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Realization of an efficient coherent combination via Michelson cavity*

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An intracavity coherent coupling Michelson erbium-doped fibre (EDF) laser (MCEDFL) is proposed and demonstrated. By using this laser system, we find a means to obtain a maximum power output at the same pumping power level. From the experiment based on fibre Bragg gratings (FBGs) with different reflectivities from 6% to 100%, we find that the reflectivity of the FBG plays a vital role in improving the performance of the MCEDFL. At the same time, the MCEDFL with a polarizer can be coherently combined effectively. This type of system, in principle, is compatible with other more powerful pumping methods, such as cladding pumping, and brings some novel perspectives to the realization of high power lasers.

Keywords: self-organization coherent combining, intracavity coherent combining, Michelson erbium-doped fibre laser, reflectivity of an FBG

PACC: 4255N, 4260, 4281M

1. Introduction

Erbium-doped fibre lasers (EDFL) are useful sources in wavelength-division-multiplexed (WDM) fibre communication systems.[1−3] In order to generate compact, highly bright and high-power lasers, coherent combination was proposed. Since an all-fibre coherent coupling laser was proposed in 1999,[4] a series of coherent laser cavities has been brought into being,[5−7] and the self-organization theory has also been studied.[5,8] It is known that the wavelength separation $\Delta\lambda$ of two individual lasers must be small enough in order to arouse the injection locking in coherent cavity. However, in Refs.[3–6] two FBGs are employed as high-reflection cavity mirrors. It is not convenient to tune the wavelength separation between the FBGs to being small enough in practical situations. Besides, the common cavity is often terminated by an uncoated fibre collimator that can provide about 4% backward reflection into the cavity. This reflectivity may be the best for the independent laser systems, but needs to be optimized for coherently combined laser systems.

In this paper, an all-fibre self-organization MCEDFL is presented, and a maximum power output is obtained at the same pumping power level. From the experiment based on the FBGs with different reflectivities from 6% to 100%, we find that the reflectivity of the FBG is very important to light-light transition, and the optimized reflectivity of the FBG is about 68%. After more than 30 minutes, a maximum power fluctuation is less than 0.18 dB when a polarizer is incorporated into the MCEDFL with a 68% reflectivity FBG.

2. Experimental setup

The experimental setup is shown in Fig.1. The laser cavity consists of two 980/1550 nm WDM couplers. Two 3dB fibre loop mirrors (FLMs), which have broad reflection bandwidth, act as all-reflection mirrors in two single-branch lasers, respectively. Two high-concentration 4.6-metre EDFs, which are not polarization-maintaining fibres, serve as the gain media in the two arms, separately. Two erbium-doped amplifiers are pumped by two 980 nm laser diodes (LDs) with powers up to 90 mW, and combined with a 3 dB 2×2 coupler, separately. One FBG, spliced to a port of the 3 dB coupler, serves as a wavelength selector and the common reflection mirror of the resonance

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cavity. An isolator is spliced to the other port of the 3 dB coupler. By inserting the isolator, this port is not able to produce oscillation, which effectively guarantees that the laser system will self-organize its optical power output to minimize the power in one port of the coupler, and most of laser power couples to the other output port.[5] A polarizer is inserted into the common cavity to coerce the two branch lasers into linearly polarized state. To assure that the linearly polarized states of the two arms can be identical again before they return to the coupler, a polarization controller (PC) is inserted into an arm.

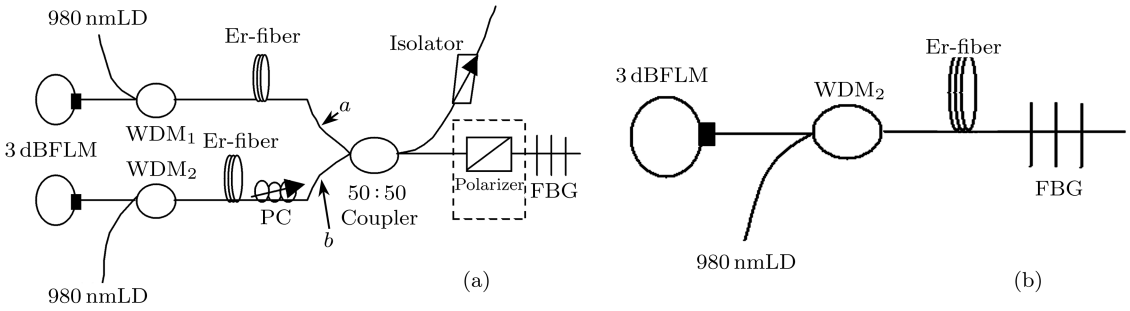


Fig.1. The experimental setup, (a) the setup of intracavity coherence of two branch fibre lasers, (b) the independent fibre laser applied field.

