Optimal Pinhole Loading via Beam Apodization

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ABSTRACT

An important consideration in the OMEGA EP laser design is the spatial shape of the beam at the beginning of the laser path. A sharp edge maximizes beam energy but also maximizes pinhole loading due to diffraction as the beam propagates. Several different beam shapes were investigated for OMEGA EP in order to minimize pinhole loading. Beam shapes from the super Gaussian family and hyperbolic tangent family were investigated. These beam designs were composed of two distinct sections, an upper portion and a lower portion, with the steepness of the curve differing between the two. Each of these beam designs was sent through an optimization function in MATLAB that optimized either the rise rate or super Gaussian order, depending on the family of the curve, and the joining point of the two portions. The function attempted to minimize the integral outside the pinhole. It was discovered that the left-handed skew from the hyperbolic tangent family performed the best.

1. BACKGROUND

1.1 Inertial Confinement Fusion (ICF)

At the University of Rochester Laboratory for Laser Energetics Inertial Confinement Fusion [1] is studied. ICF holds the promise of providing cheap, clean energy for many years to come. This process is achieved by firing 60 high power laser beams at a spherical target. This target is a plastic shell containing a frozen layer of deuterium and tritium that is about 0.1 mm thick. The 60 laser beams fire upon this pellet and deliver high amounts of energy to the target. Upon the laser beams coming into contact with the pellet, a dense plasma layer is created around the fuel. As this plasma heats up it expands outward, eventually releasing itself from the pellet.

As Newton's Third Law states, every action has an equal and opposite reaction. The outward expansion of the plasma layer results in an inward force being applied to the 0.1 mm thick fuel shell. Ideally, the implosion condenses the fuel shell to a radius approximately 30 times smaller than what it was prior to implosion, resulting in a very high fuel density. At this point, the fuel shell is under the conditions that allow for the fusion of deuterium and tritium to occur; the shell has extremely high temperature and extremely high pressure, all in a minute volume. Upon the fusion of the isotopes, neutrons escape at a high velocity. The expectation of the ICF program is to be able to produce more energy from this fusion reaction than is input through the firing of the laser beams.

1.2 OMEGA EP Laser System

The OMEGA EP laser system at the University of Rochester's Laboratory for Laser Energetics is capable of using two laser beams simultaneously to deposit 2.6 kJ of energy in a target less than one millimeter in diameter in approximately one picosecond. The OMEGA EP laser system will be used to supplement the 60-beam OMEGA system discussed in section 1.1. The combination of the two systems will result in the world's only facility capable of fully integrated fast-ignition experiments. This project dealt with optimizing the pinhole loading via beam apodization in the spatial filters of the OMEGA EP laser system.

1.3 Fourier Optics

Central to the theory behind the computational work I have performed is the concept of Fourier Optics. Fourier Optics assumes that, when dealing with a laser beam, the beam parts can be broken up into a near field and a far field. The near field is characterized by the laser beam's profile before it has passed through a spatial filter. The far field is the result of the near field after it has propagated, i.e. undergone a Fourier Transform.

Essentially a Fourier Transformation (FT) decomposes a function into a series of oscillatory functions such as sines and cosines. The equation for a Fourier Transform of a function f(t) is [2]

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{F}(\omega)\, e^{j\omega t}\, d\omega, \qquad \tilde{F}(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t}\, dt \tag{1}$$

where — denotes frequency (units of rad/s), t is time (units of s), and F(w) is the Fourier amplitude (a complex quantity).

Some of the applications of Fourier optics are indicated schematically in Fig.1 [3].

