Optimization of the Temporal Shape of Laser Pulses for a Specific Material-Process Combination

For 40 years lasers have been used in industrial processes, especially metal cutting and welding. Also they are increasingly deployed in the manufacture of high-technology products, because the laser processes can be automated easily and used to produce, on large surfaces, machined patterns of the order of a few micrometers only. Laser processes, in general, are less harmful to the environment than the traditional processes of microelectronics, which involve many chemicals. This explains why they are increasingly used in the processes for making photovoltaic panels.

A laser is characterized by the following parameters:

- its operating regime (continuous or pulsed);
- its wavelength;
- its polarization;
- its average power;
- its repetition rate (in the case of a pulsed regime);
- its pulse energy (which can be deduced from the average power and the repetition rate);
- its pulse duration;
- the temporal profile of its pulses;
- the spatial profile of its beam.

In most cases, these parameters are given for the specific process and cannot be modified. The average power and beam size (at the machining tip) can be adjusted for the chosen process; this is carried out through different optical components. The beam polarization can also be controlled (to some extent). Finally, the repetition rate of some lasers can be adjusted.

Thus when developing and optimizing a laser process, one must select a laser available on the market and optimize the process by modifying the two or three parameters that can be adjusted. At the end of the so-called optimization process, there is no guarantee that the developed process is optimal for the material to be processed. In a laser process, the energy emitted by the laser is absorbed by the material. The latter is transformed through phase transitions (e.g., fusion, vaporization, plasma emission). The control of the laser parameters allows one, in principle, to move around the phase diagram of a given material in a specified way. Thus, for a given material, the duration and temporal profile of laser pulses are likely to be different for a fusion process (e.g., polishing, welding) and a vaporization process (e.g., machining of trenches for the manufacture of molds). The same remark can be made for a given process and a variety of materials (inox steel, aluminum, copper, silicon).

Some research groups have demonstrated that the laser-matter interaction can be controlled and optimized through the adjustment of the temporal profile and duration of the pulses, in the case of lasers with ultrashort pulses (of the order of a few tens of femtoseconds up to a few tens of picoseconds). In particular, they were able to show this for

- the ablation of silicon (where one tries to optimize the roughness of the laser-ablated surface); and
- the laser inscription of optical waveguides in glass (where one tries to control the refractive index of the material, which the laser has modified locally).

In those cases, controlling the ultrashort laser pulse spectrum enables one to control the temporal parameters of the laser pulses. The aforementioned research groups have used several optimization techniques (simulated annealing, the simplex method, an evolutive approach, etc.) to carry out their work.

New fiber laser sources, based on a MOPA (Master Oscillator – Power Amplifier) architecture, are now available on the market. This architecture enables one to have an almost total (electronic) control over the temporal profile, the duration, and the repetition rate of pulses emitted by a laser diode; these pulses are then amplified in a doped optical fiber. SPI Lasers and Multiwave provide such lasers, where the duration and repetition rate of pulses can be adjusted under the nanosecond regime. ESI-Pyrophotonics also provides lasers where the temporal profile, duration, and repetition rate of pulses are adjustable under the nanosecond regime.

INO has developed its own laser platform in order to enhance this type of control for laser pulses. Using the INO laser source, it is possible

- to control the repetition rate of pulses from a few tens of kHz up to 1 MHz; and
- to define the duration of pulses, in the nanosecond regime, from 2.5 ns up to 640 ns with a resolution (bin) of 2.5 ns;
- to define arbitrarily the temporal envelope of a pulse, in the nanosecond regime, on 1024 levels (10 bits) for each bin of 2.5 ns;

- to define pulse trains in the nanosecond regime (duration of pulses from a few nanoseconds up to a few tens of nanoseconds) by setting some bins to zero within the temporal envelope (arbitrarily defined, as above). Therefore, within the train, the pulses can be spaced in time in an arbitrary fashion (with a 2.5 ns resolution). Thus each pulse train has a total adjustable duration that is less than 640 ns but can be repeated with an adjustable rate (defined above) from a few tens of kHz up to 1 MHz;

- to define pulse trains in the picosecond regime by the method described above. In this case, however, each bin of 2.5 ns contains (or not) a single pulse whose adjustable duration varies between a few tens of picoseconds and a few hundreds of picoseconds;

- to define pulse trains in the picosecond regime (pulse duration of a few tens of picoseconds) with a very high repetition rate (from 1 to 10 GHz) and an arbitrarily defined temporal envelope (see above). Each of these pulse trains must have a total duration that is less than 640 ns but is repeated at an adjustable rate (defined above) from a few tens of kHz up to 1 MHz.

All these parameters can be adjusted through a software interface by the person making use of the laser. In this fashion one obtains a very versatile platform that enables us to reproduce the characteristics of many commercial lasers.

As explained above, optimizing a laser process usually consists of letting vary the (few) adjustable parameters of a given commercial laser. Hence one may design experiments and carry out a statistical analysis of the experimental results in order to find the combination of parameter values that will make the process optimal. When other parameters, not related to the laser, are also adjustable (e.g., gas pressure, ambient temperature, ambient pressure, etc.), one can reduce the number of experiments to be carried out by using certain well-known approaches to the design of experiments (the Taguchi method, for instance). In all cases, however, one does not have any guarantee that the process considered is optimal for a given material, because the number of adjustable parameters is relatively small. A platform such as the one proposed by INO allows one, in principle, to overcome this difficulty.

How can one take advantage of this (almost unlimited) array of distinct pulsed regimes, arising from combinations of temporal profiles (including pulse trains), pulse durations, and laser repetition rates, in order to optimize a given laser process for a given material? This is the problem one must solve. The high dimension of the parameter space prevents us from using the traditional approach and new optimization techniques must be found.

The participants of the Montreal IPSW will consider one or two specific laser processes, such as

- the laser ablation of silicon or various metals (in which one tries to maximize the amount of vaporized matter per unit of pulse energy);
- the treatment of a surface through laser fusion of various materials (in which one tries to minimize the energy required per unit of surface).

One could use (simplified) analytic models of the laser-matter interaction in order to analyze the effect of the laser parameters on the control parameter (computed by solving the model and whose value may eventually be measured).

The objective of the team is to propose an approach or algorithm for optimizing laser processes; such an approach must involve a limited number of experiments (whether numerical, analytical, or carried out in the laboratory) for determining the values of the laser parameters.