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# L-band 19-Core Erbium Doped Fibre Amplifier with Power Consumption of 1.2 W/core for 20 dBm/core Output

Shigehiro Takasaka(1), Koichi Maeda(1), Ryuichi Sugizaki(1), and Yoshihiro Arashitani(1)

(1)Furukawa Electric Co., Ltd., 6, Yawata-kaigandori, Ichihara, Chiba, 290-8555, Japan, shigehiro.takasaka@furukawaelectric.com

**Abstract** *We fabricate a double cladding uncoupled 19-core EDF with cladding diameter of 166 μm. We confirm that power consumption of a cladding pumped L-band 19-core EDFA with 20 dBm/core output is as small as 1.2 W/core under 11.2W laser diode output for the cladding pump.*

## Introduction

Reduction of power consumption of optical amplifier contributes not only to reduction of power consumption of optical fibre communication systems but also to increase of communication capacity of optical submarine cable communication systems where available electric power is limited. Cladding pumped multicore erbium doped fibre amplifiers (MC-EDFA) have advantage in the reduction since multi-mode laser diodes (MM-LD) as cladding pump sources have higher electric-to-optical conversion efficiency than that of single mode laser diodes as core pump sources.

Output power of cladding pumped L-band MC-EDFAs could be constant under the same cladding pump power density regardless of cladding diameter [1-4]. Therefore, we can expect reduction of power consumption of L-band MC-EDFAs as the cladding diameter is decreased under the same cladding pump power density. In addition, we can expect that decrease of the cladding diameter causes increase of output power of C-band MC-EDFAs [1,3-5].

On the other hand, decrease of cladding diameter results in decrease of core pitch so that inter-core crosstalk (XT) is deteriorated. Thus, the decrease of cladding diameter is limited by a certain value of the XT.

In this paper, we fabricate a cladding diameter decreased 19-core EDF from 200 μm to 166 μm [2,5]. Based on cladding area ratio, we can expect 1.6 dB reduction of cladding pump power under the same cladding pump power density. Then, we measure amplification characteristics of a 19-core EDFA with cladding diameter of 166 μm in L-band and C-band, respectively, and discuss reduction of power consumption.

## Design and fabrication of 19-core EDF

We assume that small cladding diameter causes reduction of power consumption of MC-EDFAs. According to the decrease of cladding diameter, core pitch of a MC-EDF is decreased resulting in deterioration of inter-core XT. We confirmed based on simulation result of finite element method that core pitch more than 30 μm results in the inter-core XT less than -55 dB for a 100m-long MC-EDF. Thus, we fabricated a 19-core EDF with the smallest cladding diameter having a designed XT of -55 dB/100m.

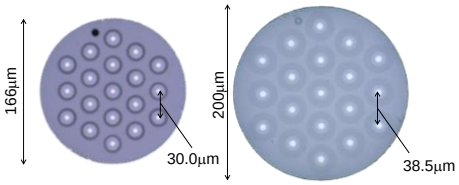


**Fig. 1:** Cross-section pictures of the double cladding 19-core EDF with cladding diameter of 166 μm (left picture) and of that with cladding diameter of 200 μm (right picture) [2,5]. Low refractive index coating is removed for taking fine picture.

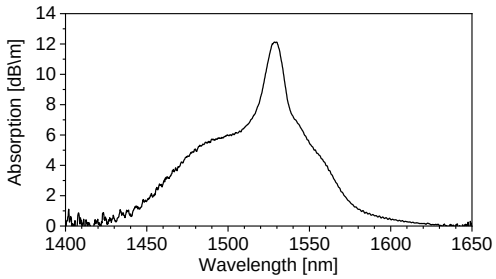


**Fig. 2:** Absorption spectrum of the 19-core EDF at centre core

Figure 1 shows a cross-section of the fabricated double cladding 19-core EDF with cladding diameter of 166 μm. Core arrangement is hexagonal lattice. Core pitch is 30 μm. Core design is the same with that of reported MC-EDFs [1,2,5]. Low refractive index resin is coated to have double cladding structure. Figure 2 shows absorption spectrum of the 19-core EDF at centre core. Absorption peak at about 1530 nm is 12.1 dB/m that is almost the same value with that of 19-core EDFs in Ref. 1, 2 and 5.

## Configuration of a 19-core EDFA

Figure 3 shows configuration of a cladding pumped 19-core EDFA. Input and output fibres are standard single mode fibre (SMF) and are

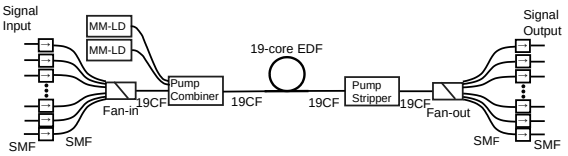


**Fig. 3:** Configuration of a cladding pumped 19-core EDFA. MM-LD: multi-mode laser diode, 19CF: 19-core fibre, SMF: single mode fibre. Arrow marks are isolators.

