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AUTHOR(S): G. Lawrence, Univ. of Arizona
P. N. Wolfe, LASL

MASTER

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APPLICATIONS OF THE LOTS COMPUTER CODE TO LASER FUSION SYSTEMS AND OTHER
PHYSICAL OPTICS PROBLEMS*

G. Lawrence
Optical Sciences Center, University of Arizona
Tucson, Arizona 85721

P.N. Wolfe
Los Alamos Scientific Laboratory
P.O. Box 1663, MS 532
Los Alamos, New Mexico 87545

Abstract

The Laser Optical Train Simulation (LOTS) code has been developed at the Optical Sciences Center, University of Arizona under contract to Los Alamos Scientific Laboratory (LASL). LOTS is a diffraction based code designed to calculate the beam quality and energy of the laser fusion system in an end-to-end calculation.

Introduction

LOTS has been developed to act as a numerical model for the laser fusion system. Factors which must be considered in predicting the performance of this complex system are

- diffraction propagation
- nonlinear gain media
- saturable absorption media
- component aberration
- apertures of arbitrary shape
- spatial filters.

The laser fusion system calculations may consider as many as 100 optical surfaces in the optical path. Calculations involve collimated and noncollimated beams. To facilitate analysis of this type of system at reasonable cost strong emphasis has been placed on developing a flexible and efficient program with modest computer memory requirements.

Organization of the Program

In its current implementation LOTS uses a 64 by 64 complex array to represent the laser pulse. All components and processes in the system are represented as operators on this laser pulse array.

Laser Pulse Matrix

The work of Frantz and Nodvick⁽¹⁾, Schappert⁽²⁾ and others has shown that for CO₂ laser amplifiers of the type used in the laser fusion systems gain calculations may be done using the time-integrated pulse irradiance. This integrated quantity has units of energy per unit area and is referred to in this discussion as intensity, I(x,y). The intensity across the width of the beam is in general neither constant nor gaussian.

In order to handle optical phase perturbations of the laser pulse due to component aberrations, LOTS uses the complex amplitude A(x,y) where

$$I(x,y) = A(x,y)A^*(x,y)$$

A(x,y) has units of square root joules per centimeter.

Information Display

Strehl Ratio. The total energy and the Strehl ratio are the most useful measures of the laser pulse. The definition of Strehl ratio used in LOTS is somewhat generalized from that in common use.

$$\text{Strehl Ratio} = \left[\frac{\iint_{-\infty}^{+\infty} A(x,y) dx dy}{\iint_{-\infty}^{+\infty} |A(x,y)| dx dy} \right]^2$$

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This definition takes into account the effect of intensity nonuniformity and does not suffer from inaccuracy with large aberration as does the Marechal approximation.

Grey Tone Representation. One of the best ways to give a visual representation of the pulse characteristics is by means of grey tone pictures. LOTS allows the user to do this on line printers or on graphic or conventional terminals. The dynamic range in an image distribution taxes the capability of the eight grey shades. However interferograms and phase maps work well with this technique.

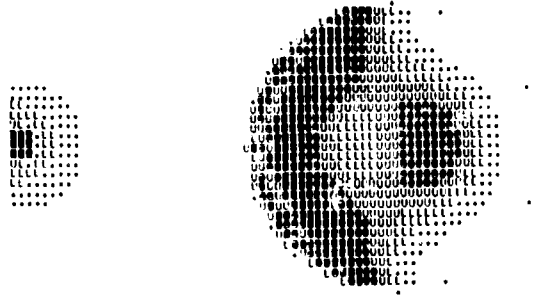


Fig. 1. Foucault test simulation. On the left is an image with spherical and focus error which is half blocked. On the right is the resulting pupil intensity distribution.

As an example, Figure 1 shows a Foucault or knife edge test done on LOTS. On the left is an image having spherical and focus error partially blocked by an opaque half plane. On the right is the irradiance distribution that would appear at the pupil of the optic under test.

Principal Operations

The principal operations are those representing the gain media, diffraction propagation, imaging and collimation, saturable absorbers, and component aberrations.

Gain Media

Even in a calculation whose primary purpose is to determine the phase errors of the laser pulse, it is necessary to include gain effects because the nonlinear gain changes the intensity distribution and therefore changes the effect of the phase errors on the final image at the target.

The gain of the CO₂ laser amplifiers as operated in the laser fusion experiments may be expressed in general form (1) as

$$\frac{dI}{dz} = a_0 I_S [1 - \exp(-\frac{I}{I_S})] - \frac{2I}{z_0 + z} \quad (1)$$

I = pulse intensity (joules/cm²)

a_0 = small signal gain

z = distance through the active medium

z_0 = the initial radius of the expanding beam

If the laser pulse is collimated in the gain media the right most term is zero and the resulting differential equation has a closed form solution. Otherwise LOTS solves the differential equation for each point in the matrix.

