Pulsed Lasers
## Introduction to Power and Energy Calculations

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Serving the Intellectually Curious

Pulsed laser or CW laser, does it make a difference?

Bursts of light cause different effects than constant streams of light.

- Pulsed lasers emit bursts of light spaced in time.
  - Between pulses, the laser emits no light.
  - The *period* is the time from the start of one pulse to the next.
  - The *pulse duration* (*pulse width*) is the time measured across a pulse, often at its full width half maximum (FWHM).

- Continuous wave (CW) lasers provide steady emission.
  - Peak, minimum, and average powers are approximately identical.
  - Period and pulse width do not apply unless the light is modulated.

- Help, harm, or underperform: it depends on the pulse width, peak power, *and* period.
  - Short pulses and long periods may protect illuminated samples from overheating, by allowing them to cool down between bursts of light.
  - Short pulses with high peak powers and long periods may destructively ablate surface material, but heat the surrounding area minimally.
  - Long pulses and/or short periods may deliver damaging total emission, even if the peak power is moderate.

Pulsed Laser Emission
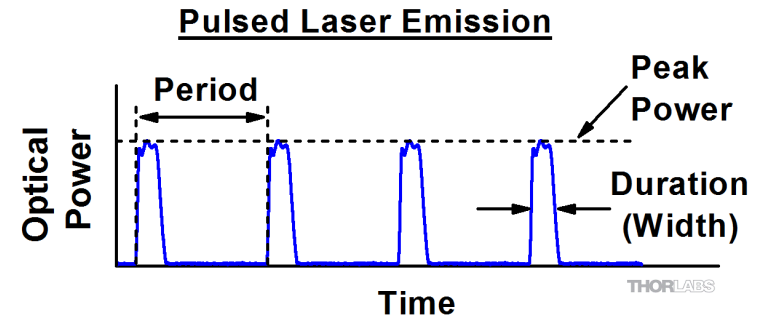
Figure 1. Pulsed lasers emit bursts of light, spaced in time. There is no emission between pulses.
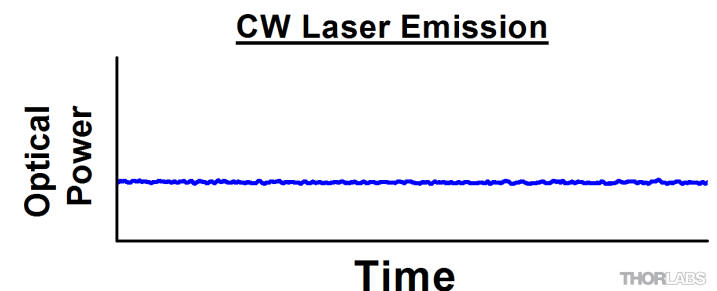
CW Laser Emission

Figure 2. CW lasers emit light whose optical power is approximately constant with time.

What do power and pulse energy describe?

Energy and power describe different, but related, aspects of the emission.

- Pulse energy is a measure of emission over one period.
  - Each period contains a single pulse, and all energy emitted during one full period is delivered by the pulse.
  - Pulse energy, shown as the shaded regions in Figures 3 and 4, is the area under one full period of the power measurement curve.

- Optical Power Parameters:
  - *Instantaneous power:* the optical power at a specific point in time.
  - *Peak power:* the highest instantaneous optical power emitted.
  - *Average power:* the constant power, if the laser emission were CW.
    - The pulsed laser delivers bursts of emission. A CW version would spread that emission uniformly across the period.
    - Both the pulsed laser and the CW version provide the same energy (shaded areas in Figure 4) during one pulse period.
    - The height of the shaded area in the lower plot of Figure 4 is:
      - The constant optical power of the CW version.
      - The average power output by the pulsed laser.

