Output Power Increase of Cladding Pumped 7-core EDFA by Using Mie Scattering

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Abstract *We fabricate a double cladding 7-core erbium doped fibre with expanded core diameter and including Mie scattering bodies in the cladding area. We measure amplification characteristics of a cladding pumped 7-core EDFA and confirm increase of output power to 18.4 dBm by Mie scattering mechanism.*

Introduction

Reduction of power consumption on optical amplifiers not only reduces the power consumption of optical communication systems, but also increases communication capacity of submarine communication systems limited by power consumptions. However, it has been difficult to reduce the power consumption of conventional EDFAs. On the other hand, cladding-pumped multi-core (MC) EDFAs using a multi-mode laser diode (MM-LD) as an optical pump source have a possibility to reduce the power consumption rather than that of conventional EDFAs that use single mode LD as an optical pump source. This is because electric power to optical power conversion efficiency of the MM-LDs is higher than that of the single-mode LD.

Amplification characteristics of the MC-EDFAs have reached those of conventional EDFAs except for some items[1-5]. Major remaining issues for MC-EDFAs are the reduction of power consumption lower than that of the conventional EDFAs and increase of output power for C-band MC-EDFAs. Both issues are caused by low absorption ratio of cladding pump light. In fact, residual cladding pump power, which is not absorbed by MC-EDF, is significantly high.

An increase of cladding pump absorption efficiency lead directly to an increase of output power of the MC-EDFAs. Reduction of cladding diameter of MC-EDFs[4] and recycling technique of cladding pump in MC-EDFAs[6,7] have been reported as effective technique for the output power increase of the MC-EDFAs. However, research for a different method for the further improvement is still important.

One method for improving the cladding pump efficiency could be an increase of core-cladding area ratio. That is, when cladding diameter is constant, core diameter may be expanded. Another method could be an insertion of scattering bodies into the cladding area. The reason why the cladding pump efficiency is quite low is considered to be existence of skew light in the cladding of MC-EDFs which does not collide with the cores. The method could change optical path slightly so that direction of the skew light may be changed to collide with the cores.

In this study, we fabricate a core diameter expanded 7-core EDF with the same cladding diameter and core pitch design as the 7-core EDFs[3-5]. In addition, we fabricate another core-diameter expanded 7-core EDF that has scattering bodies in the cladding area. Then, amplification characteristics of both 7-core EDFs are measured. Output power for the 7-core EDF with scattering bodies in the cladding area increases to 18.4 dBm while output power for the 7-core EDF with expanded cores remains 16.2 dBm that is equivalent to those of conventional 7-core EDFAs[3-5].

Fabrication of double cladding 7-core EDFs

In order to increase output power of 7-core EDFAs, we fabricated two kinds of 7-core EDFs. One is a core diameter expanded fibre. Another is a core diameter expanded fibre with bubbles in the cladding area. The core diameters for both EDFs were designed to be 1.27 times larger than that of the conventional 7-core EDFs[3-5]. That is, the core area is about 1.6 times larger than that

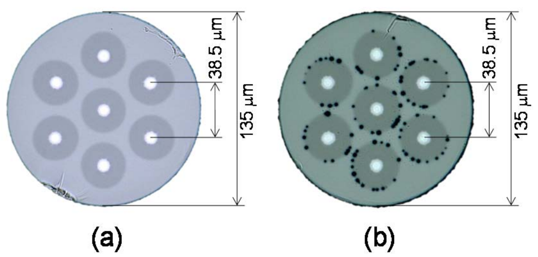

Fig. 1: Cross-section views of 7-core EDFs: (a) core diameter expanded one (EDF-7-135-3), (b) core diameter expanded one with including bubbles in the cladding area (EDF-7-135-3S). Note that low refractive index coatings were removed for taking fine pictures

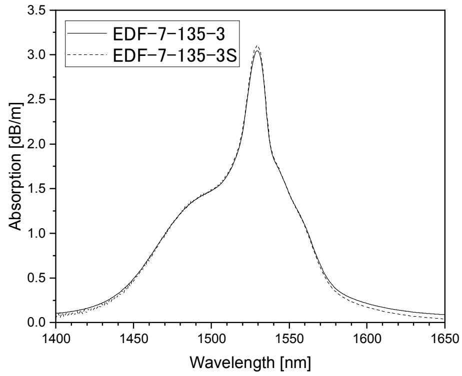

Fig. 2: Absorption spectra for EDF-7-135-3 (solid line) and for EDF-135-3S (broken line).

of the conventional 7-core EDFs[3-5]. The bubbles in the cladding area scatter cladding pump light.

