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*Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,*

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# A mature 100-W 1178-nm single-frequency linearly-polarized Raman fiber amplifier for laser guide star assisted optical ground station adaptive optics systems

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## ABSTRACT

While the next generation of satellite constellations provide improved capacity through the use of optical inter-satellite links, there is still a capacity bottleneck at the RF feeder links between satellites and ground stations, which are an order of magnitude slower in moving data. In order to move to all optical feeder links, there is a challenge to overcome the distortion associated with atmospheric turbulence. Laser Guide Star (LGS) adaptive optics systems are a key enabling technology to help solve this beam wander problem for ground to space optical systems. For guide star lasers suitable for daytime LGS operation, high power is key. To respond to this need, a 100-W continuous-wave (CW) 1178-nm narrow-band polarization-maintaining (PM) Raman fiber amplifier (RFA) has been developed and fully engineered. A linearly-polarized single-frequency 1178-nm seed laser with an output power of only a few mW is amplified up to 100 W in a two-stage RFA counter-pumped by a 200-W 1120-nm PM fiber laser. Techniques for efficient suppression of stimulated Brillouin scattering (SBS) have been optimized, resulting in the RFA SBS threshold being pushed beyond the 100-W level. The narrow linewidth of the seed laser is well preserved in the RFA, without any evidence of linewidth broadening up to 100 W. The RFA is based on true single-mode PM fibers and has excellent polarization purity and output beam quality, key factors for subsequent efficient frequency doubling to the Na absorption line at 589 nm in a resonant frequency-doubling cavity. Similar to the widely-deployed MPBC/TOPTICA *SodiumStar 20/2*, the new 100-W RFA system is a compact, modular, reliable and ruggedized off-the-shelf system ready for integration. Compared to solid-state alternatives, a guide star laser based on an all-fiber, highly-reliable, 100-W RFA not only provides excellent overall wall-plug efficiency due to its high pump-to-Raman optical conversion efficiency, but also maximizes the important “up time” for the optical channel at ground station facilities since it is a maintenance-free and turn-key system. To confirm the stability and reliability of this next-generation guide star RFA, the system was run 24/7 at the full 100 W for a total of 1300 hours. The test results confirmed that the 100-W RFA system is extremely robust and reliable, with a sufficient built-in 1120-nm pump power margin. Re-measurements of key RFA parameters, such as polarization purity and output beam quality, also confirmed that the RFA performance remained unchanged after the 1300-hour 100-W test. Assuming a conservative conversion efficiency of ~ 80% by a resonant frequency doubler and taking into account typical passive coupling losses into the doubler cavity of < 15%, narrow-linewidth CW guide star lasers with powers > 70 W at 589 nm can confidently be expected for future optical ground station adaptive optics systems.

The RFA output power was shown to be solely limited by the SBS threshold. Since all the laser components showed sufficient higher optical power handling potential, it is expected that, with further optimization of the SBS suppression, the RFA output power can be scaled significantly beyond the current 100-W level.

**Keywords:** Raman fiber amplifier, fiber lasers, laser guide star, adaptive optics, next generation telescope, optical ground station, free-space optical communication, optical feeder link

## 1. INTRODUCTION

Laser guide star adaptive optics (LGS-AO) to compensate for signal wavefront distortions induced by atmospheric turbulence has been adopted routinely as a key technology for ground-based large-aperture optical telescopes [1]. Particularly in recent years, initialized by an internal research program of the European Southern Observatory (ESO) to investigate the feasibility of an RFA-based guide star laser [2-8], then in the frame of a contract with ESO and the W. M. Keck Observatory (WMKO), TOPTICA Photonics and MPB Communications have collaboratively developed and fully engineered a fiber-based, compact, turn-key, modular, maintenance-free and ruggedized guide star laser - *SodiumStar 20/2*. *SodiumStar 20/2* lasers have been deployed and used routinely by all major ground-based VIS/IR astronomical telescopes and have become the new standard for guide star lasers for next-generation telescopes [9-10]. Compared to conventional solid-state alternatives, the new generation of fiber-based *SodiumStar 20/2* guide star lasers not only provides an exceptional beam quality and excellent overall wall-plug efficiency, but also maximizes the important observation time for the astronomical community.

