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Effect of bandwidth on beam smoothing and frequency conversion at the third harmonic of the Nova laser

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ABSTRACT

We present the results of experiments performed on the Nova laser system to determine the effect of bandwidth on third harmonic (3ω) frequency conversion and beam smoothing by spectral dispersion (SSD). Our experiments utilized a wide bandwidth fiber optic cross-phase modulated (XPM) source and a narrower bandwidth microwave modulated (FM) source, each centered at 1053 nm (1ω). The FM source produced $\sim 2 \text{ cm}^{-1}$ of bandwidth, modulated at 3 GHz; the XPM bandwidth was varied from 5 to 15 cm^{-1} , modulated by the temporally noisy output of a multimode Nd:glass laser (≤ 500 GHz). The FM beam showed no evidence of self-phase modulation in the laser chain produced by intensity fluctuations, and 1ω bandwidth was tripled upon conversion to 3ω ($2 \text{ cm}^{-1} \rightarrow 6 \text{ cm}^{-1}$). The 1ω XPM bandwidth increased by $\geq 25\%$ due to self-phase modulation in the laser chain ($16 \text{ cm}^{-1} \rightarrow 22 \text{ cm}^{-1}$) due to its relatively noisy temporal structure. A significant fraction ($> 50\%$) of the 1ω XPM bandwidth was transferred to the 3ω beam ($22 \text{ cm}^{-1} \rightarrow 36 \text{ cm}^{-1}$), yielding 0.13% bandwidth at 3ω . The maximum intrinsic narrowband 3ω frequency conversion obtained using a type-II/type-II KDP crystal array was 62%. The intrinsic efficiency obtained at the Nova 10-beam chamber is typically $> 65\%$. Frequency conversion was essentially unaffected by the 2 cm^{-1} bandwidth obtained from FM source. However, the 5 - 16 cm^{-1} of bandwidth from the XPM source reduced the conversion efficiency to $\sim 24\%$. We have developed broadband frequency conversion codes and broadband pulse simulations to model our results, and have obtained good agreement with experiment.

Using a random phase plate (RPP) without bandwidth, we obtained a smoothing level, $\sigma/I \sim 0.79$, defined by the rms variance normalized with respect to the average intensity. This is less than the theoretically expected value of 1 for an ideal speckle pattern, and could be evidence of polarization smoothing as a result of focus lens birefringence. With spectral dispersion and RPP we demonstrated an excellent level of smoothing with the XPM source, $\sigma/I \sim 0.12 - 0.15$, comparable to smoothing levels previously obtained on Nova using SSD at the second harmonic wavelength. A normalized variance of $\sigma/I \sim 0.3$ was obtained with the FM source. The reduced level of smoothing with the FM modulator was due to insufficient grating dispersion. Experiments with higher dispersion are planned to demonstrate a smoothing level equivalent to that obtained with the XPM source. Overall we are encouraged by these initial experiments, and expect that further development should yield a readily usable smoothing method for laser-target interactions at the third harmonic.

1. INTRODUCTION

For the past few years optical smoothing of the laser irradiance on targets for inertial confinement fusion (ICF) has been given increasing attention.¹⁻⁴ Wave front aberrations in high power laser systems for ICF produce nonuniformities in the energy distribution of the focal spot that can significantly degrade the coupling of energy into a fusion target, driving various plasma instabilities. In particular, hot spots can induce local self-focusing of the light, producing filamentation of the plasma which can affect the growth of parametric instabilities, such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).⁵⁻⁷ The introduction of temporal and spatial incoherence over the face of the beam, using techniques such as induced spatial incoherence (ISI)¹ or smoothing by spectral dispersion (SSD)², reduces variations in the focal irradiance when averaged over a finite time interval. The SSD technique has been demonstrated on one beamline of the Nova laser at the second harmonic wavelength, 527 nm,^{3,4} and has been successfully used for target experiments⁸⁻¹⁰. However, the main emphasis in studying nonlinear laser-matter interaction processes is on the use of short-wavelength drivers ($\lambda < 500 \text{ nm}$) in order to maximize collisional effects in the coupling of the laser to the plasma, and thereby minimize parametric laser-plasma interaction processes. As interaction lengths increase, the likelihood of significant excitation of these processes also increases, thus it is important to investigate the impact of beam smoothing techniques on these nonlinear processes. Preliminary experiments performed at the University of Rochester, Laboratory for Laser Energetics (LLE) at the third harmonic indicate that two-plasmon decay instability is only moderately affected by SSD,^{11,12} though Raman emission is significantly reduced for the long scale-length plasmas studied to date.

