

All-in-Quartz Optics for Low Focal Shifts

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ABSTRACT

High laser power levels in combination with increasing beam quality bring optics performance into focus, particularly with regard to systems with low focal shifts along the optical axis. In industrial applications, this often influences the overall performance of the process, especially if the focal shift is comparable to or in excess of the Rayleigh length. It is commonly accepted that the focal shifts are of thermal nature where lens material, lens coating, geometry and surface contamination all contribute to the direction and extent of the focal shifts. In this paper we will present a novel design of lens packages where a patented all-in-quartz concept is explored. By mounting quartz lenses in hermetically sealed quartz tubes and applying water cooling on the perimeter of the quartz tubes we will reduce or eliminate a number of contributing factors to focal shift problems. The hermetic sealing, carried out in a clean-room environment, will minimize lens surface contamination. Differences in thermal expansion between lens and housing are eliminated as the lens and housing will be of the same material. Absorption of scattered laser light will be efficient as the energy is removed quickly by cooling water and not absorbed by fixed surroundings. Finally, indirect heating from the housing transmitted by radiation and convection to the lenses is avoided. Values of the normalized System Focal Shift Factors (SFSF) for the all-in-quartz optics will be compared to standard lens assemblies at multi-kW laser power levels.

Keywords: high power lasers, focal shift, thermal lensing, all-in-quartz optics, SFSF

1 INTRODUCTION

The development of multi-kW high power continuous wave (cw) lasers with high brilliance, e.g. fiber and disc lasers, have brought the performance of external optics in focus. With the improved beam quality, low focal shift along the optical axis is becoming a crucial performance parameter. In industrial applications, such as cutting and welding, focal shifts influence the overall performance of the process, especially if it is comparable to or in excess of the Rayleigh length of the laser beam.

It is commonly accepted that focal shifts of external optics are of thermal nature, where lens material, lens geometry, surface coatings and contaminations all contribute to the direction and extent of the focal shifts. In this paper we present a patented novel design of lens packaging, where an all-in-quartz approach is explored. By mounting the fused silica collimating lenses and focusing lenses in hermetically sealed fused quartz tubes and applying water cooling on the perimeter of the quartz tubes, several of the contributing factors to focal shifts will be reduced or eliminated. Making the lens assembly in a clean-room environment and hermetically seal the optical package in the clean room will minimize lens surface contamination and protect the lenses from degradation. Differences in thermal expansion between lenses and inner housing are effectively eliminated since housing and lenses are made of the same material. Thus there will be no relative position change between individual lens elements, which could contribute to focal shifts. Absorption of scattered light and heat radiation is expected to be efficient since the energy is efficiently removed by the cooling water, which is in direct contact with the outer perimeter of the quartz tube. Finally, since there are no mechanical parts in contact with or air-spaced from the lenses, indirect heating from the outer housing transmitted by radiation or convection is avoided.

The patented all-in-quartz design of the new external optics module is presented in Sec. 2. Definitions and nomenclature for focal shifts including the normalized System Focal Shift Factor (SFSF) is summarized in Sec. 3. The experimental method used is presented in Sec. 4. Finally results and conclusions are given in Sec. 5 and 6.

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2 ALL-IN-QUARTZ DESIGN

In this section the novel all-in-quartz lens-packaging concept will be explored. The external optics module with combined collimating and focusing unit used in the experiments will also be presented.

2.1 Quartz in optical systems

In current state-of-the-art external optics for high power lasers multiple high-quality an infinite conjugate lens made of AR-coated fused silica lens elements are used to collimate the laser beam emitted from a fiber. After the laser beam has been collimated it is directed to one or more fused silica lenses that focus the light onto the surface to be processed. Although synthetic fused silica of high purity is highly transmissive in the near infrared, there is always some radiation that is either scattered or absorbed in the material or in the coatings. The absorbed radiation will heat up the material affecting the thermally sensitive properties of the material. Two factors, the thermal coefficient of expansion (α) and the temperature dependence in the index of refraction (dn/dT), are particularly important as they may alter the focal lengths of the lenses thus introducing focal shifts. Minimizing material absorption and effectively removing scattered light will minimize the thermal effects in the lens system. The cleanliness of the optical surfaces plays a decisive role in the thermal absorption of AR-coated fused silica. Continuously keeping lenses ultra-clean will reduce absorption and scattering. The scattered light should be absorbed outside the lenses and lens holders, and efficiently cooled e.g. using water.

In order to address focal shifts we suggest a patented¹ all-in-quartz lens-packaging concept. The basic idea of the invention is to mount all optical elements inside tubes of the same material and apply efficient cooling to a cavity on the outside of the tubes. A conceptual drawing is shown in Fig. 1.

