HALO – High Amplification Laser-pressure Optic

Alexandra Artusio-Glimpse, Kyle Rogers, Paul Williams, and John Lehman

National Institute of Standards and Technology, Boulder CO, USA
Corresponding e-mail address: alexandra.artusio-glimpse@nist.gov

Efforts are underway at the National Institute of Standards and Technology to drastically reduce the uncertainty of laser power measurements using radiation pressure. The High Amplification Laser-pressure Optic (HALO) system is a cornerstone of this effort as it enables amplification of the laser pressure on a high-quality mirror attached to a precision force sensor. We discuss the HALO architecture here.

MOTIVATION

Laser power measurements based on radiation pressure (RP) use the force of light as it reflects from a mirror to characterize the optical power. Here, we work to reduce measurement uncertainty by amplifying the force of the laser light. If the same light reflects multiple times from the sensing mirror of an RP detector, a passive gain can be realized [1,2]. For decades, the cryogenic radiometer standard has yielded relative measurement uncertainties of 10^{-4} at the milliwatt level. Meanwhile, power measurements above 100 W have relative uncertainties near 10^{-2} for both calorimetric-based and RP-based measurements. By amplifying the force of RP with a multi-reflection optical system, we expect laser power measurement uncertainties to approach 10^{-4} for kilowatt level incident powers.

For a RP measurement where the light reflects N times off the sensing mirror having reflectance R given a round-trip scattering and absorption loss L the signal to noise ratio (SNR) goes as

$$SNR \propto \sum_{j=1}^{N}\big((1-L)R\big)^{j-1}, \qquad (1)$$

which approaches N as $(1-L)R \to 1$. Absorption in the sensing mirror can heat the force sensor and produce a measurement error $N\eta_T\Delta T_1$ where η_T is the temperature-dependent error coefficient and ΔT_1 is the change in temperature of the force sensor for a single reflection. Thus, for low-loss, high-reflectivity optics, we approximate the fractional measurement error as

$$\varepsilon \approx (\eta_1/N + \eta_T\Delta T_1)/F_1, \qquad (2)$$

where η_1 represents the averaged noise and F_1 the measured force, both for a single reflection. We see that amplifying the force of a single reflection with N reflections, we effectively reduce the fractional contribution of the fixed noise by N, but have no effect on the thermal contribution.

Here we describe a system designed for $N \leq 15$ bounces and accommodating the 40 mm diameter beam from a 10 kW infrared laser. Current efforts emphasize the design and system tolerances, while forthcoming efforts will develop an alignment procedure and mirror reflectance and scatter measurements to meet preliminary tolerances. These are steps toward our goal of achieving relative measurement uncertainties approaching those currently found only in cryogenic radiometers. Moreover, our multi-reflection system can be used to amplify lower power lasers, enabling us to reduce the measurement uncertainty of any RP measurements.

HALO DESIGN

The NIST High Amplification Laser-pressure Optic (HALO) system is depicted in Fig. 1 with a green HeNe laser (5 mW) illuminating the beam path, reflecting off the sensing mirror 14 times, and leaving the system to the upper right.

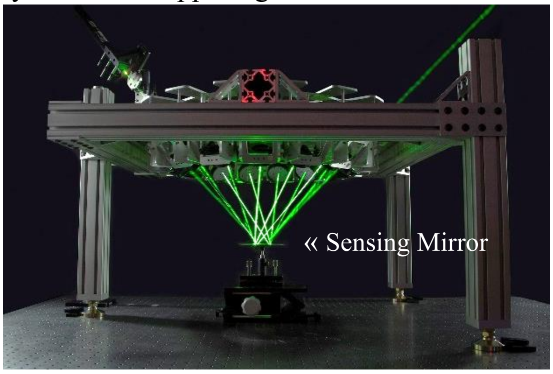

Figure 1. HALO system photograph. A green HeNe illuminates the laser path through 14-bounces and out the system to a beam dump (not shown) at the upper right.

HALO is a pentadecagonal structure with an entrance port and up to 14 upper mirror modules ("ring mirrors", see Fig. 2) that direct the input laser beam to a lower sensing mirror. Importantly, the laser incidence angle on the sensing mirror is always 45°. This both protects the mirror from thermal flexing as the reflectance need only be optimized for a single angle and simplifies propagation of uncertainties. The total structure fills a volume of about 1 m^3. Like toroidal multipass cells used for laser spectroscopy [3], the laser beam traces out a star polygon (Fig. 2). However, here the ring mirrors are pitched downward to the sensing mirror placed at the center of the star pattern. When all 14 ring mirrors are in place, the total beam path in the system is 10.124 m.

