Flexible and Programmable Pulse Shaping MOPA Fiber Laser Platform, Performances and Applications

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Optical fiber amplifiers used in a MOPA architecture open up a lot of possibilities for developing flexible laser sources, thanks to their efficiency, their high single-pass gain, broad spectral gain bandwidth and intrinsic high beam quality and stability. Combining fiber amplifiers with advanced digital electronics, used for synchronizing and modulating high-speed signals for the generation of programmable nanosecond pulse shapes and bursts of picosecond pulses, can make remarkable laser sources offering unprecedented opportunities for the exploration of laser-matter interactions on a wide and fine scale. Those monolithic laser sources show great potential as development tools for speeding up the optimization of laser materials processing as well as sufficient maturity and robustness to be used as single, multi-role laser sources, working in industrial environment and performing multiple tasks requiring wildly varying laser parameters.

Key Words: Fiber laser, Pulse shaping, Beam quality, LMA, Nanosecond

1. Introduction

Over the past five decades, the remarkable attributes of laser radiation have been exploited in numerous industrial and medical applications to achieve high-precision processing of materials and tissues. Many practical situations require efficient alteration of a limited volume of material with minimum collateral effects. In general, the process throughput and quality are determined by the details of the laser-matter interaction mechanisms. These mechanisms are themselves determined by the physical and chemical properties of the targeted materials and by the characteristics of the laser emission. Careful selection of appropriate laser parameters is therefore mandatory to achieve high precision processing. In particular, the selection of the time domain characteristics of the laser emission is of prime importance in the optimization of most laser processes. In particular, pulse durations yielding thermal and inertial confinement conditions are often required to limit collateral damages. Ubiquitous technologies, including Q-switched and mode-locked laser oscillators, allow for selecting pulse durations ranging from the femtosecond to the microsecond domains. However, only limited control over the pulse amplitude profile is possible with these technologies. As the pulse amplitude profile directly determines the rate of laser energy deposition in the target material, different profiles in general yield different processing results for the same pulse duration (typically measured at full width, half maximum) and for the same energy. For this reason, a true optimization of the time domain characteristics of the laser pulse will consider not only the pulse duration but also the pulse shape. We term pulse format this combination of the amplitude and time characteristics of a laser pulse.

New fiber laser technologies providing unprecedented control over the pulse format now offer opportunities for exploiting new processing windows that are not accessible with standard DPSS lasers. These lasers employ a different scheme to produce the laser pulses, namely a Master Oscillator Power Amplifier (MOPA) configuration based on a low power, amplitude-modulated seed laser followed by a series of fiber amplifiers. The key advantage of MOPA systems for pulse tailoring lies in their ability to control the pulse generation and the optical amplification independently. Power scaling has long been a challenging issue of fiber-based short pulse amplification because of performance degradations caused by nonlinear effects showing up for high intensities in the core of single-mode optical fibers and because of the limited extractable energy from such fibers. Over the past fifteen years, advanced large-mode area (LMA) fibers and efficient nonlinear mitigation techniques have become available to circumvent these problems.

Historically, INO introduced the tailoring of nanosecond pulse formats in MOPA fiber lasers around 1998, to produce rectangular optical pulses that were required at the output of a remote-sensing system. A few years later, the first application of pulse shaping for high-precision, single pulse nanosecond laser processing of layered structures became reality when it was employed to develop high throughput memory repair systems in the microelectronics industry. Since then, the technology has evolved to provide more power, additional wavelengths, spatial beam modulation and an extended range of...
pulse durations, encompassing the picosecond domain. Its potential was demonstrated in applications including photovoltaics, marking, cutting, micro-milling, and stealth dicing. This article reviews the capabilities and applications of these ultra-flexible, ruggedized, alignment-free MOPA laser systems.

2. The laser platform

Three core modules compose our flexible and program-mable pulse shaping MOPA fiber laser platform. Those cores can be described as 1/ the synchronous seed pulsing, phasing and pumping module; 2/ the amplification and filtering module and 3/ the power amplifier module. Figure 1 illustrates the concept.

2.1 The synchronous seed pulsing, phasing and pumping module

This module combines a high-speed digital interface with optically-active components such as the seed diode, a phase modulator and the pump laser diodes required to create a population inversion in the rare earth-doped fiber amplifier stages. The high-speed digital interface manages the synchronization and operation of those optically-active components.

Based on the desired output pulse format, calculations are made to generate a digital seed pulse allowing for gain saturation pre-compensation for all the optically active stages. Target output pulse energies that keep the system within safe operating boundaries are also calculated for each fiber amplifier stage. From the required optical gain to achieve those target pulse energies, pumping conditions are calculated as a function of the pulse repetition rate. By keeping the gain independent of the pulse repetition rate in each amplifier stage, the same digital seed pulse yields the same desired output pulse format, independently of the repetition rate.

