Tapered fiber bundle couplers for high-power fiber amplifiers

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ABSTRACT

In this work, we would like to demonstrate our results on performing (6+1)x1 tapered fiber bundle combiners using a tri-electrode fiber splicing system. In our combiners we have used 9/80 μm (core/clad) diameter fibers as single-mode signal input ports. Using this fiber, instead of a conventional 9/125 μm single-mode fiber allowed us to reduce the taper ratio and therefore significantly increase the signal transmission. We have also performed power combiner which is based on the LMA fibers: input signal fiber 20/125μm and passive double clad fiber 25/300 μm at the output.

Keywords: all-in-fiber, fiber tapers, power combiners

1. INTRODUCTION

Passive fiber components, like power combiners, but also mode-field adaptors, play a key role in high-power fiber amplifiers based on double-clad fibers[1]. These components allows to resign of bulk optics and build setups of amplifier in so called all-in-fiber technology. It makes setups more robust, simple and cost-effective, because of the vide availability of inexpensive telecom components . Moreover the amplified beam does not leave a waveguide, thus there are not any problems with adjustment of the amplifier[2].

It is a very common approach to use all-in-fiber technology, in one stage fiber amplifier or in an MOPA (Master Oscillator Power Amplifier) setups, to achieve high optical power in 1.55 μm region with good beam quality. In MOPA setups each stage can be based on different active fiber. Higher stages, usually based on an active double clad fiber, allow to use much more pumping power than in case of single mode fiber (preamplifier). The highest stage can base on the LMA fiber (Large Mode Area) – that kind of fiber allows for propagation high optical pumping power but also high power of the signal[3]. Mode-field adaptors are used to match mode field diameter between different fibers, so in the other words they are connecting next stages in a cascade of amplifiers. The power combiners are very effective for pumping the active double clad fibers in second and higher stages of MOPA. Using that king of architecture allows for high power amplification with very good beam quality[4-7].

Both mention above components are realized by a tapering process[8]. To make mode-field adaptors, tapering of one fiber is enough. Process of making power combiner is much more complicated. Bundle consisting of several multi-mode fibers (for the pump power) and a central single-mode fiber (for the amplified signal) is spliced to a passive double - clad fiber (DCF). Such combiners, made in (N+1)x1 configuration, allow for combining N pumping ports and 1 signal port to the active fiber[5,9]. Diagram of the power combiner is shown on the figure 1.

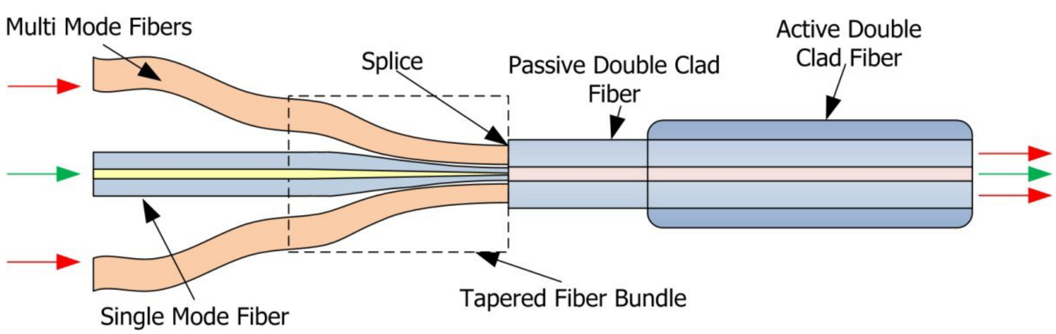

Figure 1. Diagram of the power combiner (N+1)x1 type

19th Polish-Slovak-Czech Optical Conference on Wave and Quantum Aspects of Contemporary Optics,
edited by Agnieszka Popiołek-Masajada, Wacław Urbańczyk, Proc. of SPIE Vol. 9441, 94410G

2. FABRICATION TOOL – LDS SYSTEM

In this paper we demonstrate our method and results of developing high-power fiber combiners using the 3SAE LDS System – Large Diameter Splicer[10]. This very advanced equipment has three electrodes, instead of two like in conventional fiber splicer. Those three electrodes are making so called the Ring Of Fire (ROF – shown on figure 2), which allows to more effective heating of a larger fibers. In the software, which is included to the splicer we can easily change the Arc Power to chose a proper heating for our operation.

