UCRL-JC-124507
PREPRINT

Electro-Optic Deflectors as a Method of Beam Smoothing for Inertial Confinement Fusion

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This paper was prepared for submittal to the
2nd Annual International Conference on
Solid-State Lasers for Application to ICF
Paris, France
October 22-25, 1996

January 8, 1997

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ABSTRACT

The electro-optic deflector is analyzed and compared to smoothing by spectral dispersion for efficacy as a beam smoothing method for ICF. It is found that the electro-optic deflector is inherently somewhat less efficient when compared either on the basis of equal peak phase modulation or equal generated bandwidth.

Keywords: Beam smoothing, beam deflection, smoothing by spectral dispersion, inertial confinement fusion.

1. INTRODUCTION

In recent research,[1] an electro-optic deflector (EOD) has been investigated for use as a beam smoothing method for ICF. The principle of operation is to impose a time varying angular deflection on the beam by applying a time varying field gradient across an electro-optic crystal. In a manner similar to the smoothing by spectral dispersion method (SSD),[2] which generates beam deflection by phase modulation and spectral dispersion, the EOD can shift and smooth the speckle pattern generated on the target by a phase plate and focusing lens. It is shown that in direct comparison to an optimized SSD beam smoothing system the beam divergence obtained with an EOD system using equal peak (sinusoidal) phase modulation is at best smaller by a factor of π. This reduced divergence translates into poorer asymptotic smoothing performance at equal peak phase modulation. The asymptotic effective number of averaged speckle patterns (the inverse of the normalized variance σ^2) obtained with the EOD is smaller by a factor of ~ 2.5 compared with 1D SSD of the same peak phase.

The reduced asymptotic performance of the EOD can be overcome by increasing its peak phase modulation. The limitation on peak phase modulation of a given modulator design will generally be determined by breakdown within the RF cavity owing to the large electric fields present. Therefore, one expects the maximum phase modulation of an EOD cavity to be similar to that of a frequency modulator (FM) cavity of similar design. In this case one expects that FM-SSD would have a better asymptotic performance limit than EOD when similar modulators are used. Another limit on beam smoothing is imposed by the bandwidth limitations of frequency conversion in an ICF laser. Assuming equal bandwidth one can show that, for SSD and EOD systems of equal asymptotic performance, the initial smoothing rate of the EOD will be reduced in comparison to that of SSD by a factor of ~ 2.5.

The EOD is an attractive solution to the smoothing problem in that the gratings required for SSD can be eliminated. On the other hand, the peak electric field, crystal length product is required to be ~ 2.5 times larger to achieve smoothing equivalent to SSD. If an EOD can be designed to accomplish this (while insuring adequate beam quality and a reliable RF mode), then an FM modulator based on a similar resonator concept using 1/6.3 of the RF power (or 1/2.5 the crystal length) would achieve the same smoothing using SSD. All these considerations apply for the case where the applied electric field in the EOD has zero value at beam center. If the EOD design does not have this optimal arrangement then the performance when compared to SSD can be further reduced.

2. ANALYSIS OF THE ELECTRO-OPTIC DEFLECTOR

The EOD principle of operation is to imprint a time varying phase on a beam, in which the phase also has a linear variation along the deflection direction (Fig. 1).

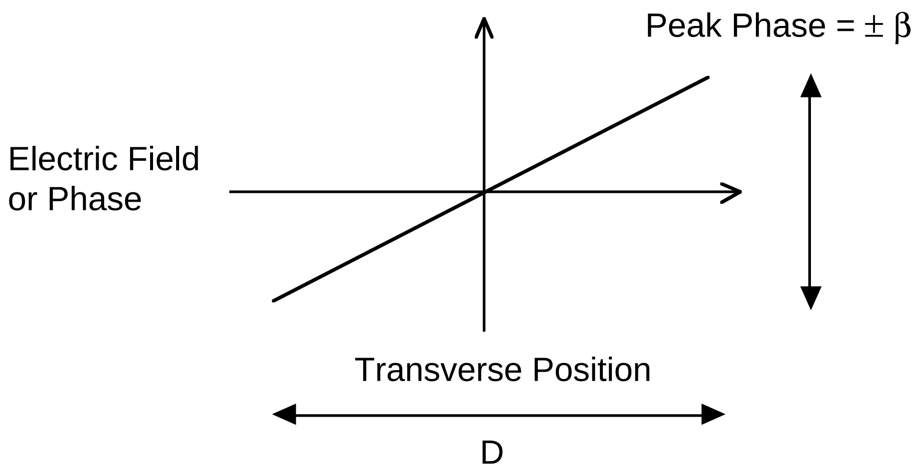

Figure 1: Electric field and phase variation across the beam of width D in an EOD.

