How to avoid beam distortion in solid-state laser design

Wavefront sensors are a practical alternative to interferometers for measurements of thermal lensing, which can impose many waves of curvature on a probe beam.

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Beam focusing and higher-order wavefront distortion due to heat dissipation in the laser gain medium are important considerations in the design of solid-state lasers because wavefront distortion--commonly known as thermal lensing and due largely to the temperature dependence of the refractive index--can profoundly influence the performance of a given laser design. Although the effects of heat dissipation in laser materials can be calculated for a particular geometry with appropriate boundary conditions, material inhomogeneity, as well as nonuniform optical pumping, are difficult to account for by numerical modeling alone. Therefore, accurate characterization of thermal lensing for each rod or slab of laser material installed in a particular laser cavity can be achieved only by careful measurement of the transmitted wavefront.

When a beam of light acting as a probe is transmitted through a heated laser rod, thermal lensing can be measured with an interferometer such as the Mach-Zehnder or with a wavefront sensor such as the Shack-Hartmann design (see "Shack-Hartmann sensors simplify slope measurement," p. 132).[1,2] For measurements of thermal lensing, where many waves of curvature may be imposed on the probe beam, wavefront sensors offer a practical, easy-to-use alternative to interferometers.

Wavefront sensors are insensitive to vibration and are able to measure large wavefront distortion (that is, they have a large dynamic range). They make differential measurements that yield only thermal-lensing information and ignore both aberrations in optical elements used to make the measurement and aberrations in the cold laser rod itself. They can operate over a broad range of wavelengths and can measure wavefronts derived from broadband thermal sources, if the spatial extent of the source is sufficiently small.

Wavefront sensors operate on the principle that light travels in a straight line. If we adopt a definition for the wavefront as the surface normal to the direction of propagation of light, then wavefront sensors measure the slope of this surface. When the wavefront is reconstructed from measured slope data, a least-squares-fit to the spatial derivatives of an appropriate set of polynomials, such as the Zernike polynomials, yields quantitative information on focusing and higher-order optical aberrations. Laser engineers can use this information to optimize cavity designs, reject laser rods or cavity optics that do not meet specifications, and design corrective optics if necessary.

A measuring system

In a typical optical system for measuring thermal lensing in a diode-pumped solid-state laser rod, thermal lensing is observed by measuring the transmitted wavefront from a collimated probe beam at the exit aperture of the rod (see Fig. 1). The exit aperture of the laser rod is imaged onto a microlens array in the wavefront sensor using an afocal imaging system constructed from a Keplerian telescope. This arrangement, sometimes known as "relay imaging," amounts to "propagation without distance" if air movement is neglected because the wavefront at the exit aperture of the rod, which serves as the entrance pupil of the imaging system, is imaged onto the sensor free from diffraction effects due to propagation.

This two-lens afocal system is particularly convenient because the entrance and exit pupils are conjugates, and for finite conjugate imagery, it has constant magnification. The linear magnification selects an image size that fits within the aperture of the sensor but does not depend on the location of the object. In the example system of Figure 1, the object plane coincides with the end of the laser rod, and the image plane with the microlens array, with each located conveniently at distances fl1 and fl2, respectively, from lenses L1 and L2.

Because wavefront sensors have a large dynamic range and make differential measurements with respect to a reference wavefront, inexpensive off-the-shelf components can be used to make the optical measurement system. The choice of optical components should be restricted, however, to those that contribute relatively small wavefront distortion. Single-element lenses or cemented achromats for use in the system shown in Figure 1, for example, should generally have f-numbers greater than 5 and 10, respectively. For optical filters, absorbing-glass materials should be used in place of interference filters when possible. The differential measurement is not a license to ignore sound design principles. It is much easier to align the optical system and record a reference wavefront for the system when residual aberrations are minimized.

Collimated output from a diode laser emitting at 635 nm via a pigtailed single-mode optical fiber provides the probe beam in Fig. 1. Because it has point-like spatial properties, a visible wavelength, and a broad, multi-longitudinal mode spectrum, it is a nearly ideal source for the wavefront sensor. Although any expanded, collimated beam will usually work, choice of wavelength is restricted because the sensor must detect the probe, but not pump light and fluorescence from the lasing medium. For this reason, an infrared absorbing-glass filter is placed near the end of the laser rod. Pump light and fluorescence are not of interest. And because they radiate from extended sources, they do not produce measurable wavefronts.

The measurement process

The first step in the measurement process, once the optical setup is complete, is to record a reference wavefront. For many applications, a uniformly illuminated plane wave will be used as an "absolute" reference for aligning the optical system, but for thermal lensing measurements, the appropriate reference is recorded with the laser rod removed or with the laser rod in place at room temperature. After the reference is recorded, wavefront measurements are made for varying levels of pump power, and the results are analyzed.

