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Measurement of PSL beam profile on IOO table in Hanford

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1 Introduction

This document describes the measurement on the PSL beam profile that we carried out on the IOO table at the Hanford site. The purposes of this measurement are:

1. to check if the PSL beam is appropriately delivered to the three electro-optic modulators (EOMs) for the sideband generation, and
2. to confirm that thermal lensing effect in the three EOMs is small enough not to affect the mode matching to the mode cleaner.

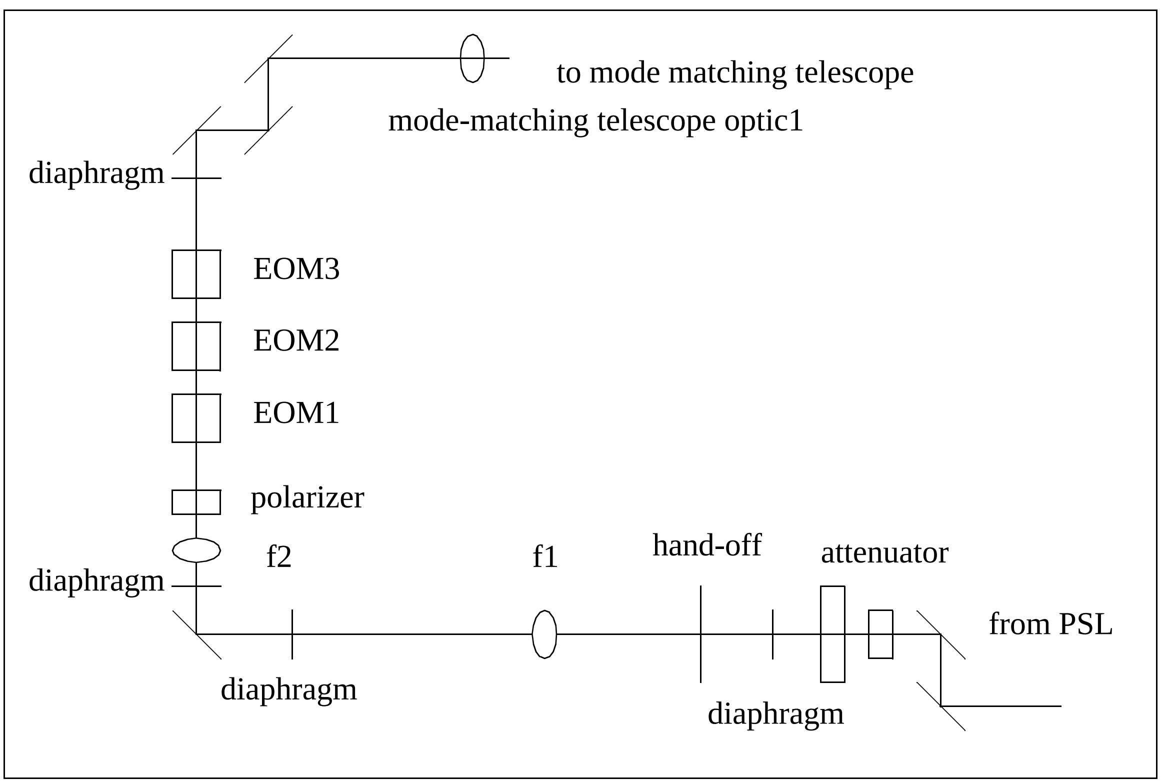
Thus the range of the measurement along the beam path was limited between the two corner mirrors before and after the three EOMs.

2 Measurement

2.1. Setup and alignment

Fig.1 illustrates the optics on the IOO table after the PSL/IOO hand-off point.

Figure 1: Optical components on IOO table



The PSL beam has a waist at the hand-off point with a waist size of 0.55 mm. In order to have the PSL beam pass through the three EOMs with the intensity loss caused by beam clipping at the apertures of the EOMs' housings less than 10 ppm, the waist size must be less than 0.395 mm at the center of the second EOM (called the designed waist location, hereafter). On the other hand, smaller waist sizes can damage the $LiNbO_3$ crystal. It is therefore important to adjust the waist size and location at these designed values as precisely as possible. This mode matching is actualized by the two mode matching lenses f1 and f2 (nominal focal length of 550 mm) placed between the hand-off point and the EOMs.