For sinusoidal modulation one has that

$$E_{EOD}(x,t) = \exp[i(2x/D)\beta \sin \omega t] \equiv \exp[ik_x(t)x] \ , \tag{1}$$

where $-D/2 \le x \le D/2$, D is the beam width, $\pm\beta$ is the peak phase modulation, and ω is the modulation frequency. In the far field the angular deflection is simply given by

$$\theta(t) = k_x(t)/k_0 = \lambda\beta \sin \omega t / \pi D \ , \tag{2}$$

where $k_0 = 2\pi/\lambda$. The peak angular excursion is given by

$$\theta_{\max} = \pm \frac{\beta}{\pi}\frac{\lambda}{D} \ . \tag{3}$$

Defining the diffraction limited divergence as $2\lambda/D$, one sees that the deflector produces a beam which is β/π times diffraction limit (TDL). Note that this result is independent of beam size and modulation frequency.

In contrast, consider simple frequency modulation with the same peak phase, (i.e. modulation depth) β,

$$E_{FM}(t) = \exp[i\beta \sin \omega t] \ . \tag{4}$$

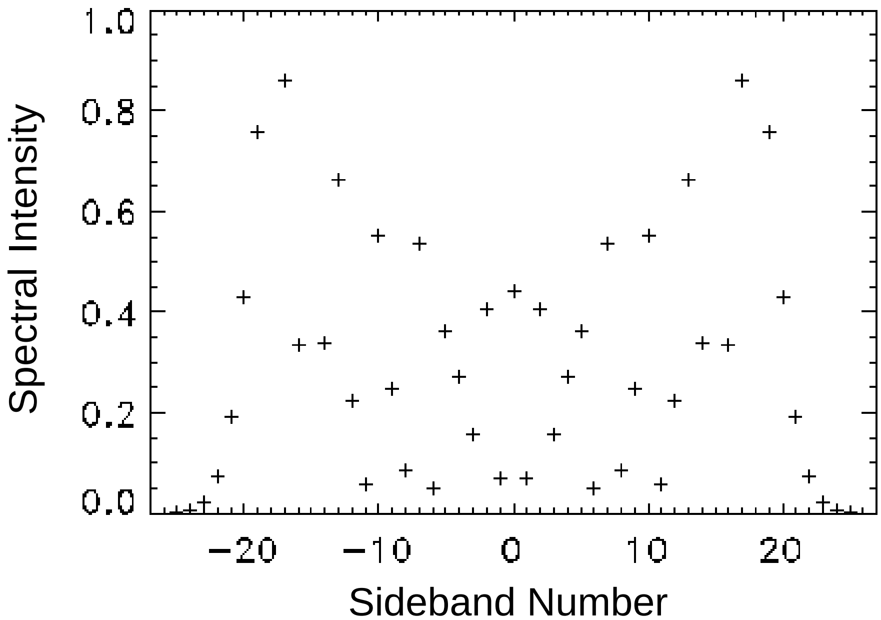

Figure 2: Spectral intensity of sidebands from FM with modulation depth $\beta = 20$.

The spectrum of this FM field has $\sim 2\beta$ sidebands (Fig. 2). In optimized SSD one chooses the grating dispersion such that adjacent sidebands are separated by the angle λ / D (the temporal skew induced by the grating is set to the modulation period). In this case, after dispersion one sees that the peak angular excursion is

$$\theta_{\max} = \pm\beta \frac{\lambda}{D} \ . \tag{5}$$

Therefore the SSD beam is β TDL, which is π times larger than the divergence of the EOD with the same peak phase modulation. Of course, if one increases the grating dispersion the SSD beam will have an even larger divergence. However, once the angle between adjacent sidebands is λ / D, further increase in divergence does not improve smoothing. The π times larger divergence of SSD ideally leads to an asymptotic smoothing level lower than that of EOD by a factor of $\sim \sqrt{\pi}$ for each dimension in which smoothing is implemented.

