fiber core diameter should not be too thin to endure the intensity of signal power when the pulse width 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}.

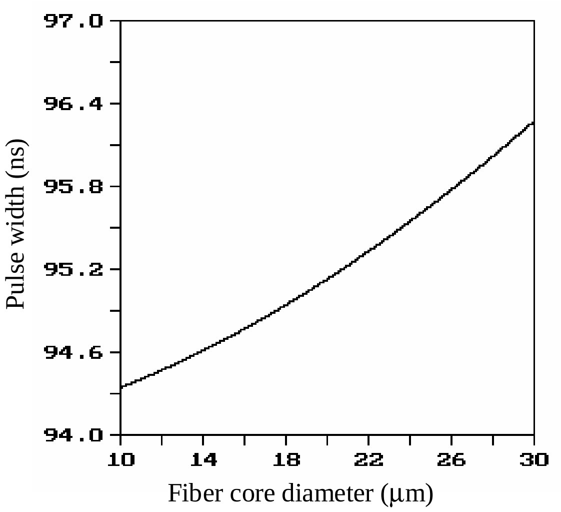

Fig. 3. Pulse width as a function of fiber core diameter.

3.3. Shortening fiber length

Shortening the fiber length can narrow the pulse width markedly. Fig. 4 shows the law that the fiber length influences the pulse width. With the lengthening of the fiber, just as increasing the fiber core diameter described in section 3.2, the non-homogenization of the pump photon distribution increases, and it makes the time of establishing the pulse in different position of active medium different. In this case, the output pulse is the combination of multi-pulses; hence the pulse width widens. From above, in order to narrow the pulse width, the fiber length should not be too long. 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}.

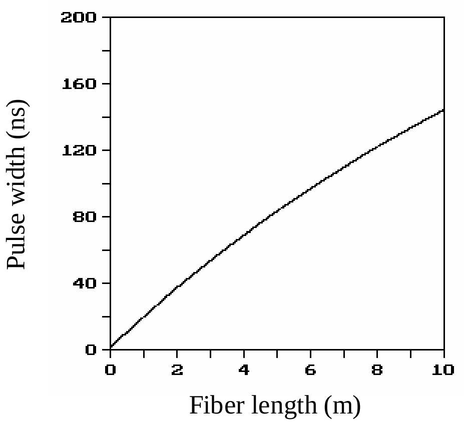

Fig. 4. Pulse width as a function of fiber length.

3.4. Increasing 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 width. As Fig. 5 shows, increasing the output transmittance is to increase the cavity round-trip loss, which makes the photon lifetime short. The pulse width hereby narrows. But the transmittance can't be 100%; otherwise the signal pulse can't be formed. Note that the greater the output transmittance is, the wider the signal linewidth will be. In this sense we think that it is inappropriate to select the too large output transmittance. 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}.

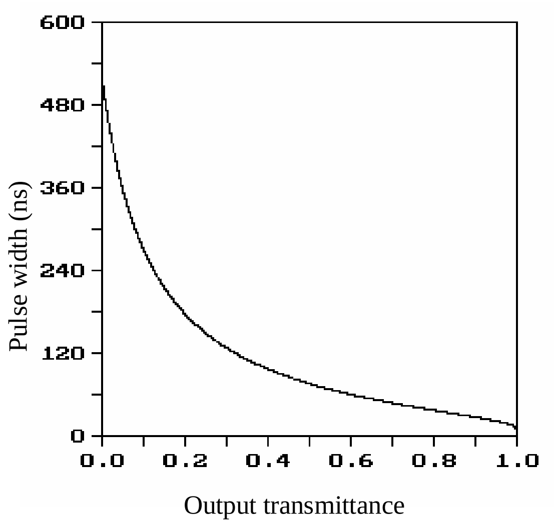

Fig. 5. Pulse width as a function of output transmittance.

3.5. Selecting fiber with larger 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 width is similar to that of the output transmittance. Fig. 6 indicates that the pulse width will narrow significantly with the increase of the inherent cavity loss. Of course, the larger the inherent loss is, the smaller the peak power and the pulse energy will be. In some circumstances, selecting fiber with large inherent loss at the cost of reducing the peak power and the pulse energy is generally 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 %.

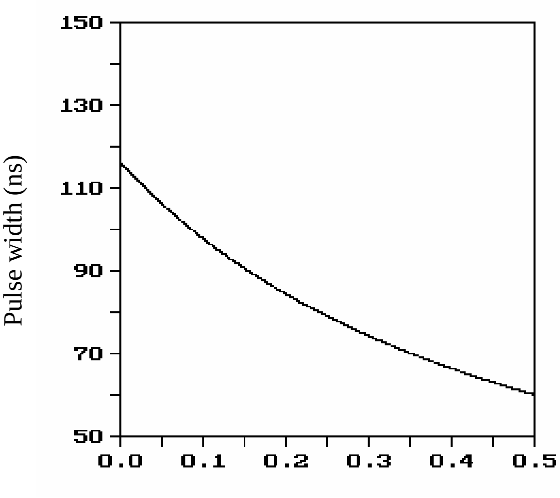

Fig. 6. Pulse width as a function of inherent loss.

4. Conclusions

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

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