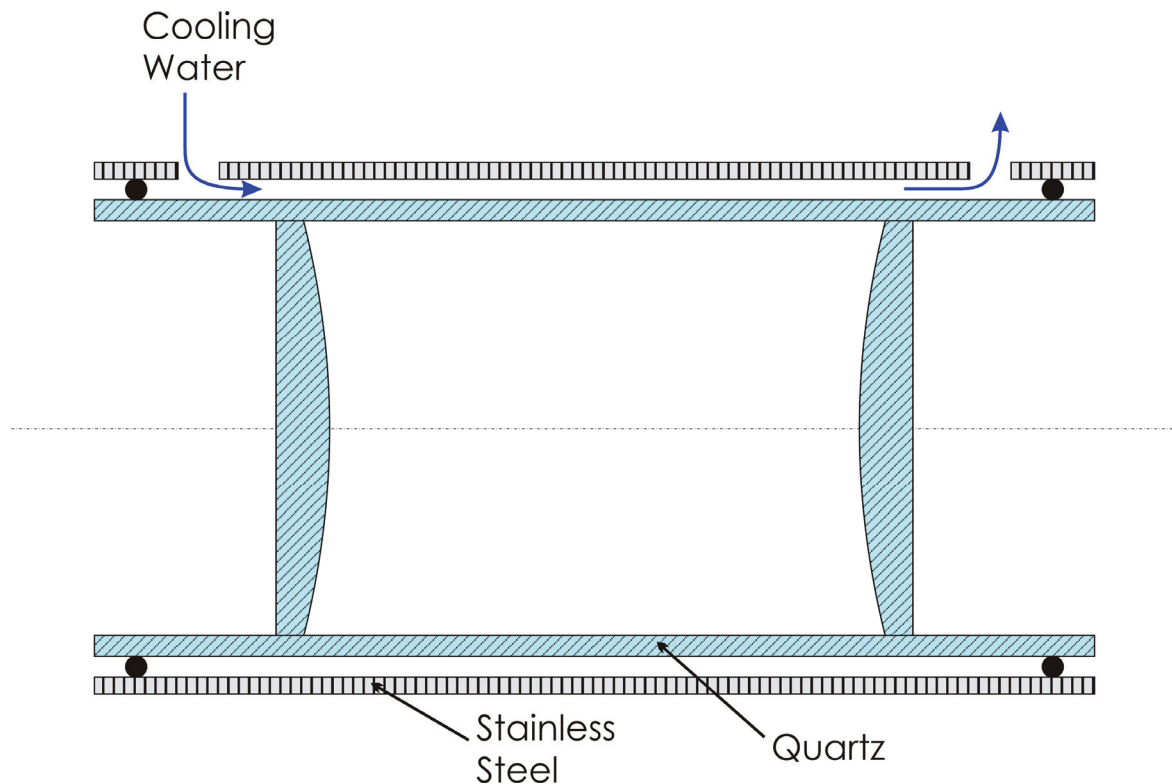


Figure 1. Conceptual drawing of the patented all-in-quartz lens packaging. Optical elements are mounted and hermetically sealed inside an optically transparent fused quartz tube. The quartz tube is mounted inside a stainless steel housing. Cooling water flows in the cavity between the quartz tube and the housing, which is enclosed by o-ring sealings.

The fused silica lenses, typically a set of collimating lenses and a set of focusing lenses, are fixed inside the quartz tube, where the first and last lenses are sealed so that the enclosed volume between those lenses is hermetically sealed. Thus no dust or particles can enter into the enclosure deteriorating the optical performance. The optical package is then positioned inside an acid-proof stainless steel housing creating a cavity where cooling water can flow efficiently. Scattered laser light will be transmitted through the quartz tube and absorbed by either the cooling water directly or by the non-transparent stainless steel housing, where the resulting heat will be transported away by the cooling water. Indirect heating of the lens elements, either by radiation or convection, is efficiently avoided since there are no heat-absorbing components (e.g. metal distances or holders) in contact with or air-spaced from the lenses. Compared to metals, fused quartz has a low thermal coefficient of expansion ($\alpha \approx 0.55 \times 10^{-6} / \text{K}$). Even though the lenses may have a elevated temperature due to absorption compared to the quartz tubes the differences in thermal expansion will be small. Thus there will be insignificant relative position change between individual lens elements, which could contribute to focal shifts. Another advantage with the all-in-quartz concept is that the unit becomes less affected by large-angle back-reflections that may occur when processing materials having strong reflectivity at the laser wavelength. The large-angle reflected light will be absorbed in the cooling water similarly to scattered light from the lens elements.

2.2 All-in-quartz collimator/focusing unit

The embodiment of the all-in-quartz unit used in the present experiments is shown in Fig. 2. The optics is based on D25 mm lenses (AR-coated fused silica lens doublets of triplets). The lenses are mounted in the quartz tube so that the two outer surfaces can be easily cleaned. A dust-sealed AR-coated protection window made of fused silica also protects the exit side of the optics. The input side of the optics has the Optoskand QB interface¹, to which the optical package is pre-aligned.