In recent years, free-space optical communications have attracted particular interest, instead of RF communications, for the next generation of low earth orbit (LEO) and geostationary orbit (GEO) satellite constellations through the use of optical inter-satellite links with the advantages of very large bandwidth, small mass and volume, low power consumption, no frequency license requirements and immunity against jamming or eavesdropping. Since the world-first inter-satellite laser communication link experiment was demonstrated successfully by the European Space Agency (ESA) in 2001 [11], inter-satellite optical links have been proven to be a viable alternative to conventional RF solutions in response to a growing demand for high-data-rate communications between satellites. After years of development, thousands of inter-satellite optical links have been deployed commercially and are turning global LEO satellite constellations into a meshed network in space to act as a backhaul infrastructure to connect rural areas especially [12-16].

However, there is still a capacity bottleneck imposed by the current RF feeder links between satellites and ground stations. Optical feeder links (OFLs) have emerged as a key technology for moving huge amounts of data bidirectionally between earth-based ground stations and satellites. Despite its great potential, in contrast to inter-satellite optical links, OFL poses additional challenges due to the atmospheric turbulence which results in multiple distortions in the light propagation as it travels through the atmosphere for both the uplink and the downlink [17-23]. To date, typical AO systems implemented at optical ground stations to estimate and compensate the detrimental effects, especially phase distortions, of the atmosphere, use either an available natural guide star or the satellite downlink signal source as a reference beacon. Unfortunately, a sufficiently bright natural guide star is not always present in the particular sky area of interest and, due to the satellite motion, especially for the LEO satellites, the uplink beam has to go through a slightly different patch of atmosphere than the downlink satellite signal reference beam, resulting in the so-called “point-ahead angle” (PAA) problem.  In contrast to astronomical telescope sites, optical ground stations are usually built at diverse low altitude locations with higher turbulence conditions and require 24/7 operation. In addition, in the case of typical LEO satellites, for 90 percent of the line-of-sight time, the viewing angle corresponds to an elevation angle below 30°, implying very long link paths through extremely turbulent layers of the atmosphere resulting in strong phase distortions and intensity fluctuations, especially in the late morning and afternoon hours. Furthermore, the fast transverse movement of the OFL through the atmosphere due to the fast LEO satellite motion causes even worse intensity and phase fluctuations of the optical communication links.

To cope with such extreme turbulent conditions and daytime operation, LGS-AO has been proposed with extra requirements to solve the point ahead problem and achieve highly-reliable high-data-rate ground-satellite optical communications [22-23]. Similar to LGS at astronomical observatories, by illuminating the natural atomic sodium layer in the mesosphere at an altitude of 80 – 100 km using a narrowband 589-nm laser source, an artificial “star” can be produced at the desired sky location as a useful alternative to a natural guide star where none exists at that sky location. In this way, the sky coverage of AO-assisted optical ground stations can be significantly increased by using sodium LGS with superior performance compared to the current ground station AO systems which use the satellite downlink signal source itself as a reference beacon.

Among those extra requirements, high power is crucial for the suitable guide star lasers to improve the spatial and spectral resolutions of the AO correction. To respond to this demand, a 100-W CW 1178-nm narrowband PM RFA, similar to the standard 36-W RFA for *SodiumStar 20/2*, has been developed for creating much brighter guide stars by pushing the RFA SBS threshold beyond the 100-W level, demonstrating that fiber-based guide star lasers are fully capable of providing the required higher powers suitable for space-ground optical communication applications [24]. In this paper, we report a 100-W RFA system which has been fully engineered with a significant improvement of thermal management and a sufficient built-in 1120-nm pump power margin. To prove the stability and reliability of this next-generation high-power guide star RFA, the entire RFA system was run 24/7 at the full 100 W for a total of 1300 hours. Test results confirmed that a compact, modular, highly-reliable and ruggedized off-the-shelf 100-W guide star laser is mature and ready for integration for future optical ground station LGS-AO systems. Characterization of the 100-W RFA before and after the 1300-hour 100-W test confirmed that the polarization and the narrow-linewidth of the seed laser were well preserved with excellent diffraction-limited beam quality for subsequent efficient resonant frequency conversion. Assuming a conservative 80% conversion efficiency by a resonant frequency doubler and taking into account typical passive coupling losses into the doubler cavity of <15%, narrow-linewidth CW guide star lasers with powers > 70 W at 589 nm can confidently be expected and have been experimentally demonstrated and proven by ESO recently [23].