We first aligned the PSL beam path without placing the mode matching lenses f1 and f2 on the table. For this alignment, we attenuated the PSL power to 160 mW before the hand-off point using an attenuator consisting of a cubic polarizer and a halfwave plate. Using optical diaphragms at a diameter smaller than 1 mm, we defined each optical path between corner mirrors. Two diaphragms were used in each optical path between a pair of corner mirrors.

Then we inserted lenses f1 and f2 at the designed locations and adjusted the transverse location and angle of incident so that the beam passed through the same trajectory as the case when the mode matching lenses f1 and f2 were not placed, using the same diaphragms as above.

2.2. Spot size measurement

2.2.1. Initial beam profile measurement and waist adjustment

On completion of the beam path alignment, we adjusted the locations of the mode matching lenses f1 and f2 on the beam path so that the beam would have the designed waist size of 0.395 mm at the designed waist location. Thus we measured the beam spot size using a beam scanner attaching it to a rail placed along the beam path around the designed waist location. This beam scanner provided the horizontal and vertical intensity profiles at a given plane perpendicular to the beam path. From these profiles we extracted the beam spot size for the respective directions. In this way, we measured the horizontal and vertical spot size as a function of the distance from the designed waist, and adjusted the locations of f1 and f2, respectively, until the measurement showed a waist at the designed waist location with a waist size as close as possible to the designed value of 0.395 mm and a circularity as close as possible to unity.

Fig. 2 shows the best profile of the horizontal and vertical spot sizes that we could achieve by the above-mentioned adjustment. Under this condition, the ellipticity of the beam around the waist was 2 - 3%. Fig.3 shows the intensity at the EOMs' housing aperture (2 mm in diameter) with reference to the intensity at the beam center. It indicates that the clipping loss is lower than 10 ppm, as designed, through out the three EOMs. Here the horizontal axis of these figure indicates the distance from the designed waist location where the positive value corresponds to the upstream side of waist, and the centers of the first and third EOMs are located +-10.16 cm (4") from the designed waist, respectively, with the EOM housing length of 55 mm.

Figure 2: PSL beam profile around designed waist location (no EOM)

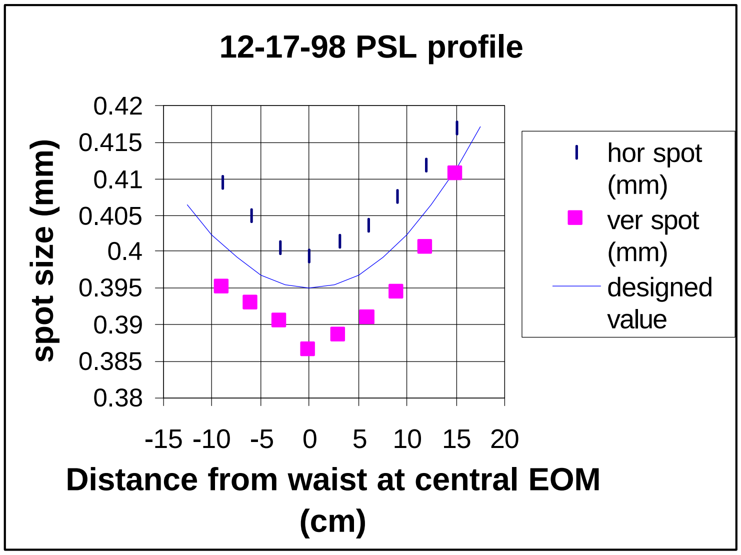
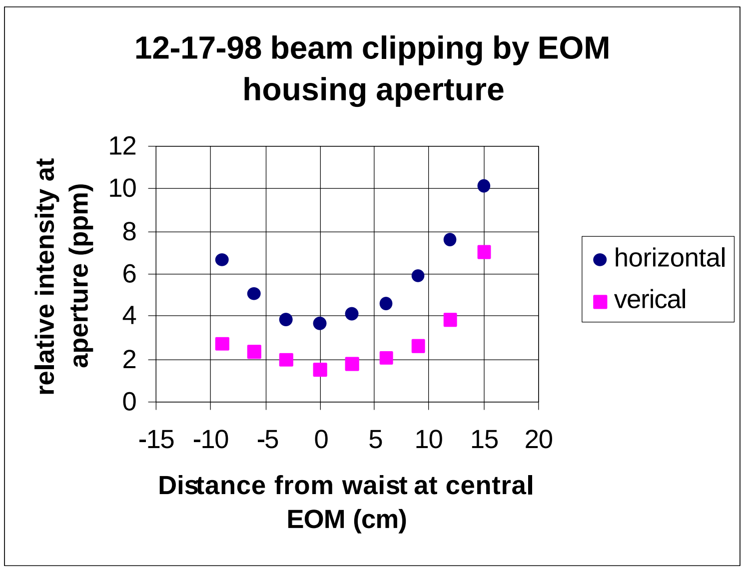