We designed the cladding diameter and core pitch to be 135 µm and 38.5 µm, which are the same dimensions with conventional 7-core EDFs[3-5], so that measured amplification characteristics can be compared with those of the conventional 7-core EDF[3-5]. Refractive index of the core was properly designed to maintain single mode operation while the cores were expanded.

Figure 1 shows cross-sections of the fabricated 7-core EDFs. As shown in Fig.1(b), bubbles were generated annularly for each core. Arrangement and size of the bubbles were different for each fibre length position since the bubbles were generated randomly. Averaged diameter of the bubbles was 1.4 µm and the total bubble area was about 0.5% of the cladding area.

Figure 2 shows absorption spectra of the centre core for the fabricated 7-core EDFs. Absorption peaks at 1530 nm were 3.0 dB/m for EDF-7-135-3 and 3.1 dB/m for EDF-7-135-3S. Hereinafter, the fibre shown in Fig.1(a) is referred to as EDF-7-135-3, and the fibre shown in Fig.1(b) is referred to as EDF-7-135-3S. The names are configured with EDF-(core number)-(cladding diameter)-(absorption ratio at 1530nm).

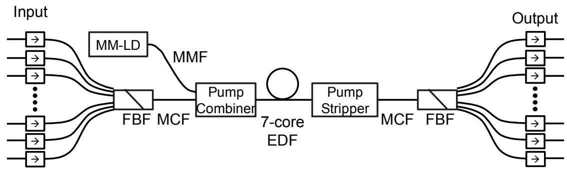

Fig. 3: Experimental setup. MM-LD: multimode LD; FBF: fibre bundled fan-in/out; MCF: multicore fibre; MMF: multimode fibre; MC-EDF

The last letter of "S" means scattering bodies included.

Amplification characteristics measurements

Amplification characteristic of the fabricated 7-core EDFs were measured. The fabricated 7-core EDFs were applied to a cladding pumped 7 core EDFAs having configuration shown in Fig. 3.

All input and output ports have individual Isolators, and are connected with corresponding cores of a non-doped multi-core fibre (MCF) through a fibre bundled fan-in/out (FBF). Here, MCF and MC-EDF have low refractive index coating to form double cladding structure. Both fibres have the same diameters of cladding and core-pitch each other to reduce splice loss. We used a side-coupled pump combiner to launch 976 nm multimode pump light output from a multimode laser diode (MM-LD) into inner cladding of the MCF. The MCF at output of the pump combiner is spliced with a 7-core EDF. Output end of the 7-core EDF is spliced to a pump stripper. Residual cladding pump from the 7-core EDF is removed at a pump stripper.

Input signal was an 8-WDM signal in C-band with total power of -5 dBm. Output power of the MM-LD was 17W. These input and output powers are set to have the same values with those in Ref. 4 and 5 to make fair comparisons. We set length of the both 7-core EDFs to be 33 m as the optimum length for C-band amplification.

Figure 4 shows amplification characteristics of the fabricated fibres. Gain for EDF-7-135-3 was equivalent to those of the conventional 7-core

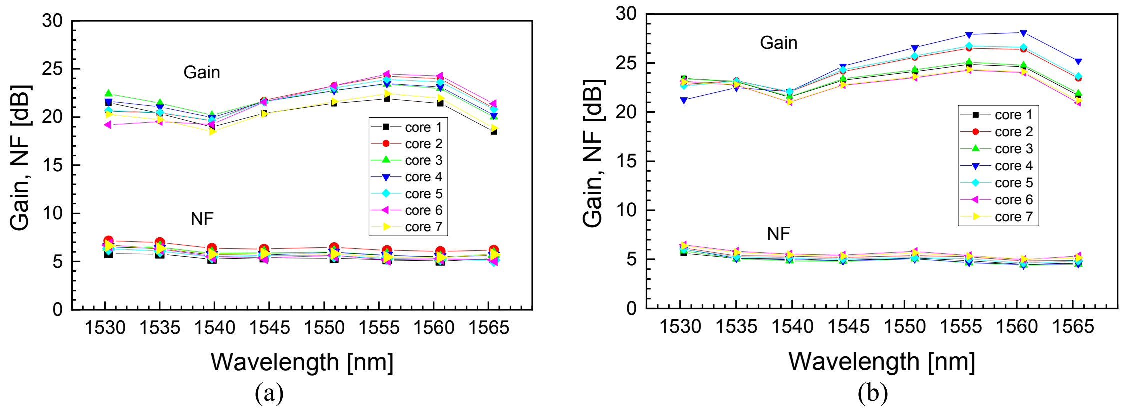

Fig. 4: Measured gain and NF spectra for EDF-7-135-3 (a) and for EDF-135-3S (b).

