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Highly Efficient Er^{3+}-Yb^{3+} Co-doped Double-cladding Fiber Amplifiers with Fiber Bragg Gratings and Shorter Fibers*

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Abstract Using fiber Bragg grating (FBG) as reflectors of the pump light, which could be made by using high power femtosecond pulse laser in the inner cladding of the DCF, shorter fiber is needed in optical fiber amplifiers, while maintaining at least the same performance as that without FBG. Based on the rate and propagation equations, numerical analysis of Er:Yb co-doped double cladding fiber amplifiers with and without FBG has been performed. The results show that amplifiers with FBG can reach the same output powers as those of without gratings, but only half-length of fibers are needed, either for forward or backward pumping. With FBG for backward pumping, the highest output power can be acquired for all cases, while using shorter fibers.

Keywords Optical fiber amplifiers; Double-cladding fiber; Erbium-Ytterbium co-doped; Cladding pump; Optical fiber communication; Fiber Bragg grating

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0 Introduction

Recently, rare-earth doped double cladding fiber lasers (DCFL) and amplifiers (DCFA) are attracting a great deal of interests for power scaling. Due to the small overlap factor between the core and inner-cladding thus low absorption coefficient of pump light in the double-clad structure, a longer fiber is needed than those with conventional fibers. So far, the fabrication of good quality double cladding fibers in domestic is still not successful. Most double cladding fibers needed are manufactured abroad, with a price of about 80 ~ 200 $/m. Therefore, optimum design of the DCFL and DCFA with the least fibers is very important.

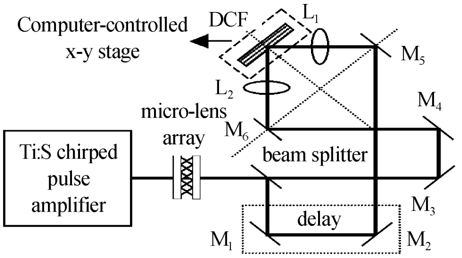
Fiber Bragg gratings[1] (FBG) have been used as optical feedbacks in the construction of compact, reliable and highly efficient optical fiber lasers. Although fiber gratings can be made by several different techniques, they are all restricted by the photosensitivity of optical fibers, which limits their uses.

In this paper, we proposed, that by using fiber Bragg grating (FBG) as reflectors of the pump light, which could be made by using high power femtosecond pulse laser in the inner cladding of the DCF (this work is ongoing), shorter fiber is needed in optical fiber amplifiers, while maintaining at least the same performance as that of without FBG. Numerical analysis of FBG as reflectors of the pump light was performed with Er:Yb co-doped DCFA pumped at 980 nm, based on the rate and propagation equations. The numerical results proved its advantages.

1 DCFA with fiber Bragg grating

In optical fiber lasers, FBG is mostly used as the feedback of laser oscillation to simplify the design of single-mode operation and to achieve better overall performances[2,3]. We proposed, however, using FBG as the reflector of pump in optical fiber amplifiers. In this situation, the FBG is made in the inner cladding of the DCF instead of the Ge-doped fiber core by using a high power femtosecond pulsed laser.

Fig. 1 illustrated the schematic experimental setup. A femtosecond laser pulse from a CPA Ti: S laser system first passes through a pairs of microlens arrays to transform into plane-top beam. A 8 × 8 mm^2 rectangle hole allows only the center of the Gaussian



L_1,L_2:cylindrical silica lens.M_1~M_6:HR mirrors

Fig. 1 Schematic experimental setup of the fabrication of FBG in the inner cladding of DCF

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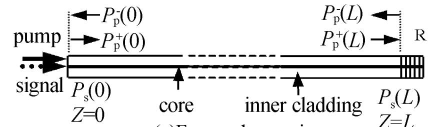
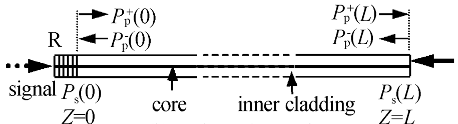
beam pass through it and irradiate on a 50/50 splitter at 800 nm. One beam is focused into the DCF directly by a fused silica lens with 60 mm focal length, while the other also through an adjustable delayer. These two optical paths must be adjusted precisely by a conventional sum-frequency method in order to generate interference temporally and spatially.

