Full C-band and Power Efficient Coupled-multi-core Fiber Amplifier

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Abstract: A coupled 12-core fiber amplifier with the highest optical power conversion efficiency of 10.2% is achieved among the reported C-band cladding-pumped amplifiers. Potential as full C-band inline amplifier is confirmed using full coupled-core SDM link. © 2020 Author(s).

1. Introduction

Space division multiplexing (SDM) amplifier is considered as a key component to realize a large capacity power efficient SDM transmission system. The cladding pumped configuration attracts much attention since it enables us to simultaneously amplify multiple signals with one multi-mode laser diode, which potentially reduces the power consumption per spatial channel. Recently various SDM amplifiers with low power consumption have been reported [1-4]. One key parameter for reducing the power consumption is the spatial density of the SDM fiber amplifier because larger number of spatial channels within a limited cross section can improve the pumping efficiency. The L-band 42 spatial channels amplifier with the low power consumption factor of 0.36 compared to that for the conventional Erbium doped fiber amplifier (EDFA) was reported [3]. However, it is difficult to improve power efficiency for the cladding pumped C-band amplifier, although the hybrid core and cladding pumping is effective to obtain 0.3~0.4 reduction of the power consumption compared to that for only cladding pumped configuration [4]. This is because the EDF length for C-band amplification is generally much shorter than that for L-band. The shorter EDF requires higher pumping power to realize sufficient absorption, thus degrading the power efficiency.

In this paper, we experimentally investigate the performance of C-band cladding pumped coupled-multi-core fiber (MCF) amplifier in terms of power efficiency. Our amplifier with a coupled 12-core EDF [5] exhibits more than 20 dB gain for whole C-band with a 5 W pumping, and achieves the highest optical power conversion efficiency (PCE) of more than 10% among the reported C-band cladding pumped SDM amplifiers. We also confirm the applicability as an inline amplifier with low mode dependent loss (MDL) penalty by conducting a full C-band and full SDM transmission over 600 km.

2. Potential of full C-band cladding pumped coupled-MCF amplifier

At first, we experimentally investigate the basic amplification properties of our coupled-MCF amplifier. Figure 1 shows the schematic diagram of our coupled-12-core EDFA. The EDF has square lattice-arranged 12 cores with a 16.4 μm core pitch and a cladding diameter of 90 μm. Compared to our previous report [4], the power coupling efficiency of the pump combiner was improved from 60% to 90% by applying the free space optics configuration instead of the side coupling type. We adjusted the EDF length at 8 m to obtain the flat spectrum gain for whole C-band. The pump stripper was deployed at the output port of the EDF to remove the residual pump light. Figure 2 shows the pump power dependence of the gain and noise figure (NF) at 1550 nm, where the input signal power was set to be -25 dBm/core and 4 CW light (1532, 1542, 1552 and 1562 nm) with a total power of -9 dBm/core was input into the EDFA to fix the spectral gain property. We measured the output power from each core with a 3D waveguide-based 12-core fan-out device. The solid line or error-bar shows the averaged or max./min. value for each

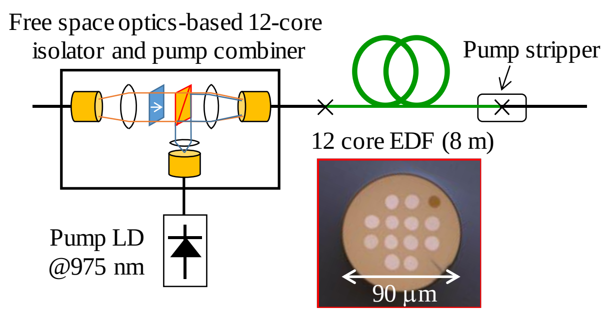

Fig. 1. Schematic diagram of our coupled-12-core EDFA

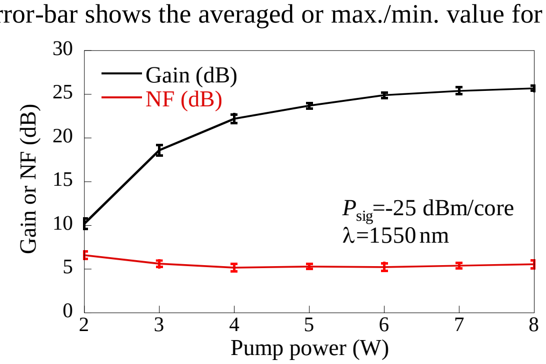

Fig. 2. Measured gain and NF characteristics

measurement. There was sufficiently small core dependency for the gain or NF within ±0.7 dB or ±0.5 dB, and up 25 dB gain with 5 dB NF was obtained for ≤8 W pumping. Figure 3 shows the measured average gain and NF spectra with a pump power of 5 W. It can be seen that the gain exceeds 20 dB for whole C-band. We obtained almost wavelength insensitive NF properties of about 5 dB across the C-band. Thus, we successfully confirmed that our EDFA has enough gain and low NF properties suitable for a long-distance SDM transmission system.