The fluence distribution of the EOD in the far field can be found from the dwell time of the deflector versus angle,

$$t(\theta) \propto 1 / \sqrt{(\beta / \pi)^2 - (\theta D / \lambda)^2} \ , \tag{6}$$

convolved with the diffraction limited far field angular spread function. The fluence is thus peaked near the extrema of deflection at $\theta = \pm(\lambda / D) \cdot (\beta / \pi)$. This angular distribution can be somewhat more uniform than that shown in Fig. 2 for FM and SSD. As a result, the smoothing performance of EOD is not quite $\sqrt{\pi}$ worse (for each dimension of smoothing) than that of SSD at an equivalent peak phase modulation. A calculation of the smoothing obtained using 1D EOD (with peak phase modulation of 40) is shown in Fig. 3.

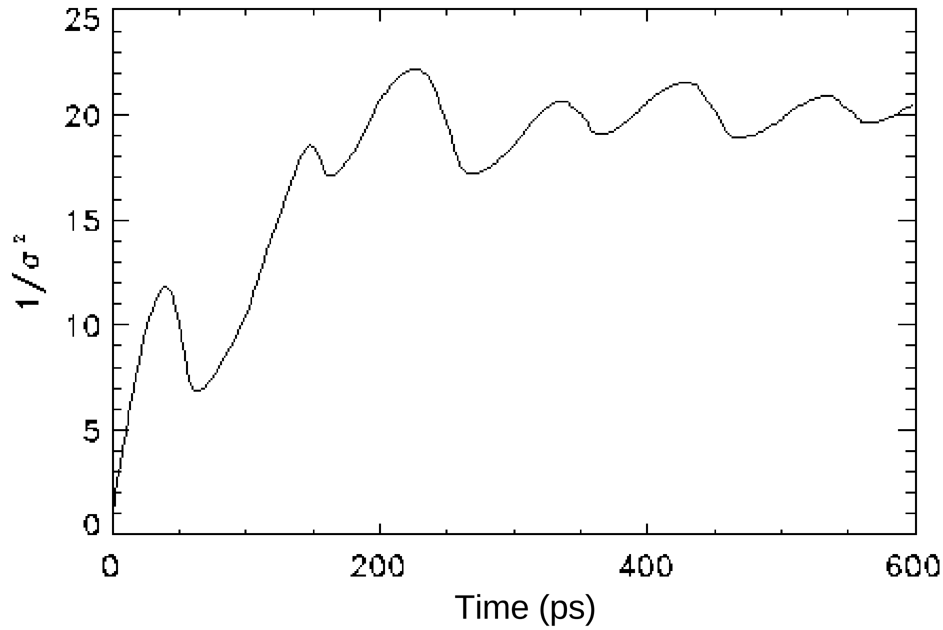

Figure 3: Effective number of speckle patterns $(1/\sigma^2)$ using smoothing with 1D EOD. The modulation frequency is 5 Ghz and peak phase is 40 radians.

