Integrating closed-loop adaptive optics into a femtosecond laser chain

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APPLICATION NOTE

Introduction

The Max Planck Institute of Quantum Optics (MPQ) has developed an Optical Parametric Chirped Pulse Amplification (OPCPA) femtosecond laser with an energy output of 100 mJ over a spectral band ranging from 700-1050 nm at a frequency of 10 Hz. The laser's pulse duration is less than 10 fs, with a post-compression diameter of 2" and a final post-amplification diameter of 10 mm.

Figure 1 shows the scheme of the laser chain.

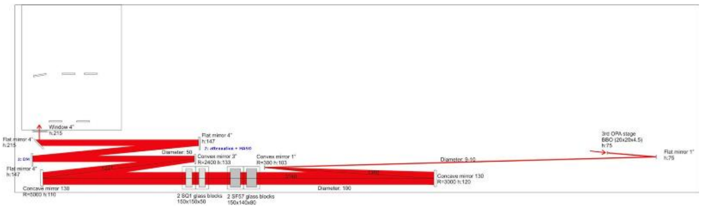

***Figure 1.** Schematic of the laser chain*

In order to maximize their laser's performance, MPQ came to Imagine Optic for a complete adaptive-optics solution including a wavefront analyzer, a deformable mirror and correction software. Imagine Optic's industry leading experience was a key factor in MPQ's choice.

For high-power lasers, Imagine Optic's adaptive-optics solutions consist of selecting the appropriate hardware and software (wavefront sensor and deformable mirror) to measure and correct for aberrations, choosing the ideal placement for the elements in the laser chain, defining the best analysis path for the system then, finally, installing and testing the equipment.

Characterizing the beam

Because the quality of the wavefront correction is directly dependant on the quality of measurements provided by the wavefront sensor, first and foremost, the aberrations present in the beam that need to be corrected must be determined. As a preliminary step in building durable relationships, Imagine Optic provides clients with a demonstration sensor to characterize their source. The HASO family of Shack-Hartmann wavefront sensors, combined with HASOv3 wavefront analysis software, guarantee measurements of unprecedented accuracy and thorough analysis of all the beam's aberrations.

Once the aberrations present in the laser chain aberrations have been precisely identified by HASO, the type of deformable mirror (bimorph, monomorph or magnetic), diameter and number of actuators need to be defined. Imagine Optic's DEMAO software enables the simulation of how different mirrors will influence the system by using the Zernike coefficients obtained by HASO, and the deformable mirror best suited to the laser chain's particular aberrations can be chosen. Depending on the client's needs and budget, they can choose from standard deformable mirrors or decide to have a mirror built to their exact specifications.

Choosing the right components

In the case of MPQ, DEMAO simulations proved that a BIM 31 bimorph deformable mirror, made by Imagine Optic's partner Cilas, would reduce an initial wavefront error of 0.2µm RMS to a post-corrected wavefront error of only 4 nm RMS. Following the results obtained, Imagine Optic proposed a complete adaptive-optics loop comprised of a HASO3-32 wavefront sensor with CASAO software to drive the BIM 31.

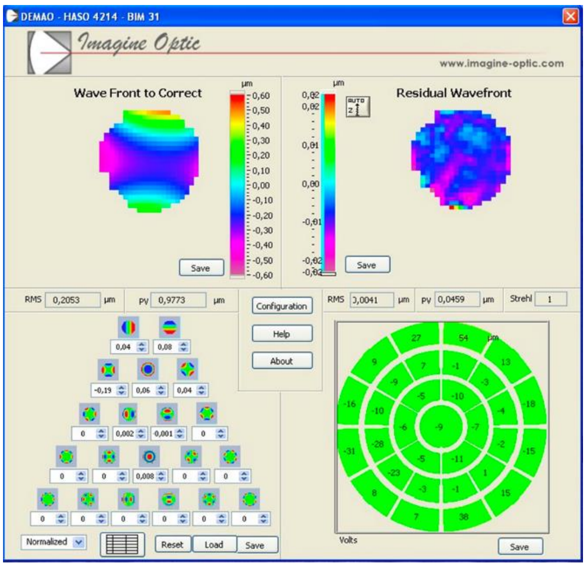

***Figure 2.** DEMAO simulations*

In addition to its capacity to correct for the laser's aberrations, the BIM31's polished silver reflective membrane, composed of a metallic and dielectric layer, has a damage threshold of 200 mJ/cm² and is therefore compatible with the laser chain's power output. Imagine Optic has installed both bimorph and monomorph mirrors on a number of high-power lasers including LIL, Alize, Orion and others at the LOA.