The laser system is a typical Michelson resonator. The mode spectral period of Michelson cavity is $\Delta\nu = c/(2\cdot\Delta L)$, where ΔL denotes the difference in effective length between the two arms. In order to optimize the oscillator cavity, we first measure the interferometric spectrum of the active arms based on two 3 dB FLMs at the output port c or d as shown in Fig.2(a). As expected, the interferometric spectrum is comb-like. The smallest wavelength separation, chosen in Fig.2(b) to calculate the ΔL, is $\Delta\lambda = 0.06$ nm. So, $\Delta L = 2.04$ cm ($\Delta L = \lambda^2/2\Delta\lambda$). The calculated result accords exactly with that of our experiment.

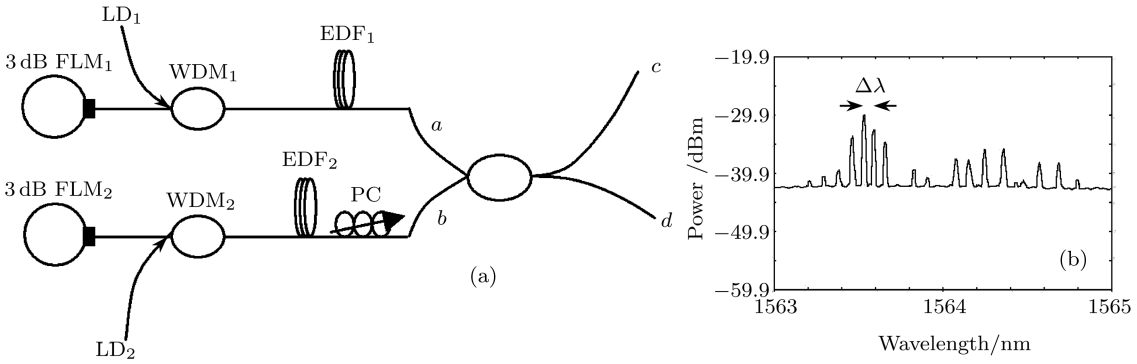


Fig.2. Experimental setup of measuring the interferometric spectrum (a) and the measured interferometric spectrum (b).

3. Experimental results and discussion

The FBGs used in the experiment have different reflectivities ranging from 6% to 100%, specifically they are 6%, 13%, 31%, 50%, 68%, 80% and 100%. The seven FBGs' central wavelengths each are at about 1563.5 nm. We compare the average power output of the MCEDFL with that of the individual fibre laser (IFL) with a 6% reflectivity FBG. The IFL is implemented, as shown in Fig.1(b), whose average power output is almost equal to the real result of the IFL in the MCEDFL. At the highest pumping level of 90 mW, the MCEDFL delivers a power output $P_{\rm out} = 23.9$ mW from the FBG port, corresponding to about 1.94 times the power output of one IFL (12.3 mW). The coupling efficiency is about 97%.

However, it is unnecessary for us to measure the power output of the IFL with a higher reflectivity FBG, because the high reflectivity (> 20%) FBG is not optimal to serve as the back mirror in the IFL.[9]

In this paper, the primary purpose is to find a means, by which we can obtain a maximum power output at the same pumping power level. We take two means to obtain the power output of the MCEDFL for each FBG at the same pumping power level. First, by adjusting the PC, we can obtain a maximum power output from the isolated port. At the same time, the power output is obtained from the port spliced with FBG. The results are shown in Fig.3. Then, by adjusting the PC again, another maximum power output from the oscillation port is obtained, meanwhile, the power output from the isolated port is noted. These power outputs are shown in Fig.4. Because of the polarization-dependent characteristic of each port of the coupler,[9] two maximum power outputs are not the same.