Figure 3: Relative intensity at the EOM housing aperture

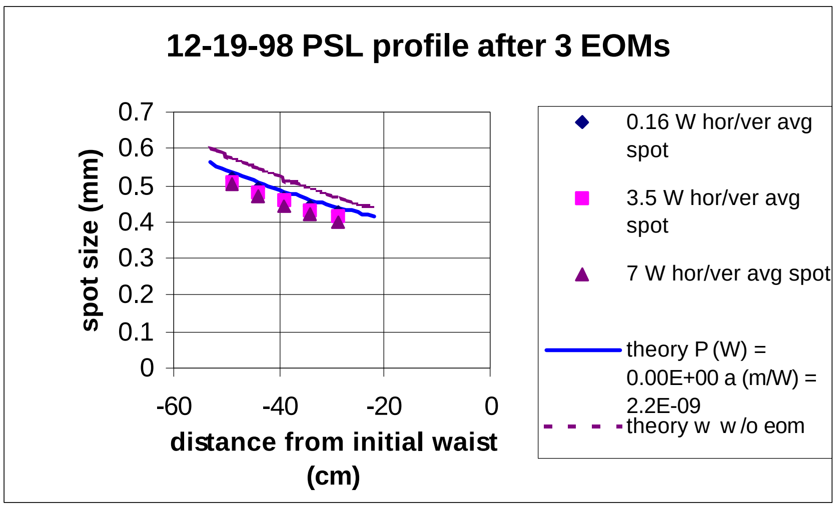


2.2.2. Spot size measurement with three EOMs

Fig. 4 shows the spot size measured at the downstream of the EOMs at three different PSL powers. The horizontal axis denotes the distance from the designed waist location, as Fig.2 and 3. The PSL intensity was varied by adjusting the attenuator placed before the hand-off point. To make the intensity incident to the beam scanner constant at the power level of 160 mW, another similar attenuator was placed between the third EOM and the beam scanner.

As the PSL power increases the spot size is seen to decrease slightly, indicating the thermal lensing effect. The dashed line represents the same theoretical curve as Fig.2, i.e., the theoretical spot size when the EOMs are absent. The solid line represents the theoretical spot size when the three EOMs are placed. The difference between these theoretical curves represents the phase change due to the difference in the index of refraction between the air and $LiNBO_3$. (For the thermal lensing effect and the theoretical curves with the EOM, see below.)

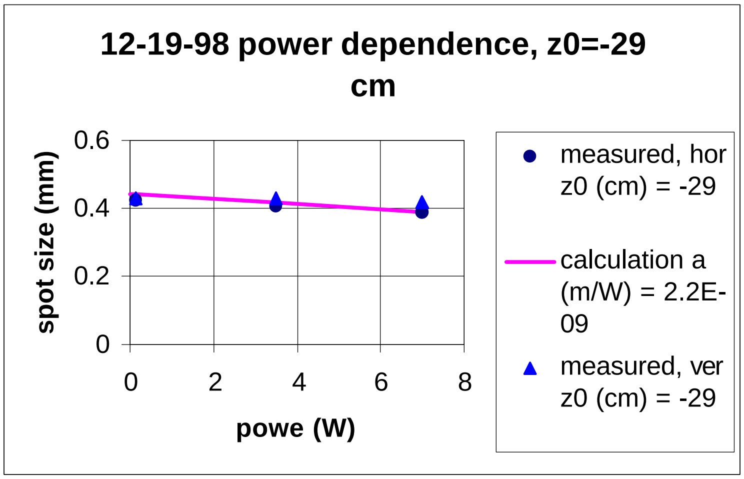
Figure 4: PSL beam profile after the EOMs