CASAO is a unique adaptive-optics command and control software package that enables users to control all of the elements in their open or closed-loop by means of one, user-friendly interface. From wavefront acquisition through to mirror shape control and instrument diagnostics, CASAO lets users work quickly, efficiently and safely with all active components available on the market today (Cilas, NightN, OKO, Imagine Eyes, etc.). It equally includes security features, specially designed for high-power lasers, that help reduce the risk of unexpected hotspots being generated, thereby protecting valuable components in the amplification chain.

The first major advance that CASAO offers in laser safety is accomplished by processes that continuously test the calculated correction. If the software detects unusual developments in the beam's aberrations, the loop gain is automatically reduced in real time to avoid such unwanted events.

On another level, two levels of security are used to manage the pupil. First, the calculation is performed only if the signal-to-noise ratio of the sensor is sufficient for accurate calculations to be performed. Second, CASAO controls the size of the pupil in order to ensure that the diameter used during the acquisition and calculation of the command matrixes is the same as that used during correction.

From simulation to integration

Once the loop elements have been selected, they need to be correctly implemented into the laser chain to ensure the system's stability and performance. Using the client's optical schematic of their laser chain, which enables Imagine Optic's engineers to calculate the focal distances, the company brings its unique experience into play to suggest the best position for the adaptive-optics loop for maximum correction as well as the right optical components (doublets and lenses) to ensure perfect conjugation between the wavefront sensor and deformable mirror's pupils

Typically, HASO is placed after a highly reflective plane mirror so that less than 1% of the power is directed to the sensor. HASO wavefront sensors only need several nJ of energy to measure accurately and, although filters can be used to limit the energy directed to the sensor, they must be precisely placed at the focal point to avoid inducing additional aberrations.

To maintain precision, Imagine Optic only incorporates optical components of exceptional optical quality (typically better than 0.002 λ PV) as to not introduce additional aberrations, aside from chromatism which is not measured by HASO. Because HASO enables true absolute measurement, the user doesn't need a reference source and the optical components used on the path "HASO diagnostic" (mainly for the pupil conjugation) are directly characterized on the laser chain. In addition to the optical components used in the adaptive-optics beam path and once the clients specifies the axis height, we equally propose or supply the various translation or rotation stages required to more easily align the optical components.

In the case of the MPQ laser, we advised using the following optics, placed in the positions indicated in figure 3:

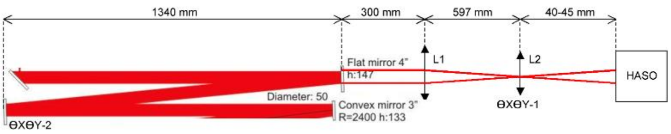

Figure3. *Proposed solution.*
L1: doublet (f=500 mm, Φ=63mm), LINOS p/n 32.2230
L2: lens (f=50 mm or 60 mm), Φ=22.4 mm), LINOS p/n 31.2315 or 31.2316
ΘXΘY-1: No adjustment are required if the original configuration is adequate.
ΘXΘY-2: Optional, depending on the laser's mecanics before the mirror.

The deformable mirror replaces the plane mirror placed before the vacuum-sealed compressor chamber.

Pre-delivery verification

In order to ensure that the solution being delivered meets the customer's specifications and that each individual component is functioning correctly, the optical system is mounted in Imagine Optic's laboratory for quality control tests. In addition to enabling us to verify the closed-loop's corrective ability, this process also provides with the mirror's "flat command file." This file is used by CASAO to set the mirror's surface to an as close to perfect flat shape as possible. Detailed documentation on the system, its components and its operation was equally prepared for the researchers at MPQ.

Onsite Integration & training

Once the closed-loop adaptive-optics system has successfully passed all factory quality control tests, one of Imagine Optic's qualified engineers installs it on the laser chain. The engineer takes special care to ensure that each element is meticulously positioned and properly aligned (neutral density filters at the focal spot for example) to reduce the risk of inducing additional aberrations. Once all of the components have been installed, the "HASO diagnostic" path is calibrated. Finally, interaction and command matrixes are generated to drive the deformable mirror.

