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Coherent combining of 7 fiber lasers using a multi-plane light converter device

A. Liméry*^a, L. Lombard ^a, P. Bourdon ^a, A.Billaud ^b, O.Pinel ^b, G.Labroille ^b, T.Le Guennic ^b, P.Jian ^b
^aONERA – *The French Aerospace Lab*, BP 80100, 91123 Palaiseau Cedex, France;
^bCAILABS, 38 boulevard Albert 1er, 35200 Rennes France

ABSTRACT

An experimental demonstration of laser beam coherent combining with active phase control has been performed using for the first time a Multi-Plane Light Converter device (MPLC). The MPLC as a beam combiner is designed as a spatial multiplexer which output modes form a Gaussian beam when superimposed constructively, reaching theoretically 100% efficiency. Moreover, reflective free-space design allows for handling high power. The experiment combines seven 1.5 μm continuous wave fiber lasers operated at a low power level in the tens of milliwatt range using the frequency-tagging LOCSET technique (Locking of Optical Coherence by Single-detector Electronic-frequency Tagging) for the phase locking. 72-% power efficiency MPLC CBC is achieved with an output combined beam close to a Gaussian beam profile. M^2 is lower than 1.8 depending on the transverse direction, revealing an excellent quality for the combined beam. The output beam is more than 94 % linearly polarized. Simulation of the impact of atmospheric turbulence on the propagation of the seven laser beams up to 1 km is performed. We demonstrate that it is possible to compensate for most of the atmospheric propagation detrimental effects and to perform efficient MPLC CBC through strong turbulence.

Keywords: Fiber laser, Coherent combining, Phase control, DIRCM

1. INTRODUCTION

Increasing laser power while preserving a good beam quality is a key challenge for many areas of physics and defense. Power scaling of fiber lasers is limited by nonlinear and thermal effects as well as damage threshold in optical fibers. Coherent combining techniques by active phase control has the potential to overcome these limits and deliver increased power¹⁻².

In typical coherent beam combining (CBC) architectures, a single CW master oscillator seeds several power amplifiers arranged in a tiled apertures configuration. The laser beams propagate in free space and interfere constructively in the far field. This configuration enables an easy combination of a large number of fibers amplifiers leading to successful CBC experiments through km-range atmospheric turbulence³⁻⁴. However, due to a limited aperture fill factor in the near field and sides lobes in the far field, this technique is limited to a theoretical maximum efficiency of 63%. The filled aperture configuration has not such a limit and experimental coherent combination using diffractive optical element has shown efficiency above 80% in the kW-regime⁵⁻⁶. Nevertheless, this filled aperture configuration seems more suited for the combination of low number of fiber lasers.

In this work, we present what is to our knowledge the first experimental demonstration of laser beam coherent combining with active phase control using a Multi-Plane Light Converter device (MPLC). The MPLC is a novel device that allows to perform any unitary spatial transform through a succession of transverse phase profiles. The MPLC as a beam combiner is designed as a spatial multiplexer which output modes form a Gaussian beam when superimposed constructively (100% theoretical efficiency). In this MPLC CBC experiment, we combine seven 1.5 μm low continuous wave fiber lasers operated at a low power level in the tens of milliwatt range using the frequency-tagging LOCSET technique (Locking of Optical Coherence by Single-detector Electronic-frequency Tagging). A stable combined output beam with good quality is obtained. Simulation of the impact of atmospheric turbulence on the propagation of the seven laser beams up to 1 km is also performed.

2. MULTI-PLANE LIGHT CONVERTER DEVICE FOR COHERENT COMBINING

MPLC is a technique for performing any unit spatial transformation⁷. Theoretically, it allows the lossless conversion of any set of N orthogonal spatial modes into any other set of N orthogonal modes. The conversion is done by a succession of transverse phase profiles each separated by a free space propagation serving as an Optical Fourier Transform (OFT) operation. The principle of the MPLC is schematically represented in Figure 1.

