The Challenge in Realizing Truly Agile Fiber Lasers

Laser-diode seeded MOPAs hold promise of arbitrarily modulated high power laser output

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The master oscillator power amplifier (MOPA) fiber laser has been around for several years but the bulk of applications use Q-switched fiber lasers. Now, with the processing capabilities of the Q-switched fiber laser fully explored, the MOPA fiber laser is getting revived attention. Laser-diode seeded MOPAs hold promise of arbitrarily modulated high-power laser output. Pulse-pumping the amplifiers to handle ON/OFF gating and low repetition rate pulse trains without overshoot or undershoot is of special interest.

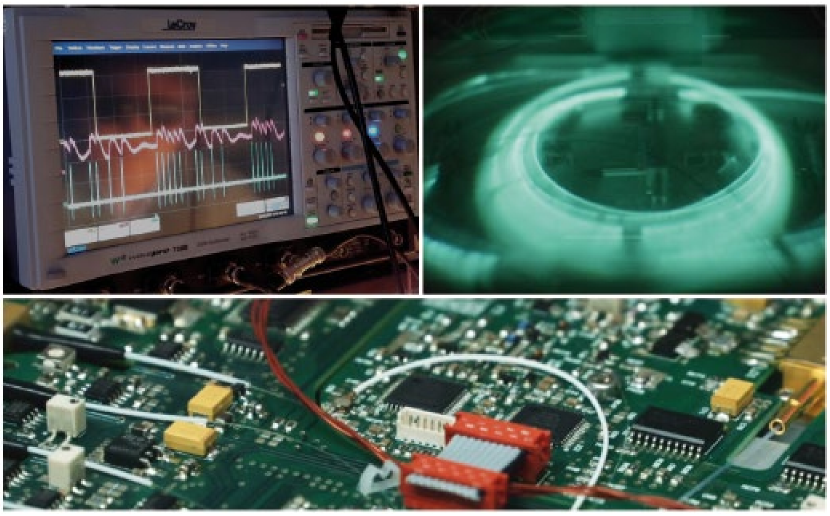

Fig. 1 Light in MOPA fiber laser and control electronics example. The oscilloscope shows an MWTechnologies fiber laser gain controller, tested with Barker code signals. The red trace is the controller output which maintain the pulses in the coded bursts (blue trace) at constant pulse energy.

The availability of a versatile fiber laser for materials processing is beneficial as it allows to parameterize a big amount of operating conditions to process new and different materials in several applications (printing, marking, cutting, drilling, trimming). This is possible with MOPA fiber lasers, capable of working in a very broad extended range in terms of pulse waveform and repetition frequency. However, to be able to extend the operating range of such lasers, actions need to be made to its controllability. A particular ever present issue is gating the MOPA output via electrical control of the pump laser diodes. This approach is more cost and power efficient than using an external modulator for gating. The turning OFF and ON a MOPA amplifier chain without overshoot or undershoot is not trivial.

This article describes recent results in control of MOPA chains using gain-control based real-time resolution of the governing rate equations. The coding of such controller in fast parallel logic arithmetic leads to precise open-loop control for arbitrary optical waveforms.

The MOPA fiber laser architecture is shown in the diagram of Fig. 2. It uses fiber-coupled laser diodes as seed (LD1) and as pumps (LD2–4). The two rare-earth doped fibers (REDF) are typically ytterbium-doped fibers for 1 µm wavelength and erbium-doped fiber for 1.5 µm wavelength range. The REDF stages are pumped by multimode fiber coupled laser diode (LD2–4) modules. The pump module contains a single emitter to give up to 10 W of optical power, or multiple emitters combined in the module to give up to 150 W of pump power in a multimode (MM) fiber. Fused pump signal combiners (PSC) are used to inject the pump into the guiding cladding of the double-clad REDF. The high gain of the fiber amplifiers allow scaling of the directly modulated seed laser to pulse energies required in applications. The control described in this article is concerned with adjusting the current through the pump diodes with the aim of keeping the output pulse energy constant.

