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Laser Beam Intensity Shaping with Low Laser Beam Quality

Author: Dr. Justin Mansell
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1 Introduction

In prior work, we have shown that shaping the intensity profile of a laser beam can be accomplished quite effectively by modifying the phase of the beam and then allowing the beam to propagate a distance away from the plane in which the phase was added. In virtually all the cases we have studied up to this point, the laser was assumed to be a beam of near perfect beam quality. In this application note, we examine the possibility that the laser is not of perfect quality but instead has a significant degradation of quality.

1.1 Laser Beam Quality

Laser beam quality can be thought of in terms of the content of higher-order spatial (aka transverse) modes. (In reality, it may be that the beam quality is reduced by phase aberrations like thermal lensing or aberrations in the gain medium, but these can be thought of as coupling mechanisms to higher-order modes). The lowest-order mode (Hermite-Gauss or Laguerre-Gauss) is a Gaussian intensity profile with perfect phase and has perfect beam quality. This perfect beam quality corresponds to an M^2 of 1.0 where M^2 is the ratio of the actual to theoretical spreading of the beam. Lower quality lasers have higher M^2. For a real laser with non-ideal beam quality, the minimum focused spot size is increased by M^2.[1] (Siegman wrote many papers on laser beam quality, but one of the classic papers is "How to (maybe) measure laser beam quality" which covers this topic in significantly more detail.[2]).

Many laser manufacturers are now reporting their lasers Beam Propagation Parameter (BPP), which is the product of the beam radius and divergence half-angle, instead of M^2. M^2 can be determined from this parameter by taking the ratio of the actual to theoretical BPP. For a Gaussian beam, the BPP is given by[3,4]

$$BPP = (w_0) \cdot \left(\frac{\lambda}{\pi w_0} \right) = \frac{\lambda}{\pi}.$$

A 1070nm laser has an ideal BPP of 0.341 mm*mrad. Therefore, if we have a laser with a BPP of 12 mm*mrad and a wavelength of 1070nm, the M^2 for this beam is 35. For a beam with a BPP of 4 mm*mrad, the M^2 is 12.

[1] https://en.wikipedia.org/wiki/Laser_beam_quality
[2] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.177.3400&rep=rep1&type=pdf
[3] https://en.wikipedia.org/wiki/Gaussian_beam
[4] https://en.wikipedia.org/wiki/Beam_parameter_product

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2 Modeling Approach

In this application note, we used a simple modeling technique to illustrate the effect of lower beam quality on laser beam shaping. We will start with the assumption that we are able to affect the phase such that the intensity profile after propagation is a rectangular top-hat. We then convolve that rectangular top-hat with a Gaussian of varying size to represent the effect of diffraction and reduced laser beam quality. The rectangular shape is always 1.0 in diameter in one axis and is varying in size in the other axis. An example 4:1 rectangular shape is shown in Figure 1. We used a 512x512 point grid throughout this modeling.

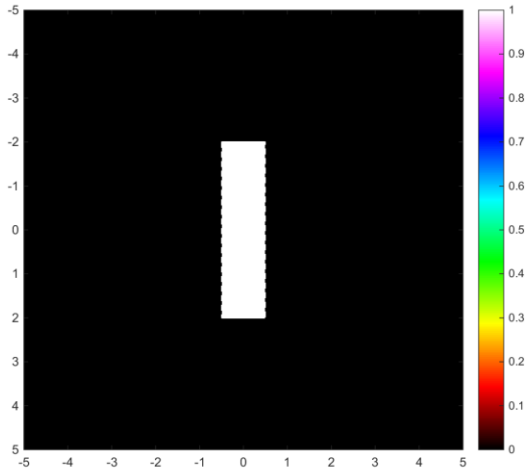

Figure 1: Rectangular Shape with Aspect Ratio 4.0

Then this shape is convolved with a Gaussian ($\exp(-(r/w)^2)$ where w is the waist) with waist varying from 0.25 units to 6 units in increments of 0.25. To evaluate the effect of the convolution on the intensity aspect ratio, the second moment was evaluated on the convolution result with a 13.6% threshold. We also evaluated the intensity profile with no convolution and called this a Gaussian waist size of 0.0. The ratio of the X and Y second moment size was then calculated and plotted for each of these Gaussian waist sizes.

3 Results

Figure 2 and Figure 3 below show the results obtained for analysis of the 4:1 and 12:1 aspect ratio rectangles. In both cases, the second moment ratio begins very near the rectangular aspect ratio, but quickly approaches 1.0 as the Gaussian convolution kernel increases.

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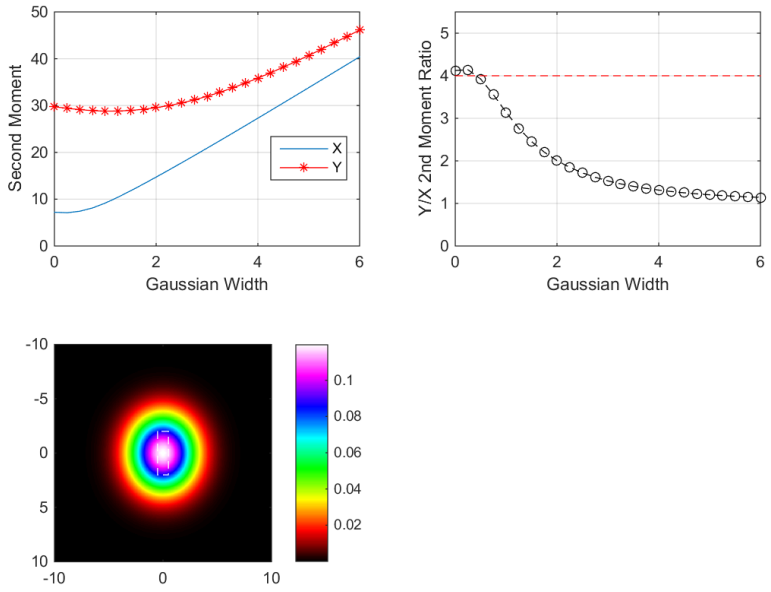