We then conducted a coupled-12-core fiber transmission to evaluate the applicability as a full C-band inline amplifier. Figure 4 shows the setup for the transmission experiment. We used a 1.25 Gb/s PM-QPSK signal at a wavelength of 1530~1565 nm. The signal was split into twelve ports and multiplexed through the fan-in device. Each signal was decorrelated by the delay line with different length. Three wavelength-multiplexed CW light ranging from 1530~1560 nm with more than 10 nm intervals except for signal wavelength was also launched into the fiber with the same input power per wavelength as the signal to fix the gain spectrum of the EDFA while tuning the tested wavelength of the signal. The transmission line consists of all SDM components such as 12-core coupler, EDFA, gain flattening filter (GFF), 60 km long 12-core fiber and acousto-optic modulator without any single-mode devices within the recirculation loop. The spectral gain variation across the whole C-band was reduced to be less than 1 dB by the GFF. The 60 km-long 12-core transmission fiber has an attenuation coefficient of 0.21 dB/km and spatial mode dispersion of about 20 ps/√km at 1550 nm. The transmitted signals were then demultiplexed through the fan-out device, and recovered by the 24×24 MIMO equalizer. The adaptive algorithm we used was IPNLMS and the number of data and training symbols was 10000 and 1000, respectively. Figure 5 shows the measured MDL penalties as a function of the number of span. It is worth to note that wavelength dependency for the MDL penalty within the C-band is relatively small and we observed an MDL increase of 0.55 dB/loop. This implies that all link components including the transmission line realize well random mode coupling nature. We actually confirmed that the measured MDL penalty of our EDFA itself was less than 1 dB in the entire C-band. Figure 5 also shows the average *Q* factors among the transmitted signals through 24 polarization/spatial modes in the inset. The error-bar shows the max./min. value for each wavelength. We observed the *Q* factor degradation for the signal at 1530 nm compared to the other wavelengths. We expect that this degradation is owing to the insufficient NF properties of our booster amplifiers deployed at the transmitter and local oscillator. The transmission distance however reached maximum 600 km with the *Q* factors of more than 5.6 dB. These results show that our coupled-EDFA has sufficient

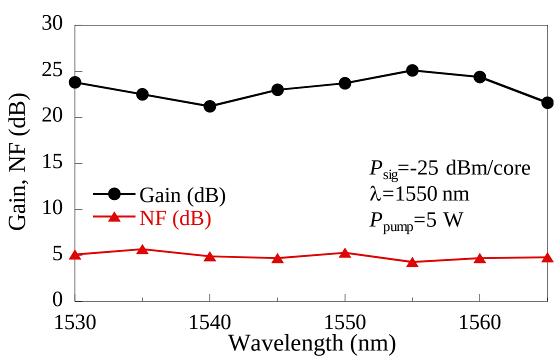

Fig. 3. Measured gain and NF spectra

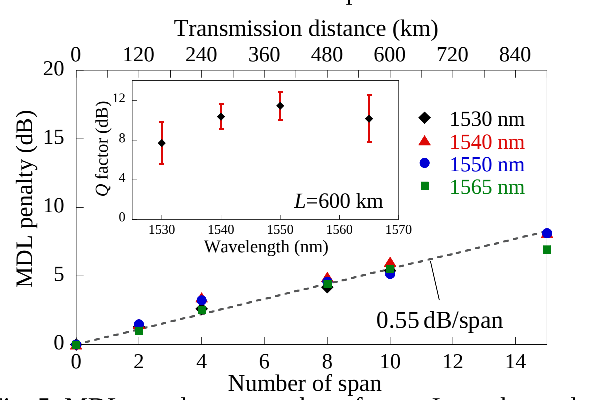

Fig. 5. MDL penalty vs. number of span. Inset shows the worst *Q* values measured after 600 km transmission.

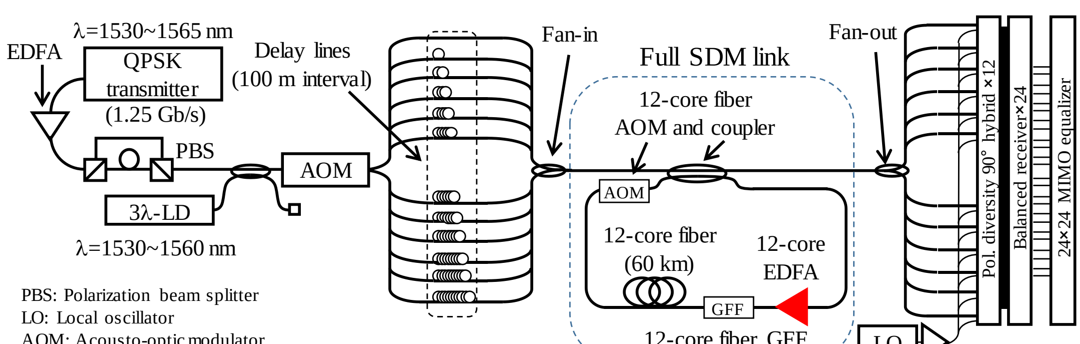

Fig. 4. Setup for C-band all SDM coupled-12-core fiber recirculation transmission

potential as an inline amplifier for full C-band SDM transmission.