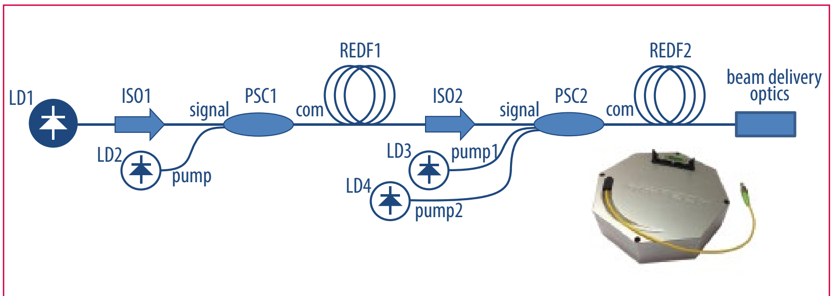

Fig. 2 MOPA fiber laser architecture and enclosure

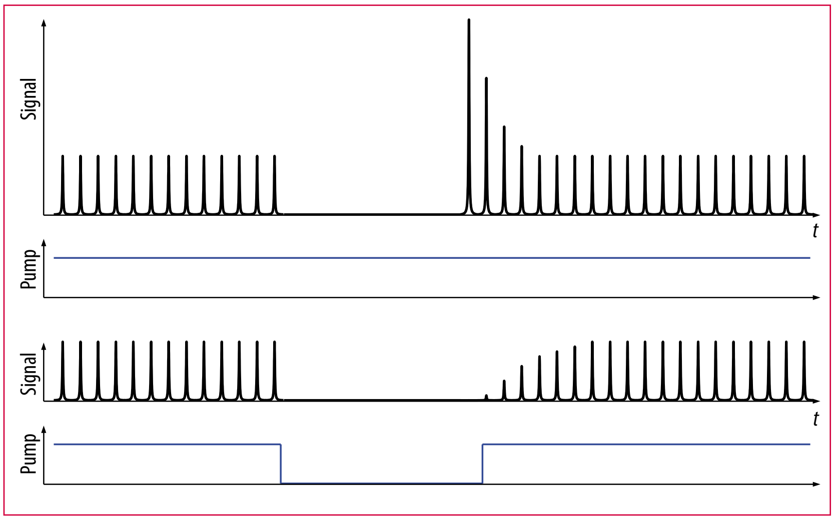

Fig. 3 Illustration of pulse burst turn on transient: with pump kept on during OFF period (top) and with pump gated off (bottom).

The problem to solve

Variations in output pulse energy can arise from gain dynamics during ON/OFF gating.

For ON/OFF gating, we can consider two extremes of pump current control. One extreme is when the pumps remain on at a constant level, even when the laser (seed) is gated off. In this case the available gain will increase in the OFF period and the first pulses will overshoot when the laser is gated on (Fig. 3, top). In the other extreme the pumps are turned off in the gated OFF period and on in the ON period. This is illustrated in Fig. 3, bottom. When the laser is gated on, the emitted pulse will experience low gain and first pulses will undershoot.

Pulse overshoot can cause damage to the processed object but it can also reach levels causing damaged to the laser itself. Coatings in optical components have limited pulse energy handling and the optical fiber itself can suffer damage by high peak power. Self-focusing can explain how high peak power can lead to intensity levels in the bulk of the fiber beyond the damage threshold. Before damage occurs, optical nonlinearities like stimulated Brillouin scattering (SBS) and self-phase modulation (SPM) can also lead to system failure.

Thus, the ideal would be if the laser, when gated ON, emits the first pulses with the same energy as in the steady-state pulse train.