Saturable Absorption

Saturable absorbers are included in the optical path to reduce parasitic oscillations and for pulse shaping. This phenomena can not be treated by the Frantz-Nodvick theory. Instead the user of the code does a four parameter curve fit to experimental data relating transmission to incident pulse intensity.

Diffraction

Diffraction calculations may be divided into near and far field regions.

Near Field Calculations. The frequency space transfer function for free space propagation⁽³⁾ is

$$H(\xi, \eta) = e^{-j\pi\lambda Z(\xi^2 + \eta^2)} \quad (2)$$

$$Z = \frac{Z_2}{Z_1} (Z_2 - Z_1)$$

Z_1 = initial wavefront radius

Z_2 = final wavefront radius

ξ, η are spatial frequency parameters

This calculation is accurate for collimated and noncollimated beams within the scalar, small angle, Fresnel diffraction approximations and within the limits imposed by the sampling grid beams. The effective propagation distance may be used to give an effective Fresnel number.

$$F = \frac{a^2}{\lambda Z}$$

F = Fresnel number
a = aperture radius
Z = effective distance
 λ = wavelength

Numerical application of Equation 2 on a finite sample grid is in error at very high or very low Fresnel numbers. The most serious errors occur at low Fresnel numbers when the amplitude distribution expands to overflow the matrix creating an aliased condition. For these low Fresnel numbers a far field calculation may be used.

Far Field Calculations. For a long propagation distance the amplitude distribution⁽³⁾ is

$$P(x', y') = \frac{e^{jkZ}}{j\lambda Z} e^{j\frac{kr'^2}{2Z}} \iint_{-\infty}^{+\infty} P(x, y) e^{j\frac{kr^2}{2Z}} e^{-j\frac{k}{Z}(xx' + yy')} dx dy \quad (4)$$

$P(x, y)$ = initial complex amplitude
 $P(x', y')$ = final complex amplitude
 k = wave number
 $r^2 = x^2 + y^2$, $r'^2 = x'^2 + y'^2$

This expression is well behaved for large Z.

To get the expression for the distribution at the rear focal plane given the distribution at the lens replace Z in equation 3 with the focal length and drop the quadratic exponential in the integral.

For a collimating lens given the distribution at the front focal plane replace Z in equation 3 with the focal length and drop the quadratic exponential outside the integral.

Spatial Filters. A spatial filter consists of an imaging operation, a clear aperture, or pinhole, and a recollimation lens, often there is a stop before the focusing lens and after the collimating lenses as shown in Figure 2.

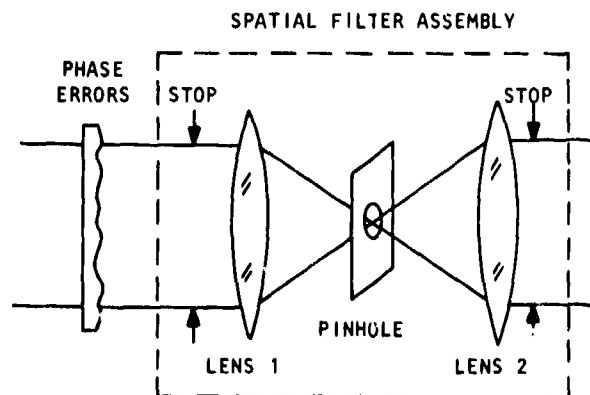


Fig. 2. Spatial filter assembly.

The pinhole will remove significant amounts of aberration.

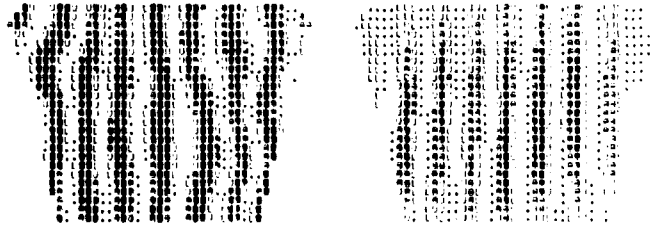


Fig. 3. Original wavefront on the left was passed through a spatial filter to achieve the improved wavefront on the right.

Figure 3 shows the phase error by means of interferograms before and after a spatial filter. In the process of removing the aberration the spatial filter introduces nonuniform illumination which appears as nonuniform contrast in the interferogram. The trapezoidal aperture is a typical one used in the Antares laser fusion system. Any general aperture may be defined in LOTS. In this example about 40% of the energy was removed by the spatial filter.

