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The Road to High Peak Power and High Average Power Lasers: Coherent-Amplification-Network (CAN)

Gérard A. Mourou[1,2], Danièle Hulin[1] and Almantas Galvanauskas[2]

[1]*Laboratoire d'Optique Appliquee, UMR 7639 ENSTA, Ecole Polytechnique, CNRS, 91761 Palaiseau, France*
[2]*Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109, USA*

Abstract. A new amplifying laser concept based on Coherent Amplification Network (CAN) is proposed to solve the high-peak high-average-power quandary. The amplification network is based on identical telecommunication diode-pumped fiber lasers. The philosophy behind the approach is to build the amplifying system from numerous small but identical parts as opposed to larger but non-identical components like in the laser Mégajoule in France or NIF in the USA. The basic amplification scheme is in-fiber Chirped Pulse Amplification. Besides the possibility to simultaneously provide high peak and high average power, the technique gives independent control of the output beam spatial and temporal coherence, as well as the pupilary distribution. In addition to being rugged, CAN offers the additional benefit of being inexpensive and low maintenance. A conceptual design based on CAN is presented that offers an alternative to the next CERN Linear Collider (CLIC).

Keywords: Lasers, fiber lasers
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INTRODUCTION

We have seen over the past years a spectacular increase in laser peak power. With the advent of Chirped Pulse Amplification [1] new regimes of laser-matter interaction have led to a plethora of novel secondary sources [2] like X-ray, γ-ray, electron, proton, etc. We are very much like in the 1960's where new laser–matter interaction regimes were revealed, that led to a novel family of coherent light sources extending from DC with optical rectification to EUV with high harmonic generation [2]. However, present applications like X-ray, γ-ray, electron and proton beam generation rely on laser-matter interaction in the relativistic regime. These applications to be practical, demand very high intensity greater than 10^{18}W/cm^2 but also very high average power. These two requirements can not be provided by today's high peak power lasers. A typical terawatt class CPA produces an average power of only few watts [Fig.1] that is far from what most X-ray applications, for instance, would demand, i.e. few kW. For applications in high-energy physics even higher average power, in the range of 150 MW, can be necessary.

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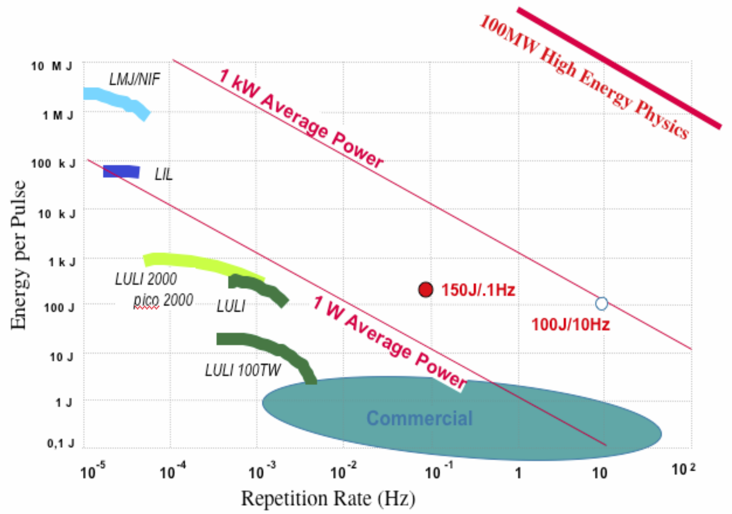

FIGURE 1. Average-Peak power of high intensity lasers. Note that most of the large high peak power systems have an average power <100 W.

A companion to high average powers must be very good laser efficiency. It would not be acceptable to produce 150 MW of average power with a typical laser efficiency of only 1%, for instance. Therefore, high efficiency becomes one of the main requirements that push us to find a solution based on laser diodes that have a demonstrated efficiency up to 80% [3]. High average power also requires a solution based on excellent heat removal. Fiber lasers with their high surface area to amplifying volume ratio can handle high average powers, over a kW per fiber.

Short pulse amplification will require an amplifying medium with a broad gain bandwidth commensurate with the desired pulse duration [4]. Finally, the laser will need to possess a good beam quality to produce the highest focused intensity and brightness. All these conditions are extremely stringent to meet, and the best approach so far has been based on thin disk amplifiers [5] in an 'open cavity' configuration. Few hundred watts has been demonstrated short of the multi-kilowatt needed for most high intensity applications.