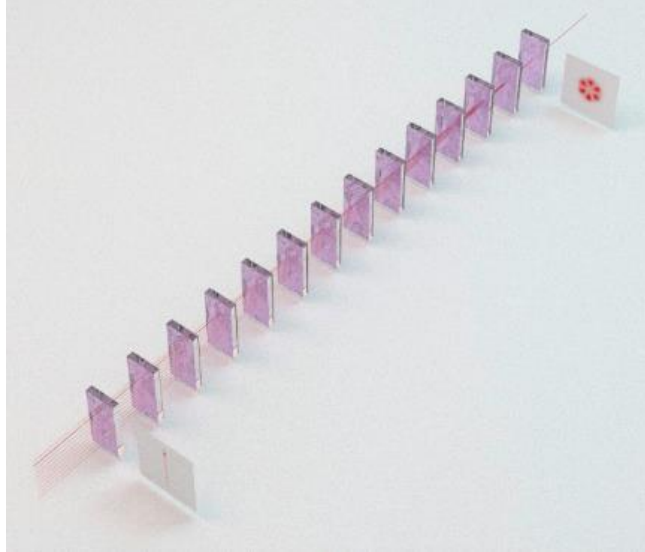


Figure 1. Multi-Plane Light Conversion principle.

In particular, the MPLC allows for mode-selective spatial multiplexing and demultiplexing, i.e. the conversion of N spatially separated input Gaussian beams into N orthogonal modes.

In practice, the MPLC is implemented using a multi-pass cavity, in which successive phase profiles are all fabricated on a single reflective phase plate. Figure 2 shows an image of an MPLC for coherent beam combining. The cavity consists of a mirror and a reflective phase plate, visible by its gold coating in Figure 2. An MPLC used in the reverse direction implements the demultiplexing operation.

In previous work, the fabrication and characterization of multiplexers with up to 45 modes has been demonstrated⁸. Moreover, this technology is particularly suitable for combining incoherent beams to combine a large number of beams while keeping $M2$ low⁹.

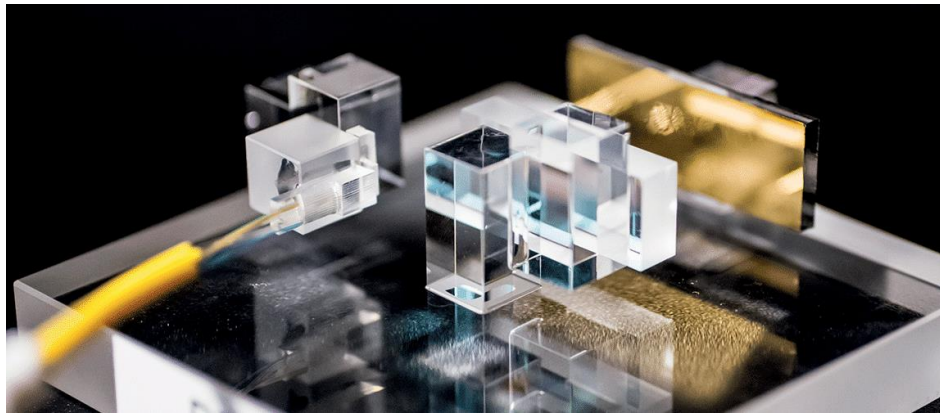


Figure 2. Photo of an MPLC as a coherent beam combiner. On the left, the input consists of an array of single mode fibers. The phase plate is gold-coated. In front of it, a mirror completes the cavity. Free space output is on the right of the picture

The realization of a coherent beam combination with an MPLC is similar to any other unitary transformation. The input basis is converted to an arbitrary output basis. Unlike a spatial mode multiplexer targeting a classical basis such as Hermite-Gaussian (HG) or Laguerre-Gaussian (LG) modes, a coherent beam combining MPLC converts the input basis into modes designed to produce a perfectly coherent sum when they constructively interfere. The profile of each individual mode is not specific, but their coherent interference is calculated to generate a Gaussian beam. Based on MPLC, some solutions exist to take into account residual errors in the phase locking scheme and mitigate their effect. In this experiment, these options have not been applied but the coherent combination of 7 Gaussian beams has been realized. The inputs are assumed to be monochromatic and polarized in a single direction. Each input mode is individually converted to an arbitrary output mode. Figure 3 shows an example of the intensity profile of an output base of modes that generate a Gaussian beam when they coherently interfere, as shown in Figure 4. Compared to other methods such as full aperture combining, this conversion is theoretically lossless - all energy going into the output Gaussian beam. In practice, some losses arise from reflections off the phase plates and losses at the fibre-air interface.