Prior work

The extremes above suggest that a pump level realizing first-pulse equalization does exist. Several approaches have been tried for setting the right pump level for first pulse equalization. One is simmering, where the laser user is given a simmering setting for the pump level in the OFF periods. The laser user or integrator will have to find the best simmer level which works for the pulse width and power setting they operate the laser at. Another approach is pre-pumping where the pumps are turned back ON some time (e.g. 200 µs) before the seed. Both approaches are based on calibration by testing. The laser manufacturer may store calibration lookup tables in the laser electronics based on the factory calibration. Alternatively, the control is left to be handled by the system in which the laser is used or integrated. Each time the pulse width, pulse repetition frequency (PRF) or power setpoint is changed, new simmering or pre-pumping time has to be applied. Thus, the calibration needs to map all possible combinations of power setpoint, pulse width and PRF.

Even if the above is implemented to perfection, one issue remains: When the OFF period is comparable to the spontaneous lifetime of the rare-earth ions (1 ms for Yb and 10 ms for Er), inversion from the previous ON period remains and the following turn-ON will produce overshoot.

A new approach

In previous systems, effort was done on also calibrating for short OFF periods. It was the complexity and effort in this that brought MWTechnologies to a rethink of the problem.

The core of the problem is keeping the pulse gain, i.e., in essence, keeping

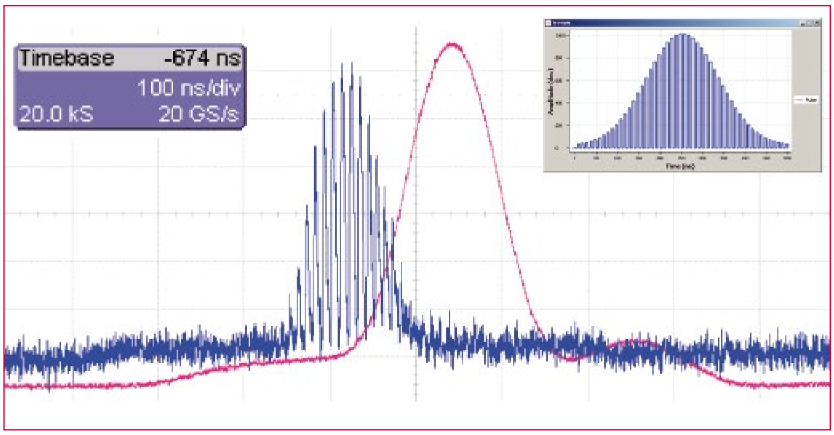

Fig. 4 Seed pulse as measured with fast 1 GHz bandwidth (blue trace) and slow integrating photodetector (red trace).

Company

MWTECHNOLOGIES
Maia (Porto), Portugal

Founded in 2012 as a spin-off of Multiwave Photonics, MWTechnologies offers innovative optical sources based on fiber-optic technologies, as well as product design, product development and engineering services. A wide range of standard products with unique features include MOPA fiber lasers with state-of-the-art control technology, optical fiber amplifiers, ASE sources, and laser diode drivers / controllers. Operating in several markets, its line of products find to be valuable is many applications such as LIDAR, remote sensing, military testing and targeting, materials processing, imaging and optical communications.

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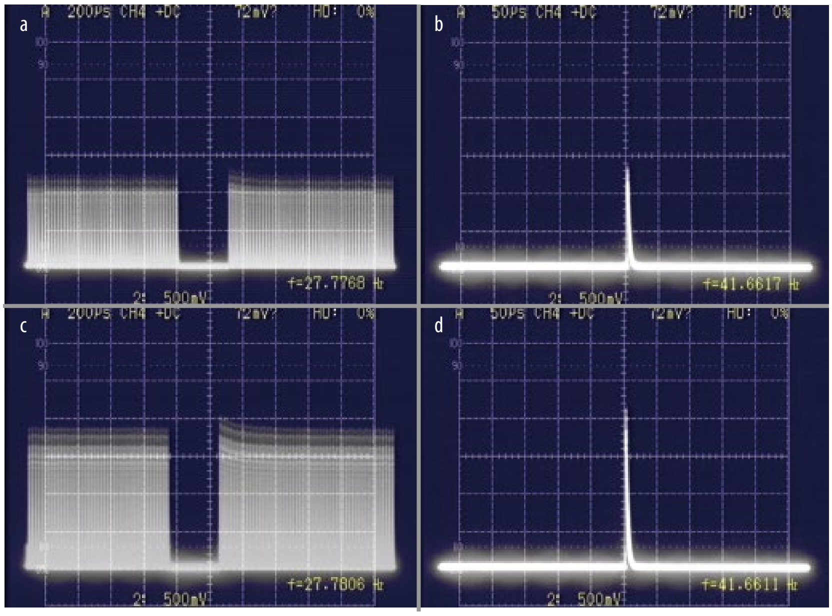