In this paper, we are proposing a solution based on diode-pumped fiber systems. The laser will rest on the fiber-CPA concept [6-8] that can deliver Fourier-transform limited sub-picosecond pulse, with up to 13W average power [8] (see Fig.2). This is a conservative value compared to the kW per fiber in the CW mode that a single mode fiber can deliver today [9].

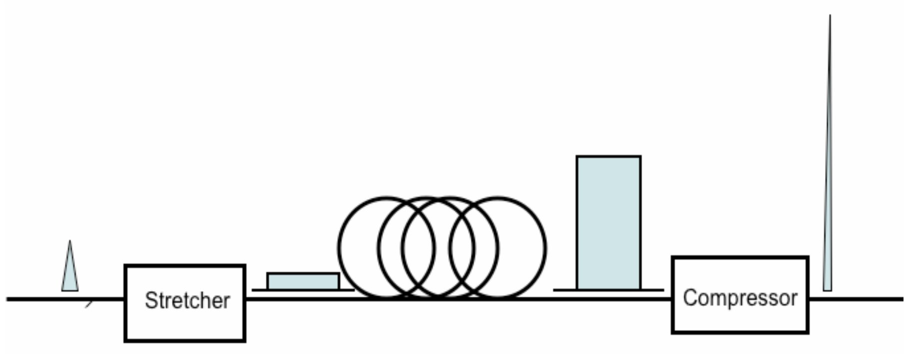

FIGURE 2. Generation Schematic of a fiber-CPA system.

As shown in Ref. 8, a single mode fiber can produce a pulse of the order of a 1 mJ at kHz repetition rate. Therefore a system delivering one joule would have to rely on a bundle composed of a thousand fibers coherently coupled. If a fiber delivers ~15 W an amplifier network composed of a thousand fibers could produce up to 15 kW at 15 kHz. The efficiency of such a system will be of the order of 30% including the laser diode efficiency and the diode-fiber coupling efficiency. Besides from providing simultaneously high peak power and average power, a fiber-based system could be built completely out of inexpensive, rugged, telecommunication parts. However, the main difficulty of a coherent fiber-based network lies in the interferometric addition of a multitude of fibers to form a Coherent Amplifying Network (CAN) system, providing simultaneous high peak and average power with high efficiency.

Pushing this idea, we will describe a more ambitious system conceived for high-energy physics consisting of over 1 million fibers. Such a system could therefore deliver 1 kJ with 15 MW of average power with 30% efficiency. As mentioned earlier, in addition the network would be very reliable and relatively inexpensive, because it could be built entirely from tested telecommunication components such as laser-diodes, fiber amplifiers, dividers and isolation elements. Again the difficulty will mainly reside in the coherent phasing of these fiber lasers. This operation will be discussed later.

COHERENT AMPLIFYING NETWORK (CAN)

The rational behind Coherent Amplifying Network

It is important to note that in most envisioned applications we need *first* the energy per pulse to reach a given threshold imposed by the desired X-ray, electron beam, etc… characteristics we want to produce. Once the energy per pulse is reached we then need the average power, i.e. pulse repetition rate. Today single mode fibers can provide over a kW [9] of average power. However the same fiber can at most deliver one mJ. The pulse energy is limited either by the saturation fluence (~50 J/cm^2) or by the fiber dielectric breakdown fluence (~50J/cm^2). Saturation and dielectric breakdown will therefore clamp the energy of a single mode fiber (with a core of 30mm) to a practical limit of one mJ.

High intensity applications especially in the relativistic regime need single pulse energy of the order of a joule in a sub-picosecond regime to reach intensity in the 10^{18}W/cm^{2} and higher. This condition will impose the coherent contribution of N=10^{3} fibers. Each one will put out ~1 mJ at 10 kHz, i.e. 10 W and the entire bundle 10 kW. The thousand fibers [Fig.3] could provide a wide variety of pupil configurations as shown in Fig. 4. After amplification these channels are combined interferometrically with the possibility to tailor the degree of spatial and temporal coherence as well as the possibility to adjust the overall beam wavefront [Fig.5].