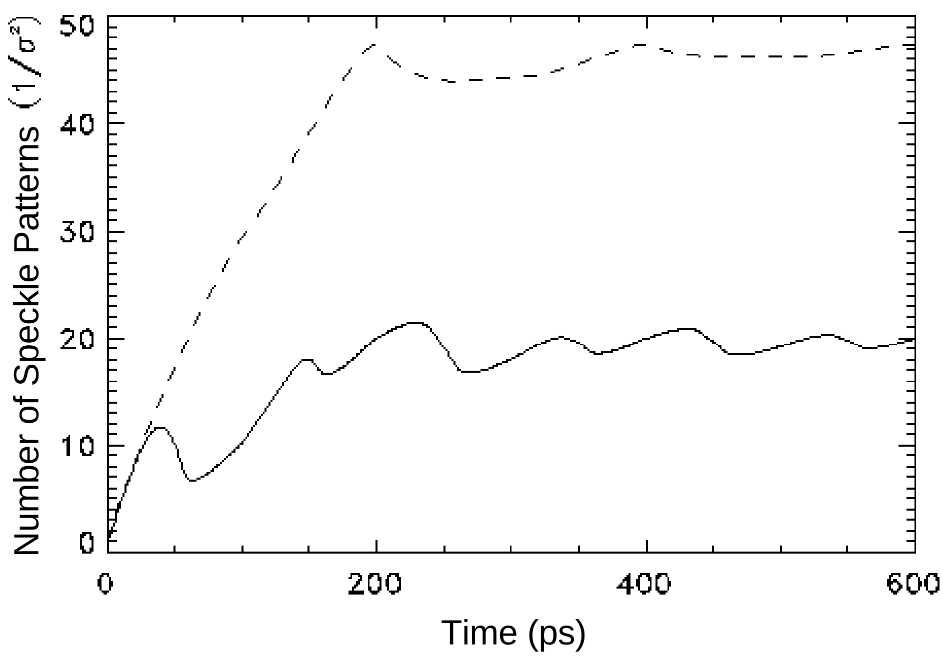

Figure 4: Effective number of speckle patterns $(1/\sigma^2)$ versus integration time using smoothing with a 1D EOD (solid curve), and 1D SSD (dashed curve). The modulation frequency is 5 Ghz and peak phase is 40 radians in both methods.

The variance of 1D EOD asymptotes to $\sim 1/\sqrt{20}$, whereas 1D SSD using FM with an equivalent peak phase yields $\sigma = 1/\sqrt{50}$ in an integration time of 200 ps (see Fig. 4). Thus, 1D EOD results in smoothing poorer by a factor of $\sim \sqrt{2.5}$ than 1D SSD of equal peak phase modulation.

This comparison is extended to 2D smoothing in Fig. 5, where a calculation compares the smoothing obtained using 2D SSD with that obtained using 2D EOD (i.e. two orthogonal deflectors in series). Identical smoothing is observed, but the 2D SSD shown is calculated assuming 2.5 times lower peak phase modulation in both directions. Thus, 2D EOD yields asymptotic smoothing ~ 2.5 times poorer than 2D SSD of equal peak phase modulation. I.e., smoothing by EOD yields an asymptotic variance larger than that of SSD of equal peak phase modulation by a factor of $\sim \sqrt{2.5}$ for each dimension in which smoothing is implemented.

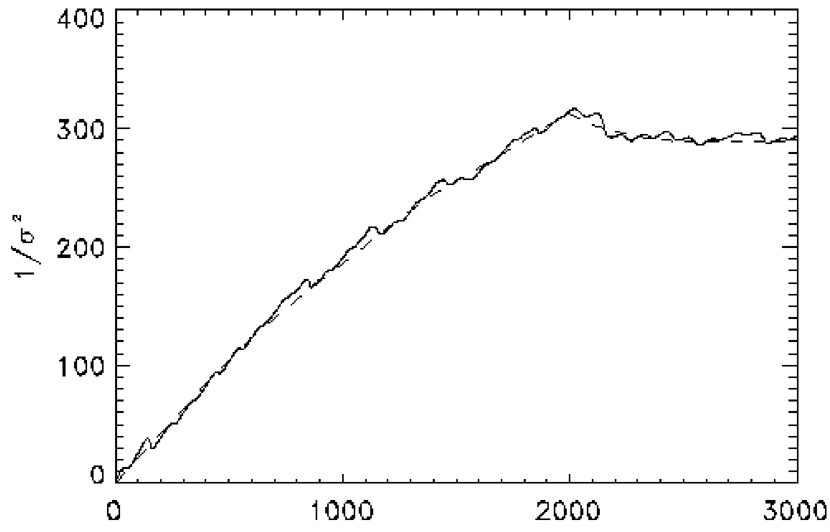

Figure 5: Effective number of speckle patterns $(1/\sigma^2)$ using smoothing with 2D EOD (solid curve) and 2D SSD (dashed curve). The modulation frequencies are 1.5 and 5 Ghz and the peak phase modulation for EOD is 40 radians. The modulation depth assumed for SSD is 17.