Fig. 5 Analog oscilloscope traces for two pulse energy setpoints: 75 % (a, b) and 100 % (c, d); and different trigger sequences: 50 kHz PRF in closely spaced bursts (a, c) and single-shot (b, d).

the inversion constant. The inversion dynamics is governed by well-known rate equations [1].

The control we present here is in general terms based on solving the rate equation iteratively and adjusting the pump power in the equations until the target inversion is reached and applying that pump power to the real laser by adjusting the current through the pump-laser diodes. All under the influence of the seed signal, as it happens in real time. This control is made possible by using an optimized numerical algorithm, implemented in parallel logic arithmetic on a field-programmable gate array (FPGA).

Basing the control in the rate equations reduces the number of constants from the previously mentioned lookup tables to the physical parameters: cross section, doping concentration, lifetime, index and doping profiles plus the seed and pump wavelengths. The control model works for all pulse energy setpoints and all pulse repetition patterns. There are no special cases to handle. Single-shot, ON/OFF gating and non-periodic or periodic pulse trains are all equalized by the model with one set of parameters. Even the pulse width can be changed on the fly.

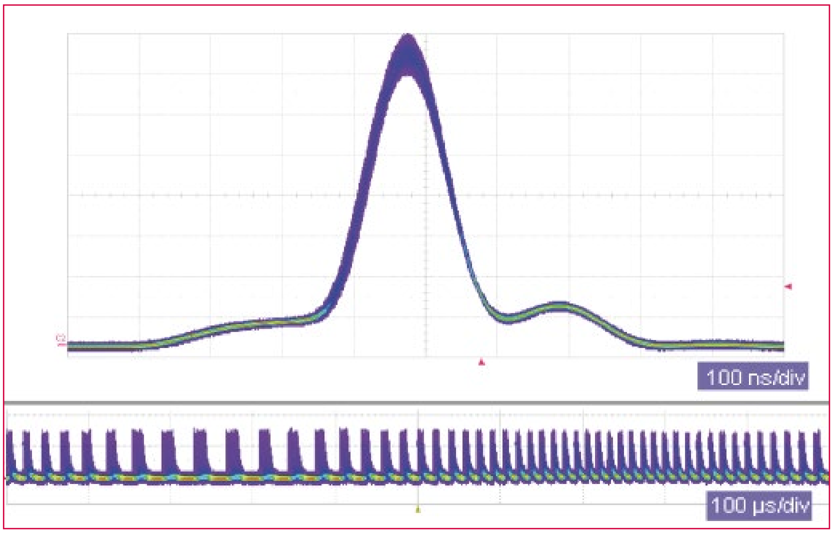

Fig. 6 Performance of the gain control with modulated PRF (50 ± 25) kHz with 1 kHz modulation rate. The bottom trace shows one PRF modulation period and the top trace show overlaid single pulses.

Advantages

In the new control approach, the user applies a pulse energy setpoint and a trigger edge whenever a pulse is desired. This control technique is as close as one can get to the agility of a directly modulated diode laser, but scaled to high pulse energy. Typical pulse energies for ytterbium-doped 1064 nm MOPA systems are on the order of 0.8 – 1 mJ (10 – 12 kW of peak power) for near single mode output and 10 mJ (100 kW of peak power) for multimode output. For traditional applications like marking, the new control brings advantages in process quality and throughput. There is no minimum OFF time to respect, and the pulse repetition frequency can be slowed or sped-up when the scanner's velocity changes.