Fig. 2 shows the configuration of the DCFA with FBG as pump reflectors, (a) for forward and (b) for backward pumping. Due to the contributions of the FBG to reflect the un-absorbed pump powers back into the DCF and reuse again, shorter fibers are expected to be needed to sufficiently absorbing the pump power, and higher output powers could be reached, for the signals experiencing lower scattering loss. Next, numerical analysis of Er:Yb co-doped DCFA, as an example, will be done based on the rate and propagation equations.



(a)Forward pumping



(b)Backward pumping

Fig. 2 Schematic illustration of the DCFA with fiber Bragg grating as pump power reflector

2 Models of Er:Yb co-doped DCFA

According to the energy - level diagram of the Er:Yb co-doped DCFA[3,4], the coupled Er^{3+}-Yb^{3+} system can be described by the following rate equations and conservation laws[4~6], for simplicity, the variable z and t are omitted:

$$\frac{\partial N_{Yb2}}{\partial t} = \left(\frac{\lambda_p \Gamma_p}{hcA}\right)(\sigma_{Ybpa}N_{Yb1} - \sigma_{Ybpe}N_{Yb2})(P_p^+ + P_p^-) - \frac{N_{Yb2}}{\tau_{Yb2}} - k_{YbEr}N_{Yb2}N_{Er1} \qquad (1)$$

$$\frac{\partial N_{Er2}}{\partial t} = -\left(\frac{\lambda_s \Gamma_s}{hcA}\right)(\sigma_{Erse}N_{Er2} - \sigma_{Ersa}N_{Er1})(P_s^+ + P_s^-) + \left(\frac{\lambda_p \Gamma_p}{hcA}\right)\sigma_{Erpa}N_{Er1}(P_p^+ + P_p^-) - \frac{N_{Er2}}{\tau_{Er2}} + k_{YbEr}N_{Yb2}N_{Er1} \qquad (2)$$

$$N_{Yb} = N_{Yb1} + N_{Yb2} \qquad (3)$$

$$N_{Er} = N_{Er1} + N_{Er2} \qquad (4)$$

In these equations, N_{Yb1} and N_{Yb2} are the population densities of Yb^{3+} energy levels $^2F_{7/2}$, $^2F_{5/2}$ and N_{Er1}, N_{Er2} the populations of Er^{3+} manifold $^4I_{15/2}$, $^4I_{13/2}$; σ_{Ybpa}, σ_{Erpa} and σ_{Ybpe} are stimulated absorption and emission cross sections of pump, and σ_{Ersa}, σ_{Erse} are stimulated absorption and emission cross sections of signal; σ_{Yb2} and σ_{Er2} are the lifetimes of the $^2F_{5/2}$ and $^4I_{13/2}$ levels of Yb^{3+} and Er^{3+}, k_{YbEr} is the cross-relaxation coefficients; P_p^+ and P_p^- are forward and reverse propagating pump fields, P_s^+ and P_s^- are forward and reverse propagating signal fields, respectively. Moreover, Γ_p, Γ_s are power filling factors of pump and signal, h is Plank's constant, c is the speed of light, A is the cross section area of the fiber core.

Propagation of the pump and amplified signal powers along the active fiber are described by the following differential equations

$$\pm\frac{dP_p^\pm}{dz} = -\Gamma_p[\sigma_{Ybpa}N_{Yb1} - \sigma_{Ybpe}N_{Yb2} + \sigma_{Erpa}N_{Er1}]P_p^\pm - \alpha_p P_p^\pm \qquad (5)$$

$$\pm\frac{dP_s^\pm}{dz} = \Gamma_s[\sigma_{Erse}N_{Er2} - \sigma_{Ersa}N_{Er1}]P_s^\pm - \alpha_s P_s^\pm + \Gamma_s\sigma_{Erse}N_{Er2}P_{0s} \qquad (6)$$

where α_p, α_s the background losses, and P_{0s} represents the contribution of the spontaneous emission into the mode[7].