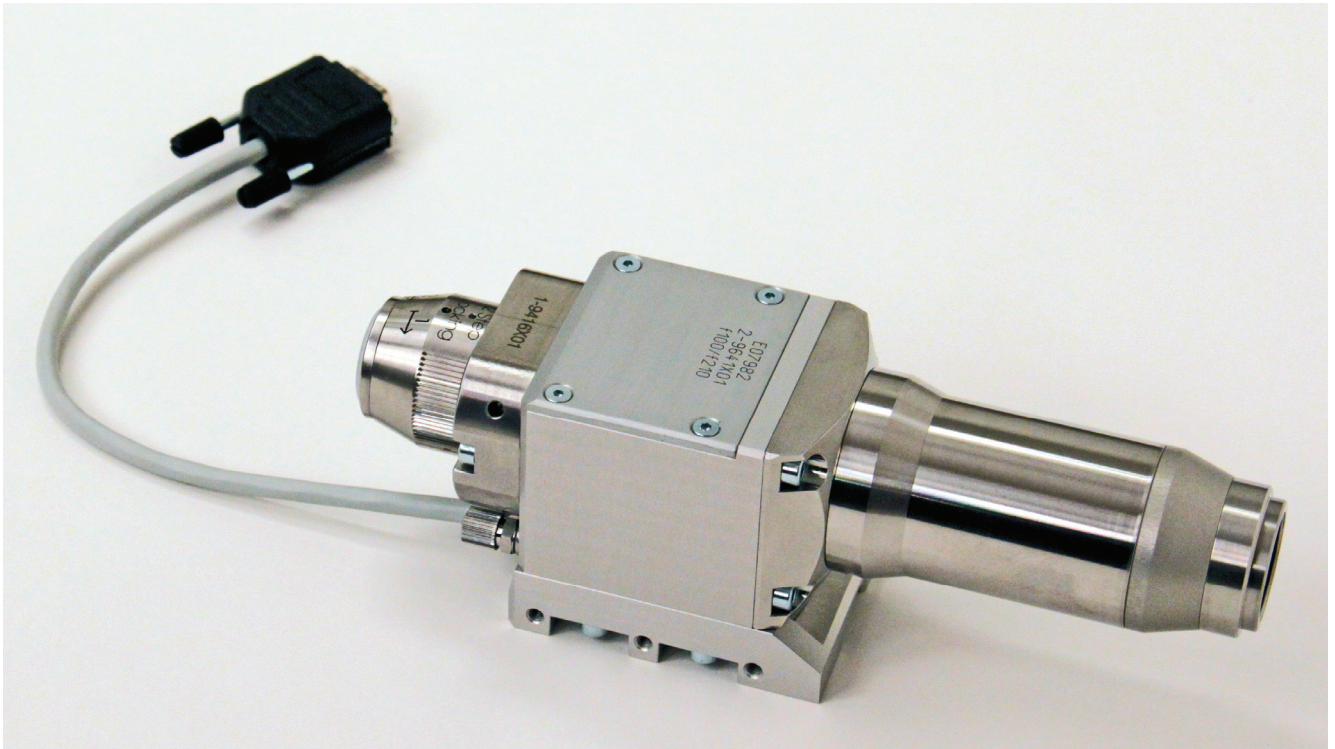


Figure 2. Image of the combined collimating/focusing all-in-quartz unit. The optics is based on pre-aligned D25 mm lenses. The input side has the Optoskand QB interface and a 9-pole D-sub handles the electronic interface.

The unit has an electronic interface through a 9-pole D-sub. Inside the unit there are detectors that measures scattered light, absolute temperature, delta-temperature between incoming and outgoing cooling water, and humidity. There are interlock break enable functions, when measured levels are higher than threshold levels, which can be set by a software interface. Also, detector values can be logged continuously.

¹ The QB interface is used with QBH and RQB fibers. The interface can also be changed to Optoskand QD (LLK-D, automotive) and Optoskand Q5 (LLK-B) interfaces.

3 DEFINITIONS AND NOMENCLATURE

In this section a summary of the definitions and nomenclature for focal shift in high power optics will be introduced. A more comprehensive description is given in a previous paper.²

3.1 Focusing of Multimode Beams

For multimode beams, the definition of beam size and other beam parameters are not as well defined as for a Gaussian beam. The calculated values are more to be seen as approximations. The beam radius, r , is defined as the radius within which 86.5% of the radiation is falling. The beam size along the optical axis (z-axis) is given by

$$r = \sqrt{r_0^2 + (z \cdot \Theta)^2}, \quad (1)$$

where the focusing angle, Θ , is approximately given by

$$\Theta = \frac{D}{2 \cdot f}. \quad (2)$$

D is diameter of the beam and f the focal length. The beam radius at the waist, r_0 , is given by

$$r_0 = M^2 \cdot w_0 = \frac{M^2 \cdot \lambda}{\pi \cdot \Theta}, \quad (3)$$

where M^2 is the ‘‘Beam Propagation Factor’’, w_0 is the waist radius of a Gaussian beam, and λ is the wavelength. The Beam Parameter Product, which is a measure of the quality of the beam, is defined for a multimode beam (indicated by the subscript ‘‘MM’’) as

$$BPP_{MM} = M^2 \cdot BPP_{FM} = M^2 \cdot w_0 \cdot \Theta = M^2 \cdot \frac{\lambda}{\pi}. \quad (4)$$

The Rayleigh length, Z_R , is defined as the distance from the beam waist, where the beam radius has increased by a factor of $\sqrt{2}$. For the multimode beam the Rayleigh length scales with the M^2 factor compared to a fundamental mode beam, and is given by

$$Z_{RMM} = M^2 \cdot Z_{RFM} = M^2 \cdot \frac{\lambda}{\pi \cdot \Theta^2}. \quad (5)$$

3.2 Focal Shift and Focal Shift Factors

The focal shift introduced in an optic system/element caused by high power, is the shift in the z-direction (along the optical axis). To be able to compare different optics and systems we introduce normalizations towards the Rayleigh length. Fig. 3 shows the definitions of focal shift in an optic system.