- **Note**: average power provides no information about peak power, period, or pulse width.
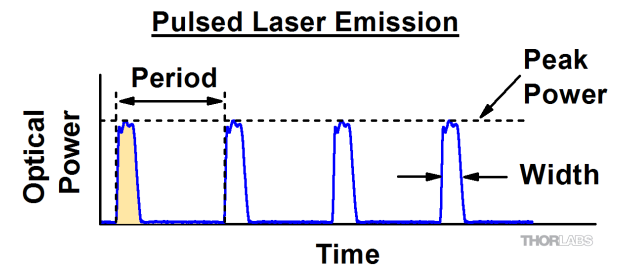
Figure 3. Period, peak power, and pulse width are used to characterize laser pulses
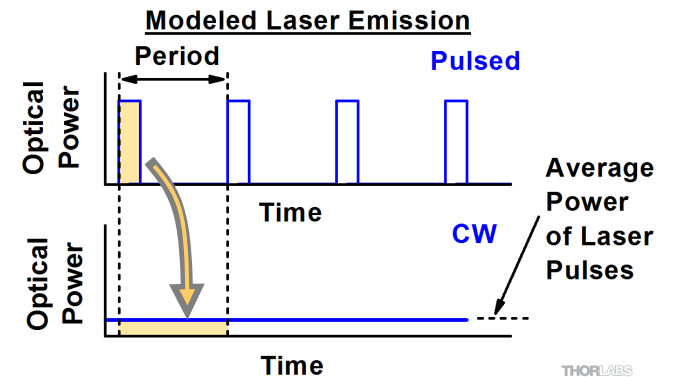

Figure 4. The modeled laser pulses (top) and CW laser output (bottom) provide the same energy per period, illustrated by the shaded areas. The CW laser's output power equals the pulsed laser's average power.

# What is the effect of changing pulse width or period?

Pulse width and period control the average power emitted by the laser.

- Pulse width:
  - Both pulse energy (shaded area) and average energy (dotted green line) depend on pulse width.
  - Increase (or reduce) pulse width to increase (or reduce) both pulse energy and average power.
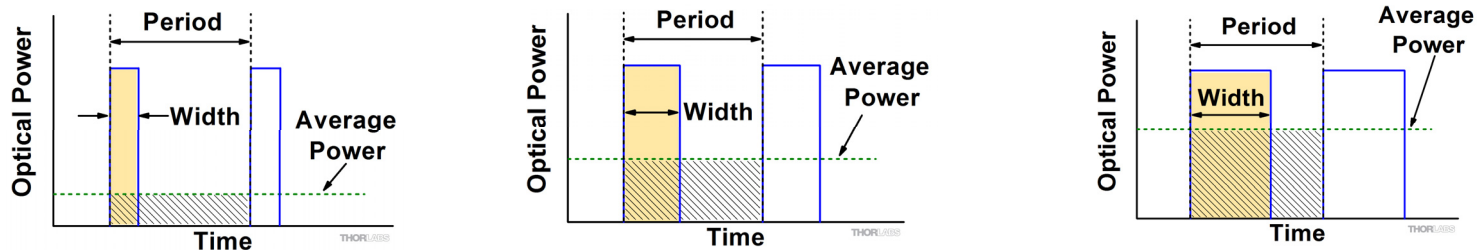
Figure 5. Changing the pulse width changes the pulse energy by changing the length of the pulses. The average power changes, since the total time light is emitted by the laser changes.

- Period:
  - Pulse energy (shaded area) does not depend on period, but average energy (dotted green line) does.
  - Reduce the period to increase the average power (or increase the period to reduce the average power).
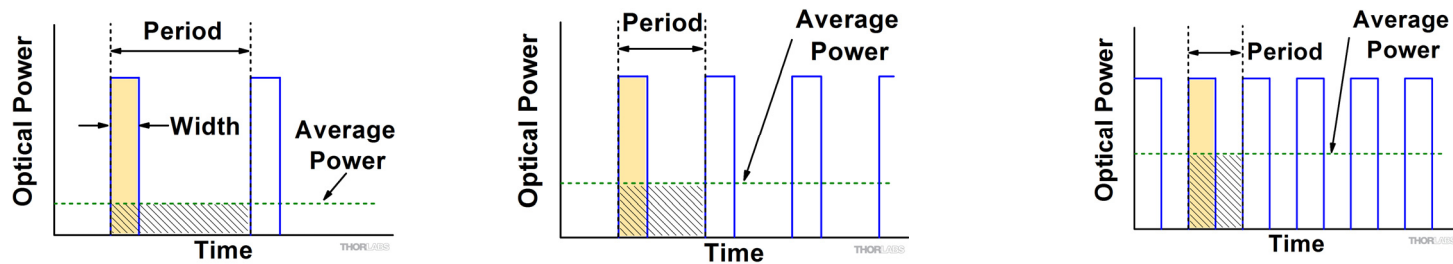
Figure 6. Changing just the period does not change the pulse energy, since the pulse width and peak power do not change. The average power changes due to pulses being delivered more (or less) frequently.