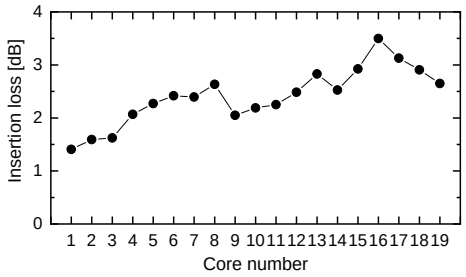


**Fig. 4:** Insertion loss of the concatenated devices of the fan-in, the pump combiner, and the fan-out that was measured at 1550 nm. Core 1 corresponds to centre core.

connected with isolators. A fan-in and a fan-out for a 19-core fibre are fibre-bundle type devices. A pump combiner consists of a 19-core fibre and is a side-coupling type fibre device having pump coupling efficiency of 93%. MM-LDs output multimode pump light with wavelength of 976 nm and have electric-to-optical power conversion efficiency about 50%. Two MM-LDs were drove when total output power beyond 30 W. The 19-core EDF was fusion-spliced with the 19-core fibre at both ends. Length of the 19-core EDF was 50 m and 8 m for L-band and C-band amplification, respectively. A pump stripper removes cladding pump light to avoid breaking the fan-out.

The fan-in, the pump combiner, and the fan-out for core pitch of 30 μm were the first trial devices. Insertion losses of concatenated these devices are shown in Fig.4. The losses tend to increase with increase of core number though the insertion loss of concatenations between the fan-in and the fan-out for core pitch of 38.5 μm is lower and more uniform [6]. Here, core 1 is centre core. Core 2 to 7 surround the centre core. Core 8 to 19 are outer cores. The devices would be improved with increase of fabrication number.

## L-band amplification characteristics

We measured amplification characteristics of an L-band 19-core EDFA with EDF length of 50 m. Input signal was an 8-wavelength division multiplexed (WDM) signal with total power of 7.5 dBm.

Figure 5 shows amplification characteristics of the 19-core EDFA. Output power of the MM-LD was 27.8 W that is almost the same density of cladding pump power with that in Ref. 1 and 2.

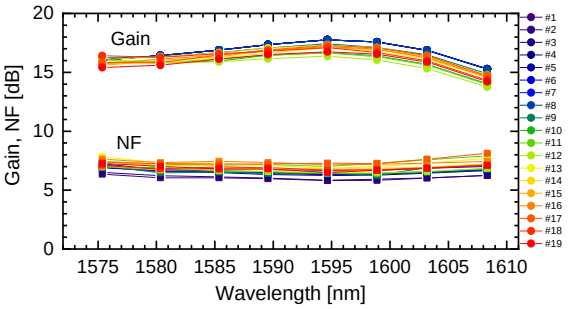


**Fig. 5:** Amplification characteristics of the cladding pumped L-band 19-core EDFA with EDF length of 50m. Input signal is 8-WDM signal with total power of 7.5 dBm. Pump power was 27.8 W.

Averaged gain and noise figure (NF) are 16.2 dB and 6.8 dB, respectively. Core-to-core difference of gain and NF are 1.5 dB and 1.9 dB, respectively.

Output signal power of the centre core was 24.3 dBm/core. This value shows good correlation with the averaged output signal power of 24.5 dBm/core that was obtained by the 19-core EDFA with cladding diameter of 200 μm under 33.2 W cladding pump power [2]. This correlation supports the assumption that the output power of MC-EDFAs is constant under the same cladding pump power density.

Figure 6 shows the MM-LD output power dependence of the 19-core EDFA output power and of the MM-LD power consumption. Both the EDFA output power and the MM-LD power consumption have linear dependence on the MM-LD output power. Here, regarding power consumption, we measured only driving power of the MM-LD. We did not include cooling power consumption since it depends on cooling conditions and environments.

EDFA output power of 100 mW/core, that is 20 dBm/core, is obtained when the MM-LD output is 11.2 W with power consumption of 22.1 W. This power consumption corresponds to 1.2 W/core. Thus, we confirmed that reduction of cladding diameter of the 19-core EDF to 166 μm

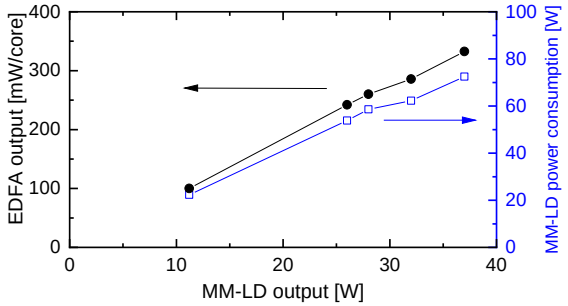


**Fig. 6** MM-LD output power dependence of the 19-core EDFA output power (closed circles) and of the MM-LD power consumption (open squares). Input signal is 8-WDM signal with total power of 7.5 dBm.