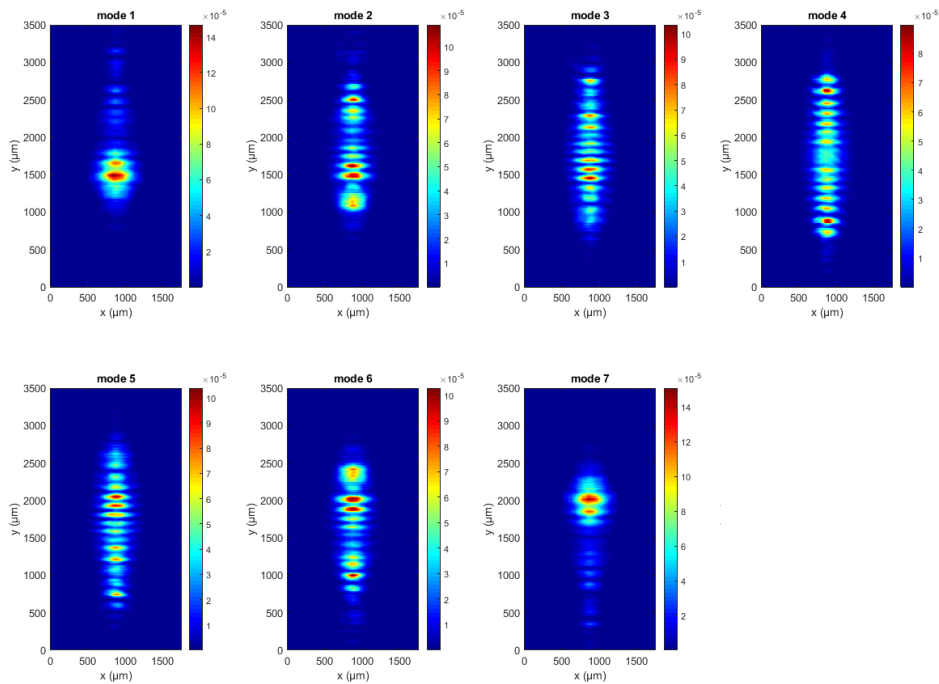


Figure 3. Intensity profiles of 7 output modes independently generated with the MPLC

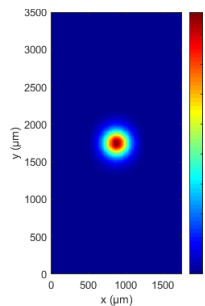


Figure 4. Theoretical sum of output modes from figure 3 where phase locking is achieved.

3. COHERENT BEAM COMBING WITH AN MPLC

3.1 Laser testbed for CBC with an MPLC

The testbed includes a 7-channel MOPFA (Master Oscillator Power Fiber Amplifier) laser system as illustrated on Figure 6. Every element of the laser system contains polarization maintaining fibers. A single-frequency low power (40 mW) master oscillator (MO) is split into 7 channels. One channel (REF) is not phase controlled while six fiber-coupled electro-optic modulators (EOM) ensure frequency tagging and laser beam phase control of the remaining 6 channels using the LOCSET technique. Each channel is tagged with low-depth modulation at a specific frequency. All the 7 channels can be amplified with Er-Yb doped fiber amplifiers delivering up to 3 W at 1545 nm. For this demonstration dedicated to confirm the feasibility of CBC with a MPLC, the 7 Er-Yb doped fiber amplifiers are removed to operate at a low power level. The 7 laser beams are easily coupled into the MPLC through single mode fibers. At the output of the MPLC, the 7 superimposed modes are collimated. Then a fraction is extracted with a beamsplitter to be collected on a photodetector. In the processing unit, each frequency is demodulated to recover the corresponding 6 phase error signals to be minimized by the controller. The phase of the unmodulated laser beam is used as a reference so that the phase locking loop drives the phase difference between each channel and the reference to zero. In order to observe and characterize the combined laser beam, a camera is disposed on the main optical path.

