APP NOTE # 2.0

JULY 16

AMPLIFYING PICOSECOND PULSES USING THE AEROGAIN-ROD-PM85

This paper describes test procedures and typical performance when using the aeroGAIN-RODPM85 for amplifying ps pulses in a single-pass configuration.

Introduction

Enabling single-mode operation in large mode area fiber amplifiers and lasers is critical to ensure diffraction limited beam quality and optimum pointing stability. The aeroGAIN-ROD-PM85 is designed and qualified to amplify signals around 1030-1040nm to average powers of 100W.

Experimental setup

The test involves measurements of: mode field diameter (MFD), polarization extinction ratio (PER), beam quality (M^2), core/clad power ratio, optical efficiency as well as beam and polarization stability. The amplification and diagnostics setups are shown in Figure 1 and Figure 2.

ROD fiber handling

The aeroGAIN-ROD-PM85 is equipped with two 0° AR coated end-caps in order to avoid end facet damage and reflections, and should be handled with great care using gloves and making sure not to touch the end facets. The ROD fiber can also be delivered with one or two angled AR coated end-caps in order to have a further reduction in reflections. Figure 3 shows a picture of an end-capped ROD fiber. In the setup, the aeroGAIN-ROD-PM85 should be supported along the full length during operation to avoid bending induced stress and movement, and carefully secured to the holder without introducing stress, as this can degrade performance of the ROD fiber. Therefore, the ROD fiber is held in an 80cm long water-cooled aluminum holder with a V-groove and subsequently covered with a thin metal sheet for fixation and heat dissipation purposes. Furthermore, cooling of the aeroGAIN-ROD-PM85 fiber may provide better performance as temperature is stabilized.

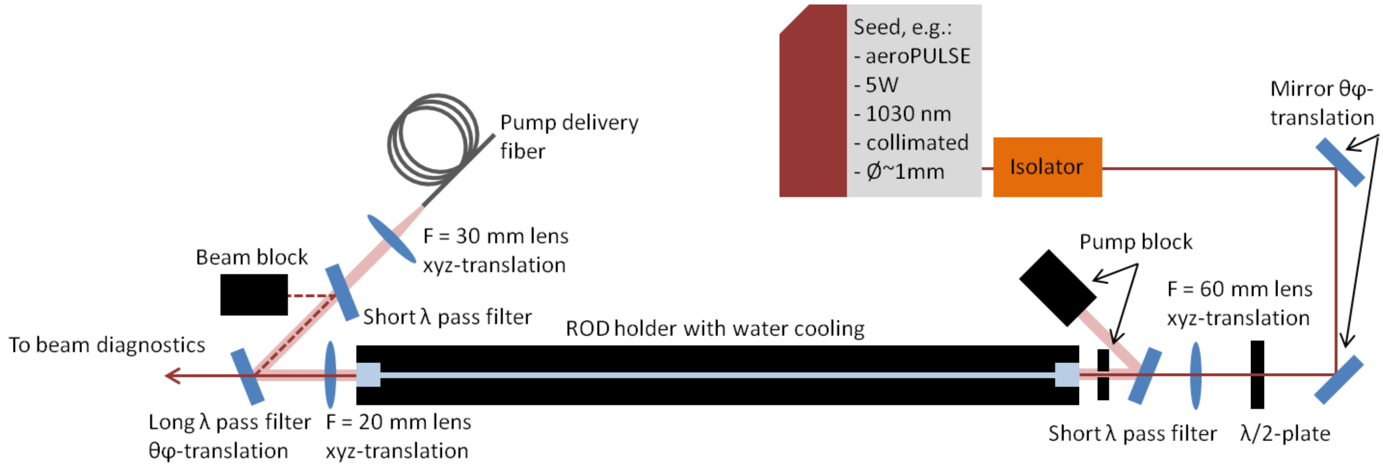

Figure 1: Setup for testing the aeroGAIN-ROD-PM85.