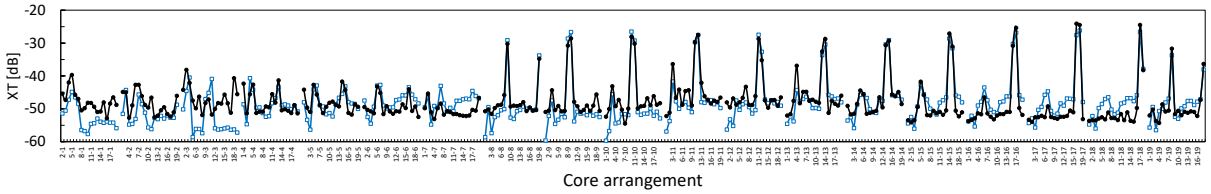


**Fig. 7:** Inter-core XT of the L-band 19-core EDFA (black closed circles) and of a concatenated device of the fan-in, the pump combiner, and the fan-out (blue open squares).

reduces power consumption of the L-band 19-core EDFA to 1.2 W/core for 20 dBm/core output power. In addition, the power consumption of 1.2 W/core is 1.2 dB smaller than estimated power consumption of the 19-core EDFA with cladding diameter of 200 μm for 20 dBm/core output condition [2].

Figure 7 shows inter-core XT of the L-band 19-core EDFA with cladding diameter of 166 μm and a concatenated device of the fan-in, the pump combiner, and the fan-out. The XT of the EDFA was measured as in Ref. 2, 4 and 5. Most of the cores have the XT about -50 dB while some adjacent cores have the XT beyond -30 dB. Inter-core XTs for the L-band 19-core EDFA are almost the same with that of the concatenated devices. This result indicates that an insertion of the 19-core EDF between the pump combiner and the pump stripper did not increase the XTs. That is, the XT is currently dominated by the concatenated devices.

## C-band amplification characteristics

We measured amplification characteristics of a C-band 19-core EDFA with EDF length of 8 m. Input signal was set to be 8-WDM signal with total power of -5 dBm. Output power of the MM-LD was 27.8 W. Since core-19 was unavailable at the measurement, we measured the other 18 cores.

Figure 8 shows gain and NF characteristics. Averaged gain and NF are 21.3 dB and 6.6 dB, respectively. Core-to-core difference of gain and NF is 1.6 dB and 1.9 dB, respectively. Output power of the C-band 19-core EDFA at centre core is 17.5 dBm/core. Output power is about 1.5 dB higher than that of the C-band 19-core EDFA with cladding diameter of 200 μm and is almost the same with 17.7 dBm/core of the C-band 12-core EDFA with cladding diameter of 90 μm [5,7]. We confirmed that a decrease of cladding diameter of a 19-core EDF increases output power of a MC-EDFA as in Ref. 5.

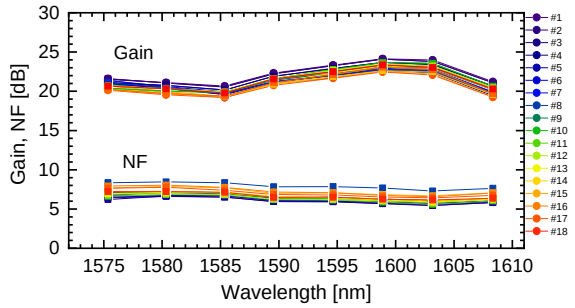


**Fig. 8:** Amplification characteristics of the cladding pumped C-band 19-core EDFA with EDF length of 8m. Input signal is 8-WDM signal with total power of -5 dBm. Pump power was 27.8 W. Core 19 was unavailable for this measurement.

## Summary

We fabricated the 19-core EDF with cladding diameter of 166 μm and core pitch of 30 μm based on the designed inter-core XT of -55 dB/100m.

Output power of the cladding pumped L-band 19-core EDFA with cladding diameter of 166 μm was 24.3 dBm/core for MM-LD output power of 27.8W and showed good agreement with the output power of 24.5 dBm/core measured on the L-band 19-core EDFA with cladding diameter of 200 μm under almost the same cladding pump power density [2]. In addition, we confirmed that MM-LD output power for 20 dBm/core signal output was as small as 11.2 W corresponding to power consumption of 1.2 W/core. The power consumption is 1.2 dB smaller than the estimated power consumption of the 19-core EDFA with cladding diameter of 200 μm and is close to that of conventional EDFAs.

Output power of the cladding pumped C-band 19-core EDFA with cladding diameter of 166 μm was 17.5 dBm/core which is about 1.5 dB higher than that of the C-band 19-core EDFA with cladding diameter of 200 μm under almost the same cladding pump power density [5]. We confirmed that decrease of cladding diameter increases output power of a cladding pumped C-band MC-EDFA.

## Acknowledgements

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