The post correction focal spot of the MPQ laser is 8 µm (diffraction limited). As Figures 4 and 5 display, the pre-correction residual wavefront error drops from 386 nm RMS down to 31 nm RMS showing that the adaptive-optics system provides significant improvements to the beam's quality.

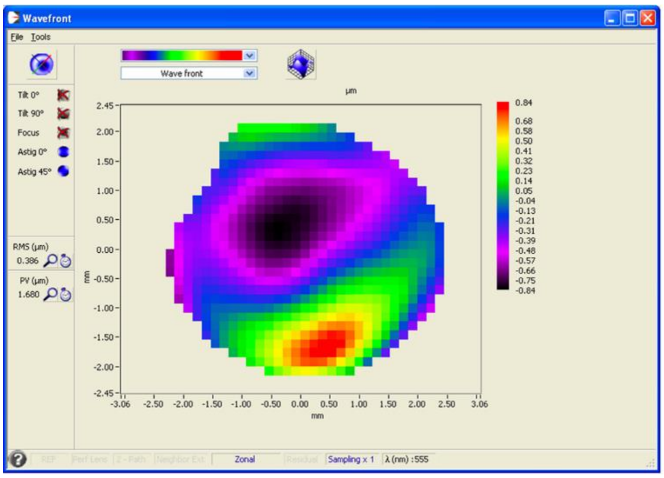

Figure 4. *Before correction: RMS 0.386 µm, PV: 1.680 µm*

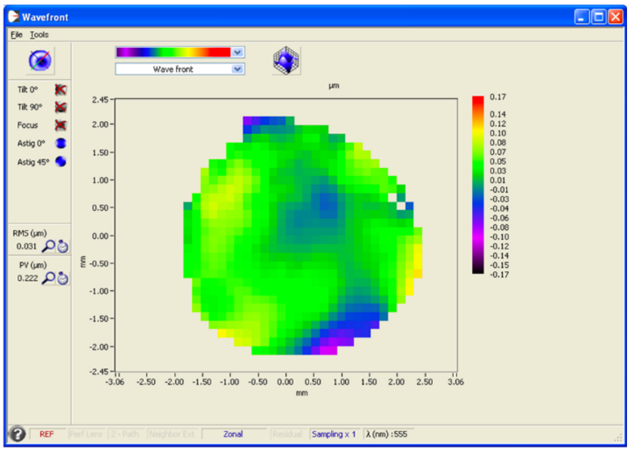

Figure 5. *After correction: RMS 0.031 µm, PV: 0.222 µm*

The images below demonstrate that, in addition to the improvement of the beam's phase, intensity at the focal spot is equally improved.

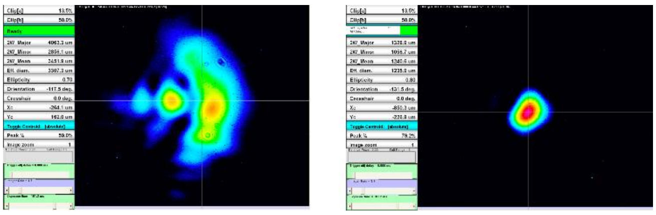

Figure 6. *Beam profile: left - uncorrected, right - corrected.*

The engineer's final on-site task it to ensure that the users of the adaptive-optics system are fully trained. He or she will go through each of the used in the system, describe their features and functionalities, both individually and as part of the system, explain how technical support can be obtained, and answer any questions users may have.

Conclusion

As this application note demonstrates, successfully integrating adaptive optics into a high-power laser's beamline is as much about technology as it is about know-how. Imagine Optic offers a complete line of products that combine accuracy and durability with versatility and ease-of-use. Moreover, and maybe more importantly, Imagine Optic provides customers with unique industry experience that guarantees them getting the most out of their investment. Thanks to our dedication to satisfying customers at every step of the way, Imagine Optic has earned a reputation for excellence in wavefront metrology and adaptive optics.

Acknowledgments

We would like to thank the MPQ for providing us with the correction results used in this document.

The MPQ was founded in 1981 and is located in Garching, Germany. The institute studies the interaction between light and quantum systems, taking both the wave and particle properties of light into account. Research is focused on four main areas: high-precision hydrogen spectroscopy; photons and individual atoms; matter at ultra-low temperatures; and attosecond experiments.

"I am satisfied with the work of Imagine Optic engineers and the closed-loop works fine," says Laszlo Veisz of the MPQ.