Figure 2. Three electrodes in the LDS System – ROF

Electrodes shown on figure 2 can be also moved to make ROF wider or narrower. All this allow for work with fiber diameter from 80 µm up to 2 mm. The splicer is also equipped with two platforms, with fiber holders, which can move along the fiber axis. This allows for making tapers and thus – tapered fiber bundles. The splicer has also inner cleave blade, so after tapering process we can cleave our taper on the exact position which we need. Attached software allows for making tapers with two methods: single direction and bi-directional tapering process (figure 3).

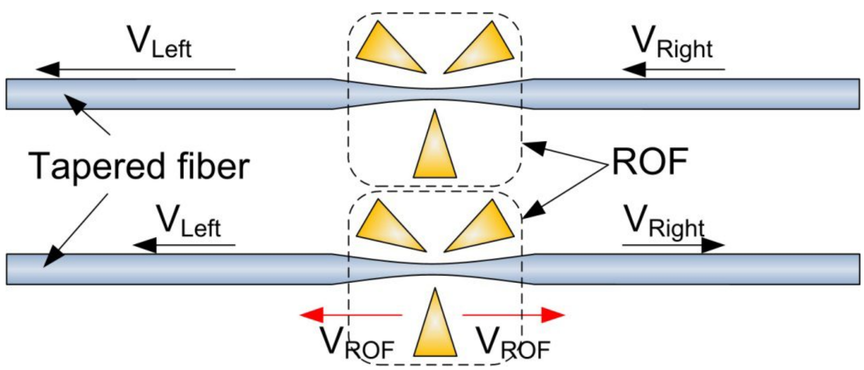

Figure 3. Two methods of tapering: single directional (a) and bi - directional (b)

The first method of tapering (fig. 3. a) is designed more for tapering e.g. capillary tubes where the shape of taper is not that important. Program requires from user to set the start and waist diameter, lengths of down and up slope and waist length and also arc power in specific section of tapering process. In this method the ROF remains in one centre position, so user can observe on the monitor turned on ROF and moving through it a tapering fiber/capillary tube. During this process, when the ROF is turned on, the platforms holding our fiber/capillary are moving to the left side – at the star with the same speed but the left one is accelerating so the fiber is pulling out while it is also heating. After proper distance (down slope length) the speed reaches maximum value with which continues during the waist length and after that is slowing down. The second method (fig. 3. b) is more precise but also more complicated to set down parameters. In this case the ROF is moving during the whole process – it is scanning fiber from left to right with one speed. The length on which ROF is moving is decreasing during process – user is setting start and end width of tapering. In meantime the platform are moving in opposite directions – left platform to the left side and right platform to the right side with accelerating speed. User controls speeds of the ROF and platforms, changing of the arc power, the width of the ROF scanning and also length on which the platform are moving out. With this method we were able to make single mode fiber taper with total length of 9 mm – up and down slope length each 4.1 cm, waist length 0.8 cm with the diameter of about 5 µm. Transmission loss in this taper was measured at level 0.12 dB. The diameter at the central position is measured during whole tapering process in both cases and after tapering user can easily scan performed taper on the total length. It shows some possibilities which offers the LDS system. After tapering fiber, beside scanning it, user can cleave it in the splicer and observe the cross sectional area of it. Some examples of cross sectional areas of tapered fiber bundles are shown in figure 4.

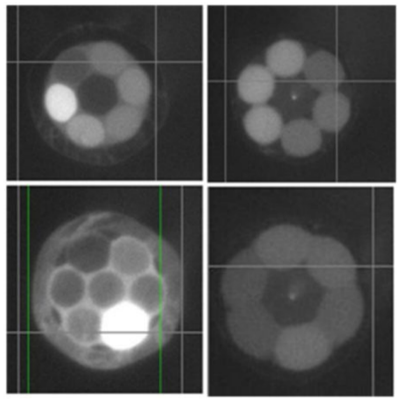

Figure 4. Examples of cross sectional area of cleaved tapered fiber bundles

3. FABRICATION PROCESS AND OBTAINED RESULTS

3.1 Tapered fiber bundle with 9/80 µm single mode fiber as a signal input fiber

Our first goal was to fabricate coupler power combiner (6+1)x1, which has at the input 6 multi mode fibers for pumping power and one single mode fiber for the 1550 nm signal, and at the output one passive double clad fiber 9/125 µm. As a signal input fiber we were using conventional single mode fiber 9/125 µm and lengths of the tapered fiber bundle was 25 mm. We have obtained pump transmission about 80-90 %, but the signal was nearly at level 40 %. For the purpose of our work we have prepared simulation of radiation 1550 nm signal through a core of a tapered single mode fiber spliced to a passive double clad fiber which we are using. Simulation were made for the conventional single mode fiber with diameters 9/125 µm and for the single mode fiber with reduced clad diameter 9/80 µm. The simulated structure and the results of simulation of the transmission are shown on the figure 5.