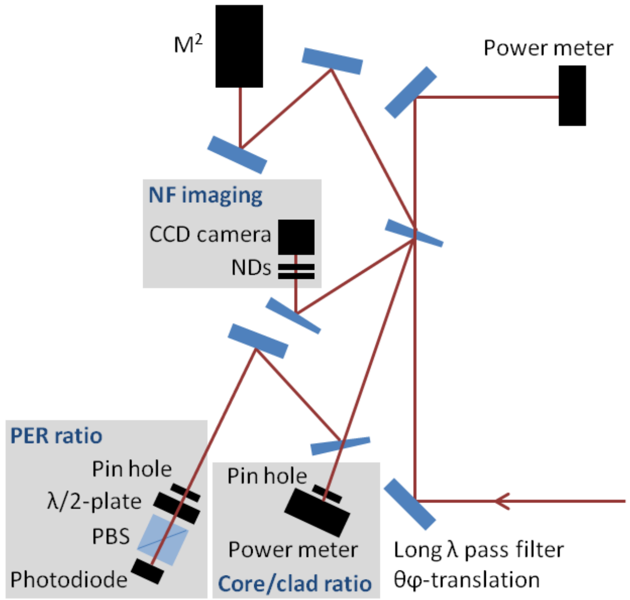

Figure 2: Beam diagnostics for testing the aeroGAIN-ROD-PM85.

Cleaning ROD fiber end facet

The aeroGAIN-ROD-PM85 end facets are clean upon delivery from the manufacturer. However, they may collect impurities when handled, and can be inspected by an optical microscope. Small impurities may be removed by blowing filtered air or Nitrogen on the end facets, or careful cleaning with lens paper wet in isopropyl alcohol. See for instance *cleaning of optical surfaces* in the *Layertec* catalog

(https://www.layertec.de/en/downloads/index).

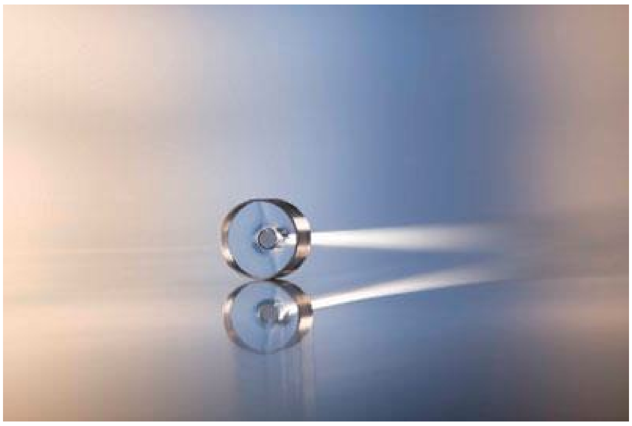

Figure 3: End-capped ROD fiber.

The aeroGAIN-ROD module

The aeroGAIN-ROD fibers can be delivered mounted as aeroGAIN-ROD modules ensuring easy and secure handling as well as easy mounting and coupling. Figure 4 shows a picture of the aeroGAIN-ROD module. This ready to use solution ensures ROD fiber mounting without any stress introduced and protects the ROD fiber from the outer environment. The module has integrated water cooling with quick coupling giving efficient thermal management and long maintenance-free lifetime of thousands of hours. The module can be delivered with a ChromitAL TCP processed surface for industrial use by customer request.

The aeroGAIN-ROD module has been severely tested with respect to climate change, vibration, and drop testing, and is very robust against transport and storage conditions. The module can tolerate large temperature changes from -30°C to 60°C and large vibrations, shock tested up to 1G at frequencies from 30Hz to 500Hz, without affecting the optical properties of the ROD fiber. Even when the module is packed for transportation it has been tested for drops of a few meters also without destroying the module or affecting the ROD fiber's optical properties. For specifications see the aeroGAIN-ROD module datasheet.

Figure 4: Picture of the aeroGAIN-ROD module.

Seeding the ROD

The beam quality of the aeroGAIN-ROD-PM85 is optimized at 1030-1040nm to deliver diffraction limited beam quality. The ROD fiber also has the highest gain in this wavelength region, as shown on Figure 5. The ROD is seeded with an aeroPULSE laser delivering an average power of 5W, an 20MHz repetition rate, a temporal pulse duration of ~20ps and a line width <1nm. The aeroPULSE seed light is linearly polarized and collimated to ~1mm. A *Light Path* gradium matching coupling lens with 60mm focal length (GPX25-60) is used to couple the seed light into the 85µm core aeroGAIN-ROD-PM85 with an approximate 65µm MFD. A *Layertec* short wavelength pass filter (108881) reflects unabsorbed pump to a beam dump. The seed system is protected with an isolator to avoid damage and instability. In addition, the seed system is protected from the counter propagating pump light using a short wavelength pass filter. A λ/2-plate is placed after the isolator to align the polarization into the ROD fiber. It is recommended to operate the ROD fiber with signal input seed having horizontal polarization.