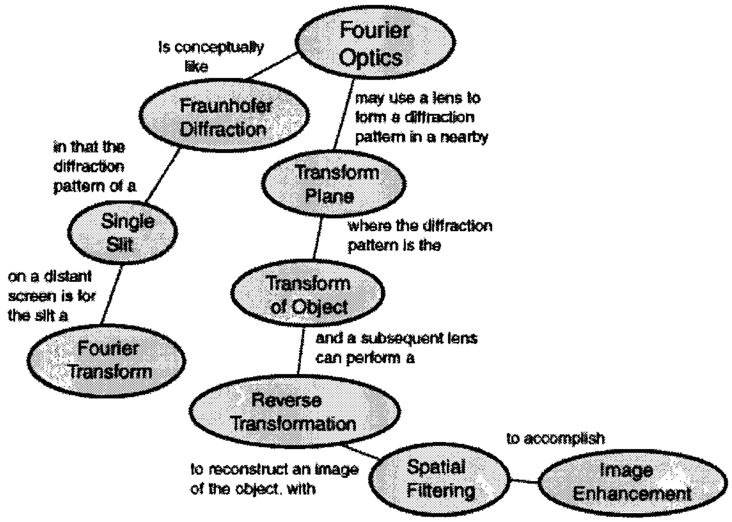

Fig. 1 – *Applications of Fourier Optics*

1.4. Problems in Laser System

As a beam propagates it picks up phase noise, which essentially acts like a lens inside the actual laser beam. Some causes of phase noise include imperfect optics, thermal effects, and self-focusing. The phase noise eventually widens the near field intensity profile. This is detrimental to the beam's proper functioning on target implosion. This phase noise leads to laser beam self-focusing and eventual laser damage, degraded image quality, and a degraded far field spot shape. All this occurs as a result of amplitude modulation, which develops as a result of the widened near field intensity profile caused by the phase noise.

In order to eliminate the beam phase noise the beam is passed through a spatial filter (see Fig. 2) [4]. The spatial filter removes the higher spatial frequencies from the beam in the far field, for it is these higher spatial frequencies that possess the greatest tendency to create phase noise. Yet excessive removal of the high spatial frequencies is detrimental to the beam as well. The greater the amount of energy outside the pinhole edge when the beam passes through the aperture, the more will be the ringing in the reconstructed near field.

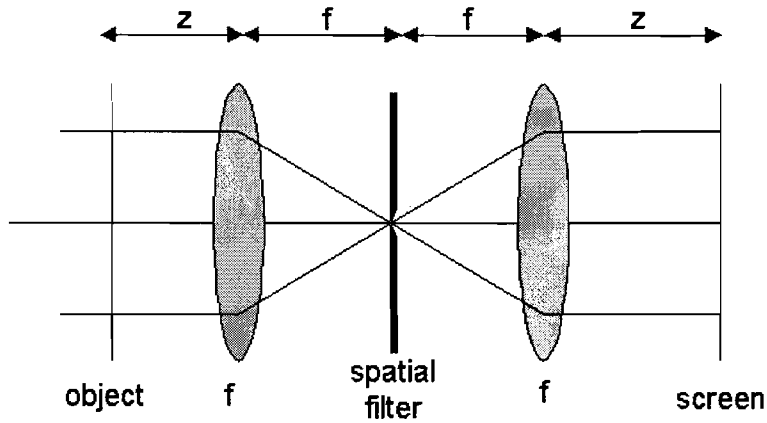

Fig. 2 – *Principle of a spatial filter: A beam is focused through a pinhole and recollimated, allowing higher spatial frequencies (or equivalently rays not propagating parallel in the incident beam) to be removed from the beam.*

Since the exact shape of the old beam's near field intensity profile can not be re-created due to the removal of the high frequencies, ringing takes place (Fig. 3). Such ringing occurs when the reconstructed near-field profile, after being recreated following passing through the pinhole with some of its original frequencies having been removed, differs from the original beam profile. Too much ringing will lead to more phase noise and then more amplitude modulation, and the cycle will continue until the laser destroys itself.

