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A Cladding-Pumped Fiber Laser with Pump-Reflecting Inner-Cladding Bragg Grating

Seungin Baek[*,§], Daniel B. S. Soh[*], Yoonchan Jeong[*], Johan Nilsson[*],

and Byoungho Lee[§], *Senior Member, IEEE*

[*] Optoelectronics Research Centre, University of Southampton,

Southampton SO7 1BJ, United Kingdom

Tel: +44-2380-593143, Fax: +44-2380-593142, E-mail: seb@orc.soton.ac.uk

[§] School of Electrical Engineering, Seoul National University,

Kwanak-Gu Shinlim-Dong, Seoul 151-744, Korea

Tel: +82-2-880-7245, Fax: +82-2-873-9953, E-mail: cherub0@snu.ac.kr

ABSTRACT

A fiber Bragg grating was inscribed in the inner cladding of a double-clad fiber, in order to reflect, and thus double-pass, the pump radiation in a cladding-pumped fiber laser. A reflectivity of 55% was obtained in the inner cladding, which is based on a broadband white light source. This increased the slope efficiency of a Yb-doped cladding-pumped fiber laser by up to 8.5%, and the output power increased by 45% with a 3 W pump source. The fiber Bragg grating provides stable and robust pump reflection, while leaving the fiber end free, for example, so that a signal transmission fiber can be spliced to the double-clad fiber.

Keywords: fiber laser, pump absorption, fiber Bragg grating, inner cladding

I. INTRODUCTION

Rare-earth-doped cladding-pumped fiber lasers have been extensively studied over recent years [1]-[4]. The double-clad fiber lasers benefit from a geometry that allows simple thermal management and a high beam quality. While the pump wave is launched into the large cladding area, the signal wave propagates in the core, so diffraction-limited can be realized even when low-brightness diode lasers are used as pump sources. However, the pump absorption rate is much lower than with core-pumped fibers because the pump overlap with the rare-earth-doped core is small. In particular, the absorption of caustic modes in circularly symmetric structures is poor. Thus, the enhancement of pump absorption is of interest to improve fiber laser performance of cladding-pump system. In particular this applies to laser systems in which a large ground-state absorption has to be overcome, e.g., 980 nm Yb-doped fiber lasers [5]-[6] and three-level lasers in general. The pump absorption can be improved by way of non-circular fibers (e.g., D-shaped inner cladding designs) and mode mixing, for example, by bending the fiber into a kidney-shape [4]. Additionally, the pump absorption can be increased by double-passing the pump through the fiber, using, e.g., an external mirror. An external mirror can simply and efficiently reflect the pump beam; however, a misalignment of optics may lead to poor performance, and the set-up can be relatively large and heavy. In addition, it prevents the cladding-pumped fiber from being spliced directly to another fiber, e.g., carrying a signal to or from the cladding-pumped fiber. If the pump reflection is realized in a more compact all-fiber device, for example, a broadband fiber Bragg grating (FBG) that reflects the pump through the inner cladding, these drawbacks can be overcome. FBGs are widely used for wavelength-selective reflection devices, mostly in the 1550 nm wavelength region, in telecommunication [7] and sensor systems [8]. Most FBGs are written in the fiber core via UV exposure. However, it is also possible to write gratings in the inner cladding if this is photosensitive. Such an FBG would provide a compact and robust way to feed back the pump wave.

In this Letter, we demonstrate a cladding-pumped fiber that employs an FBG inscribed in the inner cladding of a double-clad fiber to double-pass the pump. Pump feedback via an inner-cladding FBG simplifies the system, and eliminates the coupling loss which occurs with an external mirror. Feeding back the pump with an inner-clad FBG increases the absorbed pump power in fiber lasers that suffer from incomplete pump absorption, leading to a higher output power. Thus, pump feedback with an inner cladding FBG increases the slope efficiency of the fiber laser, while maintaining a compact fiber format with a free fiber end.

II. EXPERIMENTAL DETAILS AND RESULTS

The double-clad fiber used for the experiment has a Yb-doped alumino-germanosilicate core with a diameter of 6 μm and an NA (numerical aperture) of 0.15. The germanosilicate inner cladding has a 42 μm diameter with a 0.25 NA. There was also a pure silica outer cladding with a diameter of 125 μm. Germanosilicate is photosensitive, and the relatively high germanium-content in the inner-cladding made grating-writing easier.

