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An useful analysis of selected parameters for the double-clad all-fiber laser with continuous wave

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The double-clad fiber lasers are very attractive sources in many applications such as military affairs, biomedicine, industry, nonlinear frequency conversion, remote sensing and space communication. In order to optimize the structure of a double-clad fiber laser, we should think carefully about the problems of selecting the optimal parameters of the fiber cavity. In this paper, the output performance of a double-clad fiber laser is theoretically analyzed, which may be helpful to the design of the kindred double-clad fiber lasers. This paper also offers a personalized scheme for designing a double-clad fiber laser, with the influence of several important parameters on the output power clarified.

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Keywords: Double-clad, Fiber laser, One-end output, Numerical simulation

1. Introduction

The double-clad fiber lasers (DCFL) have many merits, which combine high conversion efficiency, excellent beam quality, simple cavity construction, small volume, low cost and fiber-coupled output etc. DCFL are very attractive sources [1-6] in many applications such as military affairs, biomedicine, industry, nonlinear frequency conversion, remote sensing and space communication [7]. In order to optimize the structure of a double-clad fiber laser, we should think carefully about the problems of selecting the parameters of the fiber cavity. In this paper several important parameters are theoretically analyzed, and the parameters' optimal values are worked out. This paper also offers the design steps of the DCFL. In what follows, we will illustrate the process of the analyses through an example of an Yb^{3+}-doped double-clad fiber laser end-pumped by a diode-laser.

2. Theoretical basis

Presently, there are various theoretical models [8-9] which can describe the performance of the DCFL. One of the representative models was developed by Digonnet [9]. The conceptual configuration of the double-clad fiber laser is shown in Fig. 1. The R_1 and R_2 are respectively the pump end reflectivity and the output end reflectivity of the fiber resonant cavity. The P_{in} and P_{out} are respectively the input pump power and the signal output power. According to the theory of the laser's rate equations [9-10], the governing equations of the forward power $P^+(z)$, backward power $P^-(z)$ and the gain factor $\gamma(z)$ along the fiber laser cavity are respectively described as

$$\frac{dP^+(z)}{dz}=+\frac{\sigma_s\tau_f}{h\nu_p}\alpha_a P_{in}e^{-(\alpha_a+\alpha_p)z}\frac{F_p}{A_f}\cdot\frac{P_0+P^+(z)}{1+(P^+(z)+P^-(z))/P_s}-\alpha P^+(z) \tag{1}$$

$$\frac{dP^-(z)}{dz}=-\frac{\sigma_s\tau_f}{h\nu_p}\alpha_a P_{in}e^{-(\alpha_a+\alpha_p)z}\frac{F_p}{A_f}\cdot\frac{P_0+P^-(z)}{1+(P^+(z)+P^-(z))/P_s}+\alpha P^-(z) \tag{2}$$

$$\gamma(z)=\frac{\sigma_s\tau_f}{h\nu_p}\alpha_a P_{in}e^{-(\alpha_a+\alpha_p)z}\frac{F_p}{A_f}\cdot\frac{1}{1+(P^+(z)+P^-(z))/P_s} \tag{3}$$

where z is the coordinate axis of one dimension coordinates system whose origin is the left end of the fiber. σ_s is the stimulated emission cross section. τ_f is the fluorescent life of active medium. $h\nu_p$ is the pump photon energy. α_a is the effective absorption coefficient at the pump wavelength. α_p is the loss coefficient of the fiber at the pump wavelength accounting for all loss mechanisms other than the resonant absorption described by α_a. F_p is a dimensionless spatial overlap coefficient between the pump mode and the signal mode. $A_f=\pi d^2/4$ is the cross-section area of the fiber core, in which d is the fiber core diameter. α is the loss factor of the signal mode in the fiber core. $P_0=h\nu_s(\pi\Delta\nu_s/2)$ is the power associated with one photon in the gain bandwidth $\Delta\nu_s$, in which $h\nu_s$ is the signal photon energy. $P_s=(h\nu_s/\sigma_s\tau_f)A_f$ is a saturation output power. The values of the parameters used in the calculation are as follows, pump wavelength $\lambda_p=975nm$, signal wavelength $\lambda_s=1086nm$, $\sigma_s=3.5\times10^{-24}m^2$, $\tau_f=600\mu s$,

$\alpha_a = 0.46m^{-1}$, $\alpha_p = 0.004m^{-1}$, $\alpha = 0.0046m^{-1}$, $F_p = 0.8$, $\Delta\lambda = 0.33nm$, $P_0 = 2.4\times10^{-8}W$.