## 2. 100-W RFA SYSTEM DESIGN AND ENGINEERING

The new 100-W RFA system includes a 200-W 1120-nm PM pump fiber laser, a 100-W 1178-nm narrow-band PM RFA and a 28-VDC fiber laser power supply. The 200-W pump laser has the same architecture [25] as the 100-W MPBC pump laser which has compiled such an enviable reputation for reliability in the *SodiumStar 20/2*. As shown in Figure 1, it consists of two Yb-doped double-clad PM fiber lasers with emission wavelengths at 1064 nm and 1120 nm, respectively. In each of the Yb fiber lasers, Yb-doped double-clad PM fiber is cladding-pumped by two 915-nm multimode laser diodes (LDs). Each multimode pump LD has a nominal drive current of 12 A, although the required 200 W of 1120-nm power from the fiber laser is obtained with LD drive currents of only 8 A; therefore, a substantial reserve of multimode pump power is available for each Yb fiber laser.

The 1064-nm and 1120-nm laser output powers are combined via a PM fused-fiber 1064/1120 WDM and launched into a Raman fiber converter where the majority of the 1064-nm power is converted to co-propagating 1120-nm power via stimulated Raman scattering. The Raman fiber converter is a length of specialty single-mode PM silica fiber which provides sufficient Raman gain for efficient conversion of the optical power at 1064 nm to 1120 nm.

At the output of the Raman fiber converter, a PM 1120/1178 WDM is added in order to remove both the residual, unconverted 1064-nm power and the 1178-nm Raman ASE (resulting from the Raman gain produced by the 1120-nm power propagating in the converter) from the useful 1120-nm power. As shown in Figure 2(a), 200 W of 1120-nm output power is obtained after the 1120/1178 clean-up WDM with only 8 A of drive current required for the pump LDs in each of the two fiber lasers. To confirm the power scaling capacity of our 1120-nm pump laser design, the individual 1120-nm laser cavity has been tested with its pump LD currents up to 12 A. As shown in Figure 2(b), the 1120-nm output power from the individual 1120-nm Yb laser cavity reaches 200 W at 12 A pump LD currents, proving a substantial 1120-nm pump laser power is available for achieving greater than 100-W RFA output powers if the SBS threshold is pushed further beyond the 100-W level by further optimizing the SBS suppression techniques in the future.

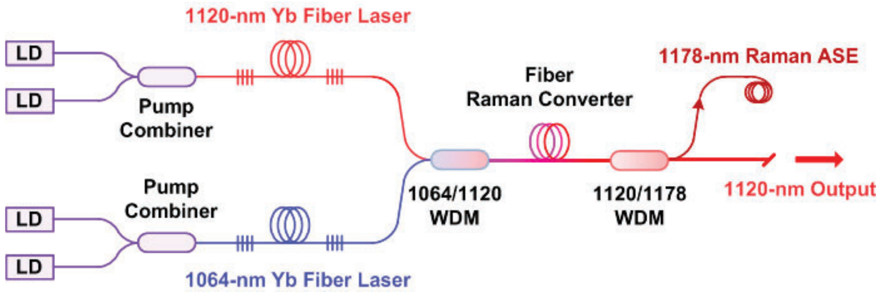

Figure 1. Architecture of the 200-W 1120-nm PM pump fiber laser.