Triggered single-shot is essential for laser ignition, a field that few other fiber laser suppliers have been able to serve.

Aperiodic pulse trains can also give advantages in light detection and ranging (LIDAR), where this technology is able to meet particular requirements, where pulse repetition frequency modulation can be beneficially used. In this way, the control enables the use of pulse coding schemes known from RADAR in the optical domain.

Experimental results

Examples of pulse patterns made possible by the control are presented below.

The results are from a test system with a single-stage double-clad ytterbium-doped fiber amplifier. Referring to Fig. 2, the LD1 is a 1064 nm Fabry-Perot (FP) seed laser diode, which is directly modulated using a model PS-LD-A pulse driver. ISO1 is a HI1060 fiber-pigtailed high-power isolator, PSC1 is a fused pump signal combiner with double-clad common output fiber, spliced to a REDF1 ytterbium-doped large SM core gain fiber, and ISO2 is identical to ISO1. The output of ISO2 is the output which is reported as the laser output below. The FP laser diode is known to have low SBS threshold for longer than 10 ns pulse duration. A burst of 5 ns pulses under a Gaussian envelope (200 ns at FWHM) was used. The short pulses mitigate SBS through spectral broadening. The envelope burst extracts more energy than a single

pulse would. The Gaussian envelope is also resilient to pulse distortion from fiber gain saturation. The pulse burst is shown in Fig. 4: the blue trace is measured with a fast (1 GHz bandwidth) photodiode, so the 5 ns pulses are visible; the red trace is measured with a slow integrating photodiode (integration time ~ 50 ns) and the individual sub-pulses are not visible.

In the following, we will refer to the enveloped burst as one pulse and the slow integrating photodiode is used for more consistent detection with a sampling oscilloscope. The seed signal was generated by the arbitrary waveform generator (AWG) of the MWTechnologies standard MOPA control platform. The AWG application waveform preview is shown in the Fig. 4 insert, where a 10-bit amplitude level can be specified for every 5-ns time slot resolution. LD2 is a 8 W 915 nm MM fiber-coupled pump module driven by a model LD-CCD. The controller adjusts the current through the pump via 8-bit digital to analog converter (DAC) to maintain constant pulse gain. The 1064 nm output power in continuous pumping is around 500 mW.

Tight burst spacing and single-shot

In this test, the trigger signal was bursts of 50 kHz PRF, repeated at 6-ms intervals and the number of pulses was varied to change the OFF period. Examples are shown in Fig. 5 for an OFF period of 150 µs, well within the range where first pulse overshoot would be a problem without the control. Overshoot of only a few percentages is seen. In the lower trace (c), the pulse energy setpoint is 100 % compared to 75 % in the case above (a). The controller adjusts the pump accordingly.

In the trace images to the right (b, d), the trigger is a single pulse and a single pulse is emitted near the pulse train energy level.

Pulse repetition frequency modulation

In a pulse repetition frequency modulation experiment, the trigger frequency is sine-wave modulated from 25 kHz to 75 kHz at 1 kHz frequency. Fig. 6 shows persistence oscilloscope traces of the PRF modulated laser output. The lower image is the full modulation period and the variation in PRF is visible while the amplitude remains constant. This is even more evident in the top trace where the oscilloscope is triggered on the individual pulses and all pulses overplayed (eye diagram).

The capability of the laser to follow a PRF-modulated trigger enables frequency modulation (FM) laser ranging techniques.

Conclusion

In conclusion, we have argued the need for a new approach to gain control in MOPA fiber lasers. We have demonstrated a working implementation of a rate equation solver based controller. Results from a system that is controlled by the controller have been shown across a wide range of operating pulse patterns. To the best of our knowledge, this is the only true pulse-on-demand solution which will produce a pulse per trigger whenever it arrives.

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[1] *E. Desurvire:* Erbium-Doped Fiber Amplifiers, Wiley, Hoboken, USA, August 2002; ISBN: 978-0-471-26434-7

Authors

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