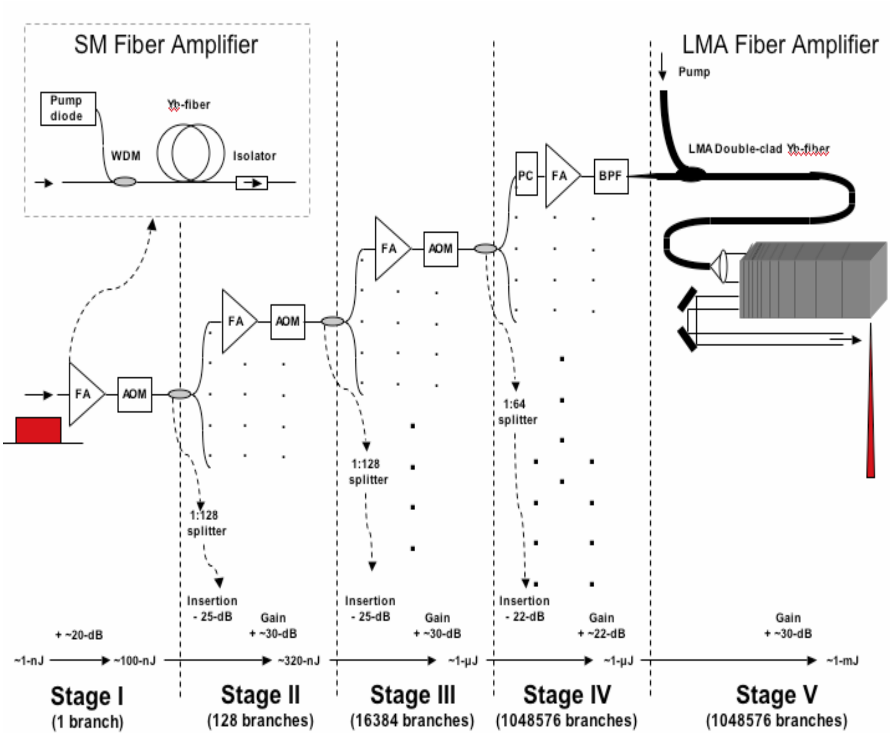

FIGURE 3. Example of a Coherent Amplification Network (CAN) system. It is built for the most part from identical telecommunication parts, pumped.

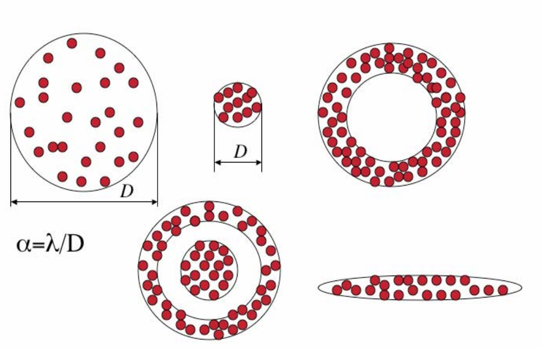

FIGURE 4. Various possible pupilary.

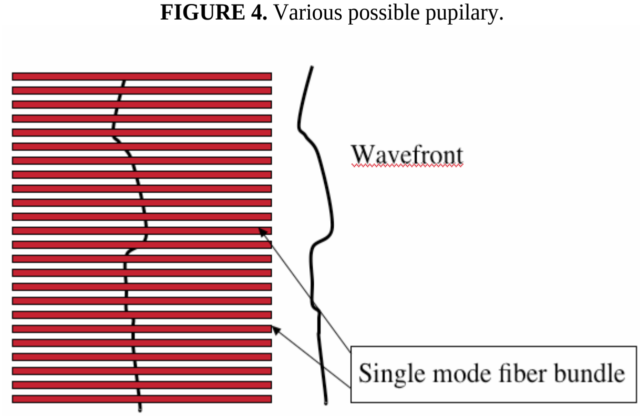

FIGURE 5. Wavefront control. The interferometric control of each fiber allows the generation of a desired wavefront.