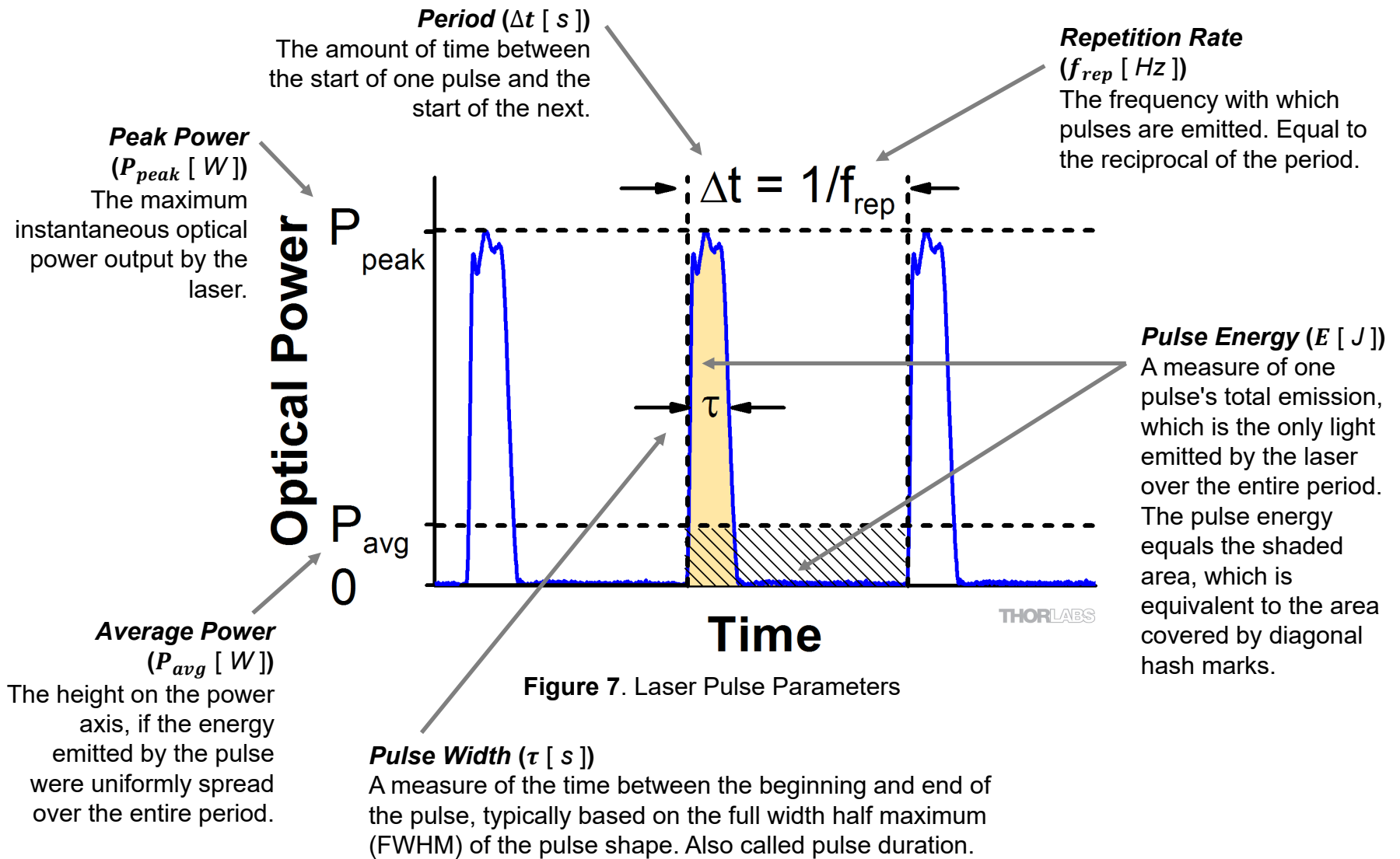# What are the symbols and units of pulse parameters?