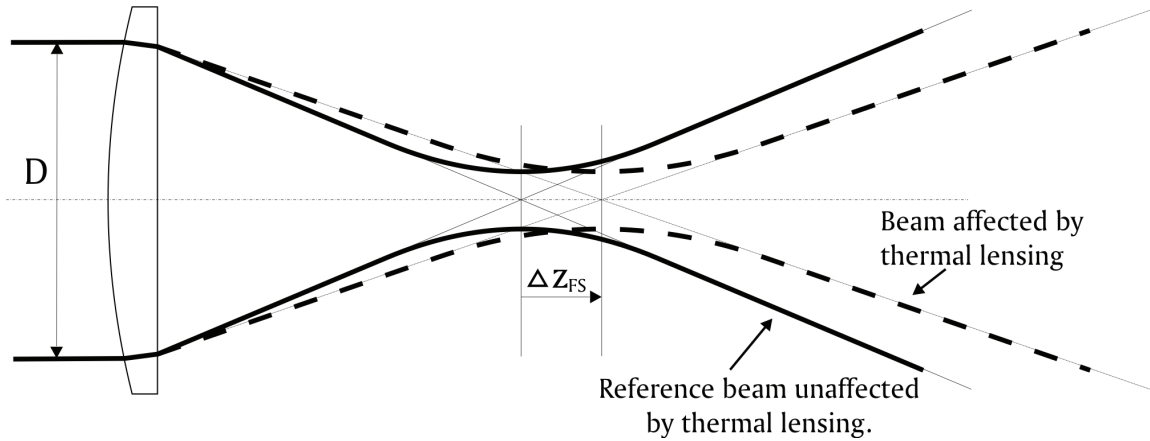


Figure 3. The figure shows the definitions of focal shift in an optic system.

To characterize a complete system, lens aberrations and the beam quality of the laser used have to be taken into consideration. To normalize the focal shift, we use the real Rayleigh length given by the high power beam. It can be estimated by the formulas in Sec. 3.1, but is preferably measured. The **System Focal Shift Factor** (*SFSF*) is defined by

$$SFSF = \frac{\Delta Z_{FS}}{Z_{RMM}}. \quad (6)$$

It has to be noted that the *SFSF* only describes the influence of focal shift, but to get a complete image of the optics performance also the *BPP* has to be given. For a multimode beam the focal shift gives rise to an increased spot size according to

$$r = r_0 \sqrt{1 + SFSF^2}. \quad (7)$$

An *SFSF* of 1 indicates a change in the spot size by approximately 40%. As rule of thumb this is the maximum change acceptable for an application.

4 EXPERIMENTAL

In the experiments the System Focal Shift Factor was estimated at various laser power levels for different all-in-quartz lens combinations. For comparison the SFSF was also measured for standard D25 collimating and focusing unit combinations.

4.1 Experimental Setup

Two different experimental setups were used. In one part of the measurements an *IPG YLR-4000-SS* with 4 kW maximum output power at approximately $\lambda = 1070$ nm was used as laser source. The output fiber was connected via a fiber-to-fiber optic switch, a feeding fiber, a second fiber-to-fiber optic switch and a process fiber to the measurement object. Depending on the magnification of the test optics a 150- μm -core ($M=2$) or a 300- μm -core ($M=1$) process fiber was used so that the focused spot approximately became 300 μm in diameter.

In another part of the measurements a 4 kW cw laser system from *Rofin-Sinar Laser (FL040)* was used. The laser system is based on four fundamental mode laser units with an output power of more than 1 kW. The output power can be scaled by the amount of used pump diode lasers, which can be easily added by help of pluggable pump fiber connectors. The optical to optical efficiency is about 80% depending on the pump wavelength. Electrical to optical efficiencies of up to 38% are achieved for the laser units (pump diode lasers plus all-in-fiber oscillator). The kW class laser units can be used for direct work piece treatment or as a basis for multi-kW, multi-mode, but still high brightness, all-in-fiber laser systems. These kW class laser units are incoherently combined by help of an all-in-fiber combiner device into a 50- μm -core fiber cable. The beam quality out of this 50- μm -core fiber cable terminated by a QBH connector was measured to be 1.8 mm-mrad (second moments) with uniform beam profile. This high brightness beam can be used for direct work piece treatment or it can be used as the feeding beam for a fiber-to-fiber optic switch. For the experiment a QBH process fiber cable with 100 μm core diameter was plugged into the fiber-to-fiber optics switch.

