UCRL-JC-112742
PREPRINT

Simulations of Spectral Broadening by Cross-Phase Modulation (XPM) with Chaotic Light Pulses

M. A. Henesian and S. N. Dixit
University of California
Lawrence Livermore National Laboratory
Livermore, California 94551-5508

C.-J. Chen, P. K. A. Wai, and C. R. Menyuk
Department of Electrical Engineering
University of Maryland
Baltimore, Maryland 21228-5398

This paper was prepared for submittal to the
Laser Coherence Control: Technology and Applications Conference 1870 of the
SPIE - The International Society for Optical Engineering Conference
January 21-23, 1993
Los Angeles, California

May 25, 1993

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Simulations of Spectral Broadening by Cross-Phase Modulation (XPM) with Chaotic Light Pulses

M. A. Henesian and S. N. Dixit
University of California
Lawrence Livermore National Laboratory
Livermore, California 94551-5508

C.-J. Chen, P. K. A. Wai, and C. R. Menyuk
Department of Electrical Engineering
University of Maryland
Baltimore, Maryland 21228-5398

Abstract

Spectral broadening of single-frequency laser pulses by optical cross-phase modulation (XPM) with chaotic laser pulses in birefringent single-mode optical fibers is investigated numerically and results are compared with experiments. By this process we have generated laser pulses of variable bandwidth (1–25 Å) at the fundamental wavelength (1053 nm) for amplification in high power solid-state Nd:glass lasers used for inertial confinement fusion research. Simulations indicate that a temporally smooth XPM pulse can be generated with intensity fluctuations of less than 10% and spectral width greater than 50 Å using a short length (~5 m) of special low dispersion and low birefringence fiber, e.g. $D = 10$ ps/nm-km (normal dispersion) and $\Delta n = 2 \times 10^{-5}$. Readily available fibers of similar length, with parameters of $D = 40$ ps/nm-km and $\Delta n = 6 \times 10^{-5}$, can give spectral widths exceeding 25 Å, but the noise will range from 25 to 60%. Broadband laser pulses generated by XPM are now routinely used at Lawrence Livermore National Laboratory for active smoothing of the laser irradiance on targets by the technique of smoothing-by-spectral dispersion.

1. Introduction

Spectral broadening of single-frequency laser pulses by optical cross-phase modulation (XPM)¹ with a "noisy" chaotic light pulse in a birefringent single-mode fiber was proposed and carried out at Lawrence Livermore National Laboratory (LLNL) in 1989.² A Nd:glass laser oscillator was developed for use as the chaotic light source with a typical spectral width of ~15 Å. The XPM broadband system was subsequently engineered and incorporated into the master laser oscillator facility of the Nova laser system at LLNL, and has been used on a regular basis for target irradiance smoothing development at 2ω (526.5 nm)³, and most recently at 3ω (351 nm)⁴ using the technique of smoothing-by-spectral dispersion (SSD) developed at the University of Rochester.⁵ In this technique, and others that rely on the conversion of temporal to spatial incoherence, the degree of smoothness, as quantified by the normalized root-variance σ of irradiance on target is improved (σ is lowered) as the coherence time of the pulse is reduced relative to other characteristic times – such as the delay time across the beam front due to spectral dispersion with a diffraction grating⁵, the delay time associated with an echelon⁶, or the time-spreading of a laser pulse due to modal dispersion in a multimode optical fiber.⁷ Propagation of pulses down a high power laser chain requires a smooth temporal shape to maximize laser power while at the same time to reduce temporal intensity peaks that enhance spatial self-focusing, and that can subsequently cause laser damage to expensive optics.⁸ Therefore, a well engineered system requires temporally incoherent pulses with control of the spectral width and temporal modulation. Most broadband laser sources such as the Nd:glass oscillator are based on the simultaneous lasing of very many (up to ~5000) uncorrelated randomly-phased frequency modes spanning the oscillating spectrum. Simple theory for the intensity statistics of an ensemble of uncorrelated laser modes follows the negative exponential statistics of complex circular gaussian random variables⁹, and shows that such an ensemble will have 100% temporal modulation, i.e. a normalized σ of intensity of 1.0. In such a "chaotic" pulse the intensity will exceed 2-times the average ~ 15% of the time, and exceed 3-times the average for ~ 5% of the time. The XPM technique in contrast, can produce pulses with significantly less intensity modulation than traditional broadband sources, with a calculated σ in the range of 0.2 ~ 0.6 depending on fiber properties and fiber length.