The beam steering mirrors are IR coated and insensitive to polarization in order to preserve the linear polarization out of the isolator. The mirrors provide angular adjustment of the seed beam. All alignment of optical components is done at low signal average output power, in addition the seeds polarization is rotated and optimized at 100W signal average output power to achieve the highest output PER.

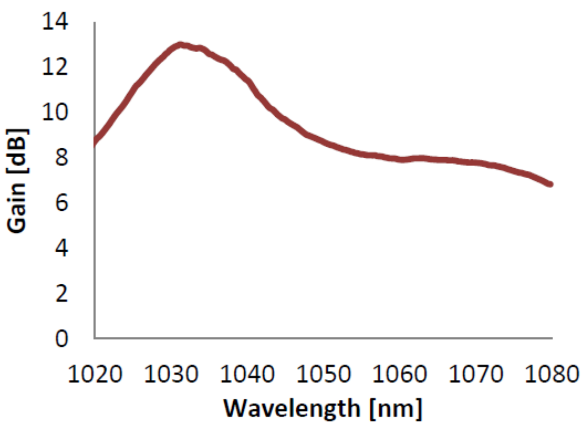

Figure 5: Calculated gain profile for the aeroGAIN-ROD-PM85.

Pumping the ROD

The pump system delivers 976nm pump light out of a 200µm fiber with an NA of 0.22. The pump light is collimated using an *Asphericon* lens with focal length of 30mm (25-30-FPX-S-B) and is coupled into the ROD fiber in a counter propagating configuration using an *Asphericon f* = 20mm lens (25-20-HPX-U-C) together with a *Layertec* long wavelength pass filter (108834). The aeroGAIN-ROD-PM85 has a 260µm pump cladding with ≥0.50 NA.

Power and core/clad ratio setup

The signal light out of the ROD is sampled with a beam sampler and sent to the characterization stage. The core/clad power ratio is determined by measuring all signal light coming out of the fiber with a fully open iris in addition to the core signal light alone, using the equation:

$$R_{core/clad} = 10 \cdot \log \frac{P_{core}}{P_{total} - P_{core}}$$

Near field imaging setup

Near field imaging of the core mode is achieved by inserting a beam sampler (BS) before the power meter and sending a fraction of the light, in this case the reflection from the back side of the beam sampler, towards a CCD camera. The core signal light is attenuated by an appropriate neutral density (ND) filter.

PER ratio setup

The reflection from the front side of the beam sampler is sent towards a PER ratio setup which consists of an iris for collecting the core signal light, a λ/2-plate, a polarizing beam splitter, and a power meter. The λ/2-plate is rotated 180° through maximum and minimum output power and the output power is recorded as a function of rotation angle. The power is fitted to the equation:

$$P = P_0 \cdot cos\left([angle - \alpha] \cdot \frac{\pi}{90}\right)^2 + P_1$$

where P_0, α and P_1 are fitting parameters. The PER ratio is calculated using the equation:

$$PER = 10 \cdot \log \frac{P_0 + P_1}{P_1}$$

Beam quality

The beam quality of the ROD fiber is measured by sampling a fraction of the light to an M^2 setup, the *Spiricon M^2-200s* camera based beam propagation analyzer.

Test conditions

Amplification tests of the ROD fiber are done using a specified set of parameters which are listed below:

Parameter	Value
Seed wavelength	1030nm -1035nm
Seed linewidth	≤1nm
Seed input power	5W ± 0.5W
Seed PER	≥15dB
Seed pulse width	~20ps
Seed repetition rate	20MHz
Pump wavelength	~976nm
Pump power	<250W
Pump NA	≤0.50

The optical performance specifications are described in the aeroGAIN-ROD-PM85 datasheet.

Core/clad power ratio

The core/clad power ratio (CCR) is a measure of the coupling efficiency to the signal core. CCR can be measured without gain with values depending on seed wavelength due to differences in core absorption. Typical values can be ~4dB at 1060nm, ~3dB at 1045nm and ~-1dB at 1030nm in passive operation. In active operation at 1030nm with 100W of signal average output power the CCR will typically be >15dB, see Figure 6. A near field image of the ROD fiber at 1030nm is shown in Figure 7.