After hydrogen-loading the fiber in order to further increase its photosensitivity, an inner-cladding FBG was written with an excimer laser and a phase mask. Since also the core is photosensitive, we can expect that a fiber grating will be written also there, depending on the absorption length of the UV-radiation in the germanosilicate. The transmission spectrum of the inner-clad FBG measured using a broadband white light source is shown in Fig. 1. The maximum reflection of the FBG is 55% at the 916 nm wavelength. We note here that the reflection property of FBG is also dependent on the modal property of the incident wave [9]. The inner cladding is a multimode waveguide. The effective indices of the modes vary from the refractive index of the outer cladding (pure silica, ~1.46, to a ~1.5% higher value, corresponding to an NA of 0.25). Therefore, with a fixed grating pitch, different modes will have reflection resonances at different wavelengths. In addition, different modes will have different overlaps with the grating, and therefore different reflection strengths, insofar as the grating is not homogeneous through the fiber. The reflection spectrum depends on which inner-cladding modes that are excited. Thus, the actual reflection characteristics, for example, with a multimode diode source in a cladding-pumped fiber laser, can be different from that of a white light source. The spectrum of the pump source used for the experiment is shown in Fig. 2. The maximum output power is 3 W and the overlap with the grating reflection spectrum is good. A cladding-pumped fiber laser with the inner-cladding FBG was set up according to Fig. 3. The pump is launched into the inner cladding of the Yb-doped fiber through a lens and a dichroic mirror. The fiber length is 8 m which leads to 65% pump absorption with a single pass of the pump wave. The unabsorbed pump wave is reflected back through the fiber by the inner-cladding FBG. The signal is fed back by an external broadband dichroic mirror that has a high reflectivity (> 99%) at ~1 μm and a high transmittivity at the pump wavelength of 915 nm. In a different configuration, this broad signal-reflecting mirror can be easily replaced by an FBG that has a narrow spectral width at a specific wavelength.

An output spectrum is shown in Fig. 4. The signal wavelength is at ~1070 nm with the pump power of 1.5 W. The power characteristics of the fiber laser are shown in Fig. 5. The squares and circles represent the output power of the Yb-doped fiber laser with and without the FBG in the inner cladding, respectively. The net pump absorption in the fiber was increased because the pump path was doubled with the inner-clad FBG reflection. The slope efficiencies of the fiber laser system based on the launched pump power were 29.8% with the inner-clad FBG and 21.3% without it, respectively. The maximum output powers are, respectively 370 mW and 257 mW with the same pump power. The slope efficiency was enhanced by 8.5% and the maximum output power increased up to 45% with the maximum pump power.

III. CONCLUSION

We have demonstrated pump feedback in a cladding-pumped fiber laser using an inner-clad fiber Bragg grating inscribed in a double-clad Yb-doped fiber. The slope efficiency with respect to launched pump power was enhanced by 8.5% compared to that of a similar fiber laser without pump feedback. As a result, the maximum output power of the fiber laser increased by 45%. Our all-fiber pump feedback system can be realized without compromising other properties of the fiber laser. Combining the pump reflecting inner-clad FBG, mirror-free feedback fiber laser systems are also possible using additional FBGs for signal reflection in the same fiber.

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FIGURE CAPTIONS

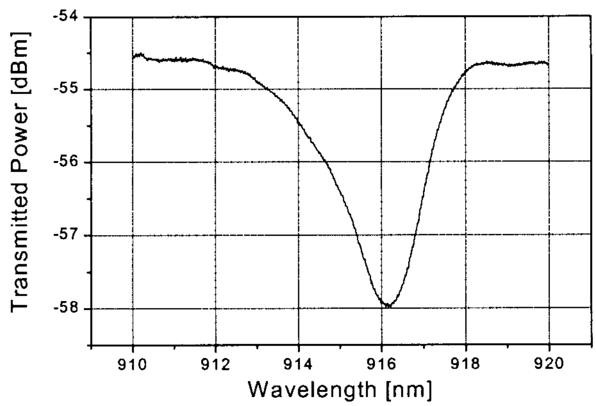
Fig. 1. Transmission spectrum of the FBG inscribed in the inner cladding as well as core areas of the Yb-doped double-clad fiber. The resonant wavelength and the maximum reflection of the FBG are 916 nm and 55%, respectively.

Fig. 2. Spectrum of the pump source. Maximum output power 3 W.

Fig. 3. Schematic diagram of the cladding-pumped fiber laser. The dichroic mirror is highly transmitting at the pump wavelength and highly reflecting in the signal wavelength region.

Fig. 4. Output spectrum of the fiber laser at 1.5 W pump power. The signal wavelength is at ~1070 nm.

Fig. 5. Fiber laser power characteristics. The squares and circles represent the output power of the Yb-doped fiber laser with and without the FBG, respectively. The enhancements of the slope efficiency and the maximum output power of the fiber laser with the maximum pump power are 8.5% and 45%, respectively.