The smoothing by spectral dispersion method used on Nova is shown schematically in Fig. 1. Broadband light is spectrally dispersed by a grating, amplified, frequency converted, and focused through a random phase plate on to a target.

Fig. 1: Schematic illustration of the smoothing by spectral dispersion technique.

Fig. 2: The smoothing level, $\sigma/\langle I \rangle$, defined as the rms variance normalized with respect to the average intensity, is proportional to $1/\sqrt{n}$, where n is the number of independent speckle fields. The sum of these independent patterns is described by the probability density:

$$P_n(I) = \frac{I^{n-1}}{(n-1)!} \pi \exp(-I/\bar{I}).$$

Each distinct frequency component produces a speckle pattern, resulting in a superposition of many patterns. The smoothing level, $\sigma/\langle I \rangle$, defined as the rms variance of the irradiance normalized with respect to the average intensity, is proportional to $1/\sqrt{n}$, where n is either the number of spectral components in the beam or the number of decorrelated speckle fields. The intensity sum of these independent patterns is described by the probability density

$$P_n(I) = P_n(I) = \frac{I^{n-1}}{(n-1)!} \pi \exp(-I/\bar{I}), \quad (1)$$

as shown in Fig 2. The intensity distribution becomes more sharply peaked (i.e., the beam becomes smoother), as the number of patterns increases. Since each frequency propagates at a different angle through the phase plate, the speckle patterns spatially shift as a function of frequency. The rapidly fluctuating interference of the displaced speckle fields for the different spectral components causes the irradiance to appear smooth on a time-averaged basis. In SSD, statistically decorrelated speckle patterns are obtained when each speckle field is spatially shifted by at least one half speckle diameter, $d_1/2 = 1.22\lambda/D$, where D is the beam diameter on the phase plate.⁴ This implies that the time-integrated smoothing level for spectrally dispersed beams is given by

$$\sigma/\langle I \rangle = \sqrt{\tau \delta v} = (\tau 1.22\lambda/(c D' d\theta/dv))^{1/2}, \quad (2)$$

where v is the effective displacement between spectral components in Hz, τ is the coherence time (inverse of the frequency converted bandwidth), $d\theta/dv$ is the grating dispersion in rad/Hz, D' is the transverse beam diameter after reflection from the

grating, λ is the wavelength, and c is the speed of light. The initial smoothing occurs on a time scale inversely proportional to the bandwidth, reaching an asymptotic level in time determined by the inverse separation between frequency components giving uncorrelated patterns. Thus the effective smoothing time is given by $1/\delta\nu$. The initial onset of smoothing is delayed due to the spatially varying time delay across the beam imposed by the grating (i.e., a delay of λ/c per illuminated grating line). It can be shown that this time delay δt is proportional to $1/\delta\nu$, and therefore the number of decorrelated fields on target is proportional to $\delta t/\tau$. Beam smoothness is strongly dependent on the amount of dispersion and spectral bandwidth a high power laser chain can support. The larger the bandwidth (i.e., the shorter the coherence time), the more rapidly the structure will change, and the more rapidly the time-averaged intensity will smooth. The primary limitation is the divergence that can be tolerated in the laser amplifier chain, and reduced frequency conversion efficiency due to bandwidth. High efficiency tripling can be achieved only over a narrow spread in wavelength for a given crystal phase matching condition, thus in order to remain within 10% of the maximum conversion efficiency, the input bandwidth should be limited to $\sim 2 \text{ cm}^{-1}$. In this paper, we will discuss experiments on the Nova laser using SSD that explore the efficiency of frequency conversion to 351 nm and the effective smoothing of two forms of frequency modulated bandwidth. We will present a comparison of the effectiveness of each type of bandwidth for beam smoothing on Nova, as well as the bandwidth limitations on frequency converting to the third harmonic. Theoretical modeling of these results will be discussed.