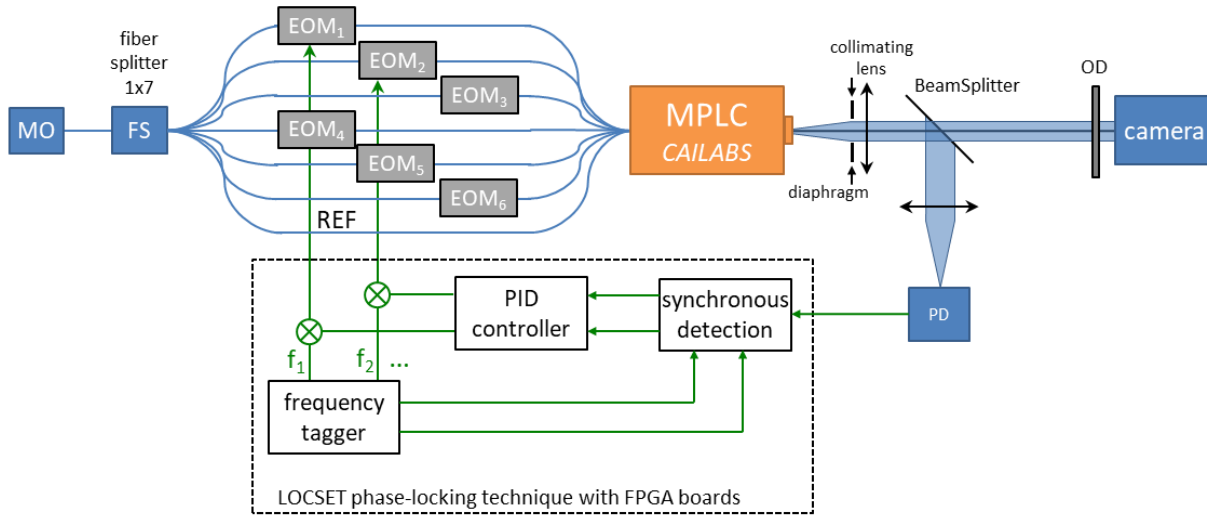


Figure 5. Layout of the laser testbed for CBC with an MPLC. MO: Master Oscillator. FS: Fiber splitter. EOM: Electro-optical modulator. OD: Optical Density.

3.2 Experimental results

Figure 7 shows the profile of combined beam measured by the camera. A very stable profile beam is observed meaning successful CBC is performed with the MPLC at all times. Nevertheless, remaining side lobes are observed on both sides of the central beam (fig. 7 left, nonlinear colormap is used to highlight these side lobes). Using a diaphragm in order to “clean” the combined beam we manage to obtain an output combined beam close to a Gaussian beam profile (fig. 7 right). However, this spatial filtering leads to a power loss of 18 %.

Taking into account the spatial filtering, the power efficiency of this MPLC CBC experiment, defined as the output beam power divided by the sum of the 7 input beams power, is measured to be $P^{OUT} / \sum P_i^{IN} = 72\%$. The combined output beam shape is close to a Gaussian profile: M^2 measurements show a beam quality of 1.4 and 1.8 in both transverse directions using the second order moments method. The output beam is more than 94 % linearly polarized.