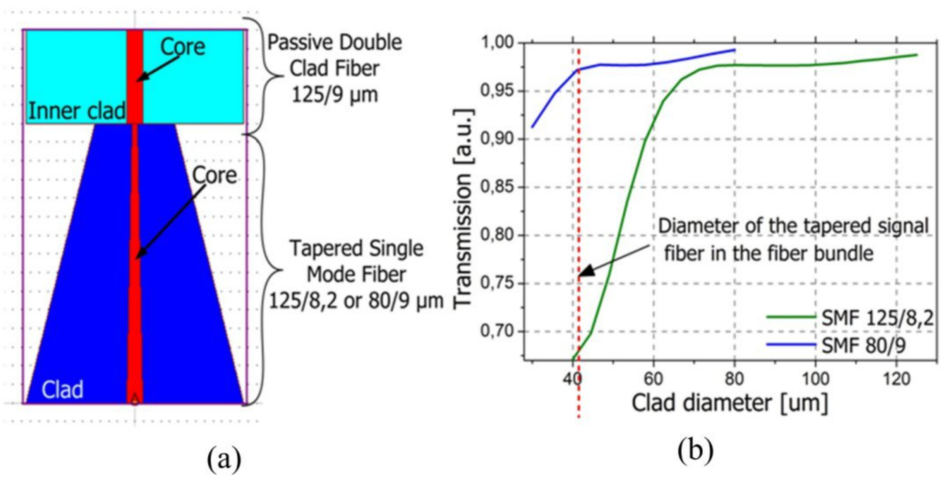

Figure 5. Simulated structure (a) and the results of the transmission through it (b)

On the figure 5 (b) can be seen transmission at the output of the structure, while decreasing clad diameter at the end of the tapered fiber. Clad diameter equal 40 µm has been selected and pointed out, because this is the diameter of each fiber in the tapered fiber bundle. It can be clearly seen that using single mode fiber with reduced clad diameter can effectively improved the transmission from theoretically less than 70 % up to more than 95 %. It is because the Taper Ratio (where TR is equal diameter at the input divided by diameter at the output) is lower in this case.

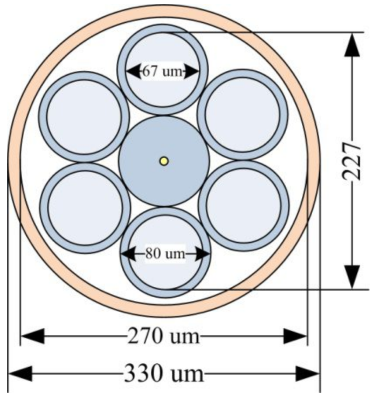

Figure 6. Theoretical cross section area – placement of the fiber inside

However to use this single mode fiber it was necessary to tapered down firstly all multimode fibers. This was required to obtain proper placement in the capillary tube (figure 6), because using one fiber with diameter 80 µm and six fibers with diameter 125 µm would result in improper placement in the capillary – there would be too much free space inside it and the fibers could change its position too easily. So firstly we have tapered down seven (not six) multimode fibers from 105/125 to 67/80 µm. Scan of one example of tapered multimode fiber is shown on figure 7. As can be seen the down slope length is about 17 mm and waist length 34 mm – it has to be very long for further steps of the whole process. All fibers were cleaved in the LDS system directly after tapering on the same position (cleaving spot at fig. 7).

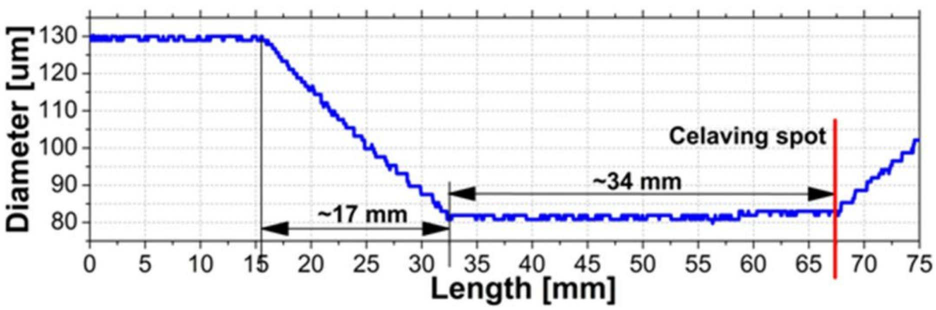

Figure 7. Example of the tapered multimode fiber

After preparing multimode fiber, capillary tube was tapered down. Scan of the prepared capillary tube is shown on figure 7. It was necessary to tapered it down because the holders in the splicer are working with 700 µm diameter as equipment which we are using to putting our fibers inside the capillary. So 530/700 µm capillary tube was tapered down to about 270/330 µm, so all seven tapered fibers could be placed inside it.