The beam parameters were measured with a *Primes FocusMonitor*. The maximum power density on the measuring tip of the Primes instrument limits the power to below 4 kW with a 300- μm spot. In the experiments with the Rofin laser a *FocusMonitor* with high rotation speed and a smaller pinhole made it possible to measure up to 4.4 kW with a 200- μm spot. The power was measured with an *Ophir* head.

A typical caustic result at a fixed power level is shown in Fig. 4. The caustics are presented for the 86.5% radius ($1/e^2$). The z-position and the Rayleigh length are used in the calculations of the SFSF.

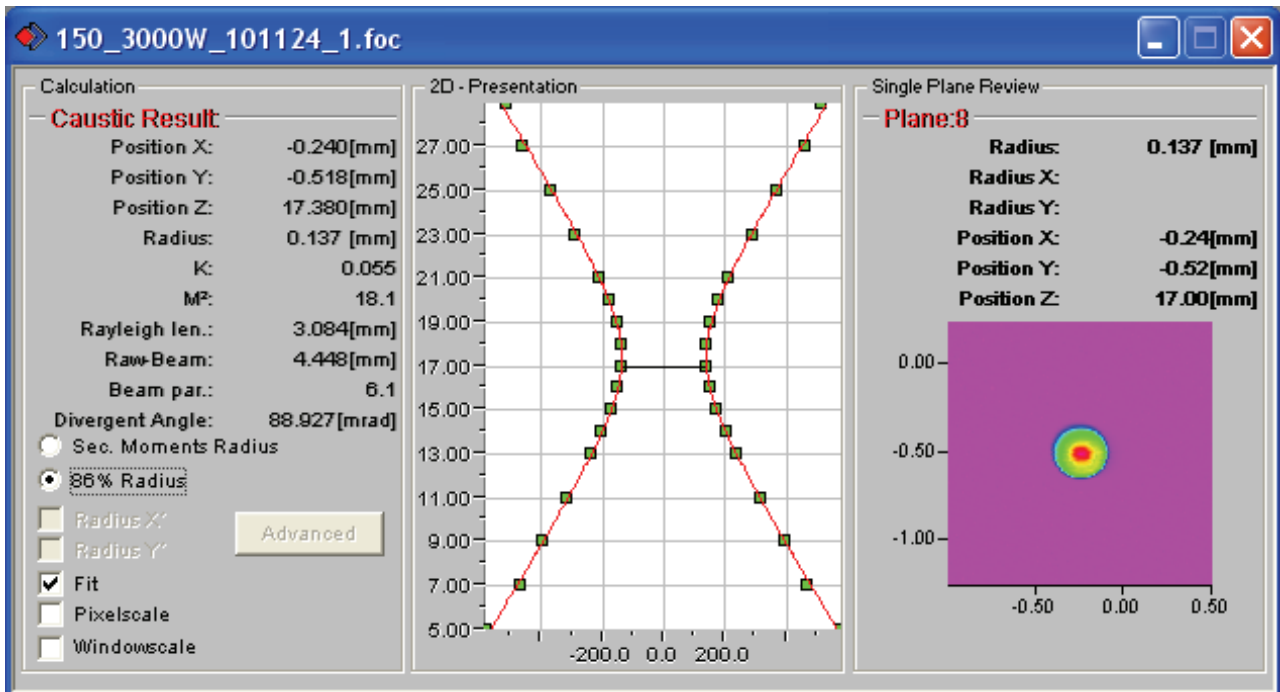


Figure 4. The beam parameters for an f50 collimating lens/f100 focusing lens all-in-quartz unit at 3 kW using a 150- μm -core input fiber. The caustic results are presented for the 86.5% radius ($1/e^2$). The z-position and the Rayleigh length are used in the calculations of the SFSF.

To reduce noise, particularly at the lowest power level (200 W), averaging was applied. Measurements started at the lowest power level and the power was incrementally increased. Before each measurement sequence the power was held constant for a few minutes to achieve thermal equilibrium.

5 RESULTS

In this section experimental results will be presented. The SFSF values for the patented all-in-quartz modules are compared to SFSF values of standard optics consisting of the same lenses. In a further experiment the SFSF values are compared for an all-in-quartz unit at normal and strongly reduced water flow.

5.1 SFSF Comparison

In the first experiment an $M=1$ all-in-quartz unit with f100 quartz doublet lenses was compared to a standard set of an f100 water-cooled collimator and an f100 focusing unit. The same f100 quartz doublet lens type was used. Because of the 1:1 magnification a 300- μm -core processing fiber had to be applied not to exceed the power density for the Primes instrument. The measured thermal shift and calculated SFSF are shown in Fig. 5. In the calculations the thermal shift is assumed to be negligible (zero) at 200 W, which is the lowest power level that give repeatable results in the Primes measurement.

The negative thermal shift implies a shorter focal length following the definition in Fig. 3. A linear increase in the SFSF values as a function of power is confirmed for both the standard optics as well as for the all-in-quartz module. The calculated SFSF values are significantly improved for the all-in-quartz unit. At 3 kW the SFSF has been reduced by 93% to an SFSF value of -0.036. One should note that in these measurements the lens assemblies are stressed by overfilling of the numerical aperture (NA). The divergent angle of the light cone to be collimated is measured to just over 125 mrad, which for a focal length of 100 mm implies a beam diameter on the lenses in the order of 25 mm, where the clear aperture of the lenses is specified to 23.5 mm.