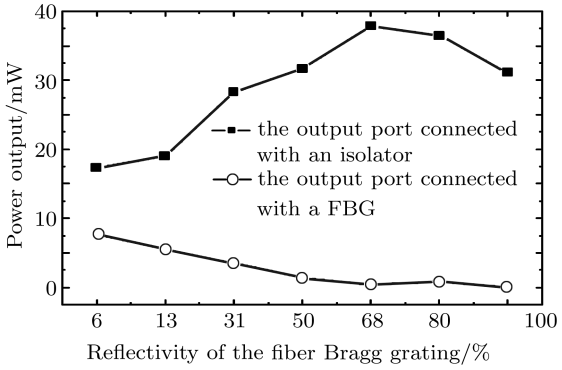


Fig.3. The curves of the maximum power output from the isolated port changing with the Reflectivity of the FBG. In the same polarization state, the power output from the other port spliced with FBG is noted at each reflectivity of the FBG.

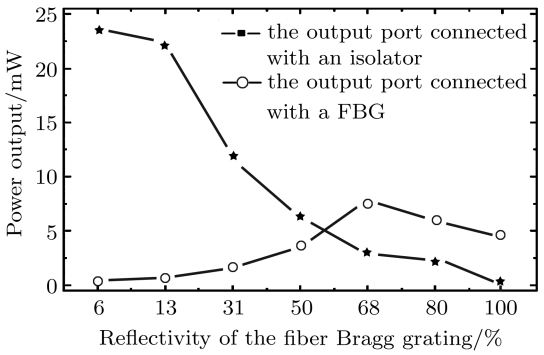


Fig.4. The curves of the maximum power output from the port spliced to FBG changes with the reflectivity of the FBG. In the same polarization state, the power output from the other isolated port is noted at each reflectivity of the FBG.

As can be seen from Figs.3 and 4, the power output of the MCEDFL, obtained from the oscillation port, decreases with the increase of the reflectivity of the FBG. However, the power output of the MCEDFL, obtained from the isolated port, increases with the variation of the reflectivity of the FBG before the reflectivity is about 68%, and then decreases with the increase of the reflectivity. The experimental results are coincided with the theoretical results from[5,11]

$$I_{\mathrm{FBG}} = (1-R^2)\sum_m [(b_1^m)^2 + (b_2^m)^2 + 2b_1^m b_2^m \cos(2\psi\delta l)]/4, \quad (1)$$

$$I_{\mathrm{ISO}} = 1 - (\cos 2y + \cos 2x)^2/(4R). \quad (2)$$

where $\psi = \kappa(l_1 + l_1 + 2L)$; $\delta l = l_1 - l_2/l_1 + l_2 + 2L$; b_1 and b_2 denote the optical fields in the two arms separately; x and y denote $x = \kappa(l_1 + L) + \alpha$, $y = \kappa(l_2 + L) + \alpha$, with l_i and L being the lengths of gain media of two arms and the common cavity respectively and α being the phase angle; R represents the reflectivity of the common mirror; I_{ISO} is the laser transmittance of the isolator spliced port. The fact is very important that the higher the FBG's reflectivity is, the higher power output of the MCEDFL at the same pumping power level in a Michelson interferometric cavity is obtained. It is obvious that the reflectivity of the FBG is vital to the power output and the self-organization ability of the MCEDFL.

According to expression (2), the maximum power output should be obtained when the reflectivity of the FBG is 100%. However, the maximum power output (38.6 mW) of the MCEDFL is obtained at the 68% reflectivity of the FBG in our experiment. The primary reason is that the higher reflectivity FBG produces a strong feedback to the 3 dB coupler. A new oscillation signal that comes from the other branch will be produced in each of the two branch lasers, resulting in the improvement of the transition of the pumping power to the signal power. However, with the increase of reflectivity of the FBG, the oscillation is strengthened, so that too much signal laser will be absorbed by the gain medium. So, the reflectivity of the FBG is neither too low nor too high, it should have an optimized value.

In order to gain an insight into the characteristics of the MCEDFL, we perform some experiments by the FBG with 68% reflectivity. First, we measure the polarization dependence of the MCEDFL. By adjusting the PC until the power output of the MCEDFL

reaches its maximum, the position of the PC and the power are reported. Then, we gradually change the polarization angle between the two polarization plates of the PC. We find that the power output diminishes with the adjustment of the PC, which results in the disagreement between the polarization states of the two arms as shown in Fig.5. So, the laser system is very sensitive to the polarization state.