A Large Accelerator (CLIC) Design using the CAN Approach

Let us deal with an example where the simultaneous need for high peak and high average power is required. Certainly the most demanding application is the CERN Linear Collider (CLIC) planned to be built at CERN to explore the frontiers of high energy physics. CLIC will be enormous with an overall length of 40km. CLIC, because of its size and horrendous cost, will certainly be the last large accelerator based on conventional technology. CLIC is planned to reach the frontier of the standard model. This system will require 1.5TeV, center of mass energy electrons and positrons. The charge per pulse will be 4nC with a repetition rate of 15 kHz. These pulses will be accelerated using the so called Two-Beam Acceleration technique (TBA). The expected wall plug power to RF power efficiency will be 40%. The RF to electron beam efficiency will be of 24% leading to an overall efficiency of 9.6% (see Table 1).

	CLIC	Laser Plasma (Fiber-based)
AC to RF/Laser	40%	40%
RF/Laser to beam	24%	20%
AC to beam	9.6%	8%

TABLE 1. Comparing the various efficiencies involved in conventional RF-based accelerator and laser-based accelerator CAN.

Let us oppose this alternative with one based on laser driven wake-field acceleration introduced by Tajima and Dawson [2], a very promising technique introduced 20 years ago and made possible with the entry of the ultra-high-intensity laser. Very recently it was shown that this technique could produce quasi-monoenergetic beam centered around 150MeV over a millimeter [2]. Multi-GeV will certainly be possible in the near future with existing lasers. Simulations reveal that much higher energies in the 100GeV and possibly TeV could be obtained in an extremely short distance, i.e. meters, using laser wake-field acceleration.

Today or in the near future we should be able to deliver lasers with multi-PW peak power, which is sufficient to produce acceleration in the 100 GeV at a mHz (one shot every 20min) repetition rate. This is not satisfactory for high energy physicists who need a repetition rate 10^7 times higher, i.e. 15 kHz. To accelerate one electron or positron pulse (1.5TeV, 4nC) with an assuming 20% optical to electron/positron efficiency at 15kHz will require 5kJ, 100fs, 50PW/pulse, leading to an average power of 150MW, six orders of magnitude beyond today's state-of-the-art (see Fig. 1).

Using the CAN approach, it would take at 1mJ/fiber, 5×10^6 fibers for the electrons, and the same number for the positrons, a total of 10^7 fibers. We now are going to base our design on a 15W per fiber. This is nowadays relatively modest compared to the 1kW/fiber average power of which a single mode fiber amplifier is capable. However the priority is first the energy per pulse and then the average power. If we assume as shown in Table 1 a wall-plug-to-fiber-laser power efficiency of 40% and a 20% optical to electron beam efficiency, we could expect an overall efficiency of 8%, very comparable to the RF approach.

CAN: Transport and Pupil Control

Here again the CAN approach makes possible the production of enormous average power with high efficiency. This power will not have to be produced on the experimental site but rather remotely, and distributed over a large volume for cooling, and transported with high efficiency by low loss fibers on site [Fig.6]. As mentioned above, the distribution across the pupil can also be chosen arbitrarily and the wavefront controlled arbitrarily.

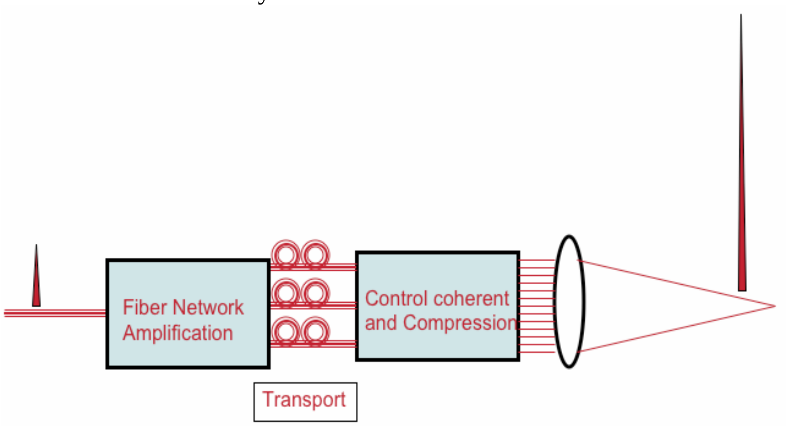

FIGURE 6. Beam transport in CAN offers an important advantage. The network can be distributed over a large volume to increase cooling performances. The light produced 'remotely' is transported by low loss fibers. The fiber can be configured on the desired location to form the desired pupil shape.