In the XPM technique discussed here, the noisy pulse called the "pump", and the single-frequency pulse called the "signal", are orthogonally polarized, and are simultaneously launched into the polarization preserving axes of a birefringent fiber. A typical optical layout is shown in Fig. 1. We assume that the pump pulse is the higher intensity field, and therefore has a stronger effect on the signal than the signal has on the pump. Through cross-field phase modulation, the intensity fluctuations along the pump polarization axis affect the phase of the electric field along the signal axis, and vice versa. Denoting the electric field envelope functions for the pump and signal fields as $u(t)$ and $v(t)$, respectively, and the intensities as $|u(t)|^2$ and $|v(t)|^2$, then neglecting material dispersion over a short fiber length z , the complex-envelope functions become¹⁰

$$(1a) \quad u(t)' = u(t) e^{i \frac{\omega_0 n_2}{c} (|u(t)|^2 + B|v(t)|^2) z}$$

$$(1b) \quad v(t)' = v(t) e^{i \frac{\omega_0 n_2}{c} (|v(t)|^2 + B|u(t)|^2) z}$$

where n_2 is the nonlinear refractive index, c is the velocity of light in vacuum, ω_0 is the angular frequency of the electric field carrier wave, and B is the cross-phase modulation parameter which is equal to 2/3 for linearly polarized beams. The first term in the exponent describes self-phase-modulation, while the second term describes the cross-phase-modulation. Since the multiplying exponential factors are imaginary, only the phase of the complex envelopes are affected. The pump and signal amplitudes will not be modulated, and Eqns. 1(a-b) are then valid over the entire fiber length. The self and cross-field phase modulations induce an ensemble of phase shifts which give statistical frequency fluctuations that are transformed into time-integrated spectral broadening at the end of the fiber. For the signal pulse, cross-phase modulation dominates, and the instantaneous frequency changes are proportional to the time derivative of the optical intensity of the pump field. This can be seen from Eqn. 1b by equating $-i\delta\omega(t)$ with the time derivative of the factor in the exponent. When the pump source is a broadband Nd:glass oscillator, the fluctuations $\delta\omega/2\pi$ can be as fast as 0.5 ~ 1 THz, and are therefore unmeasurable except in a statistical sense. With a simple model for the fluctuations in the pump field envelope, we can estimate the root-mean-square value $\delta\omega_{rms}$ of the cross-phase-induced bandwidth by finding $\langle \delta\omega(t)^2 \rangle^{1/2}$, where the brackets denote an average over a time much greater than $2\pi/\Delta\omega_p$, where $\Delta\omega_p$ is the initial pump bandwidth. We find that $\delta\omega_{rms} = (2/3\sqrt{2})(\omega_0 n_2 I_p z/c) \Delta\omega_p$, where I_p is the average pump intensity. The spectral broadening of the signal pulse in this simple approximation then increases linearly with fiber length z , and is proportional to the product of pump bandwidth and average pump intensity. The induced signal bandwidth $\delta\omega_{rms}$ is eventually limited by material dispersion at sufficiently large signal bandwidths and fiber lengths.