Component Aberrations

Because of the large f-numbers which prevail in the laser fusion system, aberration introduced by perfectly manufactured components would often be negligible. The large aperture salt windows and single point diamond turned surfaces are however particularly difficult to manufacture. These errors must be included.

Experimental Data. Where experimental data is available in the form of interferograms a fringe reduction program such as FRINGE⁽⁴⁾ may be used to fit a set of polynomial coefficients to the wavefront. These coefficients may be entered into LOTS. The original interferogram shown in Figure 4 was digitized and fit to polynomial coefficient with FRINGE. These coefficients were then used in LOTS to produce an interferogram on a line printer to give an indication of the quality of the fit.

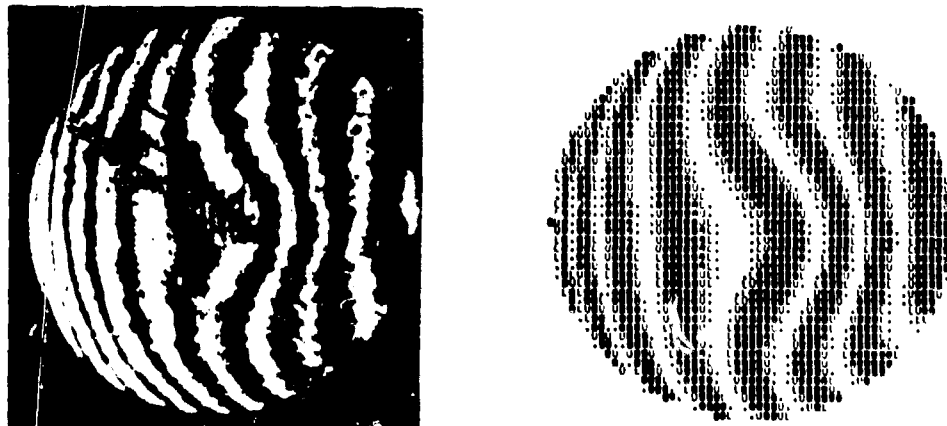


Fig. 4. The original interferogram on the left is shown on the right reproduced by LOTS on a line printer. Polynomial fit was done by FRINGE. Contrast is reversed in the computer interferogram.

Specification Data. In many cases calculations are done on systems where component aberration is defined only by specification data. LOTS can create smoothed random wavefronts of specified peak-to-valley or RMS wavefront error and with specified autocorrelation width.

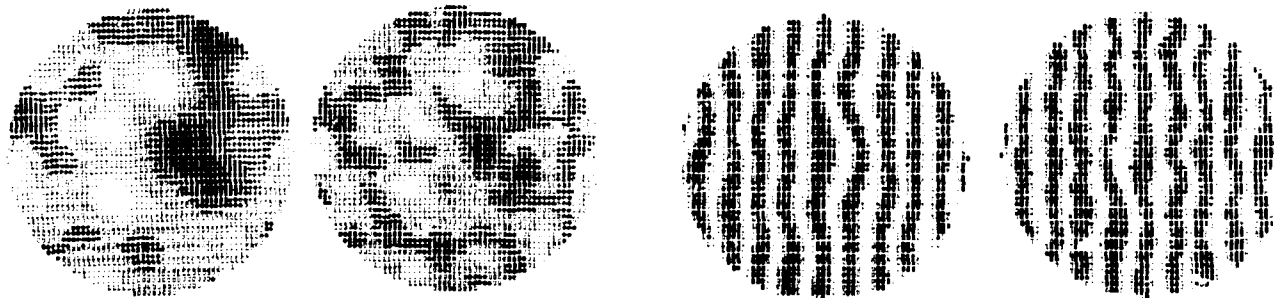


Fig. 5. Interferograms and phase maps of smoothed random wavefronts. The pair on the left has twice the autocorrelation width as those on the right.

In Figure 5 phase maps and interferograms are shown of two wavefronts which were formed with the same random function seed and with the same peak-to-valley error but with autocorrelation widths differing by a factor of two.

Application

In essentially its current form LOTS has been operating for two years at LASL and the Optical Science Center. The code is written to be user oriented. The manual for LOTS describes the approximately seventy command words and contains numerous examples illustrating the various operations.

The code has been used by V.K. Viswanathan on the Helios⁽⁵⁾ and Gemini⁽⁶⁾ laser fusion systems and by P.N. Wolfe on the Antares system⁽⁷⁾.

Conclusions

LOTS is a useful and efficient tool for analyzing a long optical train of the laser fusion type. The chief limitation is the fixed matrix size. A second version of the code with an expandable matrix to handle larger Fresnel numbers is under development.

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