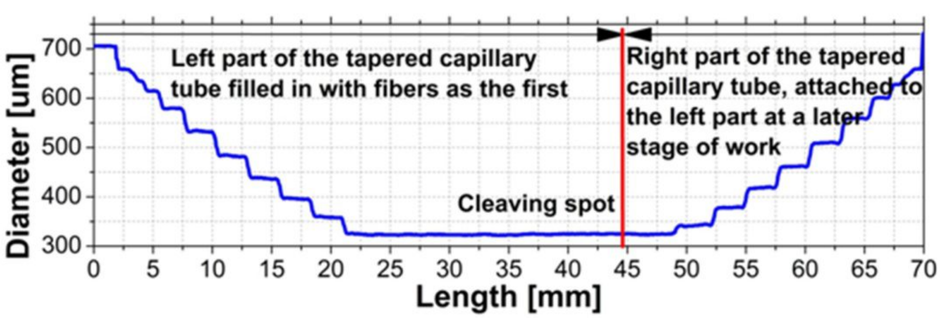

Figure 8. Profile of the tapered capillary tube

After tapering process, an empty capillary tube was cleaved, and the left part of it was filled in with seven tapered multimode fiber. By moving fibers inside the capillary we were able to set the ends of the fibers in the same position and observe them in the monitor. Figure 9 is showing an empty tapered down capillary tube and the same capillary filled with the multimode fibers. While looking at the front of the fiber bundle we could easily see which one of the fibers is the central fiber and change this fiber to 9/80 µm single mode fiber. Later the bundle was moving to right side – to fill the right part of the cleaved capillary tube (fig. 8). When the fibers were moved as far as they could the capillary was heated at the cleaving point to splice two parts together.

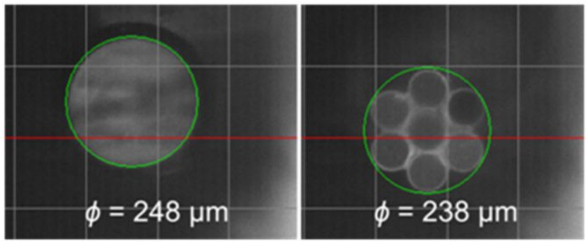

Figure 9. Cross section of the empty tapered capillary tube and capillary filled with fibers

The next step was to tapered down the fiber bundle inside the capillary tube. Result of this process is shown on figure 10. We can see that down slope has length of about 17,5 mm and waist length of about 5 mm. It was easier to cleave the bundle on the waist section, than on the slope.

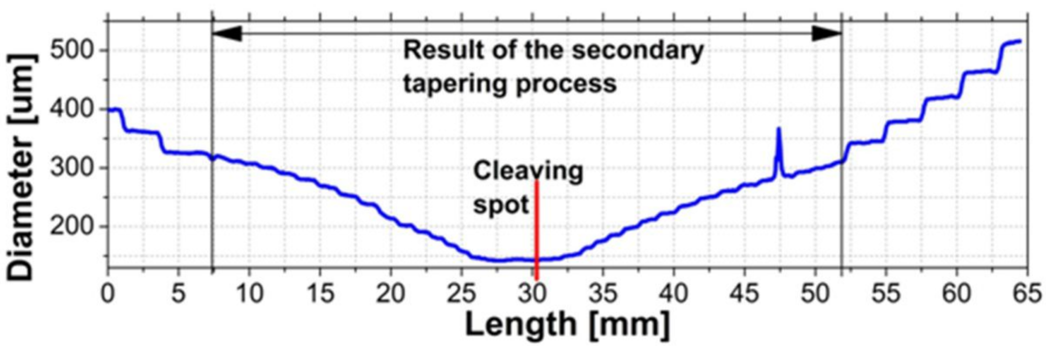

Figure 10. Profile of the tapered fiber bundle

A peak on the diameter that can be seen on the length position 47.5 mm is a result of the splicing two parts of the capillary and does not has any influence on the quality of the tapered bundle. It is because we are getting rid of the right part of the tapered bundle after cleaving. The left part is spliced to a passive double clad fiber, but before that we can visually check a placement of our fibers in the bundle. On the figure 11 is shown the cross sectional area of the cleaved bundle, and we can see that the signal fiber is in the central position. There is some free space between three multimode fiber on the left and right part of the bundle – this might be caused by slightly to small power of the ark. The diameter of the multimode fiber bundle is about 105 µm, so it appears that to match it to inner clad of our double clad fiber (125 µm) we could have tapered the bundle to the little bigger diameter.