Period (Δt [s])
The amount of time between the start of one pulse and the start of the next.

Repetition Rate (f_{rep} [Hz])
The frequency with which pulses are emitted. Equal to the reciprocal of the period.

Peak Power (P_{peak} [W])
The maximum instantaneous optical power output by the laser.

$$\Delta t = 1/f_{rep}$$

Pulse Energy (E [J])
A measure of one pulse's total emission, which is the only light emitted by the laser over the entire period. The pulse energy equals the shaded area, which is equivalent to the area covered by diagonal hash marks.

Average Power (P_{avg} [W])
The height on the power axis, if the energy emitted by the pulse were uniformly spread over the entire period.

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Figure 7. Laser Pulse Parameters

Pulse Width (τ [s])
A measure of the time between the beginning and end of the pulse, typically based on the full width half maximum (FWHM) of the pulse shape. Also called pulse duration.

How are pulse energy and peak power calculated?

Pulses are often modeled with a rectangular shape as shown in Figure 8.

- Period and repetition rate are reciprocal:

$$\Delta t = \frac{1}{f_{rep}} \quad \text{and} \quad f_{rep} = \frac{1}{\Delta t}$$

- Pulse energy calculated from average power:

$$E = \frac{P_{avg}}{f_{rep}} = P_{avg} \cdot \Delta t$$

- Average power calculated from pulse energy:

$$P_{avg} = \frac{E}{\Delta t} = E \cdot f_{rep}$$

Figure 8. Laser Pulse Parameters

- Peak pulse power estimated from pulse energy:

$$P_{peak} \approx \frac{E}{\tau}$$

- Peak power and average power calculated from each other:

$$P_{peak} = \frac{P_{avg}}{f_{rep} \cdot \tau} = \frac{P_{avg} \cdot \Delta t}{\tau} \qquad P_{avg} = P_{peak} \cdot f_{rep} \cdot \tau = \frac{P_{peak} \cdot \tau}{\Delta t}$$

Δt	Pulse Period
E	Energy per Pulse
f_{rep}	Repetition Rate
P_{avg}	Average Power
P_{peak}	Peak Power
τ	Pulse Width

- Peak power calculated from average power and duty cycle*.

$$P_{peak} = \frac{P_{avg}}{\tau / \Delta t} = \frac{P_{avg}}{duty\ cycle}$$

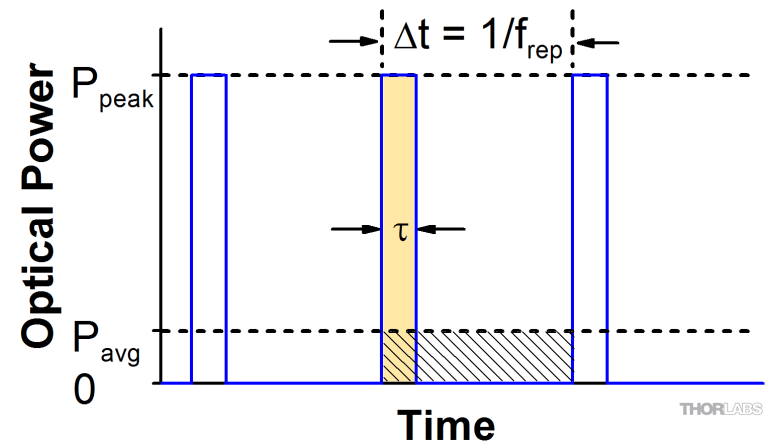*Duty cycle is the fraction time during which there is laser pulse emission.
duty cycle = $\tau / \Delta t$

Example Calculations

The attenuated average output power of a pulsed Ti:sapphire laser beam is **1 mW**. A detector specifies a maximum peak optical input power of **75 mW**. Is it safe to use this detector to measure this attenuated beam?