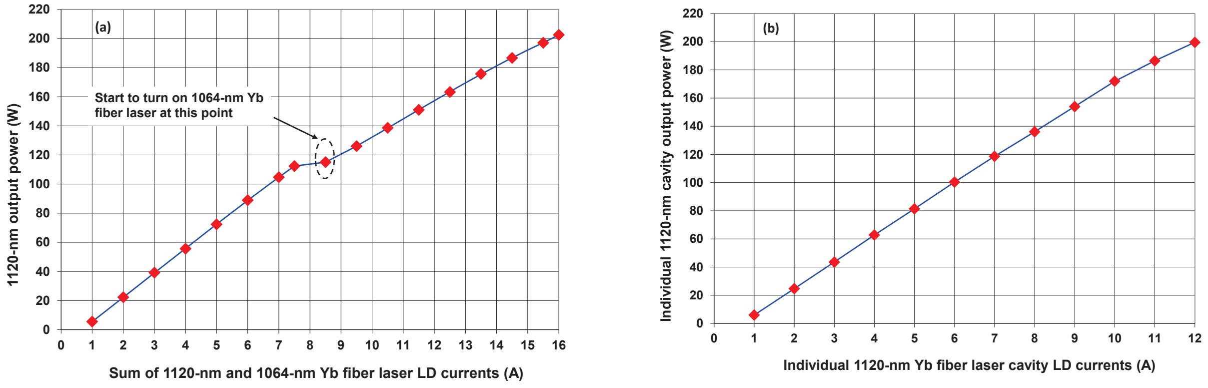

Figure 2. (a) Final 1120-nm output power versus the sum of the 1120-nm and 1064-nm Yb fiber laser pump LD currents, and (b) output power of the individual 1120-nm fiber laser cavity versus its pump LD currents.

A two-stage counter-pumping master oscillator power amplifier (MOPA) configuration is used in the 100-W 1178-nm narrow-band PM RFA, as shown in Figure 3. All fibers, including the optical component pigtails and Raman gain fibers, are true single-mode PM fibers. A narrow-band 15-mW polarized 1178-nm external cavity diode laser is amplified first in the pre-amplifier stage and then enters the booster stage for further power amplification. Optical isolators are used to isolate the seed laser, pre-amplifier and booster amplifier stages. A PM 1178-nm fused-fiber tap coupler is included to allow measurement and continuous monitoring of the backward SBS signal power from the booster stage. The RFA is pumped by the above 200-W 1120-nm PM pump fiber laser, which is spliced to the final 1120/1178 PM fused-fiber WDM to counter-pump the booster amplifier. The 1120-nm pump power used to counter-pump the pre-amplifier stage is a portion of the left-over un-converted 1120-nm pump power from the booster stage, thus increasing the overall RFA optical power conversion efficiency and simplifying the RFA configuration.

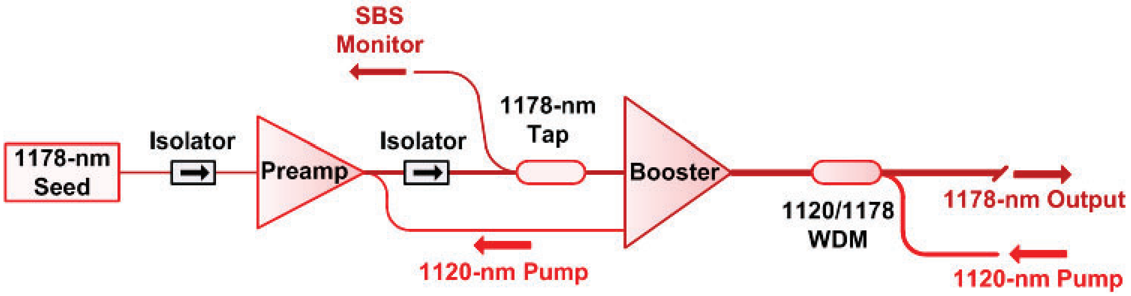

Figure 3. 100-W 1178-nm narrow-band PM RFA configuration.

The 1178-nm seed laser diode has a very narrow linewidth of only a few MHz (typically < 2 MHz). Therefore, efficiently suppressing SBS in the booster amplifier is crucial and is one of the main technical challenges to narrow-band RFA power scaling. In this RFA design, the SBS suppression method is essentially based on ESO's patented technology [26][1] of applying a distributed strain pattern longitudinally along the Raman gain fiber in order to shift and distribute the individual SBS contribution from each fiber segment over a wider SBS gain spectral bandwidth. In this way, the individual SBS contributions of the fiber segments will avoid adding up constructively and the overall SBS threshold of the RFA will be pushed up, allowing higher RFA output powers to be achieved.