Analysis of induced-phase-modulation on a signal pulse, Eqn. 1b, with a chaotic pump pulse has been carried out using statistical optics theory¹¹, neglecting dispersion and assuming an initially narrowband signal pulse. The solutions for various statistical cases are in terms of transcendental functions that do not easily lend themselves to a simple description of spectral broadening. For weak coupling, the theory indicates that the broadening should be quadratic in pump intensity or fiber length. While interesting, the theory is not useful in practical cases, since the signal develops amplitude noise due to group-velocity dispersion at even moderate signal bandwidths (~ 5 Å) and fiber lengths (~5 meters). The various spectral components of the signal pulse propagate at slightly different velocities, so that with sufficient distance down the fiber, they become de-phased and the signal amplitude is modulated. The group-velocity dispersion also changes the structure of the pump pulse, which then reduces the modulation depth accumulated along the fiber length, of the cross-field-induced phase on the signal pulse. Group velocity walk-off between pump and signal pulses due to fiber birefringence also limits spectral broadening by averaging-out the induced-phase.

Once strong amplitude noise has developed on the signal pulse, it will spectrally broaden by self-phase-modulation (SPM) and continue to get noisier. The spectrum of the pump pulse will also broaden by factors of 2-3 times by SPM. In contrast, we find that the intensity noise on the pump will decrease by spectral broadening from SPM. Other effects such as Raman scattering in the fused-silica fiber¹² can also alter the characteristics of spectral broadening. Typically, below stimulated threshold, the Raman effect will cause the pump to develop a "red" spectral wing and an overall "red" shift, which can cause a "blue" shift in the centroid of the signal spectrum. A similar "red" and "blue" shift is observed, neglecting Raman scattering, when the pump pulse is launched into the "slow" axis and the signal into the "fast" axis, and vice-versa. The pulses will shift spectrally so that the group-velocity dispersion will tend to equalize the propagation velocities and minimize pulse walk-off. We have included such effects in our numerical simulations, which are patterned after work of Menyuk and colleagues on the stability of picosecond duration soliton pulses propagating in birefringent single-mode optical fibers¹³, and we include a linearized treatment of the Raman effect.¹⁴ Practical problems include such things as twists and bends in the fiber which can

cause local birefringence changes, and cause scattering of the pump field into the polarization state of the signal, thereby artificially increasing noise on the signal pulse. Coupling of pump and signal beams into and out-of the birefringent fiber is also a problem, and can complicate comparisons with theory. These effects can be addressed experimentally.

2. Experiments

In 1989 at LLNL we implemented a novel concept in broadband light generation which employed the idea of optical field cross-phase-modulation (XPM) in a single-transverse-mode optical fiber.² The impetus for this development was our need to have a reliable, variable bandwidth laser source operating at close to the Nd:glass fundamental wavelength, with a smooth temporal envelope that would allow high finesse pulse shaping and propagation down the Nova laser chain at high power, with minimum risk of optical damage. The optical layout for the XPM system is shown in Fig. 1. The "noisy" laser source for this system was a multi-longitudinal-mode Nd:glass laser oscillator, depicted in Fig. 2, with a nominal spectral width of $\sim 15 \text{ \AA}$. The signal beam was derived from a LLNL designed single-frequency Nd:YLF oscillator and was transform limited. The Nd:glass oscillator used a 5-mm $\phi \times 3''$ Brewster angle cut Q-98 phosphate glass rod positioned at the high reflector (3-m radius of curvature) end of the laser cavity and a Brewster-angle-cut deuterated KDP Pockels cell Q-switch at the output-coupling end. Cavity length was 90 cm between mirrors, giving a longitudinal-mode spacing of 167 MHz and cavity round-trip time of 6-ns. An 85% reflectivity output coupler was typically used, although others were investigated. Separating the double-flashlamp pumped laser head ($\sim 50 \text{ J/pulse}$) and Pockels cell was an adjustable iris for spatial mode control, and a high damage threshold thin-film dielectric polarizer. A 15-ns square pump pulse was electro-optically sliced out of the 150-ns Nd:glass Q-switched pulse, and combined at the fiber input face with a 10–12-ns square slice from the single-frequency pulse. Simple 10X microscope objectives (N.A. $\sim .25$) were used for coupling the beams into and out-of the fiber. The pump and signal beams were separated by a high rejection ratio polarizer. The maximum pump energy measured at the fiber output was 10–12 μJ . The signal pulse energy was $\sim 1 \mu\text{J}$. Spectral and temporal measurements of the XPM signal and pump pulses were made using conventional diagnostics (a 1-m spectrometer and a 5-ps resolution streak camera). At the time we determined that for short lengths of optical fiber (2.9-m) the signal pulse showed only nominal noise levels at bandwidths up to $\sim 30 \text{ \AA}$. When the fiber length was increased to 6.0-m and then to 10.7-m we observed higher bandwidths, up to $\sim 35 \text{ \AA}$ and $45 \text{ \AA}$, but the XPM-induced temporal noise was noticeably increased.