Transmitted Power [dBm]
-54
-55
-56
-57
-58
910
912
914
916
918
920
Wavelength [nm]

Fig. 1.

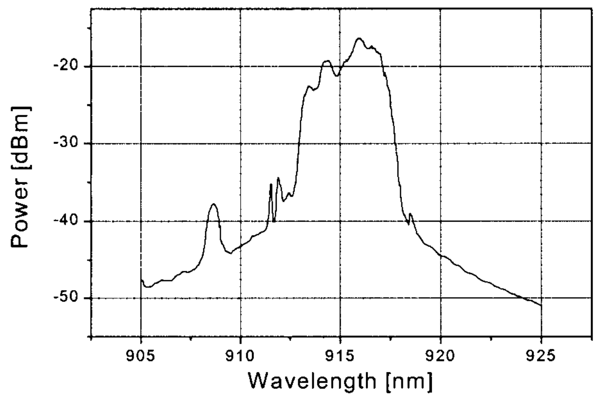


Fig. 2.

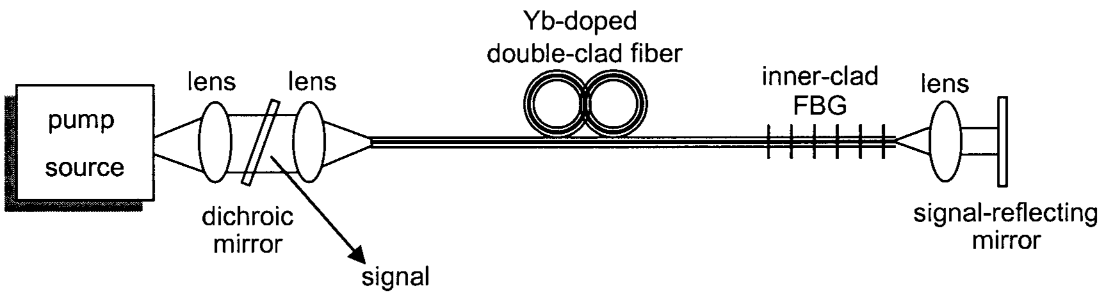
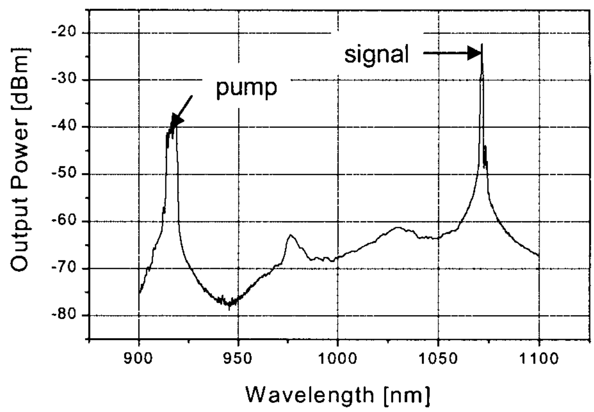

Yb-doped
double-clad fiber
lens
lens
pump
source
dichroic
mirror
signal
inner-clad
FBG
lens
signal-reflecting
mirror

Fig. 3.



-20
-30
-40
-50
-60
-70
-80
Output Power [dBm]
signal
pump
900
950
1000
1050
1100
Wavelength [nm]

Fig. 4.

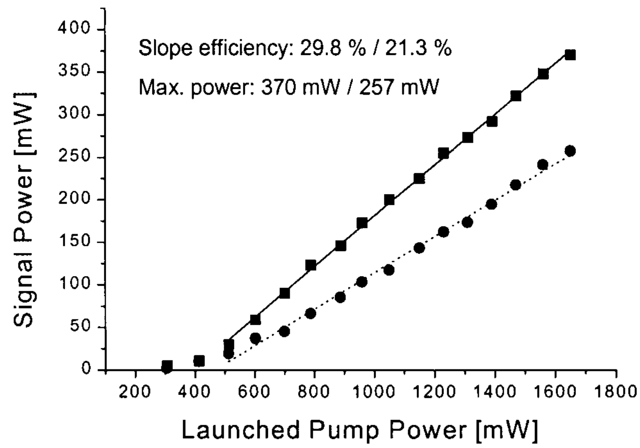

Slope efficiency: 29.8 % / 21.3 %
Max. power: 370 mW / 257 mW
Signal Power [mW]
0
50
100
150
200
250
300
350
400
200
400
600
800
1000
1200
1400
1600
1800
Launched Pump Power [mW]

Fig. 5.