2. EXPERIMENTAL PROCEDURES

The two types of bandwidth sources used for our experiments are shown schematically in Fig. 3. In the first type spectral broadening was produced via cross-phase modulation (XPM) in a birefringent optical fiber. In XPM, a broadband noisy pump pulse and a narrow band smooth signal beam are launched down two axes of a polarization maintaining fiber. Through cross-phase modulation, the intensity along one polarization axis of the fiber affects the temporal phase of the beam along the other axis, and vice versa. These phase variations induce a frequency shift which produces spectral broadening. The spectral broadening of the signal beam along one axis depends on the statistical characteristics of the pump intensity along the other axis, thus the spectral broadening of the signal beam is proportional to the intensity of the pump beam and the propagation length in the fiber. Experimentally, a single mode, single frequency Nd:YLF oscillator (line width $< 100 \text{ MHz}$) served as the signal, and a noisy broadband Nd:glass oscillator (line width $\delta\nu \leq 500 \text{ GHz}$) as the modulator. The glass oscillator typically exhibits temporal fluctuations on the order of 2 ps ($\delta\nu^{-1}$) producing a noisy output consistent with the operation of ~ 5000 randomly phased cavity modes. A $\sim 5 \text{ }\mu\text{J}$, 15 ns square pulse was sliced with a fast Pockel's cell from the 100 ns Nd:glass laser pulse and combined with a $\sim 1 \text{ }\mu\text{J}$ 10 ns square pulse sliced from the single frequency oscillator in a

Fig. 3: Two sources of bandwidth were used for the experiments described here: (a) phase modulation of a single frequency source in a microwave modulated electro-optic crystal (FM), and (b) cross-phase modulation (XPM) of a single frequency beam and a broadband noisy beam in a single-mode polarization preserving optical fiber.

20 m single mode polarization preserving optical fiber. The single frequency pulse was centered in time within the modulation envelope and was coupled into the fiber along the orthogonal polarization axis. The two pulses were separated at the fiber output by a high extinction ratio, thin film polarizer. The cross-phase modulated bandwidth was varied from 5 to 16 cm^{-1} by adjusting the pump energy into the fiber. After XPM, the signal pulse was routed to the Nova pulse shaping system, where it was temporally tailored for input to the Nova laser chain. Unlike an ideal FM source, the output of the stochastic XPM oscillator is not completely smooth in time. Chromatic dispersion in the fiber alters the precise phase relation among the various frequency components needed to make a true frequency modulated output, producing temporal fluctuations. The amplitude of these intensity fluctuations increases as the beam propagates through Nova due to the combined effects of material dispersion, the spectral dependence of the gain, and the angular dispersion of the spectral components following the SSD grating.

The second FM bandwidth source is obtained by phase modulation of the pulse in an electro-optic crystal². The phase-modulation is obtained by passing the laser beam through an electro-optic crystal driven by an oscillating microwave electric field. The effect is to produce a laser electric field of the form $E(t) = E_0 \exp(i\omega t + i\delta \sin \omega_m t)$, where δ and ω_m are the modulation amplitude and angular frequency of the electro-optic device, and ω is the fundamental angular frequency of the laser. Expanding this in a Fourier series, $E(t) = E_0 \sum J_n(\delta) \exp(i\omega t + in\omega_m t)$, we see that the beam contains side bands in increasing increments of ω_m , which extend out to approximately $\pm \delta \omega_m$, at which point the frequency spread is well approximated by $\Delta\nu = 2\delta\nu_m$, in terms of the modulation amplitude and frequency. In our case, bandwidth was generated by electro-optic phase modulation of a single mode, single frequency Nd:YLF oscillator (line width $< 100 \text{ MHz}$) operated at nominally 1053 nm wavelength. The phase-modulation was obtained by passing the laser beam through an LiNbO₃ crystal that was RF modulated at 3 GHz.^{2,14} The amplitude of the beam was relatively constant in time. The output spectrum was nominally 2 cm^{-1} at 1053 nm, with frequency components spaced at intervals of 3 GHz. The FM modulated pulse was then routed to the Nova temporal pulse shaping system, prior to entering the Nova laser chain.