2.2.3. PSL power dependence

Fig.6 shows the dependence of the spot size measured at 29 cm downstream of the designed waist location on the PSL power. The negative slope represents the thermal lensing effect that causes the PSL to be focused, thereby making the spot size smaller. This change in the beam profile caused by the thermal lensing is within the range correctable by the mode matching telescope.

Figure 5: PSL power dependence of the spot size



3 ANALYSIS

3.1. ABCD matrix and thermal lens

To investigate the thermal lensing effect on the spot size of the PSL, we calculated the spot size by modeling the EOM as a medium having a quadratic index variation. The ABCD matrix for such a medium can be written as follows.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos(\sqrt{\gamma}\cdot l) & \frac{1}{\sqrt{\gamma}}\sin(\sqrt{\gamma}\cdot l) \\ -\sqrt{\gamma}\sin(\sqrt{\gamma}\cdot l) & \cos(\sqrt{\gamma}\cdot l) \end{bmatrix}$$

where

$$\gamma = \sqrt{\frac{k2}{k}}$$

and k and k2 are related to the refractive index as

$$k(r) = k0\left(n - n2\cdot\frac{r^2}{2}\right) = k0\cdot n - k0\cdot n2\cdot\frac{r^2}{2} = k0\cdot n - k2\cdot\frac{r^2}{2}$$

and n(r) is given as

$$n(r) = n - \frac{1}{2}\cdot n2\cdot r^2$$

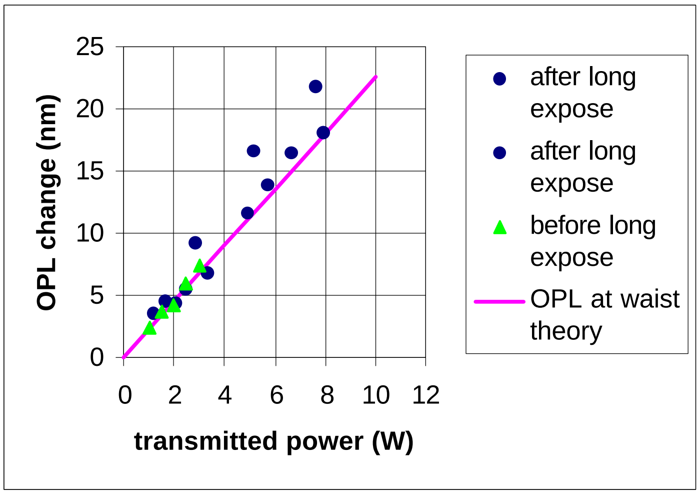
Here k0=2π/λ0, λ0 being the YAG laser wavelength in a vacuum 1.06 μm and n is the index of refraction on the beam axis, or the center of the thermal lens.

Our previous thermal lensing measurement for the same EOM by a Shack-Hartmann wavefront detector indicates that the optical path length change due to the thermal lens at a given radius with reference to the beam center (ΔOPL) is a linear function of the heating laser power, i.e.,

$$\Delta OPL = a \cdot P$$

where P is the laser power and a is the coefficient. Fig. 7 shows ΔOPL at r corresponding to the spot size of the heating beam (Nd:YAG) as a function of the laser power. From this figure, the coefficient a can be estimated as 2.2×10^{-9} m/W.

