Pulse Energy Control Through Dual Loop Electronic Feedback

Cobus Jacobs, Steven Kriel
Christoph Bollig, Thomas Jones

Laser Research Institute
University of Stellenbosch
WWW.LASER-RESEARCH.CO.ZA
Overview

- What is Laser Pulse Energy Control?
- Why do we need it?
- How do we get it?
- Simulation
- Experimental Setup
- Results
What is Pulse Energy Control:
- Reliability & Repeatability
- Accuracy & Stability
- Programmability

Why do we need it:
- Protection against component & subject damage
- Micromachining with irregular pulse rate
- Safer/improved laser surgery
- Better accuracy in laser-based scientific measurements
Sources of Instability

Pump/Gain

- Duration & intensity of pump determine energy stored in laser medium

Cavity
- Inherent instabilities due to noise, thermal & quantum effects, vibrations...

Results in timing & amplitude jitter

Graph: Q-switched Pulse Repetition Rate [Hz] vs. Pulse Energy [mJ]

- Reliability & Repeatability
- Programmability
- Pump Less
- Pump Harder
- Accuracy & Stability
Pulse Energy Control: How?

Electronic Feedback

- Inexpensive, efficient & highly flexible
- Reported prelase technique with feedback to internal Q-switch for reducing cavity instabilities at SAIP2004 & 5
- Now add 2nd feedback loop to pump for bulk energy/gain control
  - Problem: Need to measure stored energy in medium
  - Answer: Cascaded “dual” loop system
    Gain control taps of the prelase loop
Bucket Analogy

- Medium = bucket, water-level = stored energy available to pulse

- Tap Control
- Mirror: HT for Pump λ, HR for Laser λ
- Resonator
- Mirror: Partially reflective for Laser λ
- Water-level
- Outlet Height
- Switch: Switching between high and low loss
- Pulsed Laser output

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Dual loop system

HT Pump
HR Laser
Resonator
Partially reflective mirror

Prelase output (in-between pulses)

Solid-state gain medium

Energy
“water-level”
Set-point

Diode Current
“Tap Control”

Pump light from Laser Diode

Error

Loss
“outlet height”

Error

Set-point
Σ

Σ

Prelase
“flow meter”
Set-point

Acousto-Optic Modulator

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Simulation: Prelase

- Look at typical response on detector (still without feedback)
- Too low Q-switch loss produce pre-spiking before each pulse
- Observe lasing if “gain equals the losses”
Simulation: Prelase Control

- As before, allow pre-spiking but add \textit{control} between pulses
- Rejected as noise and formed into stable, low power CW \textit{prelase}

![Graph showing laser output power over time with control ON]

\textbf{Laser Output Power over time}

- Control ON
Dual Loop

- Most cases pump will already be running at full power
- Gain-loop reduces pump power and keep energy/gain constant in the presence of other losses (natural decay, heat...)

![Graph showing Gain and Loss parameters over time with annotations for Prelase Control and Energy/Gain Set-point.](image)
Analog PID Controller Design

Reference Signal

Input Signal

Proportional

Derivative

Integral

$K_p$

Error Signal

TTL Pulse Trigger

Offset

Q-switch Loss signal
Experimental Setup

CW: Max Pump 28W, Output 5.6W, 20% eff.
Results: Uncontrolled

![Graph showing pulse energy vs. repetition rate. Theoretical energy is represented by a red line, and measured energy by blue triangles.](image-url)
Results: Dual Loop

Theoretical energy

Measured Energy

Energy set-point

Pulse Energy [mJ]

Repetition rate $f$ [kHz]

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Summary

- Previous results for single prelase loop
  - CW noise reduction by a factor of 20
  - Reduced timing jitter $13\% \rightarrow < 1\%$ @ 5kHz (uncontrolled 87%)
  - Reduced amplitude jitter $5\% \rightarrow < 1\%$ @ 5kHz (uncontrolled 21%)

- Successful bulk pulse energy control
  - Improvements possible
    - Faster power supply, control hardware, optimal control (not cascade, but integrated) – ideal for a digital controller
  - A fast optimised pump setup can replace prelase loop, but with less jitter stability
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Proposing a solution

- Can not stabilize pulses directly
- Look at initial condition before each pulse

Pulses are triggered from spontaneous emission
=> pulse to pulse variations

- Force a repeatable, stable initial condition
=> pulses will be stable as well
Forced Initial Condition

- Lower Q-switch high-loss slightly
  => slight lasing occurs before pulse (~1 mW vs ~10 kW)
- This forced initial condition is called the prelase
- After short build-up time, prelase starts with spiking
- Stability worse because pulse triggered by spikes

Initial Condition

Random

Q-switch Loss vs time

<table>
<thead>
<tr>
<th>prelase</th>
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<tbody>
<tr>
<td>pulse</td>
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Actual Prelase

~10 kW

~1 mW
A Feedback Solution

- Stabilize the prelase by controlling the $Q$-switch loss through negative feedback of prelase signal
Low-power Stabilized YAG laser
Continuous Wave Results

- As a runner up to pulsed testing
- At low power, signal consists mostly out of noise
- Suppression of noise by factor of 20

![Graph showing laser power changes over time with and without control](image-url)
Pulsed Results

- Reduced timing jitter $13\% \rightarrow <1\%$ @ 5kHz (uncontrolled 87%)
- Reduced amplitude jitter $5\% \rightarrow <1\%$ @ 5kHz (uncontrolled 21%)
- Successful prelase damping allowing higher PRR