Smoothing by spectral dispersion was introduced on Nova by placing a diffraction grating at an image relay plane in the preamplifier line at the smallest aperture possible to minimize both the expense of the grating and the optical fluence.^{3,15} The beam diameter at this position was 30.5 mm. A conventional 900 groove/mm gold diffraction grating was used in a near Littrow configuration. This gave a dispersion of $41 \mu\text{rad}/\text{cm}^{-1}$ at the 70 cm diameter output beam and to a correspondingly larger divergence (by the magnification ratio) at smaller beam diameters. The spatial filter pinhole apertures in Nova produced a bandwidth cutoff at 19 cm^{-1} at this dispersion. The SSD grating caused an overall time delay of $\delta t \sim 110 \text{ ps}$ across the beam, which was shorter than the 1 ns pulse duration used. In the LLE scheme for SSD², the pulse distortion caused by this delay is corrected by temporally skewing the beam in the opposite direction by reflecting it from a grating before the bandwidth is added. Such pre-skewing is not possible with the current Nova set-up.

After amplification and propagation through the Nova laser chain, the output spectrum, temporal profile, near field intensity profile, and energy were recorded in the Nova output sensor ($\sim 13\text{-m}$ past the laser chain output). The SSD beam then propagated another 67-m in air to the Nova two-beam target chamber area. In the two-beam area, the beam was converted in frequency to 351 nm (3ω) by a type-II/type-II KDP crystal array. The main portion of the beam was focused through a 2-mm diameter pinhole at the target chamber center to remove residual 1ω and 2ω light. The transmitted 3ω light was then absorbed by a 44-cm diameter calorimeter, providing an absolute 3ω energy calibration. A near normal incidence (10°) full aperture splitter located after the KDP array sent a Fresnel reflected sample of the 3ω beam to a diagnostic station.¹⁶ The spectrally dispersed 3ω reflection was focused by a vacuum telescope with an input lens identical to that used on the target chamber, and through a bi-level random phase plate (80 cm diameter) with stretched hexagonal elements $6.4 \times 3.0 \text{ mm}$ in size, giving rise to a focal spot approximately $700 \times 350 \mu\text{m}$.¹⁷ The focal image was reimaged by the telescope and diagnostic optics, then attenuated, magnified (12X), and recorded on film for various planes around best focus and with various light exposures. The best focus plane of the image was further expanded (34X) in order to resolve the spatial speckle structure of the beam. The diagnostic station was also used to measure the 3ω energy, frequency spectrum, and temporal pulse shape.

