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Coherent Combining with Active Phase Control: A Practical Tool for Adaptive and Nonlinear Optics

(Invited paper)

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Abstract—Coherent beam combining with active phase control is more than a simple laser power scaling technique. It can also be used to perform more efficient adaptive optics and to extend the capabilities of nonlinear optical devices. In a first part of this paper, an optimized tiled-aperture configuration for coherent adaptive optics is described. In a second part, coherent combining of frequency converters emitting in the mid-infrared is demonstrated and results presented. Finally, the challenges for optical parametric oscillators combining are discussed.

Keywords: laser, coherent combining, adaptive optics, nonlinear optics, frequency converter

I. INTRODUCTION

Coherent beam combining with active phase control is a convenient method commonly used to power scale laser sources, far above their limitations due to thermal and nonlinear effects as well as damage threshold.

But it's a far more versatile technique than just a way to deliver very high laser power. It can also be used as an adaptive optics tool to compensate for turbulence effects during atmospheric propagation of laser beams. Another usage is the combination of wavelength converters such as optical parametric oscillator or more generally nonlinear optics based frequency converters.

In this paper, adaptive optics (AO) configurations of coherent beam combining are proposed and detailed. The capability of AO configurations to overcome the anisoplanatism limitations of standard adaptive optics is discussed. In a second part of the paper, recent results on coherent combining of mid-infrared wavelength frequency converters are presented. Finally, the challenges presented by the coherent combination of optical parametric oscillators are detailed.

II. LASER COMBINING TECHNIQUES FOR POWER SCALING

To overcome solid-state laser power scaling limitations, either thermal effects, damage threshold, nonlinear effects, laser combining techniques are available to perform efficient addition of laser power emitted by multiple laser amplifiers. A record 105 kW power has been achieved in 2009, combining 7

15-kW slab amplifiers¹. Multiple multi-kilowatt combining demonstrations have been done.

There are many techniques to combine lasers. Benchmarking of these techniques is generally based on a criterion of efficiency of the combining process, which is the ratio between the available combined power vs. the total power emitted by the N combined lasers. Obviously, the objective of laser combining techniques is to achieve close to 100 % efficiency.

Two very effective techniques for combining laser sources are spectral combining, an incoherent combining approach based on wavelength multiplexing. A 30 kW record has been achieved spectrally combining 96 high power fiber lasers into a single beam with a very high efficiency².

Coherent combining with active phase control is another efficient technique.

Figure 1. Schematic of a typical configuration for coherent combining fiber laser sources with active phase control.

Active phase control uses very fast waveguide electro-optic phase modulators with bandwidth going up to 40 GHz for the fastest ones. These components can be all-fibered and lead to very compact and rugged configurations of high power laser sources.

The most practical near-field geometry is the tiled-aperture configuration, where the laser output optical apertures are placed side-by-side. The laser beams propagate to the far field where they can interfere, generating a very intense central lobe in the interference pattern if the interference process is constructive. Phase-locking the lasers is needed to achieve such constructive interference in the far field.

III. COHERENT ADAPTIVE OPTICS WITH BEAM COMBINING

The tiled aperture configuration for coherent combining offers a unique design to power scale laser sources without dramatically increasing the power density, mitigating the risk of damaging optical elements placed at the output of the combined laser source.

In such a near-field geometry, as the surface of the tiled-aperture grows with the number of combined lasers, the power density can be kept below the critical level of optical damage threshold. For this reason, this near-field geometry is often preferred, especially when dealing with multi-kilowatt power levels.

But just as a deformable mirror offers control of the optical wavefront in adaptive optics, the tiled-aperture configuration coupled with active phase control of each optical aperture gives access to a similar wavefront control.

Different approaches are used to lock in phase the lasers. Vorontsov et al.³ demonstrated turbulence compensation over 7 km range with such a configuration, using an Stochastic Parallel Gradient Descent algorithm to optimize the phase shift distribution and compensate for wavefront distortion induced by atmospheric turbulence. The phase shift distribution optimization criterion is in this case the intensity back reflected by a target placed in the far-field, 7-km away from the laser.

Onera also demonstrated this capability on a reduced scale, in the laboratory, generating artificial atmospheric turbulence using a hot air blower. But an interesting configuration where frequency-tagging was implemented and backscattered light provided the feedback from the target was proposed⁴ (see Fig. 2). The main advantage of this approach is its high phase difference sensitivity, as frequency-tagging provides an error signal evolving linearly with the phase differences between the combined lasers.

Figure 2. Coherent adaptive optics configuration using frequency-tagging TIL CBC.

In these experiments, it was shown experimentally that proper detection configuration of the backscattered signal coming back from a remote surface allowed for target-in-the-loop coherent combining in a configuration that is not limited

by anisoplanatism, a classical limitation in adaptive optics. Anisoplanatism is induced by a slightly different optical path for the wavefront sensing function and the wavefront control function of the adaptive optics system.

Detailed explanation on the way of operation of this frequency tagging approach will be given.

IV. COHERENT COMBINING OF FREQUENCY CONVERTERS

Nonlinear optical processes resulting in frequency conversion, such as second harmonic generation (SHG), difference frequency generation (DFG) and optical parametric amplification rely on a phase-matching condition needed for the process to achieve maximum conversion efficiency.

This phase-matching relation allows for indirect phase control of a nonlinear frequency converter and for coherent combining of the converted waves controlling the phase of the fundamental or pump waves with standard high bandwidth, high performance all-fiber electro-optic phase modulators.

Former results obtained combining SHG⁵ are presented to demonstrate how frequency converter CBC operates and its capability and limitations. The conditions for simultaneous combining of the fundamental and harmonic waves are explained.

The proper way to perform indirect control in the case of these 3-wave coupling process like DFG is explained⁶. Wavelength control has to be obtained using injection seeding and indirect phase control can be achieved using the phase offset relation, just as in the case of the 2-wavelength process of SHG (see Fig. 3).

Figure 3. Example of coherent combining of difference frequency generators configuration.

CBC efficiency is discussed as well as the capability for simultaneous pump and idler wave combining. It is shown that for these 3-wavelengths processes, such simultaneous combining is rarely achieved.

Optical parametric oscillators (OPO) combining is discussed next. The presence of a laser cavity in an OPO adds an additional degree of complexity and difficulty to achieve CBC, especially for pulsed OPO.

Final part of this talk is dedicated to discussion of the conditions allowing for OPO CBC and the challenges yet to overcome.

V. CONCLUSION

Thanks to their versatility, some laser combining techniques are much more than just a tool for power scaling lasers.

This paper elaborates on how coherent beam combining with active phase control can be used to perform anisoplanetic adaptive optics and to power scale not only lasers, but also nonlinear optical devices.

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