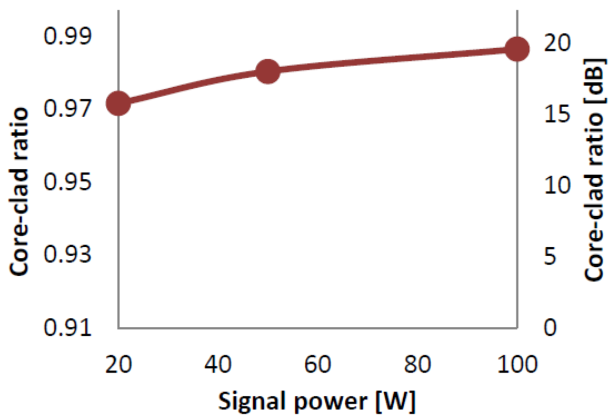

Figure 6: Core-clad ratio with increasing signal average output power.

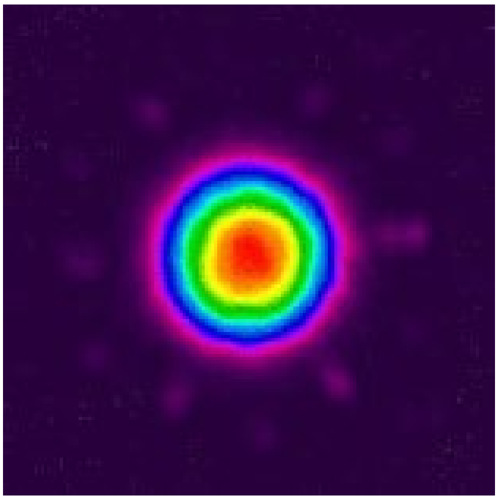

Figure 7: Near field images at 1030 nm without amplification.

The ROD fiber may appear leaky when operated at wavelengths below 1030nm indicated with a lower CCR. For wavelengths above 1030nm the CCR improves with increasing operation wavelength.

For long wavelengths the ROD fiber may appear slightly multimode. The optimal performance is achieved for operating signal wavelengths in the region 1030nm – 1040nm.

Beam quality

The near field is monitored both in passive and active operation. Figure 8 shows the near field of the ROD amplifier at 100W signal average output power. Figure 9 shows the beam quality (M^2) measured with increasing signal average output power as well as the measured astigmatism and asymmetry on the right axes in the figure.

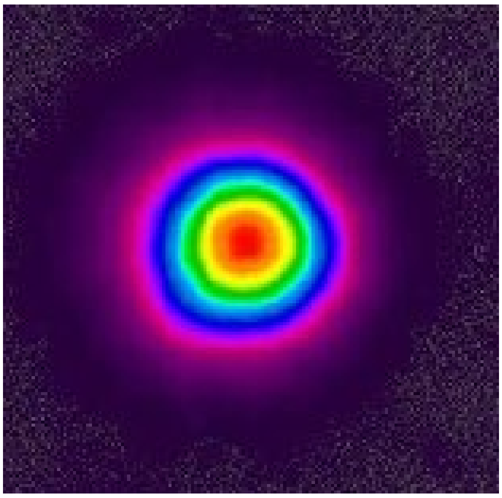

Figure 8: Near field image at 100W signal output power.

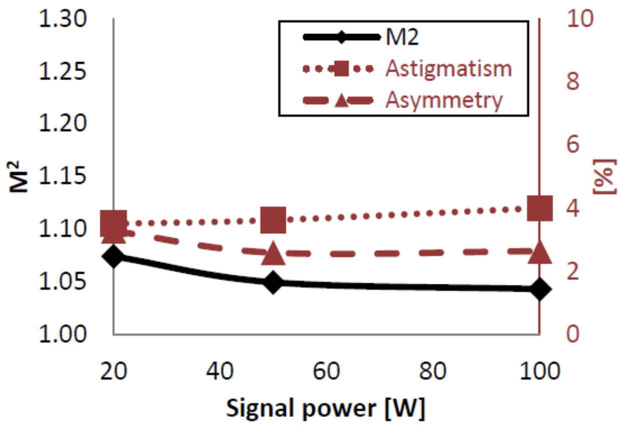

Figure 9. Left axes shows M^2 and right axes shows astigmatism and asymmetry with increasing signal average output power.