3. Potential as power efficient C-band cladding pumped amplifier

Finally, we discuss the potential of coupled-MCF amplifier for power efficient amplification. Figure 6 shows the numerical example of the ratio between core and cladding area (R_{CC}) of SDM-EDF as a function of the number of spatial channels. Circles, squares, diamonds and triangles show the results for coupled-MCF, uncoupled-MCF, 6-mode-MCF and single-core few-mode fiber (FMF), respectively. We assumed hexagonal or square lattice core arrangement, and the core pitch of uncoupled-MCF, 6-mode-MCF, and coupled-MCF are assumed to be 38.5, 45 and 16.4 μm, respectively. The cladding thickness is 15 μm for all types and minimum cladding diameter is 80 μm. The core diameter is varied from 11 to 26 μm depending on the number of mode per core. Figure 6 reveals that coupled-MCF amplifier has a larger R_{CC} slope per number of spatial channels compared to the other SDM-EDFs, and it reaches 0.2 with 19 spatial channels whereas the 6-mode-MCF amplifier requires 42 spatial channels to realize an R_{CC} of 0.2. Figure 7 shows the PCE values of the reported C-band cladding pumped amplifiers as a function of number of spatial channels. Here, PCE is defined as the power ratio between the output signal and pumping power from the LD. For our coupled-12-core amplifier, we observed the output signal power of +17.7 dBm/core with the total input signal power of -5 dBm/core and the pumping power of 7 W at 1550 nm. This amplification property corresponds to the PCE of 10.2%. This is the highest value among the reported C-band cladding pumped SDM amplifier as shown in Fig. 7, which is owing to the high R_{cc} design of the EDFA with closely-packed twelve cores and 90 μm cladding. We expect that the PCE of 10.2 corresponds to about a power consumption factor [1] of 0.6 if we take account of the relationship between the PCE and the factor reported in [3]. These results show that coupled-MCF based EDFA is useful candidate for realizing power efficient SDM transmission in C-band.

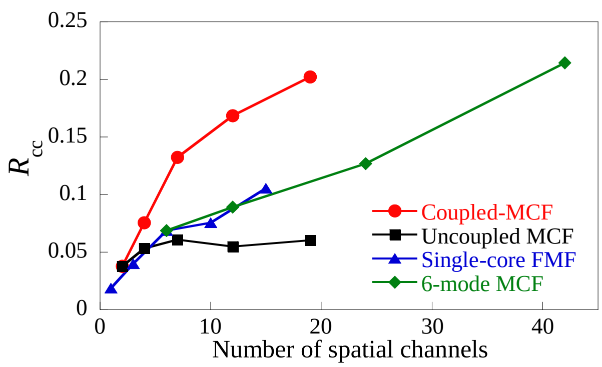

Fig. 6. Example calculated relationship between R_{cc} and number of spatial channels

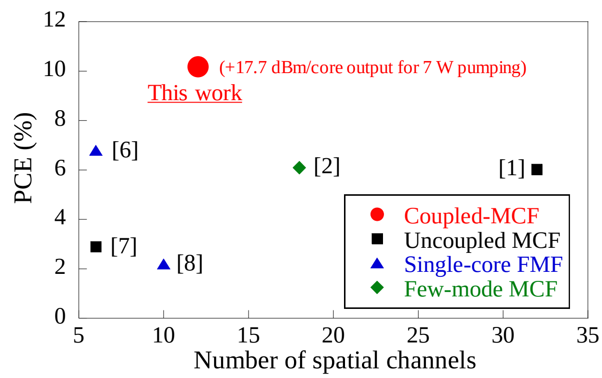

Fig. 7. Comparison of PCE among reported C-band cladding pumped SDM amplifiers

5. Conclusion

We achieved the power efficient coupled-12-core fiber amplifier with more than 20 dB gain across C-band and the highest optical power conversion efficiency of 10.2%. Potential as an inline amplifier for full C-band and all coupled-core SDM transmission was also proved as well as the low MDL penalty performance. It can be expected that our EDFA potentially realizes low electrical power consumption per spatial channel in the C-band compared to the conventional EDFA if the low power consumption multi-mode LD is used.

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