A detailed CAN Design for CLIC Applications

A proposed detailed implementation example of a fiber CAN system is shown in Fig. 3. The required ~1:10^6 total splitting ratio is achievable with a total of three splitting stages: the first two stages with 1:128 times and the third stage with 1:64 times splitting, thus producing total 1:1048576 times splitting. The inevitable loss in each splitting stage has to be balanced by a gain in fiber amplifiers inserted between the splitting stages. Also, each optical path should provide a 60-dB total net gain in order to boost initial ~1-nJ seed energy to ~1-mJ output energy per each channel. To achieve that there should be total of five amplification stages per each optical branch. Note that the number of optical branches increases correspondingly after each splitting stage, so that there are 128 branches in stage II, 16384 branches in stage III, and 1048576 branches in stages IV and V. It is important to emphasize that all branches in each particular stage are made from exactly identical components. In fact, all components in the stages I to IV most likely can be identical. This should significantly simplify parts procurement for this complex system.

There is no power splitting between stages IV and V. Stages I through IV consists entirely from standard single-mode fiber components. Only the energy-extracting stage V requires Large Mode Area (LMA) fibers with core diameter of ~50-µm and with double-clad structure to achieve cladding pumping. Therefore, all fiber-star splitters can be made with standard single-mode fiber techniques. One datasheet example of commercial 1:32 and 1:4 fiber-star splitters can be found at www.fi-ra.com This particular device can ensure 1:32 splitting ratio with 17-18-dB insertion loss (15-dB loss per each channel + 3-dB extra device loss) and 1:4 splitting ratio with ~7-dB insertion loss. 1:2 splitters are very standard with typical insertion losses of ~3.5-dB. Required splitting ratios of 128-times and 64-times can be either achieved by multiplexing the above splitters (128 = 32 x 4 and 64 = 32 x 2), or fabricating single-stage star-couplers with required splitting ratios. Consequently, we can take as an estimate of the insertion loss per splitting stage to be -25-dB per 1:128 stage and -22-dB per 1:64 stage.

Distribution of gain in each fiber amplifier stage of each optical branch is shown in Fig. 3. Gain in each stage is selected such that it compensates the insertion loss of the preceding splitting stage and, furthermore, provides additional gain necessary to achieve the total required target energy of ~1-mJ at the output of the optical branch. Note also, that the projected gain in each stage does not exceed a maximum gain of ~35-dB achievable with a typical single-mode fiber amplifier. Overall gain balance is selected such that 1-ns long stretched-pulse energy in a single-mode fiber never exceeds ~1-μJ, so that optical damage can be avoided and nonlinear effects in each fiber amplifier stage can be kept under control. We project (based on our experience with the existing single-path fiber CPA systems) that ~1-μJ energy is required to inject from the last single-node stage (stage IV) into LMA fiber in the V-th stage. Since the fiber core size between IV-th and V-th stages becomes significantly mismatched (from approximately ~6-μm mode-field diameter (MFD) for a single-mode fiber to ~ 40-μm to 50-μm MFD in the LMA fiber) adiabatically-tapered transition needs to be inserted between these stages. Such adiabatic tapers are routinely made with standard fiber processing equipment.

An important technical detail to be considered here is the use of active optical gates between different amplification stages. The purpose of these gates is two-fold. At first, optical gate at the input of stage I is used to down-count pulse repetition rate from initial 50-100-MHz from a mode-locked seed to 15-kHz in the fiber amplifier chain (necessary for high-energy pulse extraction). Second, additional gates are required at the output of each fiber amplifier at the end of stages I, II and III (and prior to each subsequent star splitter, as shown in the drawing) in order to suppress amplified spontaneous emission (ASE) between the amplifier stages, i.e. to ensure that average power in amplified chirped pulses exceeds that of the ASE background of each of the fiber amplifier stages. Based on common practice with current fiber CPA systems the best devices for this are fiber-pigtailed Acousto-Optic Modulators (AOM), since they can achieve on-off extinction ratios of higher than 80-dB. The important practical detail of the proposed design is that no AOM-driven gates are used between the stages IV and V. Instead, standard 10-20-nm fiber-pigtailed bandpass filters accommodating the complete stretched-pulse spectrum at 1064-nm, are employed at the output of each stage-IV amplifier in each separate optical branch. Such narrow-bandpass filters allow suppression of ASE background by >10-dB, since the optical signal at 1064-nm is spectrally separated from dominant-ASE peak at ~1039-nm. The significant practical advantage of this configuration is that one needs only to employ 16384 + 128 + 2 = 16398 AOM systems (modulator + RF driver and corresponding power supplies) instead of ~10^6 AOM units required if placed between stages IV and V. Instead we would use simple and inexpensive passive fiber components (bandpass filters).