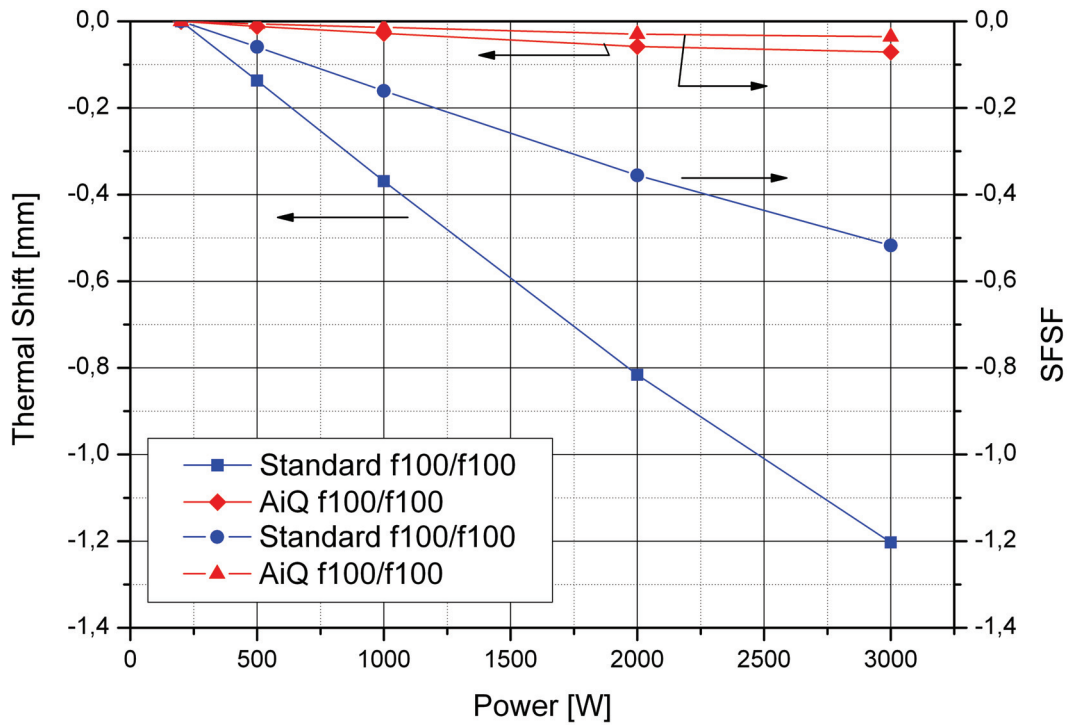


Figure 5. Thermal shift and calculated normalized SFSF for an all-in-quartz unit with f100 quartz doublet lenses and for a standard combination of a water-cooled f100 collimator and an f100 focusing unit both having the same quartz doublet lens types.

In a second experiment an $M=2.1$ all-in-quartz unit with f100 quartz doublet lens and f210 quartz singlet lens was compared to a standard set of one f100 water-cooled collimator and one f210 focusing unit. The same lens types were used in both the standard and the all-in-quartz units. Because of the 1:2.1 magnification a 150- μm -core processing fiber could be applied keeping a better overall beam quality in the test. Fig. 6 shows the measured thermal shift and calculated SFSF up to 3 kW.