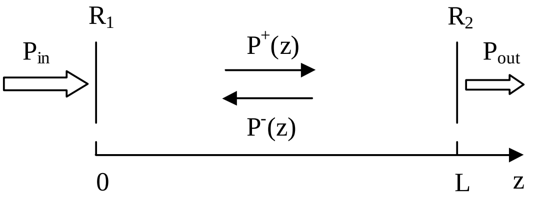

Fig.1. The conceptual configuration of the double-clad fiber laser.

The initial values of $P^+(0)$ and $P^-(0)$ are needed to solve the equations (1) and (2). The steps for numerical calculation are as follows. Firstly, we initialize $P^+(z)$ and give it an initial value $P^+(0)$, so that the initial value of $P^-(z)$ is $P^-(0)$ whose value is equal to $P^+(0)/R_1$ accordingly. Secondly, we design a program by using C language to solve the two equations, and find the $P^+(L)$ and $P^-(L)$. Thirdly, we judge the correctness of the $P^+(0)$ and $P^-(0)$ by using the boundary condition $P^+(L) = P^-(L)/R_2$. Fourthly, we change the $P^+(0)$ and $P^-(0)$ until the $P^+(L)$ and $P^-(L)$ obtained from the numerical calculation satisfy the boundary condition. Fifthly, we solve the two equations anew by using the true $P^+(0)$ and $P^-(0)$ obtained from the above four steps. Sixthly, we obtain the power $P^+(L)$ and $P^-(L)$ from the fifth step through the numerical calculation, and know that $P_{out}= P^+(L)-P^-(L)$.

According to the equations (1) and (2), Fig. 2 shows the forward and backward power distribution inside the fiber. Fig. 2 also shows the evolution of the gain factor along the fiber correspondingly. Some concrete parameters been used during the calculating are as follows, P_{in}=80 W, L=15 m, d=20 μm, R_1=1, R_2=0.04. Subsequently, we will discuss the characteristic that the output power depends on the fiber core diameter, the fiber length and the reflectivity R_2 on the basis of the above numerical calculation. Meanwhile, we only discuss the case of one-end output, that is to say R_1=1. During the numerical calculation, we will never forget judging the initial values $P^+(0)$ and $P^-(0)$ under any circumstances by adopting the above scheme.

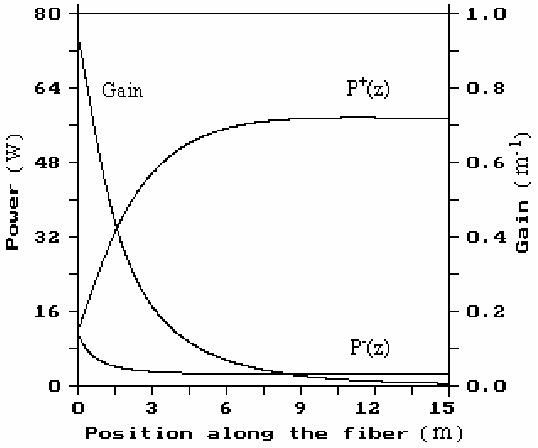

Fig. 2. Evolution of the power and the gain factor along the fiber.

3. Selecting parameters of fiber cavity

3.1. Fiber core diameter

The selection of the fiber core diameter should not only guarantee the single-mode operation of the fiber laser but also satisfy the requirement of the output power. According to our experiences the 10 μm core diameter is suitable if your desired output power is 70 W or lower. If you want higher output power such as around 100 W or more, we would suggest the 20 μm core diameter fiber. Now, let us see the dependent relation between the output power and the fiber core diameter. According to the equations (1)-(2) and $P_{out}= P^+(L)-P^-(L)$, Fig. 3 shows the case that the fiber core diameter influences the output power. As is shown in the Fig. 3, the output power will decrease slightly in case of increasing the core diameter when P_{in}=80 W, L=15 m and R_2=0.04. Although this influence upon the output power is not obvious, the size of the fiber core diameter is an important factor of designing a fiber laser because it influences the signal power density inside the fiber core directly.