For the Er:Yb co-doped DCFA with FBG as pump power reflector, as illustrated in Fig. 2, Equations (1) ~ (6) are to be solved subject to the boundary conditions, for forward pumping

$$P_s^+(0) = P_{sin} \quad P_p^+(0) = P_{pin} \quad P_p^-(L) = PR_p^+(L) \qquad (7)$$

and for backward pumping

$$P_s^+(0) = P_{sin} \quad P_p^-(L) = P_{pin} \quad P_p^+(0) = RP_p^-(0) \qquad (8)$$

where P_{sin} is the input signal power to be amplified, P_{pin} is the injected pumping power, R is the power reflectivity of the Bragg reflector at pump wavelength, and L the fiber length.

3 Numerical analysis and discussions of Er:Yb co-doped DCFA

The Er:Yb co-doped DCF used in the numerical computation is still EY801[4], which is a SM hexagonal phosphate silica fiber manufactured in INO, Canada. This fiber consisted of a core composition of 4.8×10^{19} ions/cm^3 (0.61 wt%) Er^{3+}, 5×10^{20} ions/cm^3 (6.53 wt%) Yb^{3+}, etc. The round fiber core had a diameter and numerical aperture of 4.6 μm and 0.18, respectively, while the inner cladding had a distance between parallel planes of 200 μm and NA of 0.35. The fiber had an absorption coefficient of 0.9 dB/m @980 nm, with losses <15 dB/km @1114 nm.

Equations (1) ~ (2) are iteratively solved by means of a Runge-Kutta algorithm subject to the boundary conditions (3) and (4) accordingly. In all cases, the injected signal power P_{sin} is 0.01W and the injected pump power P_{pin} is 20 W. Other parameters used for the numerical analysis, unless stated otherwise, are shown in Table 1.

Table 1 Parameters used in the computation

Parameters	Values	Parameters	Values
λ_p/nm	980	$\sigma_{Yba}(\lambda_p)/m^2$	2.0×10^{-25}
λ_s/nm	1550	$\sigma_{Ybe}(\lambda_p)/m^2$	5.0×10^{-25}
τ_{Yb2}/s	1.5×10^{-3}	$\sigma_{Era}(\lambda_p)/m^2$	2.0×10^{-25}
τ_{Er2}/s	11×10^{-3}	$\sigma_{Era}(\lambda_s)/m^2$	6.6×10^{-25}
Γ_p	5×10^{-4}	$\sigma_{Ere}(\lambda_s)/m^2$	5.7×10^{-25}
Γ_s	0.80	σ_p/m^{-1}	3.5×10^{-3}
C_{YbEr}/m^3s^{-1}	5×10^{-21}	σ_s/m^{-1}	3.5×10^{-3}

As the Er:Yb co-doped DCF is used in high power situations, the affection of thermal effect on the central reflective wavelength of the FBG should be considered. In practice, one can use temperature control device to stabilize the wavelength. So in the following analysis, the reflectivity R of the FBG for pump is supposed to be a constant of 0.98.

3.1 Er:Yb co-doped DCFA performances for forward pumping

Signal amplification and pump attenuation for forward pumping without FBG as pump reflector for EY801 fiber is shown in Fig. 3. We see that with the increasing of fiber length, the signal was amplified slowly, it reaches a maximum of less than 10 W at $z\approx$ 55 m, after which the pump power is too low to further amplify the signal so that the signal is slowly attenuated due to scattering loss.