It is important to emphasize that all the pumping of the fiber amplifiers in the stages I through IV is accomplished using standard 980-nm single-mode laser diodes used in telecom industry, which each cost in the range of $100's. Such diodes are very reliable, with expected lifetime of ~10^6 hours (>100 years of continuous operation). As for the pumping of stage-V amplifiers, one would need to use broad-stripe 980-nm multi-mode pump diodes. Again, their cost is about the same as that of SM 980-nm diodes and their life-time currently is rated at >100,000 hours (>10 years of continuous operation). It is expected to reach >500,000 hours in the near future (>50 years). Such lifetimes would make such a laser systems virtually maintenance-free, saving significant operation costs for such a facility. Pump power of 20-25-W per cladding-pumped amplifier stage is required. For maximum energy extraction pump and signal paths should be counter-propagating. This can be achieved by using various side-pumping techniques (V-groove technique, for example).

It is an important aspect of how to achieve pulse stretching and compression for implementing this CAN system. A conventional approach would be to use standard diffraction-grating stretching and compression. In this case, pulses from a mode-locked seed oscillator (at the central wavelength of ~1064-nm, for example) would be stretched in the diffraction-grating stretcher and, after amplification in the multistage optical amplifier path, be recompressed in a diffraction-grating compressor. In this case coherent combination of 10^6 optical fibers should be achieved prior to the compression stage. The technological challenge of this approach is that the diffraction-grating compressor would need to accommodate uniquely high average and peak powers. Special, very large gratings would have to be developed for this purpose. Also, an additional fiber-related technical difficulty would be that, since diffraction-grating compressors are polarization-sensitive, all fibers and fiber components in the CAN system would need to be polarization-maintaining (PM). Typically, PM fiber components are approximately order of magnitude more expensive compared to non-PM one's. Therefore, using polarization-insensitive pulse compression technologies could bring significant economic advantage here.

Alternatively, a compact (longitudinal) volume-chirped-Bragg grating compressor could be used at the output of each optical branch output. In this case, each individual compressor would experience low peak and average powers. Coherent beam combining would need to be accomplished after pulse recompression (in the far-field). Another principal advantage of using volume-grating compressors is that such compressor can be configured to be used in polarization-insensitive configuration. As a result, all CAN system could be built without using PM fiber components.

Another important advantage offered by volume Bragg compressors compared to diffraction-grating ones is that volume-grating compressors can be >90% efficient, which is much higher than has been achieved with conventional diffraction-grating compressors. Again, increase in efficiency has a dramatic effect on the economy of such a large-scale system.

Since ~ 10^6 fibers should be transversely combined into a single fiber-array, the transversal size of each individual volume-grating compressor is critically important. We estimate that for compressing ~1-mJ pulses transversal compressor aperture should be ~ 5-mm. With such an individual-compressor size, the total fiber array diameter for accommodating 10^6 fibers could be ~6 meters. This size is not excessive for such a large-scale system.

Fiber Coherent Addition

The most critical aspect of enabling the described CAN-CPA system to work is associated with coherently combining all 10^6 optical-branch outputs into a single coherent beam. Active coherent combining of several CW fiber lasers has been demonstrated already [10,11]. The principle of active coherent combining is simple – a small fraction of fiber array output is sampled with a beamsplitter and then imaged into a photodetector array, which mimics the geometry of the fiber array. This similarity between fiber and detector arrays allows linkage between each individual detector and each individual fiber in the array. Obviously, the number of detectors should match the number of individual fibers in the fiber-array output aperture. This sampled optical signal is mixed with a frequency-shifted reference signal, producing beat signal in each detector. With a proper electronic circuitry this beat signal can be converted into a signal proportional to the phase difference between the reference optical signal and the particular fiber output. This signal can be used to control individual phase modulators in each separate optical branch, so that the phase difference between the common reference and each fiber output can be eliminated, i.e. output beams from all fiber can be set in phase. Alternatively, a prescribed constant (varied from fiber to fiber) phase difference can be introduced between different branches, thus allowing steering of the phased beam or control it's focusing or defocusing.