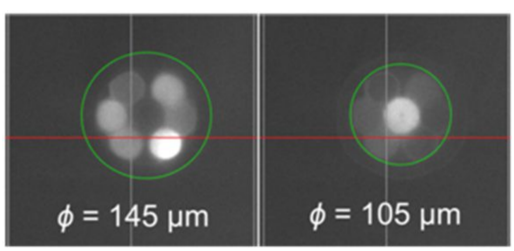

Figure 11. Cross sectional area of a cleaved tapered fiber bundle with highlight multimode fibers and single mode fiber

While splicing the bundle with passive double clad fiber the transmission of a 1550 nm signal was measured at the output of this fiber for better alignment. The result of the signal transmission after splicing was 68 %

(that is 1.7 dB attenuation). It is less than simulation shows, but it is because the taper is not ideal and also cleaving and splicing during the process has big influence on the signal transmission. The results of the transmission of the pump power is shown onthe figure 12, and it can be seen that the transmission is between 68 and 72 %.

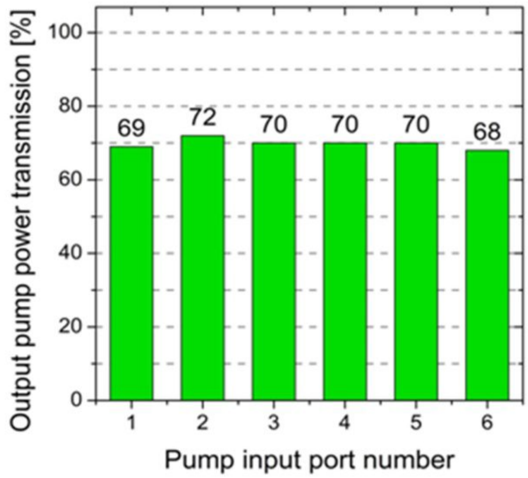

Figure 12. Transmission of a pump power through the structure

3.2 Tapered fiber bundle based on the LMA fibers

Secondary structure on which we were working out was based on the LMA fibers. It is again configuration (6+1)x1 but the signal input fiber is an LMA fiber 20/125 µm and the passive double clad fiber at the output has diameter 25/300 µm. In this case at the input all fiber have clad diameter 125 µm, so there is no need to tapered down multimode fibers. Here first step is to tapered down capillary tube from 530/700 µm to about 400/500 µm of the diameter – result is shown on the figure 13.

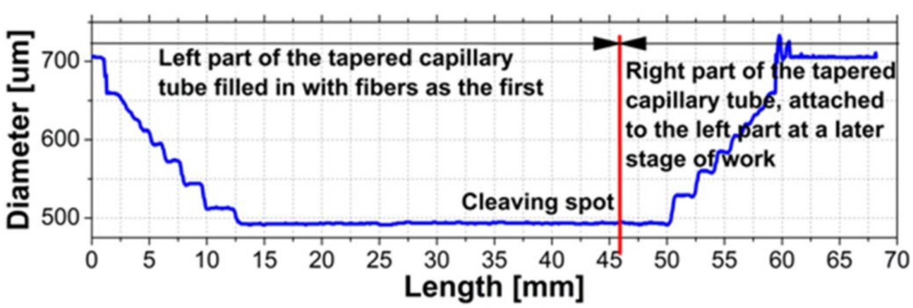

Figure 13. Profile of the tapered capillary tube

Next step is similar as in previous structure- cleaving the tapered capillary, fill the left part with seven multimode fibers (fig. 14), checking and replacing the central multimode fiber to signal fiber, and splicing with the right part of the capillary.

