High Power Laser Beam Profile and Pointing Measurement (HPLM)

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ABSTRACT

A device for continuous control of the laser intensity, together with beam profile and pointing monitoring, over very large dynamic range was developed, for adjusting a laser beam to a precise power level required by a current application. The attenuator consists of two glass prisms positioned in close proximity to each other. The evanescent field from the total internal reflection in one prism is used to tune continuously the beam intensity over 110dB. Such a device has numerous potential applications in medicine, non-destructive testing and materials processing.

Keywords: lasers; energy attenuation; laser energy control, laser surgery; laser material processing; laser illumination control.

1. INTRODUCTION

Importance: Metrology and power control of laser beams is essential for the future of photonics as key enabling technology. Nevertheless, a number of challenges related to beam sampling technique, sensitivity control of the attenuation or of the measurement device and achievable dynamic range have to be addressed. Precise adjustment of the laser beam power in a large dynamic range without a significant modification of the propagation parameters enables numerous new applications or improves the efficiency of already implemented applications in industry and medicine. The development of an inexpensive, compact device for laser beam sampling and attenuation control, further denoted as POLAR (POwer Laser AttenuatoR), is relevant for the quality control and metrology of the industrial and medical laser systems and also for the enhanced control of the laser driven processes, from engraving, cutting and drilling to surgery. This part of the former project has potentially the highest economic and scientific impact, thus it becomes the main target within the current call.
Breakthrough: Common laser beam attenuators usually cover relatively small dynamic ranges, some of them are quite sophisticated and require difficult adjustment and most of them accept low power levels. We demonstrated a continuously variable attenuation device over a high dynamic range (10^{11} power attenuation) requiring a negligible modification of the beam path as a basis for laser quality control. An inexpensive, compact device for measurement of laser beam profile (LBP) and beam pointing stability (BPS) measurement device was developed for pulsed and continuous high power lasers based on in-line beam sampling with continuous control. The device POLAR can extend the functionality of most of the existing lasers with minimal modifications, without rework. The proposed work offers potentially important improvements (dynamic range >110dB) and a simple continuous adjustment over the entire dynamic range being adaptable to any visible or near-infrared wavelength.
Main Results: During the first ATTRACT Phase we built and tested a POLAR demonstrator achieving 110dB dynamic at no wave front alterations. This is the highest reported value to our knowledge for a continuously tuneable attenuator in visible range. The demonstrator was used with a 25mW linear polarised HeNe-laser beam.

2. STATE OF THE ART

There are two major principles used on the market for attenuating laser beams having higher power levels: a) half waveplate and polariser combination, and b) diffractive attenuators. Other attenuation methods like variable ND-filters or liquid crystals are not comparable with the targeted specification of the current work. An acousto-optic Bragg cell was used to achieve 45dB range of attenuation [1] and a 81dB dynamic range variable optical attenuator, based on a novel hybrid analog-digital freespace optical design, have been reported [2].

An alternative approach based on frustrated total internal reflection (FTIR) phenomenon. FTIR was used in a variety of applications, including attenuators for microwaves [3] and infrared fields [4,5], laser output couplers [6]. The corresponding evanescent wave was used in [7] to demonstrate a 70dB attenuation ratio of a laser beam. The phenomenon can be understood as a quantum tunnelling effect of light through a quantum potential barrier. Within the phase 1 of the call, we extended the results and demonstrated up to 4 orders of magnitude continuous attenuation in addition to the reported result, reaching 110dB dynamic range of attenuation, setting a new world record. We further used this device to monitor the laser beam pointing at various power levels and also we qualified the irradiance distribution corresponding to the laser beam profile. The already developed devices LBP and BPS correspond rather to the current state-of-the art and will offer a great help for implementing the new POLAR specification. These devices will for sure need improvements and adaptation to the system, but this will be rather a side result of the proposed work.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

We have demonstrated the use of a simple attenuator as part of a beam profile measurement system and for monitoring the pointing stability. The attenuator is based on frustrated total internal reflection, capable of continuously varying the output power over 110dB range. The precise measurement of optical power variation, as a function of prism displacement, proved to be challenging, especially due to light scattering, moderate power of the laser used, prism mounts deflection and prism quality.
In general, the need to control the gap width with accuracy in the nanometre range places a constraint on the simplicity of the device. This precision can be achieved with piezo-mechanic positioners or with precision fine mechanics that can be implemented as alternative to the piezo-mechanic positioning systems.