The variation of the pump and signal powers along a 30 m long EY801 fiber amplifier with FBG as pump reflector for forward pumping, is also shown in Fig. 3. We see the output amplified signal power improved to nearly 10.5 W, which is about one watt higher than that of without Bragg reflector, and only half of the fiber length needed compared to the former one. Fig. 4 shows the output amplified signal powers with different fiber lengths and with Bragg reflector for forward pumping. We find the maximum amplified signal power that can be reached is a little more than 10.5 W with an optimum fiber length of 33 m. Compared with Fig. 3, we also find that, when the fiber length is shorter than 20 m, the amplified signal power with FBG is about 2 W higher than that without it for the same fiber length.

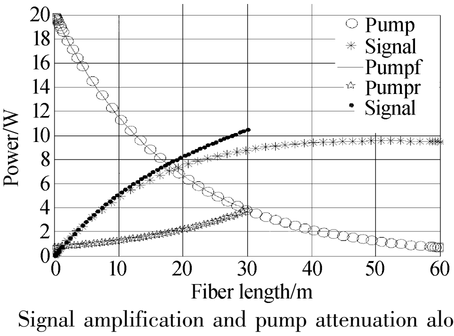


Fig. 3 Signal amplification and pump attenuation along the fiber for EY801 DCFAs without Bragg reflector for forward pumping

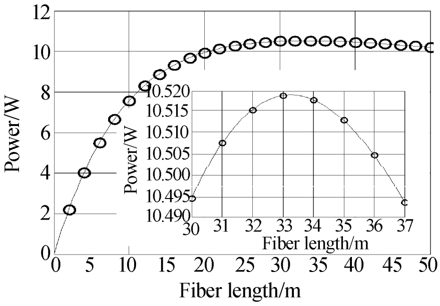


Fig. 4 Amplified signal powers for EY801 DCFA with FBG using different fiber lengths for forward pumping

3.2 Er:Yb co-doped DCFA performances for backward pumping

For backward pumping of EY801 fiber amplifier, it is reasonable to take a piece of fiber with a similar length as that of forward pumping. Fig. 5 shows signal amplification and pump attenuation for EY801 fiber amplifier at a fiber length of 60 m without FBG. Fig. 6 shows the signal amplification for EY801 fiber amplifiers with different fiber lengths without Bragg reflector for backward pumping. We can see the output powers in these cases are higher than that of forward pumping with the same fiber length, and the optimum length is 88 m, with a maximum signal power of about 10.6 W, the fiber is longer but the power is higher than the case of forward pumping. These changes are

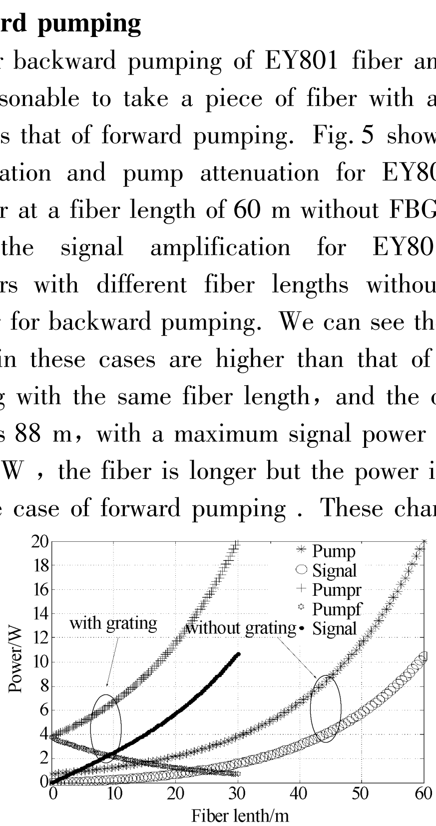


Fig. 5 Signal amplification and pump attenuation for EY801 DCFA with and without FBG for backward pumping. The fiber length is 30 m and 60 m, respectively

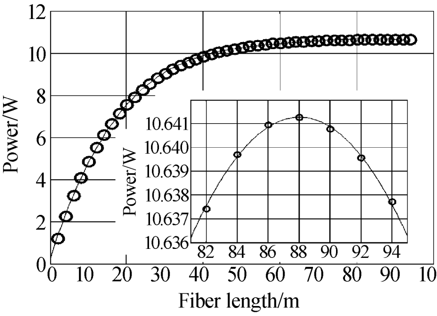


Fig. 6 Signal amplification for EY801 DCFAs with different fiber lengths without FBG for backward pumping

attributed to the similar variation tendency of the pump and signal in the fiber, so they interact strongly.