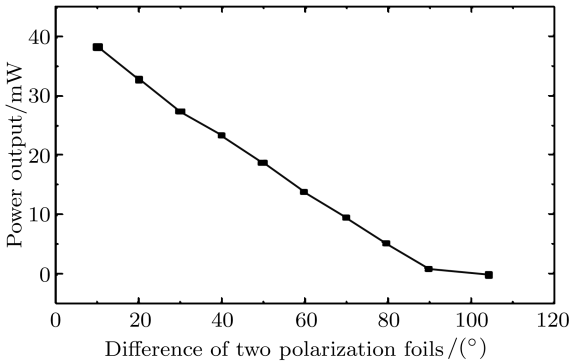


Fig.5. The coherent power output versus polarization angle between the polarization plates.

Furthermore, we compare the slope efficiency and the fluctuation of the highest power output of the MCEDFL with a polarizer and those without a polarizer. The slope efficiency of the MCEDFL without a polarizer is 21.57%, but it increases to 31.05% when a polarizer in spliced to the MCEDFL as shown in Fig.6. Then, we measure the fluctuation of the highest power output in order to evaluate the long-term (for 30 min.) stability of the MCEDFL operated at room temperature. The results are shown in Fig.7. The peak fluctuation is less than 0.18 dB when a polarizer is inserted into the MCEDFL. However, the peak fluctuation is almost 0.527 dB in the MCEDFL without a polarizer. It is very obvious that the polarizer plays an important role in improving the slope efficiency and stability of the Michelson coherent system. The basic reason is that inserting a polarizer into the common port leads to coercing the two branch lasers into a linear polarized state. After the laser signal returns to the two arms through the coupler, the polarization directions will be different again. By adjusting the PC inserted into an arm, the polarization states of the two arms can become identical again, which is the vital condition in the coherent combination. Therefore, the stability of the coherent laser from the coupler will be improved greatly compared with that without the polarizer. Accordingly, the slope efficiency of the MCEDFL with the polarizer is bigger than without the polarizer.

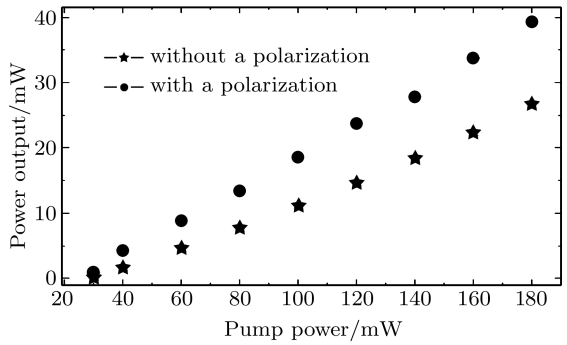


Fig.6. Power output versus pump power of the MCEDFL with a polarizer and without a polarizer.

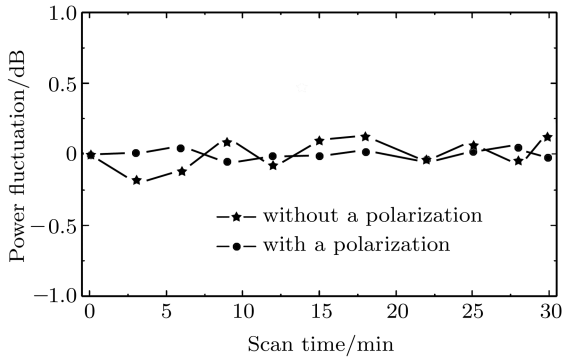


Fig.7. Power fluctuation of the MCEDFL during scanning, showing that the power fluctuation is less than 0.18 dB with a polarizer, and less than 0.527 dB without a polarizer.

4. Conclusion

In this paper, we have proposed a compact coherently coupled erbium-doped fibre laser. From the experiment based on FBGs with reflectivities ranging from 6% to 100%, we find that the reflectivity of the FBG is very important. With the increase of the reflectivity of the FBG, the power output of the MCEDFL is improved greatly at the same pumping power level, and the optimized reflectivity of the FBG is about 68%. Though the all-fibreized structure in our experiment is only a fundamental experiment with a laser power on the order of a few tens of milli-watts, this type of system, principle, is compatible with the more powerful pumping methods, such as cladding pumping, and will bring some novel perspectives to the realization of high power lasers.

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