For the sake of convenience, the SBS threshold is defined here as the RFA output power at which the backward SBS power reaches 1% of the RFA output power. As shown in Figure 4, the SBS threshold of the 100-W RFA is beyond a 100-W level.

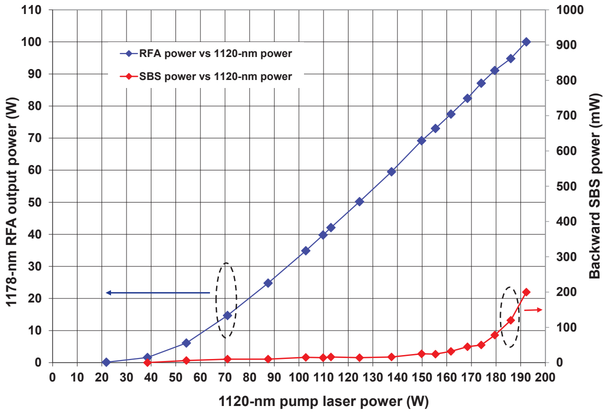

Figure 4. Backward SBS power and RFA output power as a function of 1120-nm pump laser power.

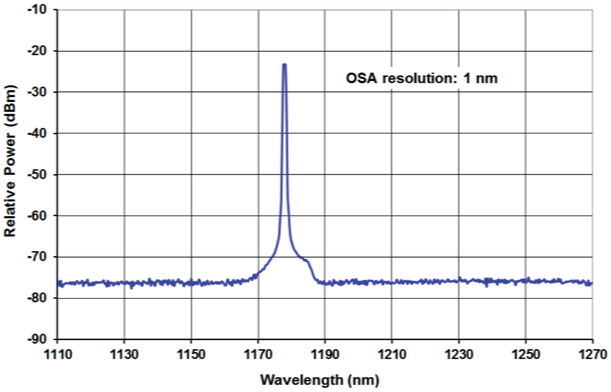

Figure 5. 1178-nm RFA output spectrum at 100-W output power.

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[1] MPB Communications Inc. is a Licensee of the ESO Fiber Raman Amplifier Technology developed and transferred by ESO (www.eso.org)

Characterization of the 100-W RFA up to its maximum output power shows that the RFA faithfully preserves the seed laser's narrow linewidth and provides an output with a PER >20 dB and an exceptional diffraction-limited beam quality, ensuring its efficient frequency conversion to 589 nm in a subsequent resonant frequency doubler. RFA output spectra were measured up to 100 W with an optical spectrum analyzer to confirm the spectral purity of the final 1178-nm RFA output. Figure 5 shows the output spectrum at an RFA output power of 100 W. It is important to note that there is no detectable 1120-nm power due to Rayleigh scattering of the pump, nor any measurable power at ~1240 nm which would have indicated power migration from 1178 nm to the next Raman Stokes. This latter finding also confirms that this 100-W RFA is still SBS-limited and scalable in output power.

The 200-W 1120-nm pump fiber laser has been fully engineered and integrated into the same MPBC mechanical package as the standard 100-W 1120-nm fiber laser pump module (FLPM) of the *SodiumStar 20/2*. Its 28-V DC fiber laser power supply (FLPS), capable of providing the nominal 12-A pump laser diode current and therefore ensuring a solid pump power margin for the 200-W FLPM, has the same enclosure as the MPBC FLPS of the *SodiumStar 20/2*. The 100-W RFA has also been fully engineered and integrated into an almost identical mechanical package as the MPBC 36-W RFA of the *SodiumStar 20/2*. The two RFA enclosures are shown in Figure 6 for comparison. Despite some minor internal engineering modifications to adapt to this higher power design, the footprint of this 100-W RFA remains exactly the same, while the overall height is even smaller than that of the standard 36-W RFA. This compact 100-W RFA design facilitates integration into a Laserhead enclosure very similar to that of the *SodiumStar 20/2* laser for LGS-AO applications.