Optical efficiency

The optical efficiency is the signal average output power measured as a function of coupled pump light (not absorbed or available pump) using 5W of seed light, shown in Figure 10. The calculated saturation power is ~2-3W, and 5W seed therefore ensures that the ROD fiber is fully saturated. The efficiency of the ROD amplifier increases to >60% as the center wavelength of the pump increases from 970nm at 10W pump power to 976nm at 160W pump power.

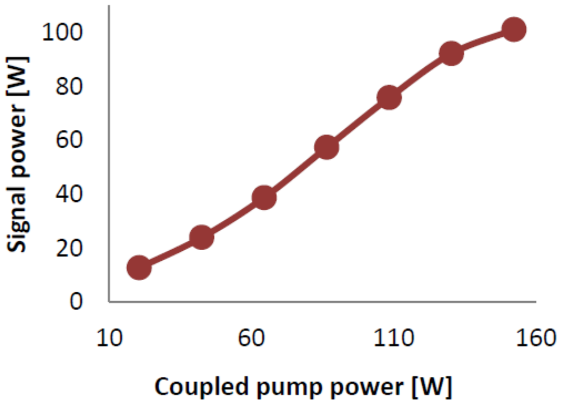

Figure 10: Signal average output power as a function of coupled pump power.

Polarization

The typical PER for the aeroGAIN-ROD-PM85 is above 15dB. Figure 11 shows the PER measurement points and fit after operating the ROD fiber >100 hours at >100W of signal average output power. In this case the PER was measured to 20.8dB. Figure 12 shows the PER with increasing signal average output power. It is recommended to operate the ROD fiber with signal input seed having horizontal polarization.

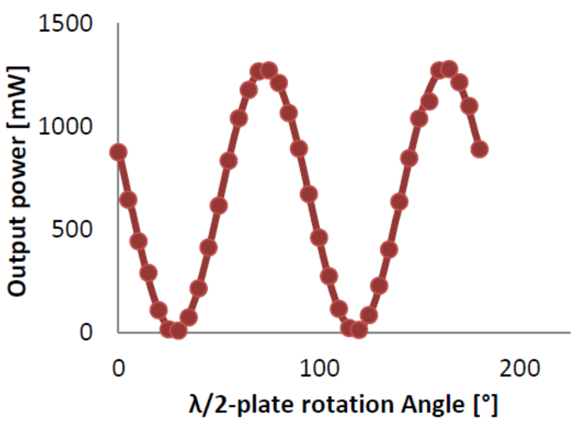

Figure 11: Output power as a function of half-wave plate rotation angle.

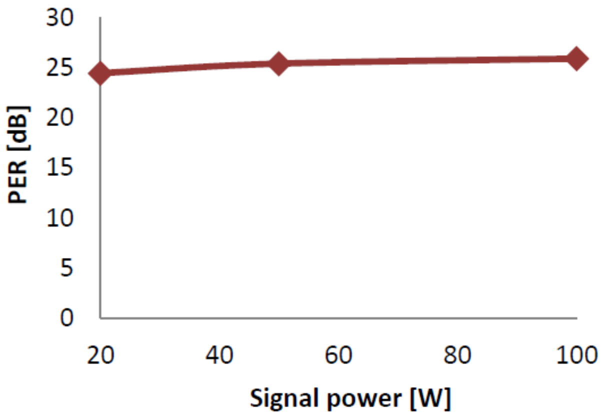

Figure 12: PER with increasing signal average output power.

Stability

The aeroGAIN-ROD-PM85 is designed for robust performance with diffraction limited beam quality using a high NA pump cladding and a low NA core. Figure 13 shows the beam quality (M^2) recorded every 24 hours over 100 hours of testing. The ROD fiber is seeded with 5W signal light and with 150W of coupled pump light and show excellent beam stability with diffraction limited output. Also, the beam quality is resilient against non mode-matched signal seeding such as a too small spot size of the seed. Figure 14 shows the beam quality (M^2) at 100W signal average output power when the seed beam has ~50% smaller mode area than the fundamental mode of the rod, and when the seed beam is mode-matched to the fundamental mode. The figure shows that the aeroGAIN-ROD-PM85 delivers diffraction limited beam quality even with a non mode-matched seed.