We show results for two sample measurements. One displays thermal lensing in an absorbing-glass neutral density filter and includes calculations in good agreement with the measurements (see Fig. 2). The other demonstrates thermal lensing with substantial wavefront distortion for a 3-mm-diameter diode-pumped Nd:YALO laser rod (see Fig. 3). Both measurements were made with optical systems similar to that in Figure 1. q

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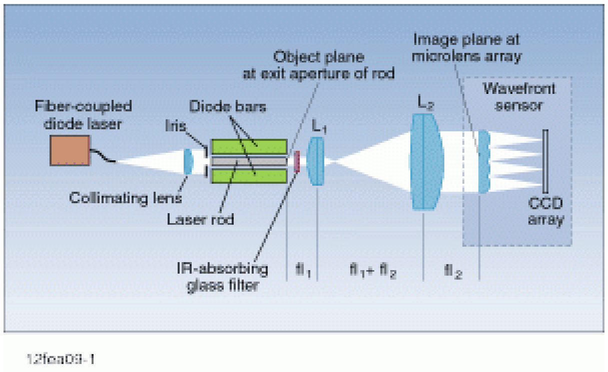
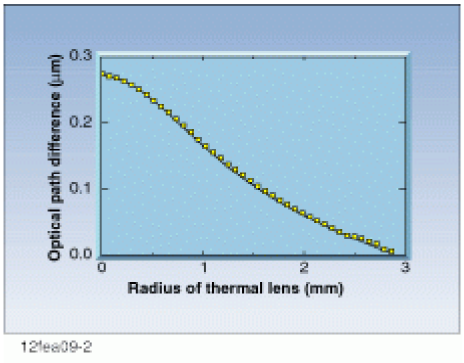


FIGURE 1. Optical setup based on an afocal imaging system measures thermal lensing in a solid-state laser rod. In this example, the diameter of the laser rod is smaller than the aperture of the wavefront sensor.



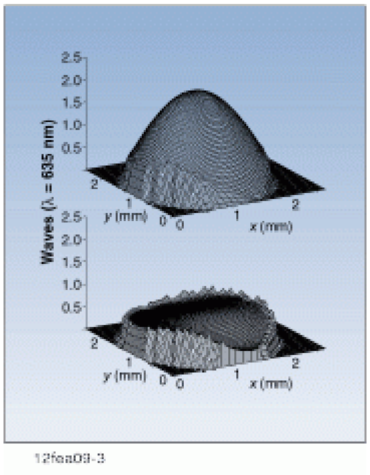


FIGURE 3. Strongly focused wavefront for a 3-mm-diameter Nd:YALO rod was reconstructed using 4th-order Zernike polynomials, with all polynomial terms retained (top) and with the tilt and focus-shift terms removed (bottom). The wavefront was measured against a reference wavefront with the cold laser rod in place. By extracting the spherical-wave component of the wavefront curvature, the distance to the paraxial focal point, measured from the end of the rod, is approximately 0.6 m. When the dominant focus term is removed, higher-order wavefront aberrations are also present.

Shack-Hartmann sensors

Shack-Hartmann (or Hartmann-Shack) wavefront sensors measure wavefront slope, where the wavefron
the surface normal to the direction of propagation of light. These sensors consist of a two-dimensional a
subapertures containing very small lenses-microlenses--mounted in front of a CCD camera (see figure).
applications such as thermal lensing, typical micro lens diameters are on the order of 100 µm, with f-nur
exceed 50.

Wavefront slope is measured by subdividing an incident light wave among the microlenses and monitori
positions of the resulting focal spots. Centroids for the focal spots are found within a group of CCD pixe
each microlens, called an area of interest (AOI). Boundaries of the AOIs, and locations of "reference" ce
the AOIs, are determined from a "reference wavefront," typically a uniformly illuminated plane-wave. T
between measured and reference centroid positions, divided by the distance between the microlens array
is used to calculate the wavefront slope at each subaperture. Wavefronts are "reconstructed" by direct nu
integration of the measured slopes, or by fitting the slopes to the spatial derivatives of a suitable set of p
difference between the reference wavefront and the re con structed wavefront, measured in meters, is cal
path difference, or OPD.

As with any sensitive instrument, there are sources of technical noise that limit performance of the wavefront sensor. One fundamental source, when measuring laser light, is interference, or coherent cross talk, between the microlenses. For this reason, smaller RMS wavefront errors may be achieved using lasers that oscillate on many longitudinal modes, or using incoherent thermal sources of limited spatial extent, such as filtered white light coupled into a multimode optical fiber.

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