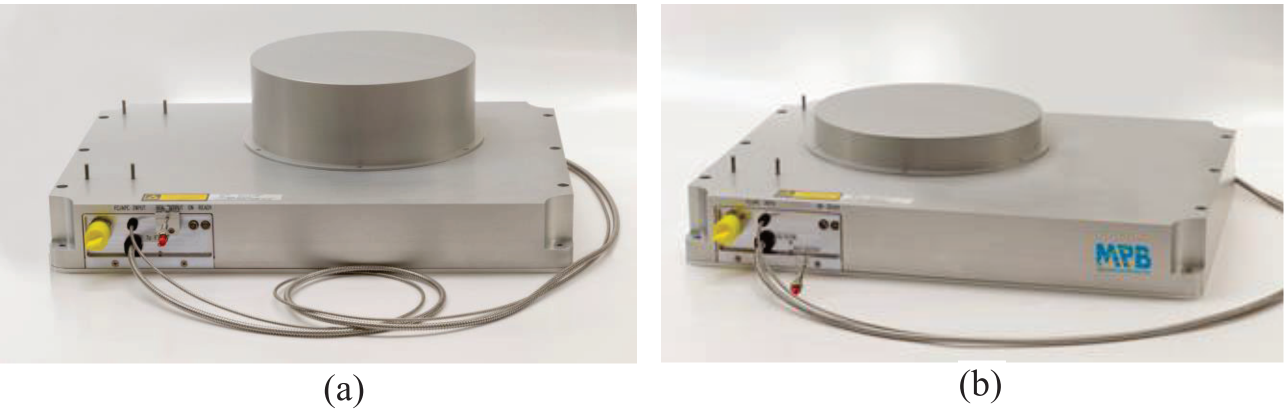
(a) (b)

Figure 6. Mechanical enclosure design of (a) 36-W standard RFA (RFA-P-36-1178), and (b) 100-W RFA (RFA-P-100-1178).

## 3. 100-W RFA LONG-TERM RELIABILITY TESTS

To confirm its long-term stability and reliability, the entire 100-W RFA system, including a 200-W FLPM, a 100-W RFA, a 28-VDC FLPS and an 1178-nm narrow-band PM seed laser, was set up in lab conditions and run 24/7 at 100 W output power in automatic power control (APC) mode for a total of 1300 hours, as shown in Figure 7. The system was water-cooled with a portable re-circulating chiller set at 13 °C with a flow rate of 4 l/min.

To protect the RFA output pigtail end face from dust particles present in a lab environment, the RFA was housed inside a plexiglass enclosure as shown in Figure 7. The RFA output power was continuously monitored and measured by a Thorlabs thermal power meter. A specially designed laser protection software was used to monitor and record all critical system parameters, and to ensure shut down the RFA system if any abnormal behavior of the system was detected.

A Toptica narrowband 1178-nm seed laser provided an input signal power of 16 mW to the 100-W RFA. The RFA was set at the nominal 100 W output power in APC mode. The 1120-nm laser of the 200-W FLPM was initially set at 127 W in APC mode, and re-adjusted to 130 W in order to re-balance the individual 1120-nm and 1064-nm laser powers/currents after the first 150-hour of the stability test. The 1064-nm power/current is automatically adjusted/controlled by the system firmware in order to maintain a constant RFA output power of 100 W.