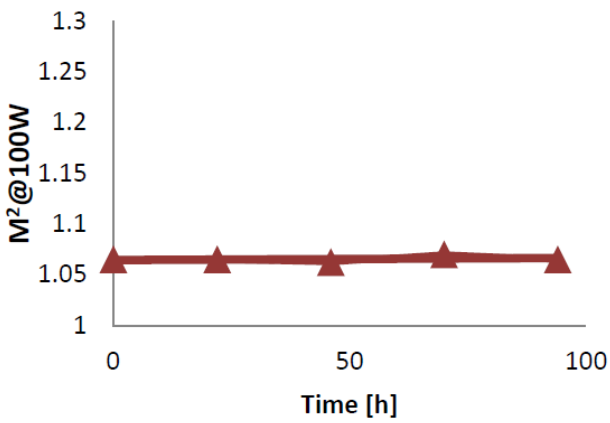

Figure 13: Measured beam quality over a 100 hour burn-in period.

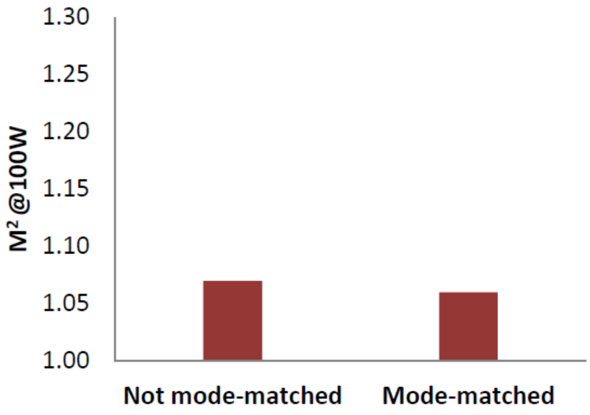

Figure 14: Measured beam quality at 100W output power for non mode-matched seed and mode-matched seed.

High peak power

The aeroGAIN-ROD-PM85 may be operated at high peak power. The ROD fiber is seeded with 5W signal light and operated at 1MW peak power and 57W average power for 90h. The beam profile stays stable during testing with a PER >15dB, see a measured near field image in Figure 15. Figure 16 shows the measured signal average output power over 90h of testing.

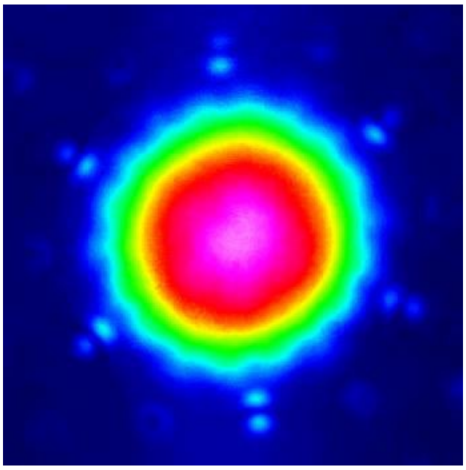

Figure 15: Measured near field image.

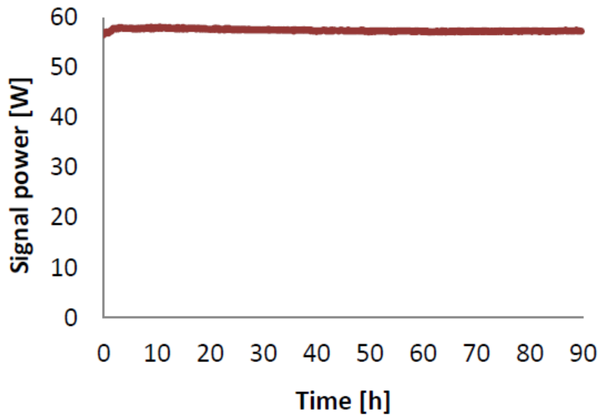

Figure 16: Measured signal average output power over 90 hours testing at 1MW peak power.

Reliability

In order to ensure reliable performance, the aeroGAIN-ROD-PM85 is tested at >100W signal average output power seeded with 5W signal light. Figure 17 shows the signal average output power over 2000 hours of testing after a 24 hour burn-in period.

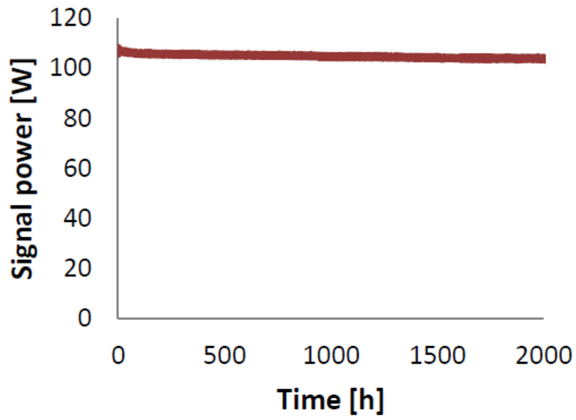

Figure 17: Measured signal average output power over 2000 hours testing.