The fiber used for these experiments (Lightwave pmf-001-920, now obsolete, but similar to new Ensign-Bickford fiber pmf-1060) was a GeO_2 -doped elliptical core, F-doped elliptical cladding, single-mode birefringent fiber with an advertised cut-off wavelength of 920 nm, with core dimensions of $4.2 \times 7.4 \mu\text{m}$, and a manufacturer's quoted polarization beat length of 9.0 mm at 515 nm, giving us a Δn of $\sim 6 \times 10^{-5}$ for the fiber birefringence. From Δn we can calculate that the pulse walk-off rate between polarizations is $\Delta n/c = 0.2 \text{ ps/m}$. We estimate the fiber V-parameter from the cut-off wavelength and core dimensions, and estimate the best elliptical gaussian beam waist dimensions for coupling into the lowest order spatial mode (HE_{11}). By the usual formulas¹⁵ we determined that the gaussian waist diameter should be 22% larger than the core dimensions for best matching, giving a laser mode area $A_m = \pi(1.22)^2(2.1 \times 3.7)/2 = 18.2 \mu\text{m}^2$. However, our fiber-optic couplers were simple microscope objectives. The pump laser mode was matched to the major axis of the core; thus giving a mode area A_m of $\sim 32 \mu\text{m}^2$. Dividing A_m and the pulse duration into the pulse energy gives an estimate of the peak spatial intensity of the beam coupled into the fiber. It is easy to show that the effective mode area of the fiber is approximated by $A_{\text{eff}} = (\int I(x,y) dx dy)^2 / \int I(x,y)^2 dx dy$, where $I(x,y)$ is the elliptical gaussian mode that best matches the actual fiber mode. Carrying-out this simple integration indicates that A_{eff} equals twice the laser mode area A_m , or ~ 1.5 times the physical area of the fiber core. For our case we take $A_{\text{eff}} \sim 64 \mu\text{m}^2$, and use the measured output energy as an approximate value for the energy coupled into the fiber.

Typical experimental spectra are shown in Fig. 3 for a pump pulse energy of $\sim 5 \mu\text{J}$, as measured at the fiber output face, and at a fiber length of 12 m. Dividing by A_{eff} from above and the pulse duration, we estimate an average pump intensity of $\sim 0.5 \text{ GW/cm}^2$ in the fiber, giving an average modulation depth of ~ 1 radian/m. Fig. 3 (upper right) shows the single-frequency spectrum ($< 0.5 \text{ \AA}$) the prior to XPM, limited in resolution by the optical multi-channel analyzer and spectrometer. With XPM from the pump laser the single-frequency line broadened symmetrically to a width of $\sim 22.7 \text{ \AA}$ FWHM as shown in Fig. 3 (upper left). The pump spectrum increased from $14.3 \text{ \AA}$ in Fig. 3 (lower left), to $\sim 23.5 \text{ \AA}$ FWHM as shown in Fig. 3 (lower right), as a result of SPM in the fiber. We typically observed a central feature ("spike") in the XPM spectrum located at the wavelength of the unmodulated signal. This "spike" was substantially reduced by adding a second output polarizer to the pulse-slicing Pockels cell used for the single-frequency oscillator, and hence we surmise that the central component was an

artifact from unmodulated light leaking through the slicer. In later experiments, however, and with the current XPM set-up on Nova, we do in fact observe a strong central component at low ($< 5 \text{ \AA}$) signal bandwidths. We also see this in numerical simulations shown in Section 4.