3. RESULTS AND DISCUSSION

3a Frequency conversion

A potential drawback of the use of bandwidth, is the enhancement of nonlinear self-focusing in the laser system.¹⁸ Since broadband pulses can have excess bandwidth compared to their pulse length, they can have intensity peaks in time that are significantly larger than the average intensity. Nearfield photographs of the FM beam at 5.5 TW with $\leq 50\%$ intensity modulation showed no effects of self-focusing. A 16 cm^{-1} 1ω XPM beam with intensity modulations of $\geq 50\%$, however, showed evidence of beam break-up at 4.4 TW. The self-focusing limit is a function of the XPM input bandwidth, decreasing from 5.1 TW for 5 cm^{-1} input bandwidth, to 4.4 TW for 16 cm^{-1} input bandwidth. It should be possible to decrease the noise associated with the XPM oscillator by shortening the fiber length to minimize the adverse affect of group velocity dispersion, without significantly reducing the overall bandwidth output of the source.¹⁹ Typical spectra from the narrowband, FM, and XPM oscillators used for these experiments are shown in Fig. 4. The narrowband oscillator traditionally used on Nova has a transform-limited bandwidth of $\ll 0.1\text{ cm}^{-1}$ at both 1ω and 3ω . The FM modulated beam has an input bandwidth of 2 cm^{-1} , which tripled upon conversion to the third harmonic, as expected. The output 1ω spectrum showed little effect of self-phase modulation in the laser chain. The 16 cm^{-1} 1ω XPM spectrum broadened to 22 cm^{-1} due to self-phase modulation in the laser chain. Because of the poor phase-matching at high bandwidth, the frequency converted XPM spectrum is only 1.5 - 2.5 times the 1ω spectrum in width. However, as the 1ω XPM input bandwidth was increased, the 3ω spectrum began to broaden on the blue side of the spectrum, as shown in Fig. 5. This increased the percent bandwidth at the third harmonic ($> 0.11\%$), but at the cost of conversion efficiency. Conversion efficiency versus 1ω drive intensity is plotted in Fig. 6 for the narrowband, FM, and XPM sources. The experimental narrowband calibrations are indicated by squares, with a polynomial fit to the data given by the dashed line. The maximum 3ω intrinsic array efficiency obtained with 1 ns narrowband pulses was 62%. This is slightly lower than the 65% typically obtained on the Nova 10-beam chamber with the same type of KDP array, possibly due to intensity-dependent polarization ellipse rotation incurred by propagation over the longer air path.²⁰ The conversion efficiency was essentially unaffected ($< 10\%$ reduction) by the addition of FM bandwidth, as indicated by the open circles and dotted line in Fig. 6. With the addition of 5 - 10 cm^{-1} of XPM input bandwidth (upward triangles), the conversion efficiency was $\sim 50\%$ less than obtained with a narrowband pulse, and $\sim 60\%$ less than narrowband for 11 - 16 cm^{-1} input bandwidths (downward triangles).

Fig. 4: Spectra for the narrowband, FM, and XPM bandwidth sources at the output of the source, output of the laser chain, and after conversion to the third harmonic.

Fig. 5: As the 1ω XPM bandwidth increased, a blue shoulder began to grow in the 3ω spectrum.

Fig. 6: Third harmonic frequency conversion efficiency versus 1ω drive intensity for narrowband, FM, and XPM bandwidth sources. The dashed, dotted, and solid curves are polynomial fits to narrowband, FM, and XPM bandwidth data, respectively.

We have modeled our results using a theoretical code which simulates broadband frequency conversion. Broadband harmonic conversion can be described as three-wave mixing in a dispersive birefringent nonlinear crystal. The coupled nonlinear Schrodinger equations are solved for each of the three fields in each conversion step using a split-operator approach. The z -integration is performed using Runge-Kutta, while the time-integration is performed using a spectral decomposition method. Several third order nonlinear refractive effects, such as self-phase modulation, cross-phase modulation, and two-photon absorption, are included. Spectral dispersion (SSD) effects are included as additional terms in the group velocity walk-off and dispersion applied to each field, as well as overall angle and central frequency detuning. The results of our model, assuming a 15 cm^{-1} 1ω XPM spectrum entering the array but no dispersion or walk-off effects in

the conversion crystal, are shown in Fig. 7a,b. The calculated 3ω conversion efficiency was 71%, and the 3ω spectrum tripled in width, as expected. When bandwidth effects were included in the simulation, the frequency conversion decreased from 71% to 30.8%, an overall reduction of 60%. The percent bandwidth transferred to the 3ω beam was also decreased (Fig. 7c). These results compare favorably with the experimental spectrum shown in Fig. 7d. The experimentally measured frequency conversion for a 15 cm^{-1} 1ω XPM input pulse was approximately 60% less than obtained with an equivalent narrowband pulse, and the 3ω spectrum was noticeably narrowed. The effect of the current level of dispersion ($41\text{ }\mu\text{rad/cm}^{-1}$) on conversion efficiency was minimal, as were effects due to group velocity walk-off. The experimentally observed blue shift of the spectrum can be theoretically reproduced to some degree by including a detuning of the central 1ω frequency by 5 cm^{-1} , however, this is not experimentally feasible. Another cause might be the effect on 3ω conversion of the substantial self-phase modulation on the XPM pulse incurred in the laser amplifier chain prior to frequency conversion. This is being investigated.