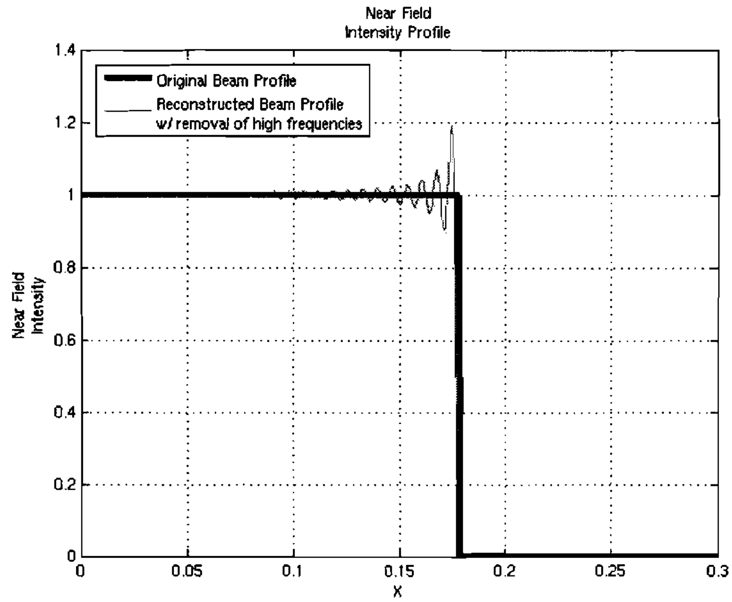

Fig. 3 – *Removing too much of the high frequency spectrum results in the reconstructed near field differing from the original near field.*

1.5 Project Goal

There are two contradictory requirements in constructing the near field beam shape. On one hand, the near-field area must be maximized so that the largest possible power can be delivered to the far field by the laser beam. On the other hand, the far field spot shape needs to be as small as possible so that pinhole loading can be minimized.

Pinhole loading occurs when excess beam energy, the side-lobes in the far field, strike the pinhole edge and, as a result, cause ringing in the reconstructed near field. In order to correct this problem, the beam must be apodized (i.e., passed through an optic that smoothens the edge of the beam profile). Unfortunately, the side lobes are a direct consequence of the diffraction of the laser beam. As we increase the near-field area, in order to get the most energy, we steepen the edge of the beam profile, the side-lobes become bigger and more pinhole loading is induced. My research task was to develop an equation for the beam shape that resulted in the most efficient balance between these two contradictory requirements.

2. METHODOLOGY AND CALCULATIONS

2.1. General Beam Shapes

Dickey and Holswade [5] have presented the theory and techniques of laser beam shaping. Approaches include geometric constraints via masks or optimization-based beam shaping algorithms. In the OMEGA EP system, the spatial shape of the beam is determined via a mask. We have adopted an optimization technique to design and shape the near-field intensity so as to obtain the optimal far-field distribution.

We investigated several different beam shapes for the OMEGA EP laser system. Each beam shape examined consisted of a flattop central portion, and a tailored "shoulder" connecting the central portion with the dark region outside the shoulder. The transition "shoulder" itself consists of two distinct sections, an upper section and a lower section, with the steepness of the curve differing between the two. We designed beam shapes using the super-Gaussian [6] and hyperbolic tangent families of curves. In order to have something to compare our new beam shapes to, a reference beam shape was created. This shape was defined as a beam with a square shaped near field intensity profile.

We used the symbolic and computational program MATLAB [7] to simulate the near field beam profiles, and to compute the far field diffraction pattern using Fourier optics. We optimized the rise-rate or super Gaussian order, depending on the family of the curve used, as well as the spatial location of the joining point of the upper and lower section. The optimization criterion we selected was the minimization of the integrated spectral power of the beam outside the pinhole.

2.2. Calculating Beam Shapes

The first beam shapes we investigated were those of a super Gaussian profile, see equation (2).

$$y = e^{-\left(\frac{x}{x_o}\right)^{sg}} \tag{2}$$

Of the super Gaussian branch of beam shapes, three were focused on, a symmetrical beam shape, a left handed skew, and a right handed skew. The symmetric beam shape has its tailored edge comprised of super Gaussian orders that are equal (Fig. 4). In the left hand skew the upper portion of the beam edge is of a higher order than is the lower section (Fig. 5). For the right hand skew, it is just the opposite; the lower portion is of a higher order than the upper portion (Fig. 6).

