Technical Memo – For Public Release

Average Power, Peak Power and Power Density

Background:

In laser applications the energy being delivered or transmitted in unit time should be known. Energy over time is Power. The units here are Joules (J) for Energy, Seconds (s) for time and Watts (W) for power were J/s=W. The next extension in analysis is to consider Power Density as in Power per Unit Area.

Obviously, if you have 5W spread over the area of your hand you might barely register the heat. However, if you take that 5W and put it in a fiber optic the diameter of single strand of hair, the Power Density is quite high, high enough, locally, to cause damage, and we need to have an idea of if that might happen.

Considerations start to get tricky fast. For example, is the consideration that of a Continuous Wave (CW) laser or Pulsed laser. A laser is called continuous-wave **if its output is nominally constant over an interval of seconds or longer** for example, a laser pointer. Whereas pulsed lasers will deliver energy in discrete pulses that are differentiable.

The problem here is that the terminology and technology has become muddled. Today we often talk in term of the Power of a laser. Someone might say I have a 5W laser, and in the old days that would mean a CW laser but, not today. If someone tells you they have a 5W laser the next question might be: “is that CW or Average Power?”

If it is true CW, which few lasers are today, then you know all you need to know. If the answer is Average Power then the follow up questions are: “what is the Rep Rate and Pulse Width?”

Rep Rate will tell you how many pulses are delivered per second usually given in Hertz (Hz) or Kilohertz (KHz) or MHz of GHz etc. and Pulse Width will tell how fast the Power is delivered in each pulse, leading to the concept of Peak Power.

Together, the information of CW or Pulsed, Average Power, Pulsed Power, Power per Pulse (Peak Power) and finally a consideration of the size of the fiber being considered for this power transmission, resolving the Power to Power Densities, is critical to determine if the fiber will suffer Laser Induced Damage (LID).

To discuss this further we offer a real world example.

Example:

An application comes across your desk and starts with the following specifications:

Laser Power: 5W Average Power

Rep Rate: 10KHz

Fiber Diameter: 100um core

Question: Can the fiber handle it?

Note: We are ignoring wavelength for this Memo because the calculations we are present are independent of wavelength, though, wavelength cannot be fully ignored in reality.

The specifications above mean there is a laser source that is pulsing 10 thousand times a second (10KHz).

That source has an Average Power of 5W and Average Power is total power delivered in 1 second.

Therefore, adding up the power from 10K pulses would equal 5W total.

For purposes of the other calculations we want to do lets converts from Power to Energy per Second.

Watts (W) is Energy (J) per unit Time (s)… so 5W average power is 5J delivered in 1 second or 5J/s.

There is 5J delivered in 10K pulses so 5/10,000 = 0.5mJ per pulse (aka 500µJ/pulse).

Oh, but wait, while we now know that there is 500µJ of energy in each pulse, we want to go back to Power and determine the Peak Power, which the power in each pulse (with assumptions as to pulse shape). To do that we must have the pulse width. The question is plain language is: “over what time was the 500µJ delivered?”

In this case, and a common specification of pulse width, we are told the pulses are 10ns wide. This is interesting on several levels but not the least of which might be a consideration of duty cycle which is how much of the time is the laser energy present? Well 10K pulses per second that are 10ns wide each means 10X10^3 X 10X10^-9 yields 100X10^-6 seconds. The laser is only “on”, pulsing energy, for 100µs each second, meaning the laser is NOT putting out energy 99.99% of each second!

This “duty cycle” consideration should result in concern as the 5W of total power are delivered over 0.01% of each second. Which should indicate that during that “on time” it seems possible that some very brief but very high powers might be reached. Which is in fact the case, which is why we then ask what the Peak Power is?

Remember we know the Average Power but, what might be the Peak Power, or the Power per Pulse?

In this example, which is again, not unusual, we have 500μJ being delivered in 10ns pulses.

Converting back to Power (Watts) its 500X10^-6 Joules / 10X10^-9 seconds = 50X10^3W or 50K Watts.

To be clear here. The Peak Power in each pulse is 50,000 Watts! It just doesn't last long.

Next question? What is the Power Density? We want to know how many Watts per Unit Area.

When considering Power Density you start to get terminology like "MegaWatts per Centimeter Squared" or something similar.

To get to Power Density we need know in what Area are we trying to cram those 50KW of Peak Power? To do that we need the area of the fiber core. A round fiber core has Area of π*r^2, so, for a 100um fiber core diameter, aka, 0.01cm (for somewhat arbitrary reasons Pulsed Power Density is typically using area units of cm^2 whereas CW Power Density will use areas units of mm^2), we get:

A = 3.14159 * 0.005^2 = 0.0000785cm^2

And so… this example is delivering 50K Watts Peak Power per pulse into an area of 0.0000785cm^2…. and dividing Power by Area you get: 50X10^3 W / 7.8510^-5 cm^2 = 6.36X10^8W/cm^2… said in plain language as "6 point 36 times ten to the eighth watts per square centimeter…

But is also 636MW/cm^2…. said as "636 Mega Watts per centimeter squared!"

From lowly 5W we end up with a very high-power application with many difficult hurdles, not the least of which is the consideration of the Laser Damage Threshold (LDT) of the materials we are considering.

For the purposes of this memo we will only address the considerations of a Silica fiber itself.

Laser Damage Threshold in Silica:

Where high power laser energy is involved, you have to account for the damage threshold of the optical fiber, in this case Silica. The entire topic of laser damage threshold (LDT) is extremely hard to pin down. It is not that this topic hasn't been researched at length but lasers rarely have nicely uniform, homogenous beam profiles. Thus, the total energy across a spot might be well within the theoretical LDT of the fiber but a spike or "hot spot" might result in localized energy densities far in excess of the allowable LDT.

As a general rule of thumb, the bulk glass of an optical fiber can accept a pulsed laser input (within the wavelength region of 400nm-2000nm) with an energy density of ~1.5GW/cm^2. If the laser is a CW laser within that same wavelength region, the allowable energy density is perhaps ~1.5MW/cm^2. This is a 3 orders of magnitude difference. Why? The mechanisms of damage are different.

First, we note again here, as we noted above, that often energy density for CW lasers is arbitrarily, but more typically, given in area units of mm^2 not cm^2, so, in mm^2 the “allowable” energy density in the fiber, as noted above, would be about 15KW/mm^2.

Why the difference in LDT for CW vs Pulsed Power lasers? For the pulsed laser, the primary damage mechanism will be photonic shock which is related to reaction of the structure of the glass to such high Power Densities in a time frame where the response is delf destructive. For the CW laser, the primary damage mechanism will either be plasma formation on flaws at the fiber facets (faces) or thermal management at the input or output point of the fiber in the assembly.

As with all “rules of thumb,” exceptions exist. But, it should be noted that in most cases, the exceptions will result in a lower LDT – rarely can these guidelines be exceeded. When it seems you may have exceeded these guidelines what you may have actually done is spread the energy out in time by using a pulse dispersive device like a waveguide taper.

This note on LDT addresses the bulk glass, it does not address the difficulty of getting such powers into the glass of the fiber itself which is a topic for another memo and which would include a discussion on the control of spot size, NA and considerations of “end capping” to distribute energy over a larger area for input.