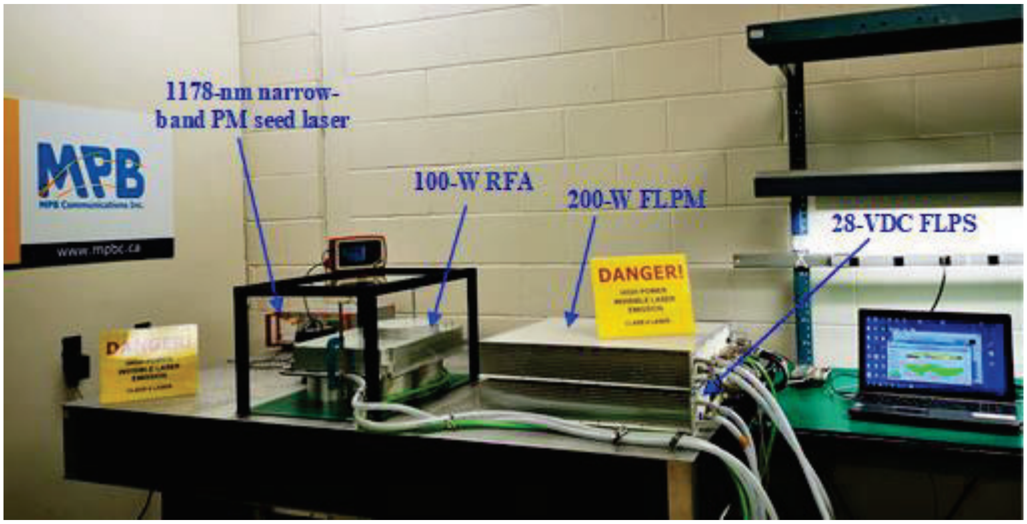

Figure 7. 100-W RFA system long-term reliability test setup.

Figure 8 shows the RFA internally monitored output power and externally measured output power, along with the internally monitored backward SBS power. Assuming the SBS threshold is 1 W (i.e. 1% of the forward 100 W RFA output power), SBS powers were well below the SBS threshold for the entire 1300-hour testing period.

It is worth noting that a power deviation of ~0.5% developed between the internal and external RFA power readings starting from about the 300-hour point. The root cause is not clear at the moment. One explanation might be that the external thermal power meter reading drifts slightly along with the ambient room temperature (the testing period coincided with the approaching winter season here in Montreal). Another explanation could be that the internal non-invasive PD reading drifted slightly for some reason, i.e. the drift resulted in the internal non-invasive PD registering an increasing RFA power, therefore the firmware automatically adjusted the Laser B power downward to maintain the internally measured RFA power at a stable 100 W.

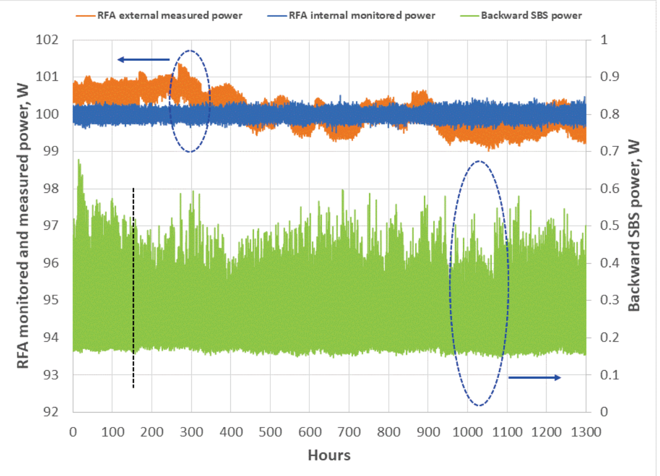

Figure 8. RFA internal monitored power, external measured output power and backward SBS power.

In Figure 9, the RFA internally monitored power is plotted along with the monitored FLPM emission power (measured by an invasive PD at the FLPM output) and the FLPM delivered power monitored at the RFA side (also by an invasive

PD). It shows that, during the first 150 hours, the required FLPM emission and delivered powers were slightly increasing in order to maintain a constant RFA output power of 100 W. This suggests that some components in the RFA were undergoing a burn-in phase.

The gentle increase of the FLPM emission/delivered powers is also confirmed by an increase in the value of the summation of the 1120-nm and 1064-nm laser pump currents during this 150-hour period, as shown in Figure 10. However, this increase in the summation of the pump currents is larger than would be required to produce the small increase in FLPM output power. This suggests that part of the current increase was due to the 1120-nm and 1064-nm lasers undergoing a burn-in evolution. There are various factors which could contribute to the initial slight degradation of the Yb lasers. First of all, high-doping-concentration Yb fibers, such as in both 1120-nm and 1064-nm laser cavities, often experience an initial degradation due to a photodarkening effect. The photodarkening-induced degradation rate of laser power is the highest in the beginning, but becomes slower and slower with continuous operation of a laser. Other causes, such as optical component burn-in degradation, might be also expected.