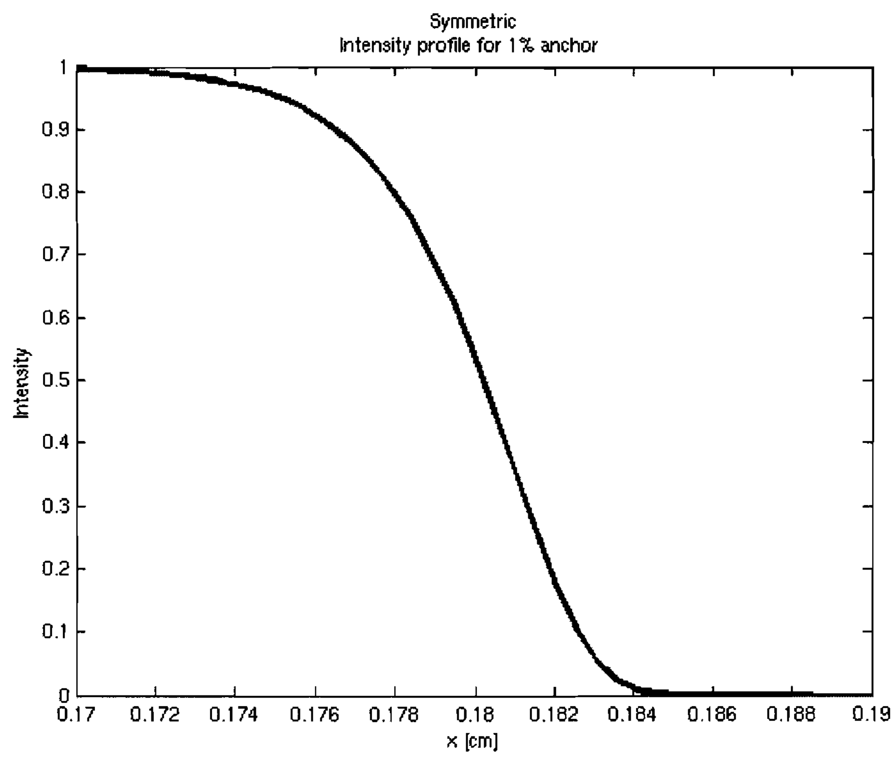

Fig. 4 – *In the symmetric beam edge, both the upper portion and lower portion have the same super Gaussian order.*

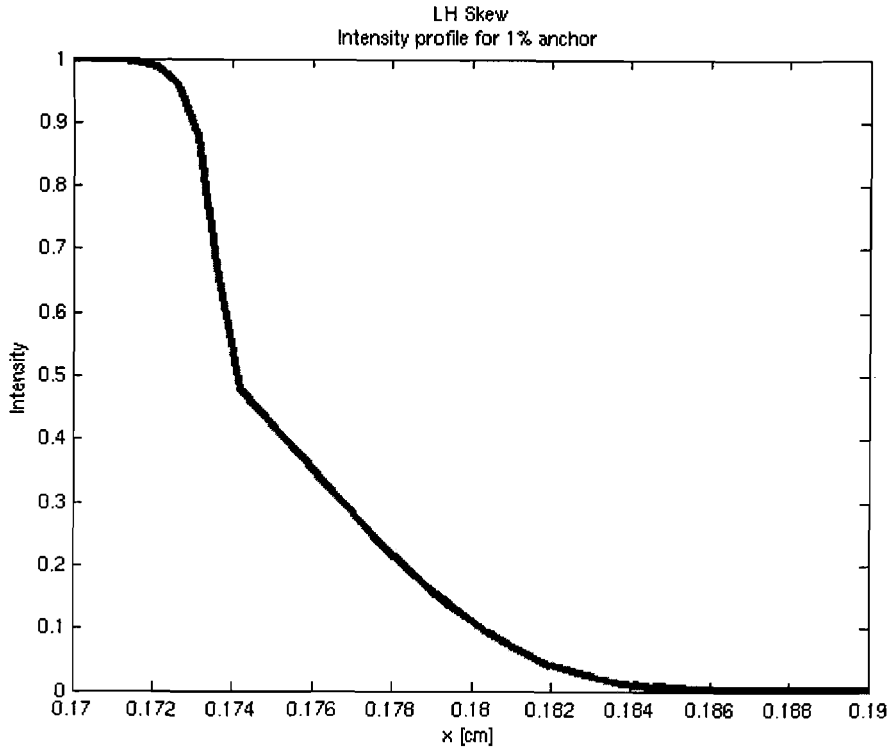

Fig. 5 – In the left handed skew, the upper portion has a higher super Gaussian order than the lower portion.

