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BLOG ARTICLE

Design challenges of industrial femtosecond lasers – Part 3: Amplification

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In this series of articles, I lay down a few of my thoughts about the constraints influencing the design of femtosecond industrial lasers and parameters I believe should be considered before even starting the design process. I'd like to state that I am not a laser design expert; I spent the last 15 years developing and commercializing components for high-power and ultrafast lasers. The observations I write about come from my own experience and discussions I held with different stakeholders over the course of the last few years. I hope they will lead to interesting discussions and hopefully help a few of you with the design of your lasers.

The amplification chain is the core of an industrial femtosecond laser. Designing the amplification chain is not an easy task and it should be well planned, as the choices made at this stage have a major impact on the other parts of the laser. As we saw in the second article of the series, starting the design process from the output pulse requirements and then proceeding backwards could simplify the design and avoid undesired subsequent iterations. In this article, I discuss the most frequently used amplification technologies and how pulse energy/peak power influence their use in the amplification chain.

Fiber amplifiers

Fibers are known as a robust and cost-effective amplification solution. They allow for a monolithic design, reducing the maintenance and alignment work compared with bulk components. They can also offer high gain per stage, typically in the 20 to 30 dB range. However, their long optical path and confined gain area limit their peak power handling capacity and the available energy per pulse. Indeed, nonlinear effects such as self-phase modulation can create pulse distortions over the propagation length, which degrade the recompressed pulse. These characteristics make fiber a logical choice for the first stages of the amplification chain, where the energy per pulse is still relatively low.

To mitigate this peak power handling constraint, fibers are available with larger mode field diameters (MFD) and increased pump absorption to shorten their optical path. Still, it can be difficult to keep single-mode operation with large MFDs, which is critical for ultrafast lasers. If single-mode operation is not maintained, it can lead to temporal pulse degradation due to modal dispersion. This phenomenon generates multiple pulses that are impossible to filter at the output, as cross-coupling between the modes re-injects some delayed pulses in the fundamental mode. Moreover, increasing the absorption will result in increased thermal load on the fiber, so thermal phenomena, such as transverse mode instability (TMI), need to be considered.

Typically, fibers with moderate MFDs in the range of 10 to 25 µm are used in the second and third stages of the amplification chain.

To increase the peak power handling even further, more advanced geometries are being used, such as tapered gain fibers, photonics crystal fibers (PCF) and fiber rods.

However, there is an obvious drawback to this enhanced performance: the more complex the fiber, the more costly it becomes. Beyond a certain price tag, other options become competitive.

Solid-state amplifiers

At very high energy, solid-state amplifiers such as slabs and disks can become more affordable than advanced fiber geometries. Therefore, solid-state amplifiers shouldn't be dismissed.

Even though choosing hybrid configurations means giving up a monolithic design, solid-state amplifiers can handle significantly more energy than fiber amplifiers before generating nonlinear effects. Because they can handle much more peak power, they reduce the need for long delay stretchers and compressors. The stretcher and compressor pair can then be more compact and cost-effective.

One of the limitations of solid-state amplifiers is that they have a relatively short optical path in comparison with fibers, which leads to a limited gain. Therefore, they can be used as a single-pass booster (3-6 dB gain), or in a multipass arrangement. However, high gain multipass configurations require more components, leading to higher costs.

In the table below, you will find a comparison of the different amplification technologies and some of their pros and cons.

Technology	Typical MFD range	Typical length	Cost	Properties	Peak power handling
LMA	10-25 µm	1-5 m	$	High gain, high average power handling, limited energy handling	+
Tapered gain	25-50 µm	1-4 m	$$	High gain, high average power handling, medium energy handling	++
PCF/Rod	30-70 µm	Less than 1 m	$$$	Medium gain, medium average power handling, high energy handling	+++
Solid-state	Millimeter scale	Hundreds of microns to a few centimeters	$$$	Low gain, high average power handling, high energy handling	++++

The following two examples recap how to choose the amplification stages based on the final pulse requirements. In order to simplify the calculations, we assumed a negligible power loss in the compression stage.

Example 1 – Typical entry-level industrial femtosecond laser

A typical entry-level industrial femtosecond laser with pulses of 20 uj and 250 fs provides a peak power in the range of 80 MW.

To reduce the peak power in the amplification chain, the stretcher/compressor pair will typically stretch the pulse to 500 ps.

The peak power in the power amplifier will reach 40 kW [80 MW * 250 fs / 500 ps = 40 kW].

In this case, all the stages could conceivably be made of fiber. This would also be the most economical amplification chain for this laser.

Example 2 – High-end industrial femtosecond laser

A high-end industrial femtosecond laser with pulses of 100 uj and 200 fs provides a peak power in the range of 500 MW.

Taking into account the stretcher/compressor pair, which typically stretches the pulse to 500 ps, the peak power in the power amplifier will reach 200 kW. Therefore, a few different amplifier combinations could be used.

Considering the level of peak power that will go through the power amplifier, using a solid-state amplifier would allow the use of a more compact stretcher/compressor pair, as a delay of 200-300 ps would be sufficient.

Conversely, in order to use a fiber amplifier, advanced fiber geometries would be required and the stretching duration would need to be increased to ~1 ns. To reach this delay, a less compact, high-end stretcher/compressor pair would be required.

Since more than one technology could be used, other parameters such as laser footprint, amplifier cost and pulse duration would also influence the final choice.

In the next article, I will discuss the impact of pulse duration on the laser architecture. In the meantime, I'd be interested in reading your own thoughts about amplification. How do you choose the technologies to be used in your amplification chain?

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