However, after the initial 150-hour burn-in period, the entire 100 W RFA system becomes very stable with only a very slight increasing of the summation of the 1120-nm and 1064-nm laser pump currents.

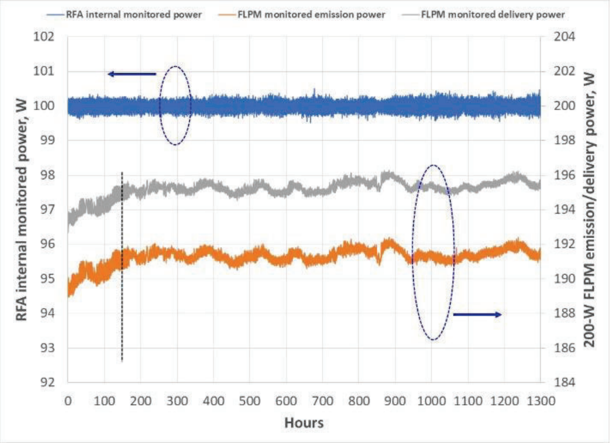

Figure 9. RFA internal monitored power, FLPM emission and FLPM delivered powers.

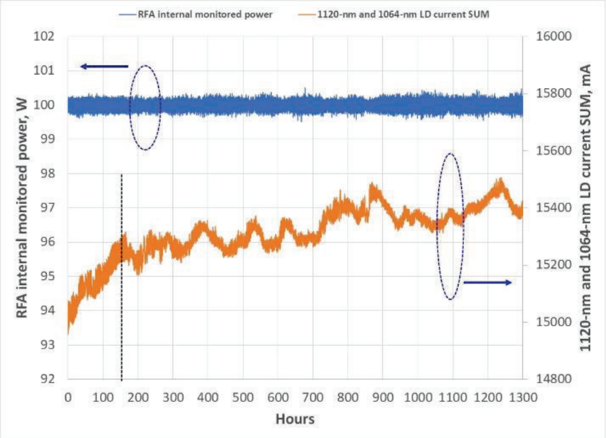

Figure 10. RFA internal monitored power and the summation of 1120-nm and 1064-nm laser currents.

## 4. SUMMARY AND DISCUSSION

A compact, modular, highly-reliable and ruggedized off-the-shelf 100-W 1178-nm RFA for guide star lasers has been designed, fully engineered and ready for integration for future optical ground station LGS-AO systems which require 589-nm powers > 70 W to create a brighter sodium guide star in order to overcome the highly turbulent atmospheric conditions with 24/7 operation of OFL wideband communications. To obtain 100 W of RFA output power, the 200-W FLPM is operating at ~192 W of 1120-nm pump power with less than 8 A of pump LD drive current for both the 1064-nm and 1120-nm Yb fiber lasers, which represents a current margin of at least 34% relative to the 12-A nominal LD operating drive current specified by the LD manufacturer. To ensure system reliability, the Yb-doped 1120-nm and 1064-nm fiber laser cavities have been optimized for better pump-to-laser conversion efficiencies. Meanwhile, the critical optical components in both the FLPM and the RFA have also been specially re-designed for handling such high powers in this next-generation 100-W RFA. The thermal management of the active Yb fibers and all critical optical components has been enhanced for more efficient thermal dissipation and heat removal by a coolant chiller. Thermal images taken by a FLIR thermal camera reveal that the temperatures of the fibers and optical components are well within the safe operating temperature range for long-term reliable operation of the entire RFA system, and this has been proven by the 1300-hour test.

The current 100 W is not the power limit of such a narrow-band 1178-nm PM RFA. One avenue to pursue for scaling the RFA output power is to further optimize the SBS suppression of the booster amplifier stage with either more suitable Raman gain fibers or improved strain pattern designs. From the standpoint of the optical components, the current test measurements confirm that the optical components have further optical power handling potential and are therefore not an impediment to achieving RFA output powers higher than 100 W. In addition, the two Yb lasers that provide the 1120-nm pump power for the RFA clearly have ample margin to increase the pump power delivered to the RFA.

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