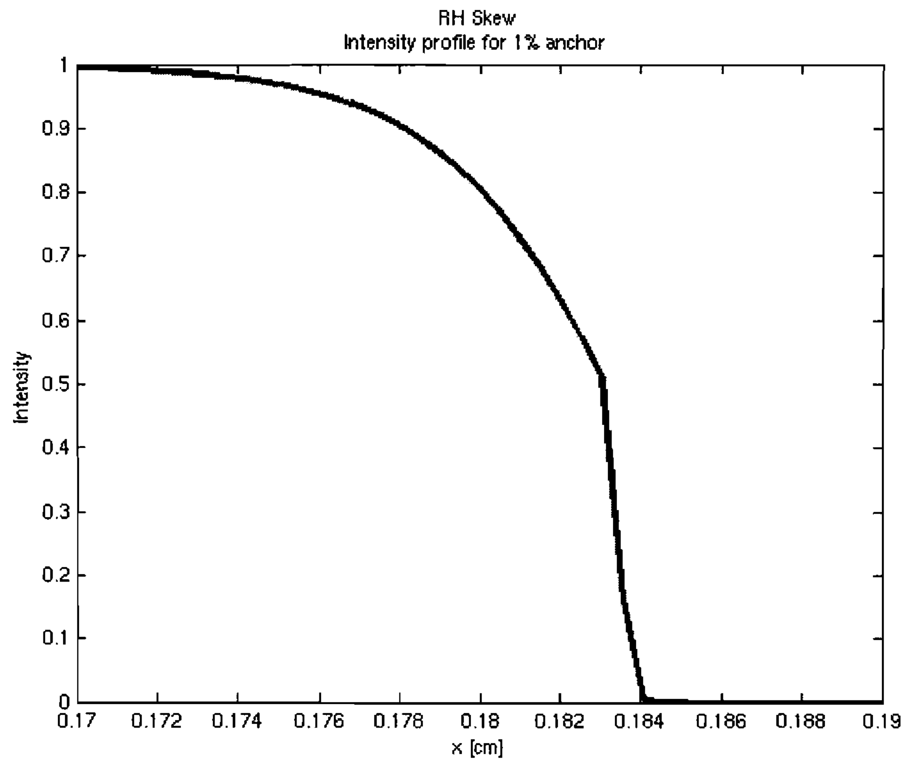

Fig. 6 – *In the right handed skew, the lower portion has a higher super Gaussian order than the lower portion.*

In addition, there were two important criteria that our tailored beam shapes had to meet. The first criterion was that the beam edge had to rise from the 1% intensity level to the 99% intensity level in 1.2 cm. The second was that the beam's intensity full width half maximum needed to be 35.6 cm.

We first began by manually calculating what the super Gaussian orders should be in each of the beam edges. Three distinct "anchor" points were used throughout the calculation. An anchor point is the point on the beam edge at which all of our calculations would originate. The calculations were made assuming a 1% intensity level anchor point, Xo as an anchor point, and a 99% intensity level anchor point. We proceeded to calculate what the super Gaussian orders would be with respect to each anchor point; the expectations were that each time each super Gaussian level would turn out the same regardless of which anchor point we used.

Upon receiving slightly different results with each anchor point, we constructed a MATLAB script that would optimize the area outside the pinhole edge, the rise rates, and the anchor points. In addition to investigating the super Gaussian family, we also tested the family of hyperbolic tangents, see equation (3).

$$f(x) = \tanh(\beta x) = \frac{e^{\beta x} - e^{-\beta x}}{e^{\beta x} + e^{-\beta x}} \tag{3}$$

The hyperbolic tangents operated in the same manner as did the super Gaussians: there were 2 pieces to the edge with the rise rate differing between the two and the MATLAB program sought to find the optimum rise rates that would minimize pinhole loading.

3. RESULTS

Our main conclusion was that the left-handed skew shape from the hyperbolic tangent family performed the best (Fig. 7). The spectral power outside the pinhole decreases by more than ten thousand times as compared to the uniformly shaped square beam.