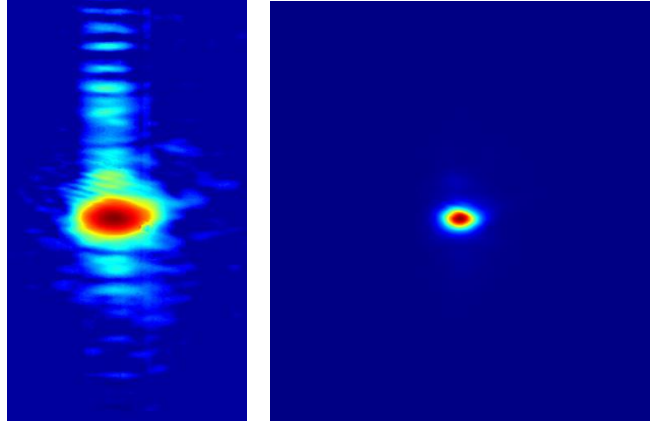


Figure 6. (Left) Combined output beam without spatial filtering. A nonlinear colormap is applied in order to highlight side lobes. (Right) Combined beam with spatial filtering leading to a profile close to a Gaussian beam. Here a linear colormap is used in order to appreciate the real beam profile.

This first experimental result of CBC with an MPLC is promising since the combining efficiency is already higher than the theoretical limit of tiled aperture configuration CBC. Yet, since spatial filtering removes 18 % of the optical power, this combining efficiency could be significantly higher. The presence of residual side lobes, making spatial filtering necessary, may come from slightly distorted individual modes. Indeed, distortions compared to theoretical modes independently generated have been observed and may originate from misalignment of the MPLC input fiber array that occurred during shipment. Another source of the side lobes presence could be an imbalanced power between all the 7 channels since it's difficult to seed each channel with the same power up. With this first component, we even observed up to 25 % power difference from one channel to the other. Moreover, the transmission per channel inside the MPLC can also be slightly different. This last point can be evaluated with the study of the power balance requirements for CBC with an MPLC presented below.

3.3 Input power balance requirement

For many applications, the conservation of a high beam quality is important. It has to remain as high as possible regardless of input power variation of one or several channels. We studied the impact of imbalanced input power on the theoretical combined beam profile.

For a normalized input power average ($\sum P_i^{IN} / 7 = 1$), we changed the standard deviation of the input power distribution between 0 (perfectly power balanced) and 0.5 (highly imbalanced power distribution). Figure 8 shows theoretical combined output beam profiles for four different power distribution standard deviations. For a perfectly power balanced configuration, an almost perfect Gaussian beam profile is obtained. A slightly distorted beam profile is observed for a relative standard deviation of 0.2-0.3. Finally, a distorted profile with side lobes, is obtained for a very high-power disparity between input beams ($\sigma=0.5$).

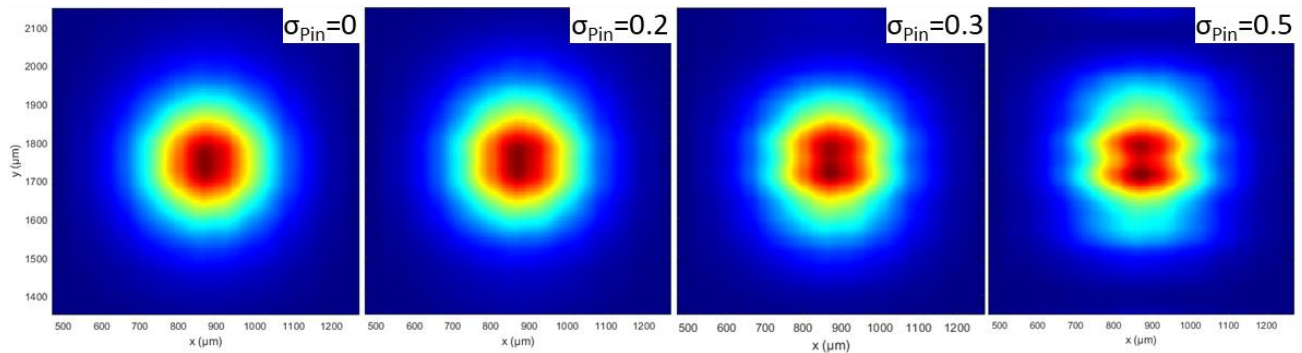


Figure 7. Theoretical combined output beam profile for different standard deviation (0, 20 %, 30 %, 50 %) of the input power distribution. A very distorted profile, with side lobes apparition, is only obtained for a very high power disparity between input beams ($\sigma=0.5$).