Upon detection of a trigger signal, the pumping sub-module synchronously pumps all amplifier stages, the amount of energy deposited in each amplifier being a function of the last few trigger periods so as to keep the gain constant even in the case of dynamically varying trigger signals. Once this pumping phase is over, the digital seed signal is converted by a high-speed DAC to allow the direct modulation of the seed diode current with high-fidelity for the generation of the optically formatted seed pulse. Pulses with duration ranging from 1 ns to 1 μs can be programmed with a temporal resolution of 1 ns and using 8192 levels for the amplitude control.

The module also generates a phasing signal, synchronously with the nanosecond digital seed pulse. This phasing signal is then amplified and sent to the phase modulator. The phase modulation of the seed optical pulse broadens its optical spectrum, allowing for Stimulated Brillouin Scattering (SBS) mitigation for operation in the nanosecond regime. The mitigation of SBS is a necessity as the scattered light associated with this nonlinear effect can cause serious damages to the system since it is traveling in the opposite direction of the optical signal and consequently experience gain while going upstream the amplifier chain.

Alternatively, the extremely fast phase variation within the nanosecond pulse envelope can be employed to eventually generate bursts of picosecond pulses upon spectral filtering downstream from the phase modulator.

2.2 The amplification and filtering module

The phase modulated and shaped optical seed pulse is sent to the energized first stage of amplification which is a double-pass, single mode optical fiber amplifier with a choice of two reflective elements for the return path within the amplifier. An optical switch controlled via the high-speed digital interface allows for selecting either an optical broadband mirror for the reflection of the signal when operating in the nanosecond regime; or a fiber Bragg grating having a center frequency shifted from the seed diode central wavelength so as to reflect only portions of the phase modulated signal. When the system is operated with the fiber Bragg grating, a burst of picoseconds pulses (30 ps) having a nanosecond envelope is generated, the period between those picoseconds pulses being given by the period of the phasing signal. By adjusting the latter, either tightly packed burst of picosecond pulses (1.6 GHz) or isolated single pulses can be generated, as shown in Fig. 2.

2.3 The power amplifier module

The power amplifier module is composed of two cascaded fiber amplifiers using double-clad fibers for efficient pump injection. The maximum output average power that can be extracted from the current version of the power amplifier module in the platform is ~ 50 W with maximum pulse energy of ~ 1 mJ and a maximum peak power of 50 kW.

Ytterbium-doped fiber amplifiers offer the advantages of optical efficiency, high average power and high beam quality independently of the operating conditions. Achieving high peak powers in pulsed fiber lasers requires fibers with large cores for efficient nonlinear effects mitigation including Self Phase Modulation (SPM), SBS and Stimulated Raman Scattering (SRS). This need for increased effective mode areas

![Fig. 1 Schematic of INO’s flexible MOPA platform.](image-url)
implies that most of the available LMA fibers are actually slightly multimode fibers. To limit beam degradations associated with the presence of higher-order modes, a common practice is to rely on modal filtering based on differential bending losses upon coiling of the fibers. However, even for a numerical aperture (NA) as low as ~ 0.06, the filtering becomes less effective for core diameters exceeding 30 microns. A possible way out of this is to take advantage of the fact that, in general, the fundamental mode is more confined near the propagation axis than the higher-order modes. This suggests that by confining the rare-earth dopant within a fraction of the core size, one can selectively amplify the fundamental (LP01) mode. Our group has developed a 35-μm core fiber for the non-PM version of its flexible MOPA platform based on selective Yb doping. The core NA is ~ 0.07 and the calculated effective mode area is ~ 450 μm². The measured beam quality factor M² is below 1.15. Because the filtering of higher-order modes comes from a preferential gain, the fiber shows a low sensitivity of the beam quality with respect to the coiling diameter. The core chemistry has also been developed to make the fiber photodarkening-resistant. With a pump guide diameter of 250 μm, the measured pump absorption is ~ 3.5 dB/m at 975 nm.

A PM version, compatible with harmonic generation for material processing at different wavelengths, was also recently developed. The effective mode area has been slightly increased to ~ 500 μm² and the beam quality was measured as M² = 1.1 with the 4σ method. This excellent beam quality comes from a custom fiber design that, besides the selective doping of the core, also includes a depressed-cladding feature, as depicted schematically in Fig. 3. We proposed this type of design as a way to extend the efficiency of higher-order modes filtering by differential bending losses to LMA fibers with cores exceeding 30 μm in diameter. The parameters of the depressed ring (depth and width) were optimized for a coiling diameter of 12 cm.