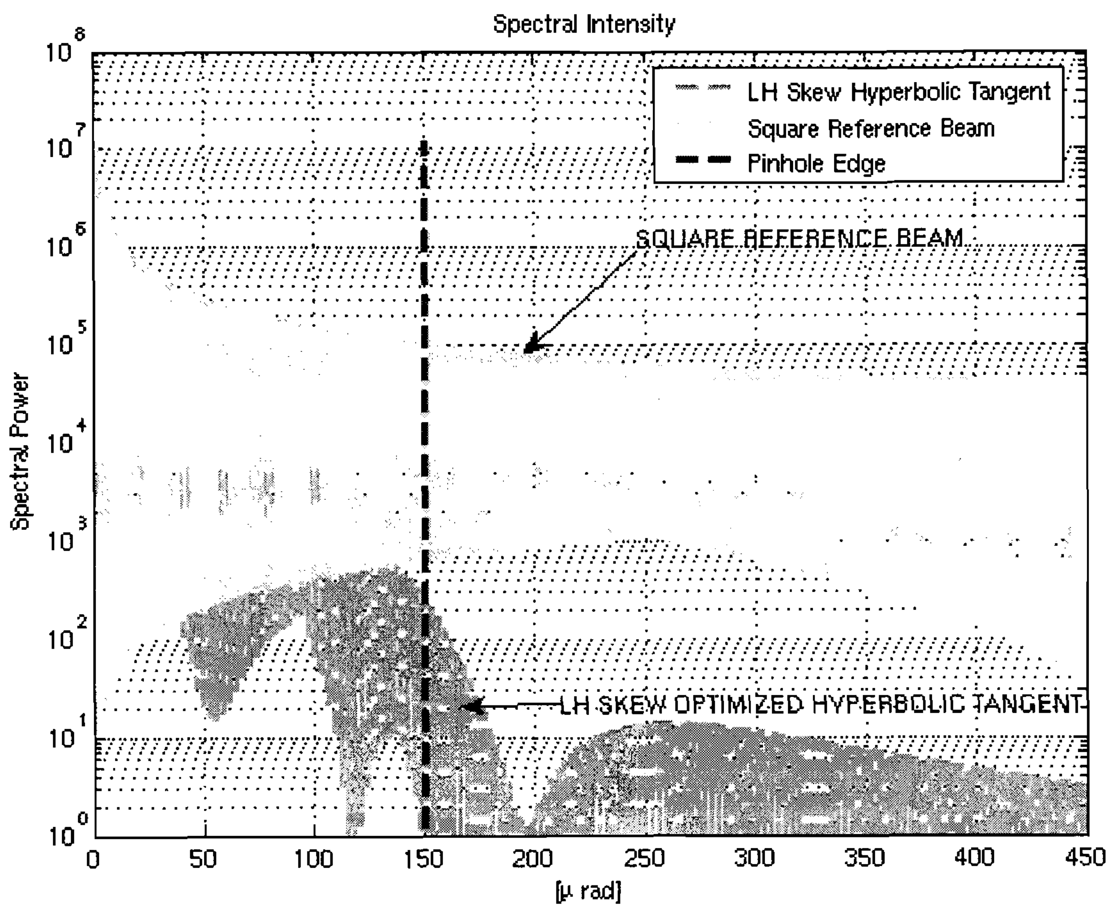

Fig. 7 – *The optimized hyperbolic tangent edge performed remarkably better than did the square reference beam. While producing very little spectral power outside the pinhole edge, the optimized beam edge nearly matched the square reference beam's spectral power inside the pinhole edges.*

The optimized profile eliminates nearly all "ringing" outside the pinhole by reducing phase noise (Fig. 8, Fig. 9), and concurrently allows the beam to be as powerful as possible in the near field.