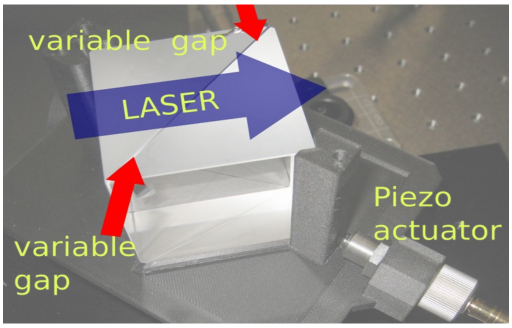

Fig. 1. Image of one demonstrator POLAR having 50mm x 50mm aperture. The laser direction is indicated with the blue arrow.

As a consequence, the FTIR attenuator becomes inexpensive, easy to build from standard optics laboratory components and can have the relatively high laser induced damage threshold associated to bulk glass, as it does not rely on special materials or coatings to provide attenuation. In this way it becomes practical to use it as a mean to continuously attenuate the power of millimetre and centimetre sized laser beams, over more than eleven orders of magnitude dynamic range.
Direct implementation of the attenuator in the laser beams can tremendously extend their applicative capabilities in terms of laser-matter interaction control and processing quality. A major use will be the pre-alignment and check of the laser beam positioning at low energy, without any further modification or detuning of the laser system, as an essential step in the enhancement of the quality control of the laser-matter interaction process.
Lasers are necessary for a large number of applications, from material processing (see fig. 3) to medical treatment and non-destructive testing (NDT). Like a scalpel which is as good as sharp, a laser beam needs to have a constant quality and a precise adjustable power. This is achievable with the POLAR device.

4. PROJECT RESULTS

We demonstrated a simple laser attenuator having frustrated total internal reflection as the underlying phenomenon.
Whenever a beam travelling in a medium is totally reflected at the interface with a lower refractive index medium, an evanescent field appears behind the reflecting surface. This field is known to decay exponentially with a characteristic length which is comparable with the wavelength of the beam. This fast decay can be exploited to sample a small and adjustable part of the incident beam by bringing a second medium within the range of the evanescent field. In practice, this can be achieved by using prisms as the propagation media for the beam, with an air gap between them. As the gap has to be comparable with the laser wavelength, the control of the gap width becomes increasingly challenging for near-infrared and visible lasers. This is why the technology was not used up to now. Our work demonstrated the feasibility of the extension for such an attenuator to these wavelength ranges, as follows:
1. A prototype of such FTIR attenuator was realized using 3D printing for the enclosure of the double prism. Various tests demonstrated the importance of the stiffness of the enclosure of the device (see fig. 1). Optical quality of the prisms is essential and it was successfully demonstrated.

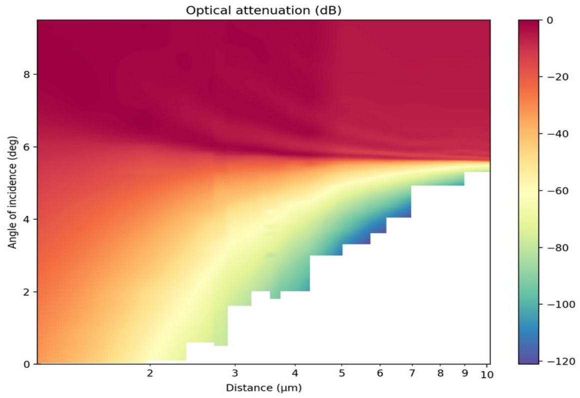

Fig. 2. Map of the attenuation as function of incidence angle and gap distance, as measured in the lab.