Fig. 7: Assuming the calculated 15 cm^{-1} 1ω XPM input spectrum shown in (a), but no dispersion or walk-off effects in the conversion crystal, the 3ω XPM spectrum in (b) is theoretically predicted, with 71% 3ω conversion efficiency. When bandwidth effects are included in the simulation, the 3ω conversion efficiency decreases from 71% to 30.8 %, and the 3ω spectrum no longer triples in width (c). These results compare favorably with the experimental spectrum in (d), obtained with equivalent 1ω input conditions.

3b. Beam smoothing

The effect of beam smoothing at 3ω with random phase plate only, FM bandwidth with SSD, and XPM bandwidth with SSD as compared to an unsmoothed beam can be seen in the equivalent target plane images shown in Fig. 8 and corresponding spatial profiles (Fig. 9) taken through the center of each image. The far field image of the unsmoothed single frequency beam shows significant structure due to laser system aberrations and beam obscurations in the near field. With a random phase plate (RPP), this structure is broken up into a homogeneous well-controlled speckle pattern with a $\sigma/\langle I \rangle = 0.79$. This is less than the theoretically predicted value of 1, indicating there may be additional polarization smoothing due to the birefringence in the focus lens. Note also that the peak intensity has been reduced from $\sim 10 \times 10^{15}\text{ W/cm}^2$ unsmoothed, to $3 \times 10^{15}\text{ W/cm}^2$ with the RPP. The addition of the microwave modulated FM bandwidth and SSD reduces the clarity of the individual speckles, smoothing to $\sigma/\langle I \rangle \sim 0.29$. Peak intensities are further reduced to $\sim 2.5 \times 10^{15}\text{ W/cm}^2$ with the addition of FM bandwidth. The slight streaking in the horizontal direction is due to the 1-dimensional dispersion of the SSD grating. With the further addition of bandwidth using the XPM source, the individual speckles become almost indistinguishable, reduced by about an order of magnitude in size as compared to the random phase plate alone. The profile is smooth and uniform in intensity, with $\sigma/\langle I \rangle = 0.11 - 0.15$ and a peak intensity of $\sim 0.6 \times 10^{15}\text{ W/cm}^2$. This is comparable to the level of smoothing previously obtained at the second harmonic with XPM and SSD.^{3,4} Comparison of the intensity histograms shown in Fig. 10 for the RPP, FM/SSD, and XPM/SSD data in Fig. 8, with the

Fig. 8. The effect of beam smoothing at low scattering angles. The plot shows $M(\theta)$ versus θ for $\theta < 10^\circ$ with SSD as compared to beam smoothed data. The solid line is the experimental data, the dashed line is the fit to the data, and the dotted line is the fit to the smoothed data. The dotted line is evident in the low scattering angles of the beam smoothed data. With a larger number of particles the fit to the data is obtained at $\theta = 0^\circ$. With a smaller number of Monte Carlo simulations, the fit to the data is obtained at $\theta = 0^\circ$. With a smaller number of Monte Carlo simulations, the fit to the data is obtained at $\theta = 0^\circ$. With a smaller number of Monte Carlo simulations, the fit to the data is obtained at $\theta = 0^\circ$.

Fig. 9 Horizontal spatial profiles taken through the center of each image in Fig. 8.