CAN Group Delay Adjustment

For CAN systems, phase-control of each separate optical branch is not sufficient. One also needs to control absolute time delays between each of the optical paths as well. Physically this can be accomplished by using fiber stretching (through piezoelectric modulators, for example) in each optical branch. Location of these optical-length/optical-phase modulators could be at the input of each fiber in the IV-th stage of the system, as shown in Fig.3. However, for this to work one needs to devise a method of measuring not only optical phase difference between the reference and each individual fiber output in the array, but also to measure the relative time delays between them and to apply the proportional feedback signal to each fiber-length and phase modulators in order to correct the length and phase mismatch *simultaneously*. Indeed, this can be accomplished in a setup very similar to the one used in CW case. The fiber CAN system reference path also should be an amplifier chain for the same stretched pulse obtained from the initial seed pulse. It can be sampled at the input of the stage I prior to any optical-path splitting, as shown in Fig.3. The amplified reference signal should be also frequency shifted with respect to the seed signal, for example using additional AOM modulator in the reference beam path, operating at a *different* RF-driving frequency compared to the AOM modules used in the main CAN system in the optical gates described above. The amplified reference optical signal should be compressed in an identical pulse compressor, as used at the output of each individual fiber at the end of stage V. This reference beam should be mixed with the sampled fiber-array output in a manner identical to the method used for CW coherent combining. After this, these overlapping beams should be passed through a single pulse stretcher (diffraction-grating stretcher for example) and then imaged into the photodetector array. As it is well known, if two stretched chirped pulses are delayed with respect to each other then there will be a beat signal with a frequency proportional to the delay between these two identical chirped pulses. Consequently, by measuring a beat frequency from each individual detector one could determine optical path difference between the particular optical branch in the array and the reference beam. This beat frequency can, therefore, be converted into electronic feedback signal proportional to the measured time-delay in order to control the optical-path modulator. A feedback control loop should ensure that the beat signal is kept at the shift-frequency of the reference signal, thus matching optical path lengths for all fiber outputs with high accuracy. In addition, fine-tuning of the residual phase-difference to the degree sufficient to achieve phase-compensation can be accomplished within each of the channel by measuring phase difference between the reference and individual channel signal in a manner identical to the method used for CW coherent beam combining. Such a system would ensure accurate compensation of both the time delay and the phase difference across the fiber-laser array.

Some Numbers About a CAN-Based "CLIC"

CLIC will require 10^7 fibers, 2 meter long. The overall fiber length will be 10^7 meters or ~20,000 km i.e. on the order of the earth's circumference. This is a fraction of the world wide network. The average system power of 150 MW is one sixth of a nuclear plant of 1GW. The number of diodes involved (~10^7) is a fraction of the annual telecommunication laser diode production. If we assume $100/watt such a system will cost $\$10^5$ per kW very inexpensive compare to solutions based on conventional pump technology.

CONCLUSION

CAN-based amplifiers, offer the very important advantages of simultaneously providing high peak power, high average power, and high efficiency. They can be built out of telecommunication parts that will guaranty unsurpassed reliability (laser diode expected lifetimes are between 50 and 100 years), low maintenance and low cost. This approach offers the additional benefits of wavefront and pupil control. It will also give the possibility to produce laser energy at a distance that can be relatively far from the experiment. However this approach will demand a large effort in coherent addition techniques. A similar one is being developed by the large-telescope community where 50 and 100m telescopes are being designed. They are composed of thousands of mirrors controlled at a frequency >100Hz to compensate for the atmospheric turbulence. In our case the number of elements is much larger but the frequency much lower <1Hz, since the entire system will be built in a controlled environment and entirely pumped by very stable diode lasers.

This path to building a new TeV accelerator has the advantage of utilizing support from worldwide telecom capability, while it would also provide a significant market for that industry.

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