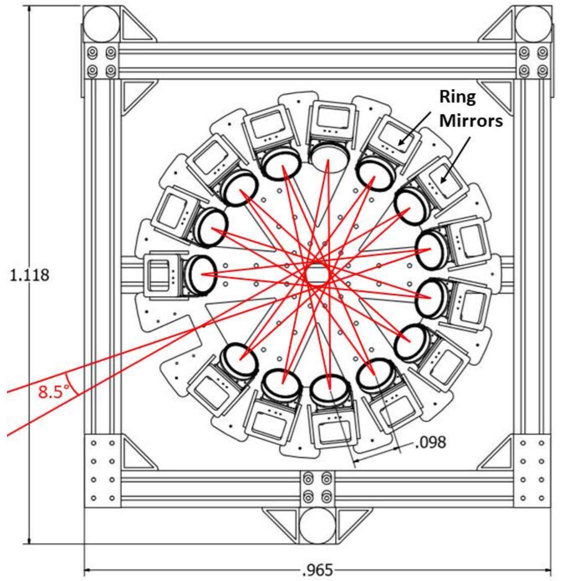

Figure 2. Upper ring mirror modules and star polygon laser path when all 14 mirrors (76.2 mm diameter) are in place. Laser enters through the empty port and exits through the same port, rotated by 8.5°. Alternatively, the laser may exit through any other port when the respective mirror module is removed. (labels in meters)

The spot pattern of the laser on the 150 mm diameter sensing mirror forms two open crescent shapes as the laser beam rotates and expands through the system (Fig. 3). Given the short (90 µm) coherence length of our laser and the large incidence angles and long path length differences between adjacent spots in this system, interference is not a concern.

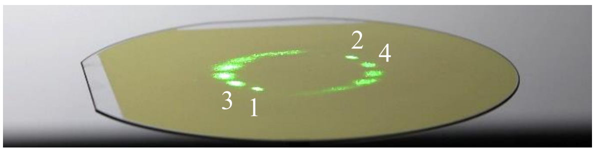

Figure 3. Green HeNe laser spot pattern is visible on the surface of a gold coated fused silica 150 mm diameter wafer. First four bounces of 14 total are labeled.

TIGHT TOLERANCES AND OUTLOOK

In order to reach 10^{-4} uncertainty, near perfect laser alignment and highly-accurate optical characterization of each mirror (reflectance, scatter, absorptance) will be required. As such, our first goal is to reach a relative measurement uncertainty of 10^{-3} at 10 kW.

We simulated laser propagation through the HALO system and modulated geometric and optical parameters to obtain system tolerances. The results of the ray-tracer and Monte Carlo algorithm are listed in Table 1 (totals exclude the force sensor [4]).

Table 1. Alignment and optical measurement tolerances needed to reach two relative uncertainty goals.

Rel. Unc. Goal	10^{-3}	10^{-4}
Sensing Mirror Angle	60 µrad	30 µrad
Ring Mirror Angle	300 µrad	30 µrad
All Mirrors 3D Position	2 mm	2 mm
Reflectance/Scatter	20x10^{-6}	1x10^{-6}
Total Optical Rel. Unc	0.7x10^{-3}	0.75x10^{-4}

In addition to tight system tolerances, if the sensing mirror is bowed, the laser will accumulate astigmatism, as is the case in Fig. 3 where the spots grow in ellipticity as the number of bounces increases. The HALO structure must also be rigid and isolated from vibrations to maintain these tolerances. To reach the 10^{-4} uncertainty goal, simply knowing total scattered power is not enough. The full bidirectional scatter distribution function must be accounted for in the momentum calculations else the calculated laser power from the measured force will be in error by an order of 10^{-4}.

The NIST HALO system has been built and its alignment demonstrated with a low-power, small diameter laser. We now set our attention to alignment with high reflectivity IR mirrors and measurement of a 500 W laser. This incremental advancement is necessary as we progress toward a RP laser power measurement system that will yield measurement uncertainties of 10^{-4} at 10 kW.

REFERENCES

1. S. Vasilyan, et al., Total momentum transfer produced by the photons of a multi-pass laser beam as an evident avenue for optical and mass metrology, Opt. Express, 25, 20798-20816, 2017.
2. G. Shaw, et al., Comparison of electrostatic and photon pressure force references at the nanonewton level, Metrologia, 56, 2019.
3. B. Tuzson, et al., Compact multipass optical cell for laser spectroscopy, Opt. Letters, 38, 257-259, 2013.
4. G. Shaw, et al., SI traceable electrostatic balance to measure laser power, NewRad 2020 extended abstract.