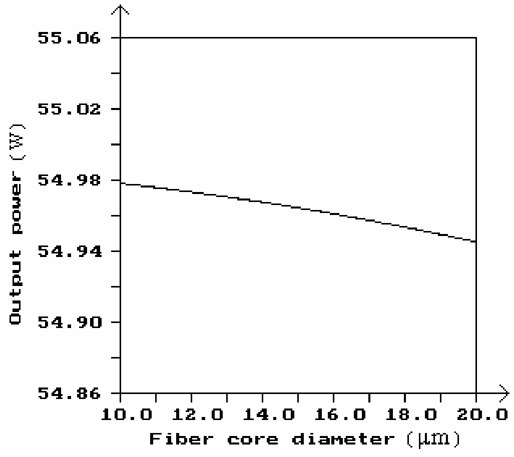

Fig. 3. Output power as a function of fiber core diameter.

3.2. Fiber length

The selection of the fiber length should also be appropriate. Because of the inherent loss of the fiber, the output power depends on the pump absorption and the signal loss. So there is an optimal length of the fiber which makes the output power maximum when the input pump power is definite. Fig. 4 shows the case that the fiber length influences the output power when P_{in} = 80 W, d = 20 μm and R_2 = 0.04. The numerical calculation indicates that the output power reaches a peak at an optimal fiber length of about 9 m. Now, let us see the evolution of the gain factor again. From the just analysis, Fig. 2 shows that the signal gain decreases gradually with the increase of the fiber length. So the law of Fig. 2 and Fig. 4 gives us a conclusion that the signal gain is smaller than the signal loss at the fiber length which is longer than the optimal fiber length.

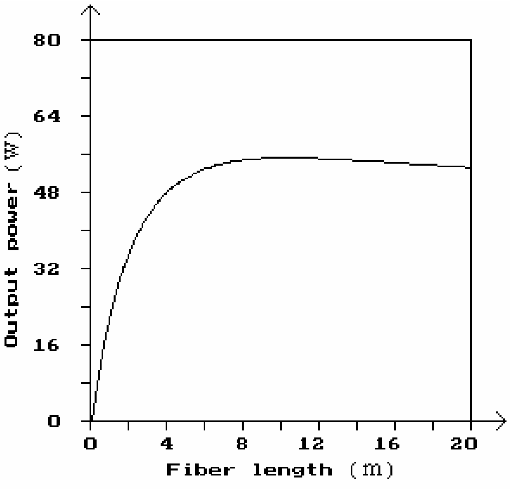

Fig. 4. Output power as a function of fiber length.

3.3. Reflectivity of output end

The reflectivity of the output end is another important factor influencing the output power. Fig. 5 shows the case that the reflectivity R_2 influences the output power when the other conditions (P_{in} = 80 W, L = 15 m and d = 20 μm) are definite. According to the law of Fig. 5, the output power will decrease significantly with the increase of the reflectivity R_2. Although increasing the reflectivity R_2 makes the output power lower, the signal light linewidth narrows. That is to say, the narrower signal light linewidth can be obtained through increasing the reflectivity R_2. But this narrower signal light linewidth is at the cost of decreasing the output power. Even now, in some circumstances, this processing is practical, which perhaps makes the fiber laser's characteristic optimum. However, there is another fact that the larger reflectivity R_2 can make the signal power density inside the fiber core higher, which perhaps makes the fiber's damage easy. Fig. 6 indicates the various power distributions along the fiber core when the reflectivity R_2 is respectively 0.04, 0.15 and 0.30. Therefore, there should be an eclectic consideration when we ascertain R_2.