When the pump energy was doubled to $10 \mu\text{J}$, at an estimated average intensity of $\sim 1 \text{ GW/cm}^2$ in the 12-m fiber, we observed that both the pump and signal spectra developed large asymmetries. One particular case is shown in Fig. 4. The signal spectra, Fig. 4 (right), developed a noticeable shift towards the "blue" spectral side. The pump spectra, Fig. 4 (left), exhibited the opposite behavior, developing a shift in the centroid of the spectra to the "red" side. The leakage from the pulse slicer provided a wavelength fiducial for the un-modulated light. The overall "red" shift in the broadband pump spectrum could be due to Raman scattering effects, but is also consistent with simulations that indicate that the pump should "red" shift and the signal "blue" shift to minimize group-velocity walk-off, when coupled into the "slow" and "fast" polarization axes, respectively. In more typical operation, Fig. 5 shows XPM induced bandwidth as a function of measured pump energy for several fiber lengths tested on Nova. As fiber length is increased the XPM bandwidth increases at constant pump energy, but not much is gained in going from a 10-m to 20-m fiber. Also there appears some limiting of the XPM bandwidth as pump energy goes up. Simulations indicated that at longer fiber lengths the walk-off effect was limiting the XPM. A second fiber was tested, one commonly used for SPM in an optical pulse compressor, at a length of 17-m, and gave very poor results. An XPM spectral width of only $1.5 \text{ \AA}$ was obtained with $8 \mu\text{J}$ of pump energy. The walk-off rate for this fiber was estimated at 1.1 ps/m , about 5 times greater than our standard XPM fiber. One experimental consideration is that the central pump wavelength was measured as 1054.1-nm (for Nd:glass), whereas the signal wavelength was measured as 1053.3-nm (for Nd:YLF). With a group-velocity-dispersion of $\sim 40 \text{ ps/nm-km}$ at 1053 nm , the refractive index difference due to dispersion is $\sim 1 \times 10^{-5}$, which corresponds to a walk-off rate of $\sim 0.032 \text{ ps/m}$, which we ignore compared to the birefringence walk-off rate of 0.2 ps/m .

The Raman effect for monochromatic fields is described in terms of the pump and scattered (Stokes) field intensities, denoted by I_p and I_s , where the growth-rate of the frequency-shifted Stokes field is proportional to the product of pump and Stokes intensities, given by $dI_s/dz = G_R I_p I_s$. The coefficient G_R depends on the frequency difference between pump and Stokes fields and is proportional to the pump frequency. For SiO_2 glass fiber, G_R has a maximum value of $0.91 \times 10^{-13} \text{ m/W}$ at a frequency difference of 13.2 THz estimated for a pump wavelength of 1053 nm .¹¹ For a 10–12 m length of fiber we can use the growth equation to estimate the stimulated threshold intensity. Neglecting pump depletion, the growth in the Stokes field at peak gain is $\exp(G_R I_p z)$, where z is the fiber length. Approximately 30 Nepers of gain is required to reach threshold from spontaneous noise conditions; therefore, the pump intensity required is $\sim 3.3 \text{ GW/cm}^2$, or $\sim 30 \mu\text{J}$ energy in a 15-ns square pulse. From simulations in Section 4, we will see that Raman scattering effects should be observed at energies below threshold.