2. We also qualified the use of the FTIR attenuator for near field and far field characterization of the beam (beam profile and pointing measurements). POLAR is adequate for collimated laser beams and its functionality is dependent on proper polarization status.

3. The attenuation in excess of 110 dB was demonstrated a single device (see fig. 2). In this figure, the reference 0º angle is considered the total internal reflection angle. The attenuation variation is driven by two major factors, the incidence angle at the interface between the two prisms and the gap between the prisms. The value reported for the attenuation is limited by the detection sensitivity of the set-up. Through cascading two such

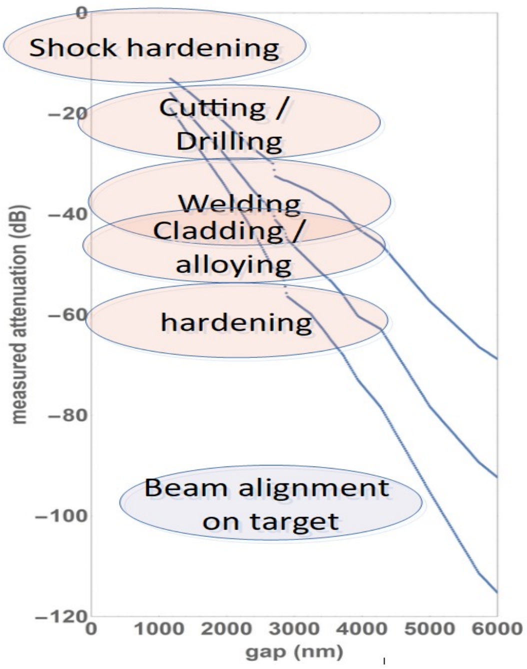

Fig. 3. The measured attenuation curves corresponding to the variation of the gap between the prisms from 0 - 6 μm, for three incident angles of the laser beam. The bubbles indicate the required attenuation needed for specific industrial laser material processing, relative to the laser operation in shock hardening regime.

devices or by extending the gap between the prisms, one can further increase this attenuation value several orders of magnitude.

4. We also performed tests for manual and remote control of attenuation. They aim to precisely control the gap between the two prisms. Precision mechanics was necessary for controlling the gap and the incidence angle. The remote gap control was implemented using piezoelectric actuator.

5. Results were presented at the Laser Congress held in Vienna, Advanced Solid State Lasers, 29 September–3 October 2019, and the corresponding proceedings were published in [8].

5. FUTURE PROJECT VISION

The development of the POLAR technology aims to provide ultimate laser power control. POLAR has also the potential to be used for isolating the laser source from back-reflections generating laser instabilities. Since both emerging laser beams from POLAR do have the same quality as the incident one, both are useful for applications.

5.1. Technology Scaling

The two major development directions are related to the *range of usable wavelengths* and to *the power range* of the incident laser beam. The development will include both theoretical part (optic- and material simulations) and the practical part (material testing). In parallel with this effort, a representative range of applications in different areas (NDT, laser material processing and medicine) will be analysed in order to generate the final specs of the prototypes to be manufactured.

For a precise adjustment of the POLAR working-point, a prism position feedback and a beam dump are necessary. The closed-loop positioning system and the design of a matched beam dump will consume about the half of the development efforts.

As feedback for the prism location, a new fast acting chromatic confocal or interferometric system with sub-nanometre accuracy will be integrated. In case that the secondary emerging beam needs a beam dump, this will be designed as a precise calorimeter (by measuring the flow rate and the temperature difference between inlet and outlet of the cooling water). These two solutions will provide the required information about the working point.

The validation of POLAR as device for pulsed pump power will take place at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) where the most powerful laser system (2x10PW peak power) is now running using 48 pump lasers. Pump laser from ELI-NP will be used for these tests. (TRL5). Demonstration and tests will further be performed with three different laser systems, defined and provided by the members of the consortium as relevant for the identified immediate applications. The development of a maximum of 3 devices will cover the main application classes in non-destructive testing, medicine and laser material processing (TRL6).