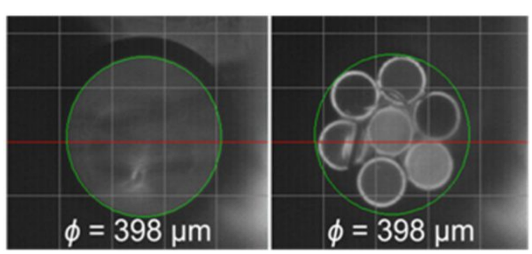

Figure 14. Cross section of an empty tapered capillary tube and capillary filled with fibers

After that the bundle was tapered down to the diameter about 350 µm. The cleaving in this case was problematic, because the diameter is larger than in previous case, so the tension during cleaving should be bigger. But it might caused breaking of the capillary on the external parts (figure 15 - length from 0 to 10 mm and 60 to 65 mm) because there the fibers are not welded with the capillary tube, so there is some free space. However launching lower tension than calculated allows to cleave bundle without broken it.

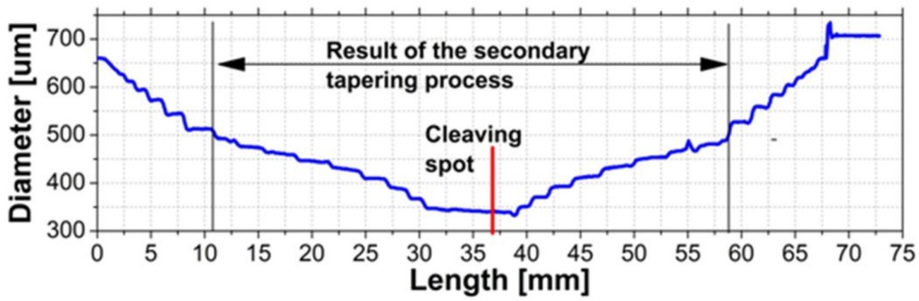

Figure 15. Profile of the tapered fiber bundle

The cross section view of cleaved tapered fiber bundle is shown on the figure 16. The diameter of the bundle made from multimode fibers inside the capillary tube is about 255 µm, so also in this case the final diameter of the bundle could be larger.

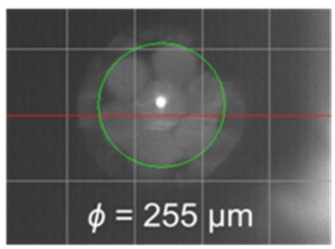

Figure 16. Cross sectional area of a cleaved tapered fiber bundle with highlight multimode fibers and single mode fiber

The tapered bundle was next spliced to a passive double clad fiber 25/300 µm, also while measuring the signal transmission for better aligning. The result for the signal transmission after tapering is 78 % (1.05 dB of the attenuation). The transmission of the pump power is shown of the figure 17 and it is about 96 – 99 %.

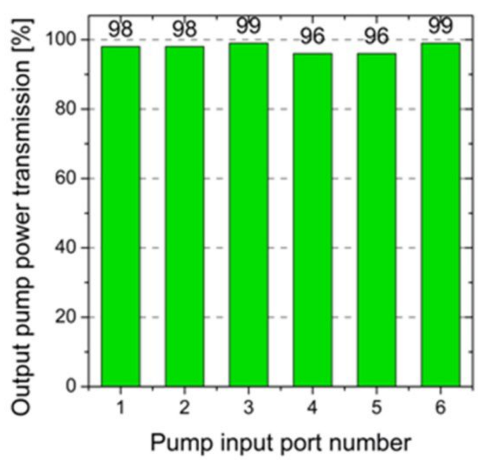

Figure 17. Transmission of a pump power through the structure

4. SUMMARY

In conclusion we have fabricated tapered fiber bundles using tri-electrode fiber splicing system – LDS system. Both structures were fabricated in (6+1)x1 configuration. The first one, with 9/80 µm single mode input fiber for the signal and 9/125 µm passive double clad fiber at the output achieved transmission of the signal about 68 %, while pumping transmission was about 68- 72 %. The second structure which was based on the LMA fibers achieved signal transmission at level 78 %, and pump power transmission at level 96 - 99 %. In our further work we are planning to optimize fabrication process to achieve higher levels of the signal transmission in both cases and improve the signal transmission in the first one. Next step will be to build setups of amplifiers with tapered fiber bundle couplers fabricated by us.

ACKNOWLEGMENT

The work presented in this paper was supported by Wroclaw Research Center EIT+ under the project "The Application of Nanotechnology in Advanced Materials" - NanoMat (POIG.01.01.02-02-002/08) financed by the European Regional Development Fund (Innovative Economy Operational Programme, 1.1.2). The research fellowship of one of the authors (D. Sliwinska) is co-financed by the European Union as part of the European Social Fund

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