Fig. 5 also shows the signal amplification and pump attenuation for EY801 DCFA with FBG at a fiber length of 30 m for backward pumping. The output amplified signal power is almost the same as that of backward pumping with 60 m fiber without Bragg reflector. Fig. 7 shows signal amplification for EY801 fiber amplifiers with different fiber lengths with Bragg reflector for backward pumping. We can see it clearly that the maximum output signal power that can be reached with Bragg reflector for backward pumping is about 10.9 W with a fiber length of 45 m, the power being higher and the fiber being shorter than the case of without Bragg reflector. Once again, amplifiers with Bragg reflector have about the same output signal powers as those of without it, but only using half-lengths of fibers.

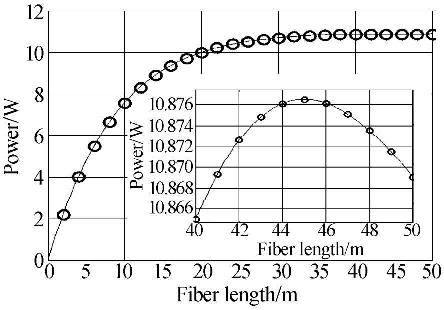


Fig. 7 Signal amplification for EY801 DCFAs with different fiber lengths with Bragg reflector for backward pumping

4 Conclusions

In conclusion, we have proposed that using FBGs as reflectors of the pump light, shorter fibers are needed in optical fiber amplifiers, while maintaining at least the same performance as that without gratings. Numerical analysis of Er:Yb co-doped DCFAs with and without FBGs has been performed. The results show that amplifiers with FBGs can reach higher output powers than those of without gratings, but only half-length of fibers are needed, whether for forward or backward pumping. The maximum output power and gain that can be reached is about 10.9 W and 30.3 dB, with Bragg reflector for backward pumping, and a fiber length of 45 m. The pumping scheme and numerical results should be useful for the realistic optimized design of DCFA in the near future.

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使用FBG及更短光纤的高效Er^{3+}-Yb^{3+}共掺双包层光纤放大器

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摘 要 提出在光纤放大器中,使用光纤布喇格光栅作为泵浦光反射镜,所需的双包层光纤可以缩短,同时至少保持了与没有光纤布喇格光栅作为反射镜时光纤放大器相同的性能.基于速率及传输方程,对使用和不使用光纤布喇格光栅的铒、镱共掺双包层光纤放大器的性能进行了数值模拟.结果表明,使用光纤布喇格光栅作为反射镜时光纤放大器可以获得与无光栅时相同的输出功率,但仅仅需要后者长度一半的光纤,无论是前向泵浦还是后向泵浦.对后向泵浦方式并使用光纤布喇格光栅作为反射镜,可获得最高的输出功率及光增益,同时使用了较短的光纤.

关键词 光纤放大器;双包层光纤;铒、镱共掺;包层泵浦;光纤通信;光纤布喇格光栅

Dong Shufu was born in 1971, in Qingdao, China. He received the B. S. degree in optical fiber communication and M. S. degree in communication & electronics from Air-force Telecommunication Engineering Institute, China, in 1994 and 1997, respectively. He is now a associate professor and a Ph. D. candidate in the State Key Laboratory of Transient Optics Technology, Xi′an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, where he is engaged in research of optical fiber lasers & amplifiers. His interests cover optical communication system and devices.