Fig. 10 Intensity histograms for the RPP, FM/SSD, and XPM/SSD data in Fig. 8.

probability density plotted in Fig. 2, confirms that the far field irradiance with spectral dispersion has a much narrower intensity distribution than the narrowband RPP case. An estimate of the number of frequency components in the pulse contributing to smoothing can be obtained by fitting the probability density function to the intensity histograms for RPP, FM/SSD, and XPM/SSD data. The FM source appears to have 15 - 20 components, while the XPM has 35 - 45 independent components. It should be noted, however, that the smoothing level obtained is dependent on the dispersion used as well as the number of spectral components in the beam. The grating used was chosen to prevent the XPM bandwidth from being clipped in the laser chain spatial filter pinholes, however, the dispersion was not optimal for microwave modulated bandwidth source. By increasing the grating dispersion until each frequency component produces a decorrelated speckle pattern, it should be possible to obtain the same level of smoothing with 2 cm⁻¹ of FM bandwidth as obtained with 16 cm⁻¹

of XPM bandwidth at the current dispersion. However, this is the fundamental limit on the smoothing obtainable with the FM modulator, because of its limited number of spectral components. Any greater dispersion would not lead to improved smoothing as the number of decorrelated speckle patterns is now determined by the number of frequency components and does not change with dispersion.

Calculations show that temporally, smoothing by spectral dispersion occurs at a rate determined by the bandwidth, as shown in Fig. 11a. An initial reduction in $\sigma/\langle I \rangle$ occurs in a time of the order of the inverse of the bandwidth. This corresponds to $\sim 1 - 2$ ps for the XPM source and ~ 6 ps for the FM source. Longer time asymptotic smoothing occurs in a time given by the inverse of the frequency separation between the spectral components, i.e., $1/\delta\nu$. This level is reached in ~ 90 ps for both sources used in these experiments. The asymptotic level, $\sigma/\langle I \rangle$, is approximated by $1/\sqrt{n}$, where n is the number of uncorrelated speckle patterns. The FM/SSD spectrum consists of discrete frequencies separated by the modulation frequency, whereas the XPM/SSD spectrum has a continuous distribution of frequencies. Thus simulations indicate that the long-time limit of the normalized variance of the intensity distribution is lower for the XPM/SSD case than for the FM/SSD case, due to the greater number of frequency components in the former. Increasing the dispersion for the FM source increases this separation, thus the smoothing will improve, but at the cost of longer smoothing time. The smoothing level as a function of time for the FM/SSD case is shown in Fig. 11b. Note that the degree of smoothing achieved is dependent on the phase of the input beam relative to the electro-optic modulation cycle upon entering the crystal. By appropriately matching the timing of the beam entry into the crystal with the phase of the modulation cycle, it should be possible to optimize the smoothing at early times.

Fig. 11 Smoothing by spectral dispersion occurs at a rate determined by the bandwidth. Normalized variance vs. smoothing time calculated for (a) the FM and (b) the XPM bandwidth source.

4. CONCLUSIONS

We have presented the results of recent experiments on Nova which demonstrate our ability to generate significant bandwidth (>50 cm⁻¹) and smoothing at 351 nm with the XPM bandwidth source, and reasonable smoothing with an FM modulated bandwidth source. The third harmonic conversion efficiency was reduced by $\leq 10\%$ with 2 cm⁻¹ of FM bandwidth and $\geq 50\%$ with 5 - 15 cm⁻¹ of XPM bandwidth as compared to narrowband efficiency, in agreement with theoretical simulations. The level of smoothing produced by the XPM source ($\sigma/I \sim 0.12$) was significantly better than that produced by the FM source ($\sigma/I \sim 0.29$). However, smoothing by the FM source was limited by the grating dispersion, and is expected to improve with greater dispersion. Smoothing at 351 nm using the XPM source was comparable to previous XPM data taken at 532 nm. In both cases, a substantial portion of the bandwidth on the fundamental beam was transferred to the third harmonic beam. Greater than 36 cm⁻¹ of XPM bandwidth ($\sim 0.11\%$) and 6 cm⁻¹ of FM bandwidth ($\sim 0.02\%$) was generated at 351 nm.

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