Figure 6: Previously observed thermal lensing in the same EOM



Since ΔOPL is related to the refractive index as

$$\Delta OPL = \Delta nl = \frac{1}{2} \cdot n2 \cdot w^2 \cdot l = a \cdot P$$

where l is the length of the medium and P is the power of the heating beam, n2 can be calculated for a given spot size. Thus from the above equations, γ at r corresponding to the spot size w can be expressed in terms of a, l, n and P as shown below.

$$\gamma = \sqrt{\frac{k2}{k}} = \sqrt{\frac{n2}{n}} = \sqrt{\frac{\frac{2aP}{w^2 \cdot l}}{n}}$$

Then taking into account the refractive index of $LiNbO_3$ by using the following two matrices at the entrance and the exit surface, respectively, of each EOM, the spot size can be calculated in the whole optical path. The theoretical curves shown in Fig. 4 (solid line) and Fig.5 were calculated in this fashion.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1/n \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & n \end{bmatrix}$$

3.2. PSL at various power

In Figures 7 and 8, we show the measured spot size at two PSL powers respectively over a longer beam path than Fig.4, comparing them with the case where the EOMs were not placed. It is clear from Fig. 5 that when the PSL is 160 mW the thermal effect is negligibly small. Therefore, in Fig.7, the difference between the two theoretical lines represents the change in the refractive index caused by the insertion of the three EOMs.

Figure 7: Spot size along PSL beam path at 160 mW

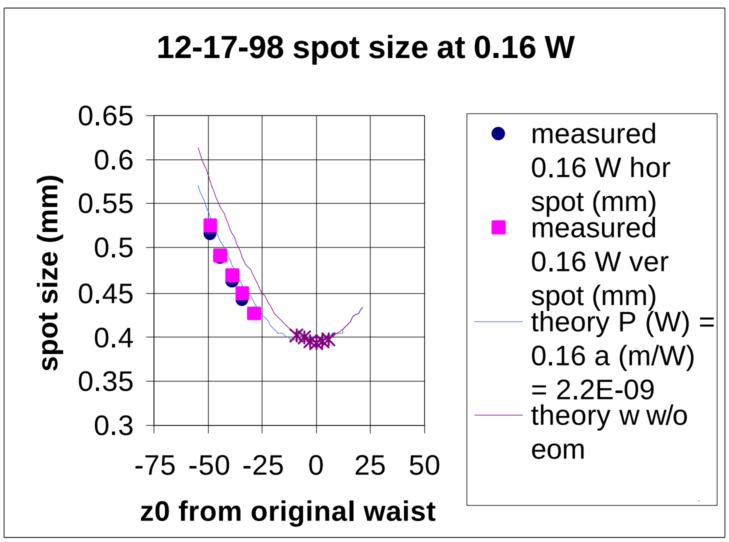
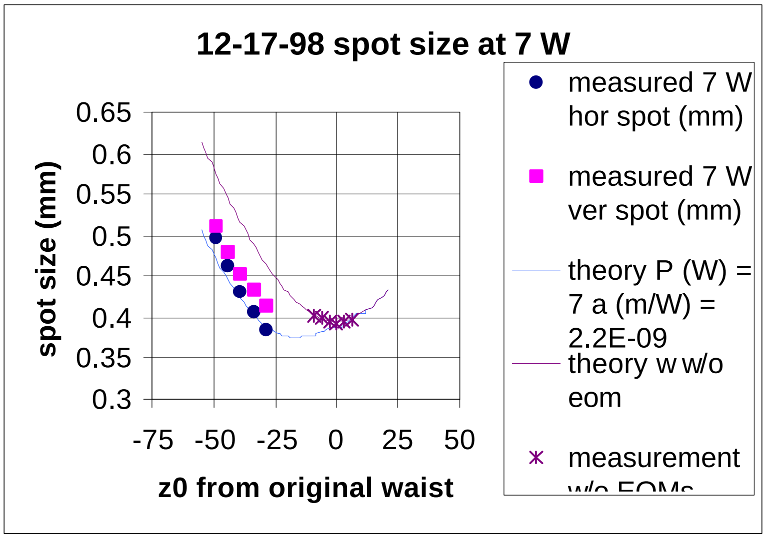


Figure 8: Spot size along PSL beam path at 7 W



4 SUMMARY

We have measured the spot size of the PSL beam along the beam path near the three EOMs. The mode matching by two lenses were successful in the sense that the clipping loss by the apertures of the EOM housing was lower than the designed value of 10 ppm. The change in the beam profile caused by thermal lensing effect at 7 W was small enough to be corrected by the mode matching telescope.