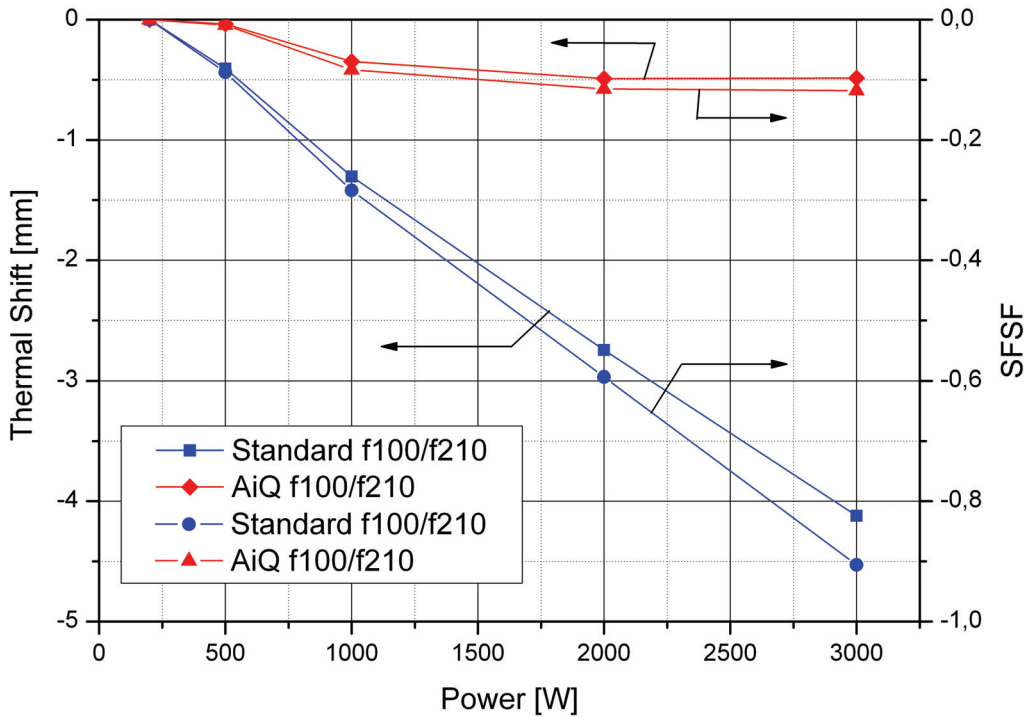


Figure 6. Thermal shift and calculated normalized SFSF for an all-in-quartz unit with a f100 quartz doublet lens and an f210 quartz singlet lens and for a standard combination of a water-cooled f100 collimator and an f210 focusing unit both having the same lens types as the all-in-quartz unit.

Once again significantly improved SFSF values are measured for the all-in-quartz units. At 3 kW the SFSF has been reduced by 87% to an SFSF value of -0.12. As the collimating lens still is an f100 the optics are again stressed by overfilling the NA. A measured divergent angle of 140 mrad at 3 kW implies a theoretical collimated beam diameter in the order of 28 mm. The overfilling of the NA is also noted in a lower power transmission of around 100 W at 3 kW.

With the RoFin FL040 system an all-in-quartz M=2 module consisting of an f50 quartz triplet lens and an f100 quartz doublet lens could be tested up to 4.4 kW using a 100- μ m-core processing fiber. For this measurement no comparison to standard optics was available. Fig. 7 shows the measured thermal shift and calculated SFSF.

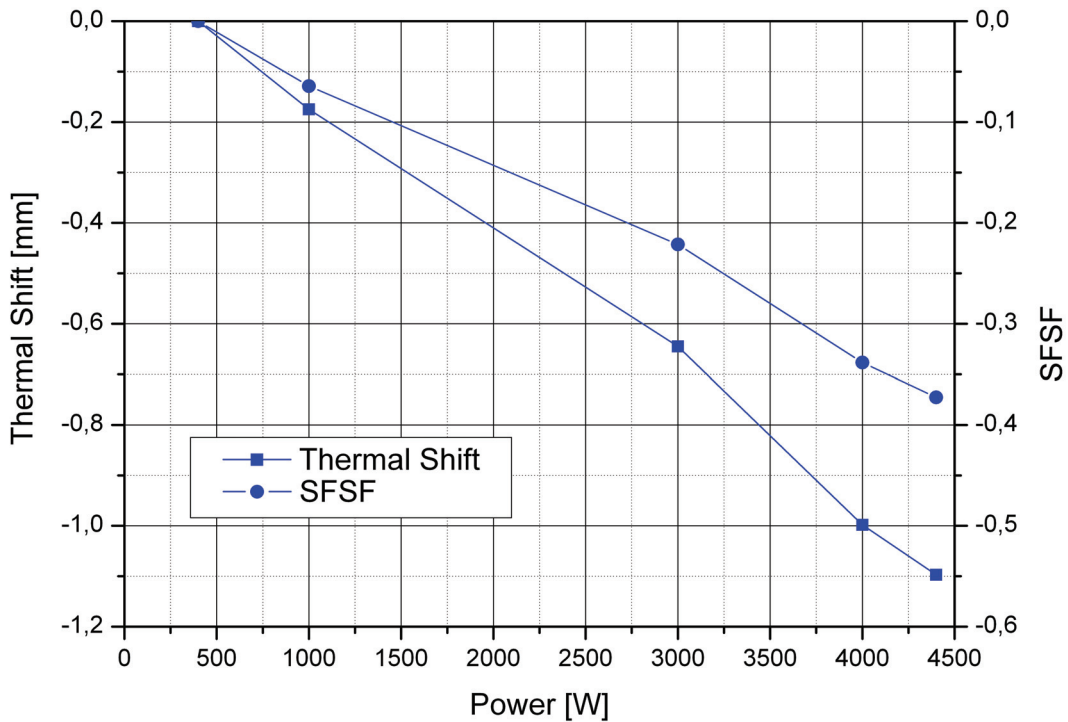


Figure 7. Thermal shift and calculated normalized SFSF for an all-in-quartz unit with an f50 quartz triplet lens and an f100 quartz doublet lens using the RoFin FL040 laser with a 100- μ m-core processing fiber.

A relatively linear increase in the SFSF is noted up to 4.4 kW, where the SFSF was determined to -0.37. Only 2.6% power losses between the combiner output and the 100 μm fiber plus the f50/f100 all-in-quartz optics had been found, thus the BPP-measurements with power levels of up to 4.4 kW out of the optical head has been possible.