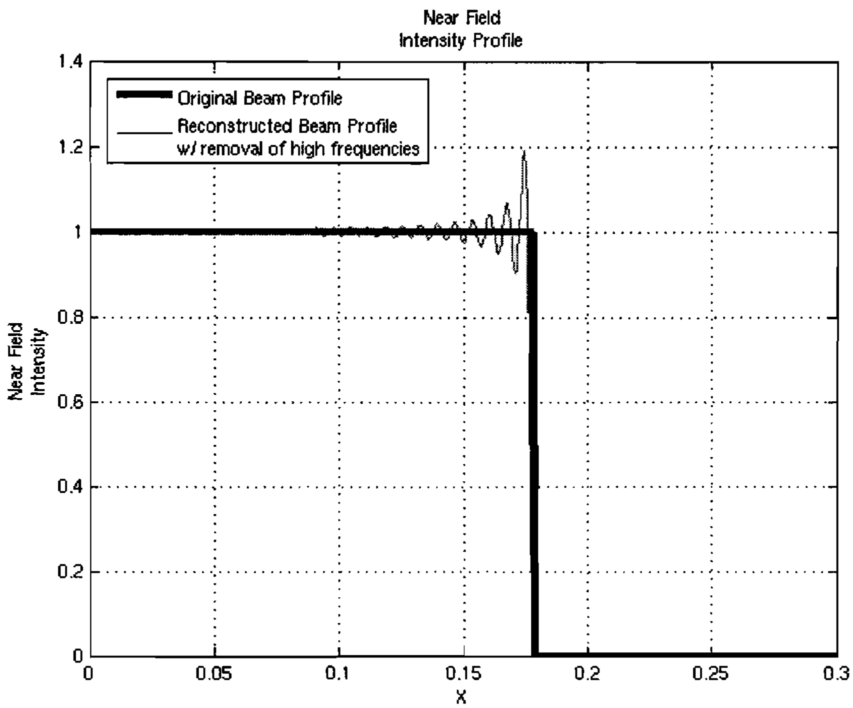

Fig. 8 – *Before optimization: The square reference beam's reconstructed near field profile shows very evident signs of ringing.*

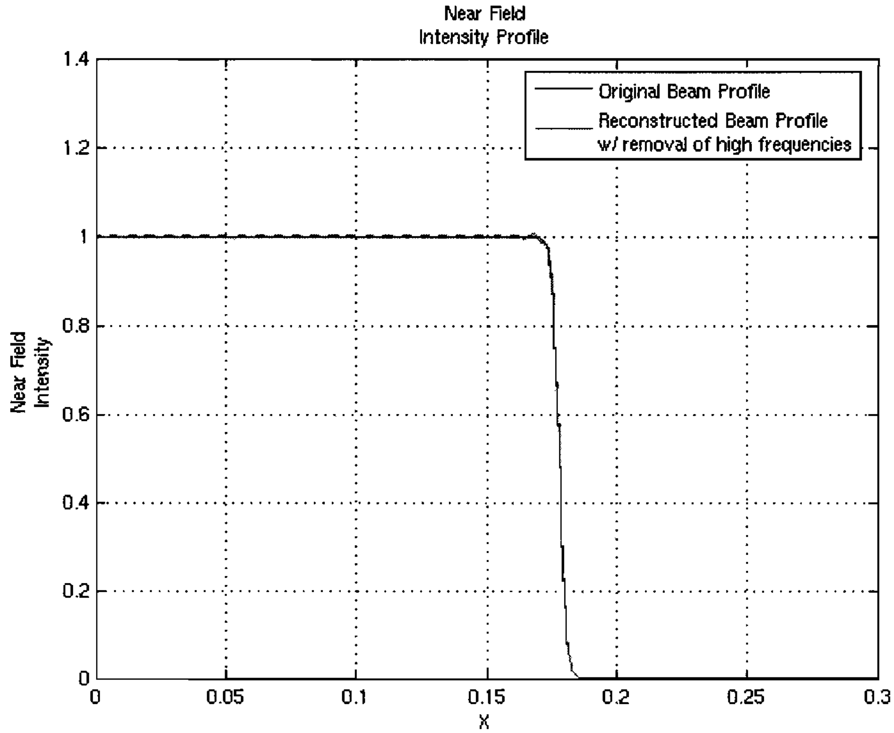

Fig. 9 – *After optimization: The reconstructed beam profile of the optimized beam is practically the same as before passing through the pinhole. The design goal has been met.*

This laser shaping technique may be applied to biomedical optics, laser surgery involving small blood vessels, and laser micropatterning of silicon or polymer materials used in displays or light emitting diodes.

ACKNOWLEDGMENTS

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