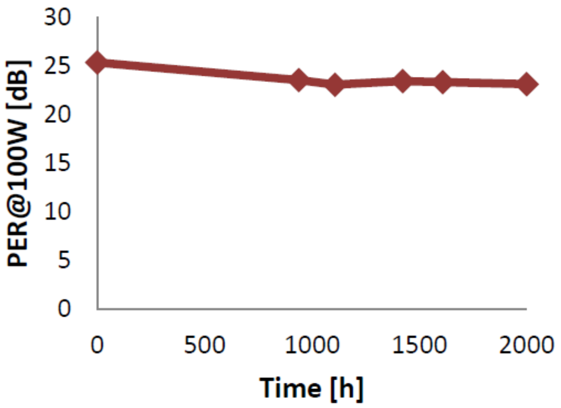

Figure 18: Measured PER over 2000 hours of testing.

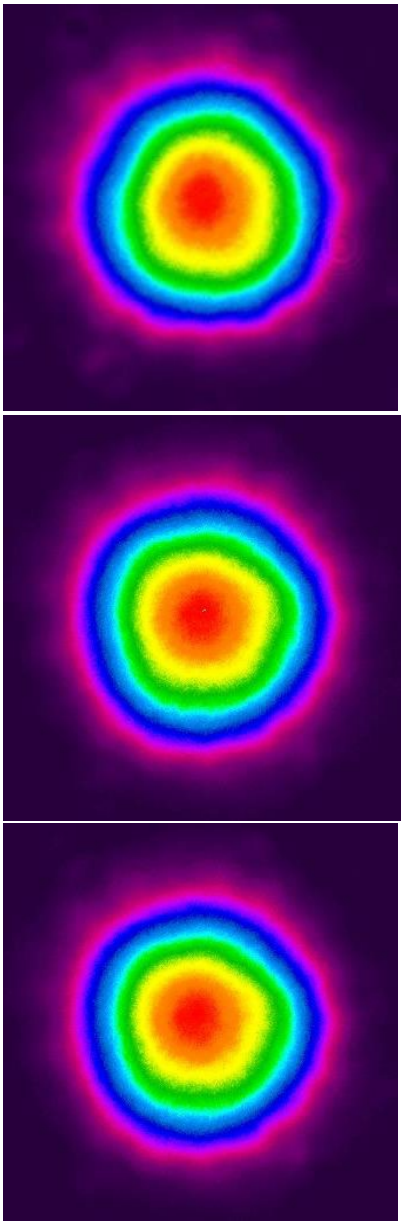

Figure 19: Measured near field at the beginning of testing, after 1000 hours and after 2000 hours of testing.

After 100 hours the slope and drop in signal average output power is <-1W per 1000 hours showing excellent stability with very low degradation. Figure 18 shows the measured PER over 2000 hours of testing, all values above 23 dB.

Safety

It is important to use the necessary laser safety equipment when operating the aeroGAIN-RODPM85 and the equipment associated with testing. Also, an interlock should be installed, that can monitor the signal average output power and shut down the pump and seed laser on a ms time level, if any irregularities are observed.

Summary

This whitepaper describes the test procedures and the typical performance of the aeroGAIN-ROD-PM85 for amplification of ps pulses. The aeroGAIN-ROD-PM85 is optimized for 1030- 1040nm signal amplification and delivers 100W signal power with >15dB PER and >15dB CCR, resulting in >93% useable polarized core power with diffraction limited beam quality. The beam quality is robust and the optical conversion efficiency is >60%.

MORE ABOUT AEROGAIN-ROD

The aeroGAIN-ROD module is the ultimate high-power fiber amplification module for ultrafast pulsed lasers. With its 3300 µm^2 mode field area and high pump absorption, it gives you a power handling previously only available in solid-state configurations. The rugged aluminum body makes the module easy to handle and mount for OEM integration and scientific laboratory setups.

Key features:

- Diffraction-limited beam quality
- High NA pump cladding
- High peak power damage threshold
- Optimized for 1030-1040 nm range
- Compact format
- PM and non-PM amplification