Pumping of 7-Core Erbium-Doped Double-Clad Fiber Amplifier Based on Higher-Order Mode Coupling

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***Abstract*—We investigated the pumping performance of 7-core erbium-doped double-clad fiber amplifier with novel pumping method which we proposed. The pumping method achieves compact assembly of the amplifier based on higher-order mode coupling of pump radiation. BPM calculation shows coupling efficiency of about 95 %.**

I. Introduction

Multi-core fiber (MCF) is recognized as an important technique to accommodate the increase of growing internet traffic [1, 2]. MCF can transmit parallel optical signals along through parallel multi-cores. However, it is needed to amplify the attenuated optical signals in parallel. Some different types of amplifiers have been investigated [3-6]. Especially, multi-core (MC) erbium-doped fiber amplifier (EDFA) with double-cladding construction is one important candidate because of its compact assembly without using fan-in and fan-out optical components [7, 8]. In this case, all the cores in the MC-EDFA are pumped simultaneously by the pump radiation propagated through the common cladding. However, one key-issue is the method to couple the pump radiation to the cladding. Special tapered fiber bundles [7] and side-coupling using a tapered multimode fiber (MMF) wound around the side of MC-EDFA [8] have been investigated. In this paper, we studied the pumping performance of 7-core MC-EDFA with double-cladding construction with novel pumping method which we have proposed [9]. The pumping method achieves compact assembly of the amplifier based on higher-order mode coupling of pump radiation. Beam propagation method (BPM) calculation shows coupling efficiency more than 90 %.

II. Pumping Method Based on Higher-Order Mode Coupling

Figure 1 shows the structure of a MC-EDFA with double-cladding construction [9]. Parallel optical signals are propagated through multiple cores embedded in a common first cladding which is covered by second cladding. The multimode propagation of the pump radiation along through the first cladding pumps all the cores simultaneously. Fig. 2 explains the proposed method to couple the pump radiation from a MMF to the common cladding. A mode of the pump radiation propagated through the MMF is selected by using a phase plate placed on the input end of the MMF [10]. The MMF is placed beside the MC-EDFA whose second cladding is stripped. The optical power of the pump radiation is coupled to the common cladding of MC-EDFA [9].

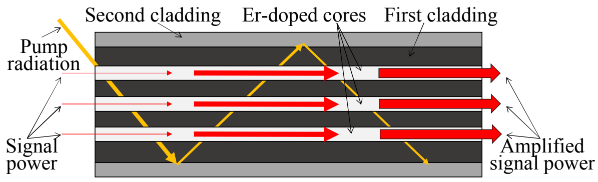

Fig. 1. Structure of multi-core Er-doped double-clad fiber amplifier and pump/signal power.

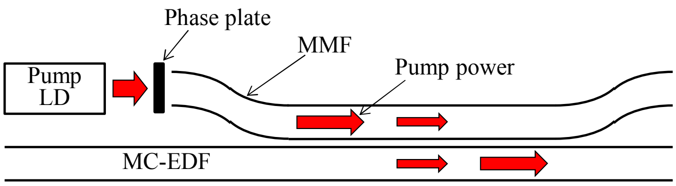

Fig. 2. Multimode optical coupling between multimode optical waveguides in MC-EDFA.

III. BPM Calculations

BPM calculation was performed to investigate the coupling efficiency and coupling length between a MMF and the first cladding with 7-cores. In the calculation, diameters of the common first cladding and MMF were set at 100 μm. Wavelength of the pump radiation was 1.48 μm. Figure 3 shows geometrical configuration of the cores, the common cladding and the MMF. The core-spacing is 41 μm. Refractive index of the multiple cores and the common cladding are set at 1.4500824 and 1.450128, respectively. LP_{11} and LP_{21} modes of the pump radiation were selectively propagated along through the MMF, adjusting the refractive index of the MMF to control propagation constant and coupling efficiency of the pump radiation.