- Beam Specifications:

  - Average Power: 1 mW

  - Repetition Rate: 85 MHz

  - Pulse Width: 10 fs

Δt	Pulse Period
E	Energy per Pulse
f_{rep}	Repetition Rate
P_{avg}	Average Power
P_{peak}	Peak Power
τ	Pulse Width

- Energy per Pulse:

$$E = \frac{P_{avg}}{f_{rep}} = \frac{1\ mW}{85\ MHz} = \frac{1\ x\ 10^{-3} W}{85\ x\ 10^6 Hz} = 1.18\ x\ 10^{-11} J = 11.8\ pJ$$

… this *seems* low, but ...

- Peak Pulse Power:

$$P_{peak} = \frac{P_{avg}}{f_{rep} \cdot \tau} = \frac{1\ mW}{85\ MHz\ \cdot 10\ fs} = \frac{1\ x\ 10^{-3} W}{85\ x\ 10^6 Hz \cdot 10\ x\ 10^{-15} s} = 1.18\ x\ 10^3\ W = \mathbf{1.18\ kW}$$

This scenario is **not safe**. The peak power of the pulses is *>5 orders of magnitude higher* than the detector's specified maximum peak optical input power!

Example Calculations

A pulsed laser provides the option of adjusting its pulse width and repetition rate independently, while keeping the peak power constant at 50 mW.

- **Adjusting the pulse width**: How does average power change if pulse width is reduced from 39 ns to 12 ns, while keeping the repetition rate at 1 MHz?

  - Equation: $P_{avg} = P_{peak} \cdot f_{rep} \cdot \tau$

  - Average power for 39 nm pulse width: $P_{avg} = (50 \ mW)(1 \ MHz)(39 \ ns)$

    $$= (50 \ x \ 10^{-3} \ W)(1 \ x \ 10^6 \ Hz)(39 \ x \ 10^{-9} \ s)$$

    $$= 1.95 \ x \ 10^{-3} W = 1.95 \ mW$$

  - Average power for 12 ns pulse width: $P_{avg} = (50 \ mW)(1 \ MHz)(12 \ ns) = 0.6 \ mW$

  - **Average power drops by same factor as pulse width**: $\dfrac{12 \ ns}{39 \ ns} = \dfrac{0.6 \ mW}{1.95 \ mW} \approx 0.31.$

Δt	Pulse Period
E	Energy per Pulse
f_{rep}	Repetition Rate
P_{avg}	Average Power
P_{peak}	Peak Power
τ	Pulse Width

- **Adjusting the repetition rate**: How does average power change if repetition rate is increased from 5 MHz to 10 MHz, while maintaining a 20 ns pulse width?

  - Equation: $P_{avg} = P_{peak} \cdot f_{rep} \cdot \tau$

  - Average power for 5 MHz repetition rate: $P_{avg} = (50 \ mW)(5 \ MHz)(20 \ ns) = 5 \ mW$

  - Average power for 10 MHz repetition rate: $P_{avg} = (50 \ mW)(10 \ MHz)(20 \ ns) = 10 \ mW$

  - **Average power increases by same factor as pulse width**: $\dfrac{10 \ MHz}{5 \ MHz} = \dfrac{10 \ mW}{5 \ mW} = 2.$

Average power scaling is proportional to changes in pulse width and repetition rate.

What are some options for characterizing pulses?

Sensor Type	Recommend Use	Measurement Provided	Comments
Photodiode	Low CW Power; Low Pulse Power and Energy	Power; Average Power	Optical power is converted to current within a semiconductor material. When the system response is fast enough, the instantaneous power can be displayed and pulse rate and width measured.
Thermopile	CW and Pulsed Lasers	Average Power	Pulse energy is converted to heat. The flow of heat to a heatsink is measured.
Pyroelectric	Pulsed Lasers Only	Pulse Energy	An electrical signal is generated by crystalline material in response to being heated by the laser pulses.

Photodiodes generally have the fastest response times and thermopiles the slowest.

Always protect sensors by considering both the pulse energy and peak power.

- Peak pulse power can be high when the pulse energy is low, and high peak powers can damage sensors.

- Since photodiodes typically have relatively maximum peak optical input power limits, the laser pulses should be attenuated as necessary to protect the sensor.

- Consider the pulse width and energy, even when peak power is low. The average power increases as the pulse width increases, and the illuminated object has less time to cool between laser pulses. If the average power is too high, the object's temperature may increase to harmful levels as pulse shots accumulate.