3. Theory

The coupled wave equations that describe the space and time evolution of the pump and signal electric fields inside a birefringent optical fiber can be derived from Maxwell's equations using the slowly varying envelope approximations. They resemble the Schrodinger equations for pulse propagation in dispersive media, except that the nonlinear self- and cross-field coupling terms are added from the third order electric susceptibility,¹⁰ and we also add terms describing the self- and cross-field Raman effects, in a linearized treatment.¹⁴ We treat the fields as plane-waves in the direction transverse to the fiber optical axis, which we take here as the z -axis. To simplify the computational effort, we also transform the time-derivatives of the fields, denoted by operators $\partial/\partial t$ and $\partial^2/\partial t^2$ to a local time variable, $\tau = (t - z/v_g)$, describing a reference frame moving along with the two pulses at the average group-velocity v_g . We also define a parameter δ which is $1/2$ the reciprocal group-velocity difference, that is $\delta = (1/2)\Delta(1/v_g)$. We can approximate this as equal to the reciprocal phase velocity difference from fiber birefringence, Δn , so that $\delta = (1/2)(\Delta n/c)$, which we take as a positive number. We shall suppose as is customary that the pump and signal envelope functions, taken here as $u(z, \tau)$ and $v(z, \tau)$ respectively, represent the spatially-averaged mode field amplitudes for the two polarization eigenvectors of the fiber. We write the equations in the mks system where the field amplitudes $u(z, \tau)$ and $v(z, \tau)$ are in units of $(\text{W/m}^2)^{1/2}$. When we launch the pump field $u(z, t)$ into the "slow" polarization axis, the wave equation becomes

$$(2a) \quad i \frac{\partial u}{\partial z} + i \delta \frac{\partial u}{\partial \tau} - \frac{g}{2} \frac{\partial^2 u}{\partial \tau^2} + \frac{\omega_0 n_2}{c} (|u|^2 + B|v|^2)u + i \left(\frac{\partial u}{\partial z} \right)_{SRS} = 0$$

and for the signal field $v(z,t)$ launched into the "fast" polarization axis, the wave equation is

$$(2b) \quad i \frac{\partial v}{\partial z} - i\delta \frac{\partial v}{\partial \tau} - \frac{g}{2} \frac{\partial^2 v}{\partial \tau^2} + \frac{\omega_o n_2}{c} (|v|^2 + B|u|^2)v + i \left(\frac{\partial v}{\partial z} \right)_{SRS} = 0$$

where the $(\partial/\partial z)_{SRS}$ derivatives denote the Raman scattering terms, for pump field,

$$(3a) \quad i \left(\frac{\partial u}{\partial z} \right)_{SRS} = - (c_1 u \frac{\partial |v|^2}{\partial \tau} - c_2 u \frac{\partial |v|^2}{\partial \tau} + c_3 v \frac{\partial uv^*}{\partial \tau})$$

and for the signal field,

$$(3b) \quad i \left(\frac{\partial v}{\partial z} \right)_{SRS} = - (c_1 v \frac{\partial |v|^2}{\partial \tau} + c_2 v \frac{\partial |u|^2}{\partial \tau} + c_3 u \frac{\partial vu^*}{\partial \tau})$$