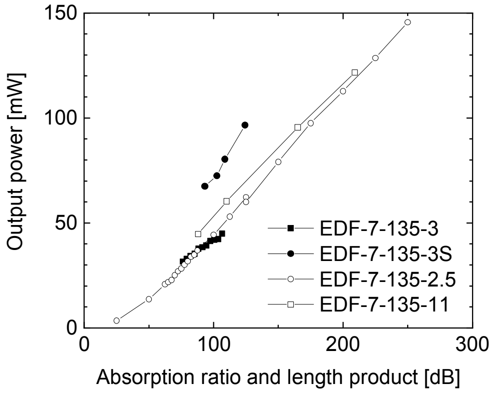

Fig. 5: Product of absorption ratio and EDF length dependence of output power for EDF-7-135-3 (closed squares), EDF-7-135-3S (closed circles), EDF-7-135-2.5 (open circles)[5], EDF-7-135-11 (open squares)[3,4].

EDFs[4,5]. Output power of the EDF-7-135-3 was 16.2 dBm that is equivalent power to the conventional 7-core EDFs[4,5]. These results indicate that core expansion does not improve the cladding pump efficiency.

Gain for EDF-7-135-3S increased more than 2 dB to that of the EDF-7-135-3. Output power of the EDF-7-135-3S was 18.4 dBm which is 2.2 dB higher than that of the EDF-7-135-3. These results indicate that scattering by the bubbles significantly improves cladding pump efficiency.

Core-to-core difference of noise figure (NF) is 1.3 dB for EDF-7-135-3 and 0.8 dB for EDF-7-135-3S indicating that little dependence on existence of bubble in the cladding area. The difference is equivalent to those of conventional 7-core EDFAs[4,5]. Core-to-core difference of the gain was 3.2 dB for EDF-7-135-3 and 4.3 dB for EDF-7-135-3S. These differences are larger than those of the conventional 7-core EDFAs[4,5].

If generation of the bubbles is random in position, integration of effect of the bubbles in longitudinal direction would be uniform so that the core-to-core gain difference might be small. Improvement of bubble generation processes would make uniform bubble generation so that the core-to-core gain difference would be reduced.

Figure 5 shows dependence of output power on product of core-absorption ratio and length for 7-core EDFs. The plot for EDF-7-135-3 almost overlaps with the plot of EDF-7-135-2.5 and agrees well with the plot of EDF-7-135-11. This suggests that efficiency of cladding pump absorption has little dependence on core-absorption ratio and core-diameter in case that cladding diameter and core-pitch is the same.

On the other hand, the slope of EDF-7-135-3S plot is 2.3 times larger. This suggests that the inclusion of bubbles as scattering bodies in the cladding area increases the cladding absorption rate.

Discussion

We discuss appropriate size of the bubbles. In the case where the mechanism for scattering of the cladding pump light is Rayleigh scattering, the cladding pump light is scattered in all directions although there is a certain incident angle dependence. In particular, light that are scattered perpendicular to the incident direction are likely to go outside the cladding resulting in loss. On the other hand, when the cladding pump light is scattered by Mie scattering mechanism, ratio of forward scattered light increases while ratio of perpendicularly scattered light decreases. In other words, Mie scattering mechanism changes propagation direction of the cladding pump light slightly while reducing loss of the pump light. Therefore, Mie scattering mechanism is better mechanism for increasing the cladding pump absorption ratio.

Mie scattering is occurred when the size of the scattering bodies is in the range from 1/10 to 10 times to the pump wavelength of 976 nm. The average bubble diameter of 1.4 um in this study is suitable for Mie scattering.

Summary

We have fabricated the core diameter expanded 7-core EDF (EDF-7-135-3) and the core diameter expanded 7-core EDF with bubbles in the cladding area as Mie scattering bodies(EDF-7-135-3S). Output power of the EDF-7-135-3 was 16.2 dBm that is equivalent to those of conventional 7-core EDFAs[4,5]. On the other hand, that of EDF-7-135-3S was as high as 18.4 dBm that is 2.2 dB higher than that of EDF-7-135-3. That is, the effect of the output power increase by the core diameter increase was little, but the effect of the output power increase by the bubbles was large.

We confirmed that insertion of Mie scattering bodies such as the bubbles increases cladding pump absorption efficiency resulting in the output power increase.

Acknowledgements

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