INO is now developing a fiber with an effective mode area of 1000 μm² and modeling suggests that very good beam quality is still within reach of the MCVD technology used for the two fibers described herein. Indeed, we showed previously that preferential amplification of the fundamental mode by selective doping is scalable; at the targeted mode area, the difference in small-signal gain can still be as high as ~ 20%. And the depressed-clad design is also sufficiently scalable for this purpose.

### 3. Material processing, advantages and applications

For long time, in order to develop a given industrial laser-based manufacturing process, the main approach has been to select the most appropriate set of fixed laser parameters among commercially available laser sources. As an example, although appropriate pulse duration has long been recognized as a key laser parameter to reach better material removal efficiencies (MRE), it could hardly be adjusted independently of the other laser parameters (such as the repetition rate, pulse energy, peak power) using conventional Q-Switch laser technologies.

This drawback can be overcome using a programmable pulse shaping MOPA fiber laser architecture, as discussed in Sections 1 and 2. As an example, the optimization of silicon percussion drilling efficiency has been demonstrated by independently adjusting the duration (in nanosecond timescale regime), repetition rate and energy of square-shaped laser pulses. Going a step further, one can use programmable arbitrary pulse shapes to tailor the temporal energy distribution onto the material, control of the laser-matter interaction thresholds and ablation mechanisms, and determine the process parameters in a material-centric and/or process characteristic-centric approach. That makes the programmable pulse shaping MOPA fiber laser platform a powerful tool for both probing a process dynamics and speeding up its optimization. The following examples of some experimental results obtained with INO MOPA fiber lasers running at 1064 nm in either nanosecond or ps-burst regime illustrate their capabilities.

#### 3.1 Nanosecond regime

Experiments on nanosecond pulse shaping have shown that the most appropriate pulse shape is not necessarily the same for each characteristics of interest of a laser process applied to a given material. For example, the MRE as shown on Fig. 4 and the surface roughness are dependent on the pulse duration for the same pulse energy. With squared shape pulses of a few microjoules incident on an aluminum plate, MRE is optimal for 20 ns-long pulses whereas the surface shows less roughness for shorter pulses. The flexibility of the MOPA platform to generate optimized pulse shapes according to desired process features and its agility to produce those shapes on demand allow the implementation in real time of laser processes of high throughput. In this case, an efficient laser process can be established by making enough passes to reach the desired depth of a milled surface with the pulse shape for maximizing MRE followed by a few passes with the pulse shape improving the surface quality. One can note in Fig. 4 that the MRE can be further improved by refining the shape of the pulse. In this case, a sloped-top pulse increases the MRE with respect to a flat-top pulse.
More elaborate pulse shapes can be produced with the flexible MOPA laser in order to distribute the energy within the pulse more efficiently. In high-thermal conductivity metals such as aluminum, the rise time to reach vaporization threshold $t_v$ ($t_v \approx 7 \text{ ns for a power density of } 122 \text{ MW/cm}^2$ in our case) plays a non-negligible role for laser material removal. The pulse can be shaped in a way that no more than sufficient energy is contained in that first period of time of heating and leaving enough energy subsequently to exceed the ablation power density to vaporize a maximum quantity of material.

Similar experiments have been conducted on a ceramic material (Ce:YAG). Results show again dependence with pulse shapes for the MRE and the surface roughness (see Fig. 5). In this case, we observe that, with pulse duration, pulse energy, and other parameters being constant, some two-level and multiple pulse shapes are more efficient to ablate material than a typical Gaussian-like pulse from a Q-switch laser (represented by shape #8). In particular, pulses with a leading peak result in higher ablation efficiency compared to their mirrored shapes. As for aluminum, different distributions of the energy within the pulse lead to more or less energy left for ablation after the material reaches the temperature of vaporization.

In some applications, in particular with respect to material processing using high power lasers, it can be advantageous to control or modify the spatial properties of the beam at the output. We can take advantage of the phasing features of the flexible MOPA laser platform to control the width of the beam or the spatial distribution of power therein. Only one additional optical element such as a diffraction grating needs to be incorporated in the beam delivery system to convert the spectral sweeping of the laser emission into a transverse or longitudinal spatial sweeping of the laser beam. Contrary to typical Gaussian beams that do not deposit uniformly the energy onto the targeted zone, fast beam sweeping during the pulse duration allows to spread out the energy of the pulse in one axis creating a quasi flat-top profile along that axis. Figure 6 shows an example of laser scribing of a transparent conductive oxide (TCO) being a component of photovoltaic cell, SnO$_2$:F on SiO$_2$ in this case, by using the method of beam sweeping. The beam was scanned vertically at 500 mm/s using a galvonomeric scanner (one pass for each energy value) while swept on the horizontal direction at a frequency of 1.8 GHz. Consequently, the beam profile, initially round, has been extended by a factor of 3 in one direction. The pulse used for this experiment is 60 ns long (resulting in ~ 108 back and forth sweeps) and has a trapezoidal temporal shape with a negative slope as shown in Fig. 6 insert. One can observe that the surface state exhibits a uniform aspect in the axis of the beam sweeping regardless of the energy per pulse used in this case. This characteristic brings a great advantage for milling or scribing processes where material has to be removed on a specific area with a constant depth or with a minimum damage to the remaining substrate. In the case of scribing processes for PV cells, the energy density and the process speed can be easily adjusted to obtain clear wide streets with uniform bottom surface. Flat-top beams can also be produced using beam shapers made of a diffractive optical element. However, the uniformity of the energy distribution into the beam near the focal point depends greatly on the alignment of the element and on the dimensions and the profile of the input beam. Moreover, the use of this type of element usually reduces dramatically the depth of field where the uniformity of the beam profile remains almost unchanged. Beam sweeping offers a great advantage from that standpoint.