Figure 2: Results for the 4:1 Aspect Ratio Rectangle

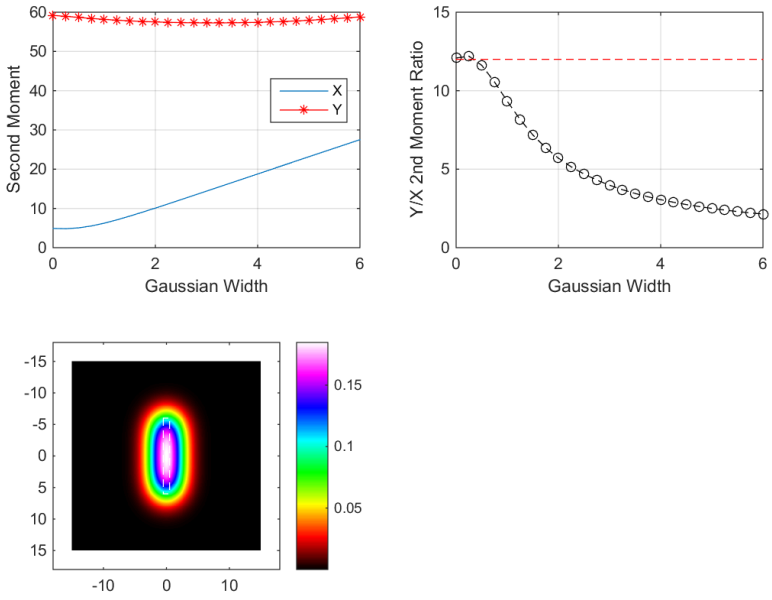

Figure 3: Results for the 12:1 Aspect Ratio Rectangle

4 Conclusions

From this result, we see that a low-quality laser beam will reduce the efficacy of the phase-based beam shaping. Shaping with this kind of beam can still be accomplished, but will likely require more phase amplitude to achieve good results.

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5 Appendix: Example Matlab Code

The following Matlab code was used to obtain the results in this application note. Some of the dependent functions are not available. This code is here to show the core functionality.

```
Setup;
ppt=1;

if (ppt)
    TitleSlidePowerPoint('Analysis of Gaussian Convolution on the Beam Aspect
Ratio');
end;

nxy = 512;
thr = 0.136;
wvec = 0.25:0.25:6;
ratiovec = 4:2:12

nf([1,1,1]);
for ratioval = ratiovec;
    Dap = (ratioval+max(wvec)*2)*1.25;
    dxy = Dap/nxy;
    x = (-nxy/2:1:nxy/2-1).*dxy;

    c=1;
    ap = RectAp(nxy,dxy,1,ratioval);
    [xc(c),yc(c),x2(c),y2(c)]=MomentsWithThreshold(ap,thr);
    wvecplot(c) = 0;
    ap = RectAp(nxy,dxy,1,ratioval);
    clf; show(x,x,ap);
    ax=(ratioval+1).*[-1 1 -1 1]; axis(ax);
    hold on; plot(0.5.*[-1 -1 1 1 -1],ratioval.*0.5.*[-1 1 1 -1 -1],'w--');
    if (ppt)
        ToPPT('Aperture');
    end;

    for w = wvec;
        c=c+1;
        kernel = Gaussian(nxy,dxy,w/2);
        kernel = kernel ./ (sum(kernel(:)));

        out = conv2(ap,kernel,'same');

        [xc(c),yc(c),x2(c),y2(c)]=MomentsWithThreshold(out,thr);
        wvecplot(c) = w;

        clf;
        subplot(2,2,1);
        plot(wvecplot,x2);
        hold on;
        plot(wvecplot,y2,'r*-');
        xlabel('Gaussian Width'); ylabel('Second Moment');
        legend('X','Y','Location','Best');
        ax=axis;ax(3)=0; axis(ax);
```


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```
        grid on;
        subplot(2,2,2);
        plot(wvecplot,y2./x2,'ko--');
        hold on; plot(wvecplot,wvecplot.*0.0+rationval,'r--');
        ax=axis; ax(3)=0; ax(4)=ax(4)+1; axis(ax);
        xlabel('Gaussian Width'); ylabel('Y/X 2nd Moment Ratio');
        grid on;
        subplot(2,2,3);
        show(x,x,out);
        ax=(rationval+max(wvec)).*[-1 1 -1 1]; axis(ax);
        hold on; plot(0.5.*[-1 -1 1 1 -1],rationval.*0.5.*[-1 1 1 -1 -1],'w--
');
        drawnow;
        if (ppt)
            if (wvec(1)==w || wvec(end)==w)
                ToPPT();
            end;
        end;

        drawnow;
    end;
end;
```


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