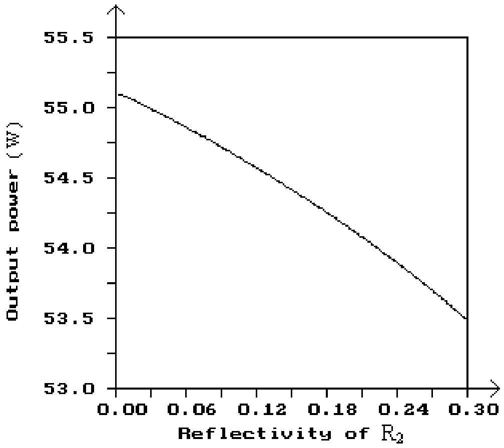

Fig. 5. Output power as a function of reflectivity R_2.

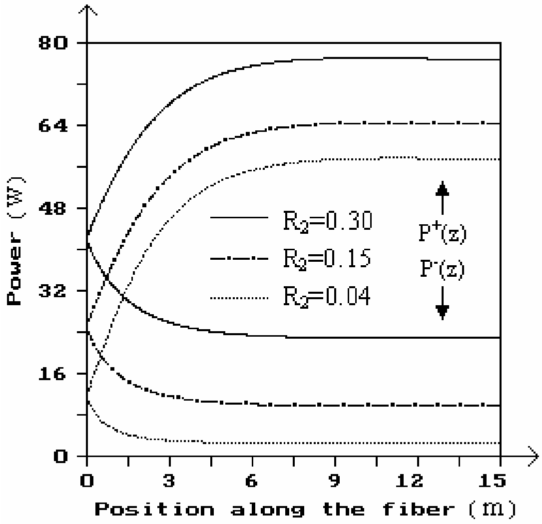

Fig. 6. Evolution of total power along the fiber when R_2 is different.

4. Realization of the R_1 and R_2

It is common to adopt the method of filming to realize the reflectivity R_1 and R_2 by using the dichroic mirrors and the corresponding lenses [5-6,11]. But the lens cannot couple the light into the fiber completely, and the loss of the lens is greater. Therefore the efficiency of this scheme sometimes is not high. In recent years, it is attractive to adopt the Fiber Brag Grating (FBG) instead of the separate mirrors [12-13]. The DCFL which are designed by using the FBGs are often named all-fiber lasers especially when the pumping diode-laser's pigtailed fiber and double-clad fiber's input end are fused directly or coupled through a fibered multimode combiner. Presently, there are heated researches about the double-clad all-fiber lasers. According to the theory of the fiber grating [14-15], the

FBG can reflect a certain incident light wave with a certain reflectivity. Its spectrum of reflection has a width, and its reflectivity will decrease when the incident wavelength deviate from its central wavelength, so that the signal wave near the FBG's central wavelength can only resonate in the laser cavity. As far as the high power double-clad fiber laser is concerned, the FBG not only has the function of selecting the signal wave but also has the function of coupling the output signal light. Furthermore, the fiber laser's linewidth can be determined by the bandwidth of the FBG's reflective spectrum in a sense because the FBG's reflective spectrum narrows as its reflectivity is increased. So the narrower linewidth can be obtained through selecting the larger reflectivity of the output end FBG. But this processing might lead to the decrease of the output power for the reflectivity R_2 is increased.

5. Conclusions

In conclusion, the comprehensive consideration of the various important parameters of influencing the laser's performance is needed to design the double-clad fiber lasers. On the basis of our practical experiences, we present the following design steps. (1) Selecting the appropriate fiber core diameter according to your desired output power. (2) Estimating the required input pump power, and hereby calculating the optimal length of the fiber. (3) Ascertaining the reflectivity R_2 according to the requirements of the output power and output linewidth. (4) Writing the Fiber Bragg Grating to realize the reflectivities R_1 and R_2. The above design steps which only offer some references to design the kindred double-clad fiber lasers are not unchangeable. On all accounts, the keys of designing a laser are to consider all the possible factors comprehensively, to pay attention to the consistency momently and not to consider the influence of one aspect independently. At the end of this paper, as far as the two-end pumped double-clad fiber laser is concerned, the difference is the distribution of the pump power inside the fiber. The similar problems can be discussed by adopting the above scheme when the R_1 and R_2 vary simultaneously.

Acknowledgements

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