The advantage of programmable pulse shaping is even more striking for the laser processing of multiple layer substrates, where a lower limit of the process threshold for each layer has to be reached without exceeding an upper limit threshold, in order to avoid damaging an underlying layer. This capability has been successfully demonstrated for the scribing of photovoltaic materials such as CIGS and CdTe and blind-via drilling in PCB processing.
3.2 Picosecond-burst regime

We have carried out experiments of micro-milling, similar as for aluminum, on silicon with nanosecond shaped pulses and ps-burst shaped pulses provided by of the INO pulsed fiber MOPA laser platform. One objective was to explore the potential improvement that can be expected from the burst regime with respect to the nanosecond regime for optimizing laser micro-milling in an industrially important material. For each tested amplitude profile and duration, the burst energy was set to the same value than the corresponding nanosecond pulse. Another objective was to determine the impact of the pulse or burst amplitude profile and duration on the MRE and the surface quality.

Figure 7 shows the MRE obtained at 9 \( \mu \)J per pulse for different pulse formats. The shapes having an energy distribution such that more energy is delivered at the beginning than at the end of the pulse are generally more efficient. This can be understood by considering the time required to produce significant evaporation and the energy and time left for evaporating the material thereafter. It is also shown that in most cases (but not all) the ps-burst mode increases the MRE with respect to the nanosecond mode.

Figure 8 illustrates the average MRE (among all tested shapes) obtained as a function of the pulse (or burst) duration for a pulse (or burst) energy of 9 \( \mu \)J. The shallow heat penetration depth (<0.2 \( \mu \)m) corresponding to short durations of the pulse is probably responsible for the limited MRE for pulse durations < 10 ns. Moreover, in that case, the ps-burst regime does not show improvement over the nanosecond regime in MRE, probably due to a stronger plasma shielding effect occurring at shorter durations; the intensities exceed anyway the reported threshold intensity of ~5–10 GW/cm\(^2\) for plasma ignition in silicon. However, for longer pulse durations where we observe higher MRE in both pulse regimes, improvement factors of more than 25% were obtained with ps-burst regime compared to nanosecond regime.

The ps-burst regime have also shown a good potential for developing laser-assisted cutting processes in reinforced glasses such as Gorilla® glass. Although the material is transparent at \( \lambda = 1064 \) nm, the peak power of each individual pulse within the burst emitted by the flexible MOPA can reach up to 100 kW and create defects into the material volume by nonlinear absorption processes. The intensity needed to reach the bulk damage threshold is easily obtained by focusing the laser beam onto a spot with a size of less than 5 \( \mu \)m into the material. No complex focusing objective is necessary. Figure 9 shows an example of a Gorilla® glass sheet that has been laser processed with a ps-burst regime at 100 kHz and then mechanically cleaved. In this case, two lines of defects have been generated at different depths into the volume. The sharpness and the straightness of the cleaved edges will depend on the number of passes, the depth of the lines and the energy per burst. Preliminary results have shown that the deviation of the cleaved edge from a straight line can be less than ± 25 \( \mu \)m. The separation of the pieces can be done by mechanical or thermal cleaving, and both methods result in similar edge quality. Increasing the number of passes at different depths will improve the edge quality but at the expense of a slower final laser process. Nevertheless, the repetition rate of the flexible MOPA platform can go up to 1 MHz allowing the development of a laser process that can reach the speed limit of the fastest motion systems available on the market.

4. Conclusion

We have introduced a novel type of laser source that has clearly demonstrated its potential for advanced laser processing applications both in its fine-tuning capabilities and its broad range of adjustable laser parameters. By bringing to-
gether advanced fiber designs, high-speed digital electronics, and reliable, telecom-derived optical components, potent laser sources can be developed that offer in a single package capabilities that could only be matched previously by multiple single-role laser sources. Significant gains in efficiency, quality and throughput can be expected in the future, with a broader use of this type of sources at their fundamental or harmonic wavelengths.

References