Finally, it should be noted that the 1D-EOD beam has spectral content generated by FM of varying depth across the beam. Thus at the location of peak field in the modulator, the bandwidth generated has extent equal to FM of the same peak depth (see Fig. 6). Therefore, not only would the asymptotic smoothing level be inferior to 1D-SSD by a factor of $\sim \sqrt{2.5}$, but the full extent of the bandwidth generated by EOD is the same as that of the FM modulator of equal frequency and peak phase modulation (note however that the FM spectrum has a much more abrupt edge). This means that if one increased the EOD maximum phase shift by the factor of ~ 2.5 to achieve the same asymptotic smoothing limit as SSD, the bandwidth of the EOD would necessarily be larger by a factor of ~ 2.5, which would be more stressing on the harmonic conversion efficiency. However, this assumes a comparison based on equal modulation frequency. If the EOD modulation frequency is reduced, then asymptotic smoothing equal to that of SSD can be achieved using EOD of the same bandwidth. However, if the EOD modulation frequency is reduced, the smoothing rate is reduced as well. Therefore, it is most concise to say that the EOD smoothing rate will be less by a factor of ~ 2.5 than that of an SSD system of equal full bandwidth extent. One must note, however, that the FM spectrum has a very abrupt drop in the wings (see Fig. 2), whereas the EOD spectrum has slowly decreasing wings. Thus, although at equal peak phase depth the full extent of the FM and EOD spectra are equal, the EOD has ~1/2 the FWHM of the FM spectrum. Therefore, if one bases the smoothing performance comparison on spectral FWHM, the smoothing rate of the EOD is only ~ 1.2 times less than that of SSD of equal spectral FWHM. The proper figure of merit to be used in such a comparison should be determined using complete modeling of the frequency conversion process. However, based on the above observations it appears likely that the SSD smoothing rate will be found to be faster than that of the EOD of equal bandwidth by a factor of ~ 1.2-2.5.

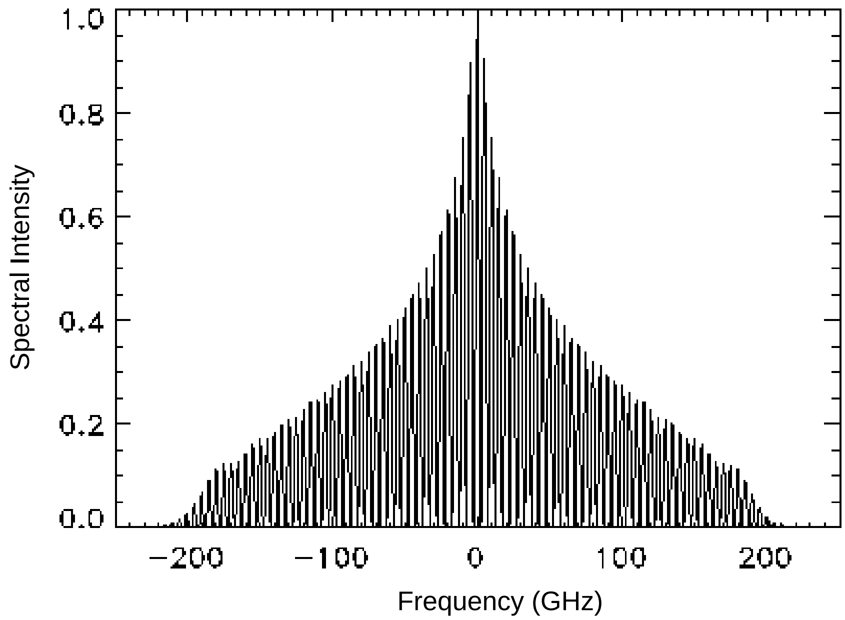

Figure 6: Spectrum of beam after passing through an EOD with a modulation frequency of 5 Ghz and peak phase of 40 radians.

3. CONCLUSIONS

The EOD (of Fig. 1) effectively produces π times less divergence than that of an optimized SSD system of equal peak phase modulation. Smoothing simulations show that the asymptotic reduction of variance by the EOD will be poorer by a factor of $\sim \sqrt{2.5}$ than that of SSD with equal peak phase modulation, for each dimension in which smoothing is implemented. Therefore, to achieve an asymptotic smoothing level equivalent to that of SSD, the EOD requires a ~ 2.5 times larger electric field, crystal length product. Furthermore, even in this case, the smoothing rate of the EOD will be ~1.2 - 2.5 times less than that of an SSD system of equal bandwidth.

4. ACKNOWLEDGMENT

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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