5.2 Cooling Water Influence

Efficient cooling is essential in removing scattered light and keeping the all-in-quartz modules at a stable, low operating temperature. In order to test the cooling water influence an experiment was performed with an all-in-quartz M=2 module consisting of an f50 quartz triplet lens and an f100 quartz doublet lens. With this configuration a 150- μm -core processing fiber could be used, and having an f50 collimating lens, overfilling of the NA is avoided. Two rounds of measurements were performed – first with normal water flow (1.5 l/min) and then with reduced water flow (0.2 l/min). The results are shown in Fig. 8.

Only small focal shifts are seen up to 3 kW, where the spot size on the collimating lens is estimated to 19 mm. For the measurement with normal water flow there appears to be an initial increase in SFSF, but this is probably due to the uncertainties in determining the z-position at 200 W. Qualitatively, the change in SFSF is larger for the measurement with reduced water flow. A slower heat removal is also confirmed by larger ΔT readout from the cooling water sensor.

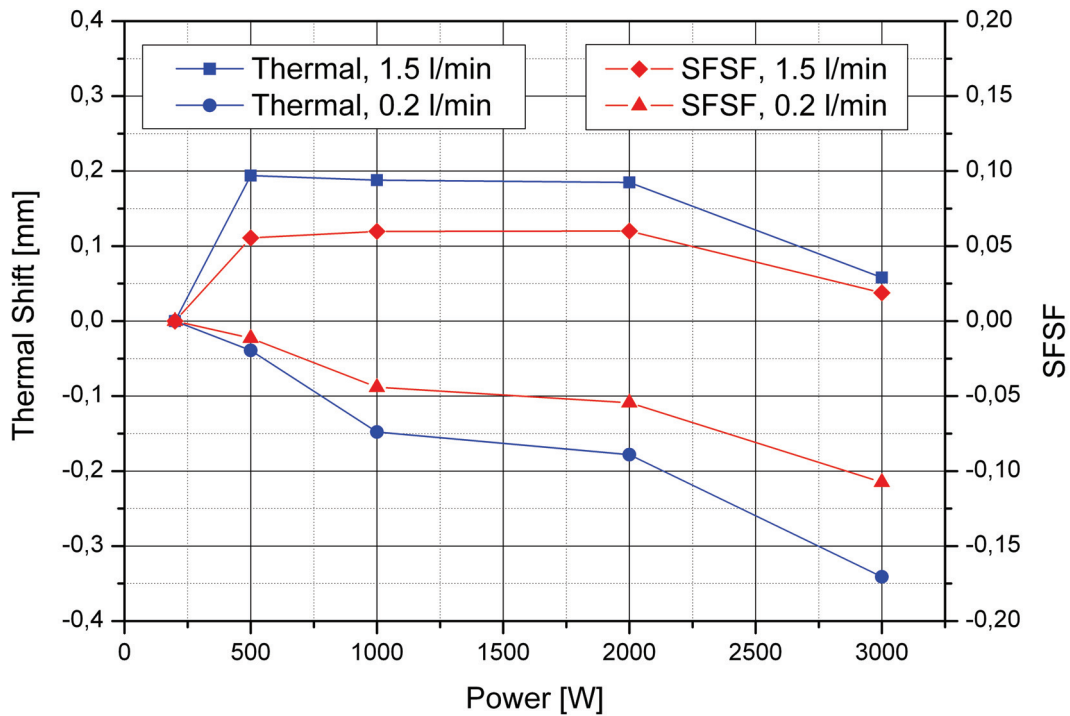


Figure 8. Thermal shift and calculated normalized SFSF for an all-in-quartz unit with an f50 quartz triplet lens and an f100 quartz doublet lens at standard and reduced water flow.

6 CONCLUSIONS

In conclusion, a patented novel design of lens packages based on an all-in-quartz concept has been explored with the aim of reducing thermally induced focal shifts of external optics in high-power laser applications. By mounting fused silica lenses in hermetically sealed fused quartz tubes and applying water-cooling on the perimeter of the quartz tubes we have reduced or eliminated a number of contributing factors to focal shift problems. The hermetic sealing, carried out in a clean-room environment, minimizes lens surface contamination. Differences in thermal expansion between lens and housing are strongly reduced as the lens and housing are made of the same material. Absorption of scattered laser light is efficient as the energy is removed quickly by cooling water and not absorbed by fixed surroundings.

Comparisons between standard collimating/focusing units and the all-in-quartz units show a reduction in the normalized system focal shift factors around 90%. SFSF values of -0.036 to -0.12 have been calculated at 3 kW. Using a Rofin FL040 system with a 100- μm -core process fiber an SFSF value of -0.37 was determined at 4.4 kW output power for an f50/f100 all-in-quartz module. As all these values are well below SFSF=1, the novel all-in-quartz units are suitable in multi-kW applications using high-brilliance fiber- or disc-lasers.

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REFERENCES

- [1] Roos, S-O., Bengtsson, D. and Blomster, O., WO 2008/153468 A1.
- [2] Blomster, O., Pålsson, M., Roos, S-O., Blomqvist, M., Abt, F., Dausinger, F., Deininger, C., and Huonker, M., "Optics performance at high-power levels," Proc. SPIE 6871, 68712B-68712B-10 (2008).

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