Based on these results, the requirement for input power balance to maintain a high beam quality is to limit the standard deviation of the input power distribution below 0.2. In our MPLC CBC experiment, such condition is verified so the input power imbalance cannot explain the presence of side lobes. Moreover, in a 7 MOPFA operating system with identical architectures, such condition should also be verified and then provide a stable beam profile.

In the extreme case that a channel is switched off (e.g. system failure), the impact on the beam profile is highly dependent on the mode number that is switched off. The combined beam can vary from an almost unchanged profile to a profile with many parasitic side lobes. Cailabs have been working on a new *supermode* approach to propose an MPLC robust to input power variations and phase locking errors¹⁰.

4. SIMULATION OF THE IMPACT OF PROPAGATION THROUGH TURBULENCE

To assess the sensitivity of the MPLC CBC approach, we simulate the impact of atmospheric turbulence on the propagation of the seven laser beams up to 1 km using a phase-screens numerical model. We used as input the theoretical amplitude and phases maps of the 7 modes. The phase turbulence is simulated using a Von Karman model with small and large scales of 1 mm and 100 m, respectively. As an example, one of the phase screens is shown in Figure 5 (left). Figure 5 (center and right) shows the combined beam obtained after numerical propagation through 1 km turbulence if the phase-control loop is closed by a photodetector before and after the atmospheric propagation. We observe that if the phase-control loop is closed by a photodetector placed after atmospheric propagation, compensation for most of the atmospheric propagation detrimental effects is possible and efficient MPLC CBC through strong turbulence is achieved. Just as can be done in a CBC tiled aperture configuration, the MPLC provides the ability to act on and reshape the combined wavefront by changing the relative phases of the 7 combined modes. The MPLC CBC advantage lies in the combining efficiency, which can be higher than the 63 % limit in the main interference lobe of the tiled aperture CBC technique.

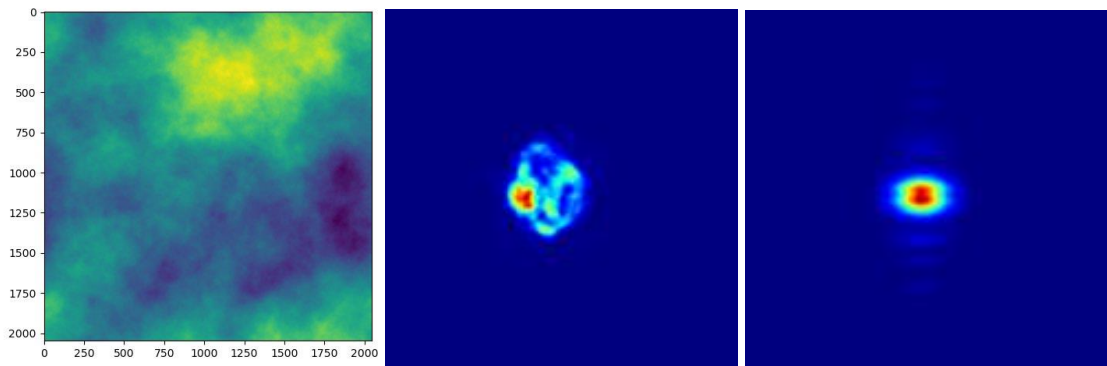


Figure 8. (Left) Example of one phase screen used in the numerical simulation $C_n^2 = 10^{-12} \text{ m}^{-2/3}$, $l_0 = 1 \text{ mm}$ et $L_0 = 100 \text{ m}$.

Combined beam obtained after numerical propagation through 1 km turbulence if the phase-control loop is closed by a photodetector before (center) and after (right) the atmospheric propagation.

In this paper, we present a first experimental demonstration of laser beam coherent combining with active phase control using a Multi-Plane Light Converter device.