In order to reach TRL7, a strategy diversification adapted to the specific requirements of industry, laboratories and medical environment will be implemented. First, the demonstrator tests have to be disseminated (conferences and editorials). On this base we expect to be able to integrate POLAR into production lines at least for a limited period of time. Industrial NDT facilities will probably be attracted for extended integration in a similar way. For the medical field, special design issues (like the german MedGV = medizinische Geräteverordnung pre-scribes) have to be addressed during the manufacturing process. Then, advice from specialised clinics and universities will be followed in order to get the permission to integrate POLAR in serial production.

5.2. Project Synergies and Outreach

The envisioned collaboration will include the two existing partners, National Institute for Physics and Nuclear Engineering – Horia Hulubei, Romania (host of ELI-NP facility) and MGM Star Construct SRL and at least three partners: manufacturer of beam delivery accessories, a so called “integrator” of lasers into customised machines, and a laser technology transfer center together with further technology beneficiaries from academia and industry. They will help to implement possible requirements for integration in medical systems. The dissemination strategy covers two aspects:

1. Protection of intellectual property, and
2. Information of potential users via conferences, exhibitions and editorials in professional magazines.

As soon as possible, the first mentioned step will be implemented. This is important in order to have sufficient time for the 2nd step after patent publication. The 2nd step is essential for achieving TRL 6 and 7.

5.3. Technology application and demonstration cases

POLAR improves the efficiency of the technical resources enabling a more precise adjustment of the beam power level in concordance with the application requirements. POLAR enables also applications where the lasers have a good M^2 only at nominal power, but need less power for the application. As laser beam splitter, one laser beam could be distributed sequentially or simultaneously to several patient treatment stations. Such a concept can be implemented in the industry.

POLAR improves also safety issues concerning the beam delivery system due to the integrated monitoring features. Due to the feedback controlled working point, POLAR enables closed-loop control implementation of laser cutting, engraving or welding by feeding back optical signals from process (e.g. reflected power or thermal irradiance).

The concrete benefit of the POLAR photonics device – key enabling technology – can be reflected in Scientific Research, Industry and Societal Challenges such as Health, demographic change and wellbeing (from laser surgery to laser hair removal) or Climate action, environment, resource efficiency and raw materials (more efficient material processing).

Also, laser research facilities in Europe will benefit through the involvement of ELI-NP as partner of the consortium.

5.4. Technology commercialization

Based on the existing experience, best potential distribution partners are accessories manufacturer and integrators. Traditionally the laser manufacturers do not deliver the beam delivery systems, but could profit from POLAR in their development facilities, thus contributing to the general dissemination efforts.

A major task will be to achieve reference installation and a first step will be arrangements at the consortium members for opening the access for interested potential POLAR-customers.

Additional distributors will be identified for different market segments after a solid reference base exists.

5.5. Envisioned risks

High power levels generate the distortion of the wave front which might limit the range of applications. Mitigation is based on changing the material of the prisms (e.g. sapphire), increasing the beam aperture inside POLAR and/or active compensation of thermal lensing using adaptive optics. Delay in the intellectual property protection and dissemination could limit the available time for reference installations within the frame of the current call. Major efforts will concentrate to address the IP protection and dissemination in the first year of the project.

5.6. Liaison with Student Teams and Socio-Economic Study

Each partner in the POLAR consortium will nominate an experienced person to facilitate MSc. level explanation materials of POLAR and to get together MSc. students for generating new implementation ideas towards addressing Societal Challenges. These communicators will have periodic meetings to specifically address the communication strategy and dissemination of the information in the project. These representatives will contribute with information to the expert-driven socio-economic study of the ATTRACT initiative and ecosystem (e.g. interviews, technology impact references, etc).

6. ACKNOWLEDGEMENT

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