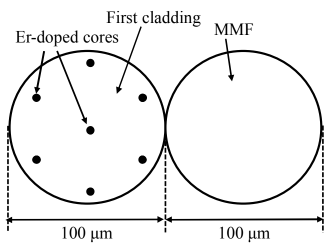

Fig. 3. Geometrical configuration of the cores, the common cladding and the MMF

IV. Results and Discussion

At first, BPM calculation was performed for a case that the number of cores was only one (single-core EDFA) for comparison. Figures 4 (a) and (b) show the results of propagated LP_{11} and LP_{21} modes, respectively. In the case of LP_{11} mode (Fig. 4 (a)), coupling efficiency was about 98 % and coupling length was 128 mm. In the case of LP_{21} mode (Fig. 4 (b)), coupling efficiency was about 95 % and coupling length was as small as 70 mm. In this single-core case, we could not observe significant difference from a simplified calculation in which the influence of embedded cores was omitted [9].

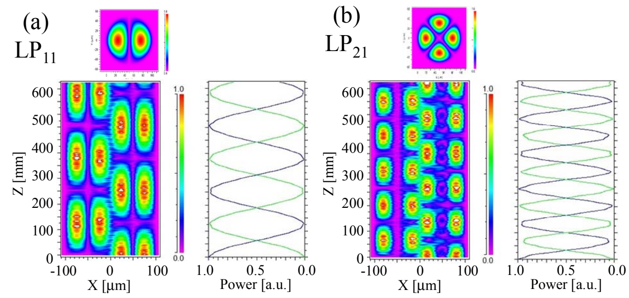

Fig. 4. BPM calculation results of optical power distribution and coupled optical power in a case of single core with pump radiation of (a) LP_{11} and (b) LP_{21}.

Next, we investigated the case of 7-core EDFA with pump radiation of LP_{21}. Figure 5 (a) shows the result of the BPM calculation. The coupling efficiency was about 10 %. This small coupling efficiency is considered as a result of the influence of the embedded cores. To compensate this influence, we adjusted the refractive index of MMF to control the propagation constant. Figure 6 shows the calculated coupling length and coupling efficiency versus the refractive index of MMF. We could observe a peak coupling efficiency as high as 95 % with coupling length of about 100 mm when the refractive index was 1.450128. Fig. 5 (b) shows the optical power distribution and coupled optical power at this optimized condition. The result successfully demonstrated that the influence of the embedded multiple cores could be compensated by adjusting the refractive index of MMF. However, the coupling efficiency was quite sensitive to the refractive-index. It is needed to relieve this strict condition on the next step of this study.

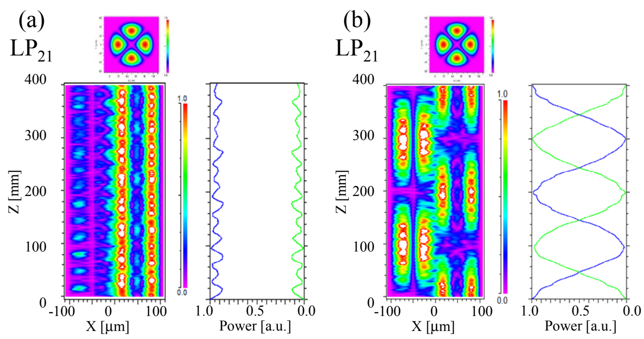

Fig. 5. BPM calculation results of optical power distribution and coupled optical power in a case of 7-cores with LP_{21} pump radiation. (a) Refractive index of MMF was not adjusted. (b) Refractive index of MMF was adjusted.

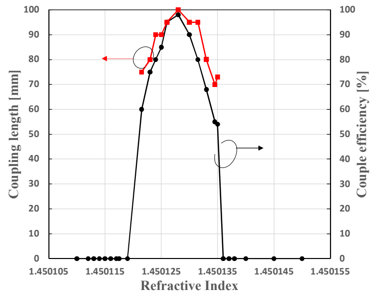

Fig. 6. Calculated coupling length and coupling efficiency versus refractive index of MMF with pump radiation of LP_{21}.

V. Conclusions

We investigated a novel pumping method for MC-EDFA with double-cladding construction. The BPM calculation shows that coupling efficiency of about 95 % and coupling length less than 100 mm can be achieved in case of 7-cores. We hope that the results would open up new applications of compact and efficient MC-EDFAs.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 25420351.

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