The CBC laser testbed is comprised of seven 1.5- μm continuous wave fiber amplifiers capable of emitting up to 3 W each. In this experiment, we operated the amplifiers at a low output power level, in the tens of milliwatts range, as it was mainly dedicated to confirm the feasibility of CBC with a MPLC device and not to test its high-power sustainability.

5. CONCLUSION

72-% power efficiency MPLC CBC is achieved with an output combined beam close to a Gaussian beam profile. M^2 is lower than 1.8 depending on the transverse direction, revealing an excellent quality for the combined beam. The output beam is more than 94 % linearly polarized.

Simulation of the impact of atmospheric turbulence on the propagation of the seven laser beams up to 1 km is performed. We demonstrate that it is possible to compensate for most of the atmospheric propagation detrimental effects and to perform efficient MPLC CBC through strong turbulence.

The power balance requirements for the seven channel inputs have been discussed. The high beam quality obtained with the MPLC CBC technique is robust up to an input power distribution with a relative standard deviation of 0.2-0.3, higher than that which will occur with a 7-channel MOPFA laser system.

In order to provide a MPLC with a beam quality and a combining efficiency insensitive to larger input power variations (or even to a channel extinction) and phase locking errors, Cailabs is working on a new *supermode* approach. Its robustness with 7 fiber lasers or more can be tested in a future CBC experiment¹⁰.

6. ACKNOWLEDGEMENTS

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REFERENCES

- [1] A. Flores, T. M. Shay, C. A. Lu, C. Robin, B. Pulford, A. D. Sanchez, D. W. Hult and K. B. Rowland, "Coherent beam combining of fiber amplifiers in a kW regime," CLEO: 2011-Laser Science to Photonic Applications (pp. 1-2) (2011)
- [2] Shekel, E., Vidne, Y. and Urbach, B., "16kW single mode CW laser with dynamic beam for material processing," Proc. SPIE, 11260 1126021 (2020)
- [3] T. Weyrauch, M. A. Vorontsov, G. W. Carhart, L. A. Beresnev, A. P. Rostov, E. E. Polnau, and J. J. Liu, "Experimental demonstration of coherent beam combining over a 7 km propagation path," Opt. Lett. 36, 4455-4457 (2011).
- [4] B. Rouzé, L. Lombard, H. Jacqmin, A. Liméry, A. Durécu, and P. Bourdon, "Coherent beam combination of seven 1.5 μm fiber amplifiers through up to 1 km atmospheric turbulence: Near and Far Fields experimental analysis." Applied Optics DOI: 10.1364/AO.433872, (2021).
- [5] S. J. McNaught et al., "Scalable Coherent Combining of Kilowatt Fiber Amplifiers Into a 2.4-kW Beam," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 20, no. 5, pp. 174-181, (2014)
- [6] A. Flores, T. Ehrehreich, R. Holten, B. Anderson, I. Dajani, , Multi-kW coherent combining of fiber lasers seeded with pseudo random phase modulated light, Proc. SPIE 9728, Fiber Lasers XIII: Technology, Systems, and Applications, 97281Y (2016)
- [7] G. Labroille, B. Denolle, P. Jian, P. Genevaux, N. Treps and J.-F. Morizur, "Efficient and mode selective spatial mode multiplexer based on multi-plane light conversion", Opt. Express, vol. 22, pp. 15599-15607, (2014).
- [8] S. Bade *et al.*, "Fabrication and Characterization of a Mode-selective 45-Mode Spatial Multiplexer based on Multi-Plane Light Conversion," 2018 OFC, pp. 1-3 (2018).
- [9] L. Garcia, O. Pinel, P. Jian, N. Barré, L. Jaffrès, J.-F. Morizur, and G. Labroille "Fast adaptive laser shaping based on multiple laser incoherent combining," Proc. Of Photonics West Conference LASE, 10097-3, (2017).
- [10] A. Billaud *et al.*, "Optimal Coherent Beam Combining Based on Multi-Plane Light Conversion for High Throughput Optical Feeder Links," IEEE ICSOS, 2019, pp. 1-5, (2019).