In Eqns. 2(a-b), ω_o is the angular frequency of the electric field carrier, c is the velocity of light in vacuum, n_2 is the nonlinear refractive index, which for SiO₂ glass fibers we take as $3.2 \times 10^{-20} \text{ m}^2/\text{W}$.¹⁴ The group velocity dispersion is denoted by $g = \partial^2 k / \partial \omega^2 = (2\pi c / \omega_o^2) D(\text{s/m}^2)$, where D is the group-velocity dispersion parameter which we take to be positive for wavelengths in the normal dispersion regime. In the linearized fiber Raman theory¹⁴ we take the spectral-widths of the pump and signal pulses to be much less than 13.2 THz, and then the coefficients in Eqns. 3(a-b) can be approximated as being proportional to the slope of the spectral shape of the Raman gain coefficient G_R evaluated at zero-frequency shift. For SiO₂ glass fiber, G_R has a peak value of $0.91 \times 10^{-13} \text{ m/W}$ for a 1053-nm wavelength pump pulse, at a Raman shift of 13.2 THz.¹² In this approximation, $G_R = C_R f_R$, where $f_R = 13.2 \text{ THz}$, and $C_R = 8.3 \times 10^{-27} \text{ m-sec/W}$. The Raman coefficients in Eqns. 3(a-b) are then given as $c_1 = C_R/2$ for the parallel (self) Raman term, $c_2 = C_R/3$ for the perpendicular (cross-field) Raman term, and $c_3 = C_R/3$ for the perpendicular (4-wave mixing) Raman term.

The nonlinear equation set, Eqns. 2(a-b) and 3(a-b), can be solved in variety of ways¹⁶ - including the split-step Fourier method which is what we have adopted.¹⁷ In this method the coupled partial differential equations (PDE's) are converted to coupled ordinary differential equations (ODE's) by eliminating the $\partial/\partial t$ and $\partial^2/\partial t^2$ operators in Eqns. 2(a-b) by Fourier transforming. Ignoring the self and cross field interactions, over a small distance δz :

$$(4a) \quad u(z + \delta z, \tau) = \frac{1}{2\pi} \int d\eta e^{-i\eta\tau} G(\delta z, \eta) \left[\int d\tau e^{i\eta\tau} u(z, \tau) \right]$$

solves the linear part of the PDE describing the pulse time evolution, and similarly for the signal field $v(z+\delta z, \tau)$. The Fourier propagator $G(z, \eta)$ is given by

$$(4b) \quad G(z, \eta) = e^{i(\pm\delta\eta + \frac{1}{2}g\eta^2)z}$$

where $\eta = \omega - \omega_o$ is the angular frequency difference from the carrier wave, and we take the plus (+) sign on δ for the pump field and the minus (-) sign on δ for the signal. Substituting $u(z+\delta z, \tau)$ and $v(z+\delta z, \tau)$ back for $u(z, \tau)$ and $v(z, \tau)$ in Eqns. 2(a-b), and with time-derivatives in Eqns. 3(a-b), we calculate the interaction effects for all times τ at position z , and solve the coupled ODE's over the space step from z to $z+\delta z$, using simple trapezoidal integration. The time derivatives at position z which are required for the Raman interactions can be determined by Fourier methods or by finite differences in τ once the various products of the fields are computed. The integration proceeds from z to $z+\delta z$ by repeating the time evolution operation with $u(z+\delta z, \tau)$ substituted for $u(z, \tau)$ on the right-hand side of Eqn. 4a, and similarly for $v(z+\delta z, \tau)$. This numerical approach is sometimes called the "leap frog" method, and is accurate to $O(\delta z^2)$.

4. Simulation Results

A number of simulations were first carried out to verify our estimate of the effective pump beam area at the fiber faces by comparing the resulting XPM-induced bandwidth as a function of fiber length to the maximum bandwidths that were

observed experimentally in a "standard" case. We took the data shown in Fig. 3 to be representative, but not the best results achieved; that is, for a broadband pump pulse with 5 μJ in 15 ns, with a nominal spectral width of ~ 14 to $16 \text{ \AA}$, and for a single-frequency signal pulse with 1 μJ in 10 ns, we measured a maximum spectral broadening of $\sim 30 \text{ \AA}$ at 3-m, $\sim 35 \text{ \AA}$ at 6-m and up to $\sim 45 \text{ \AA}$ at 12-m fiber length. It is not practical to simulate entire pulses at the spectral widths involved, so instead we simulated a narrow time-slice. The computational grid consisted of 2048 time-points in a 200-ps window, sufficient to resolve sub-ps variations, and a minimum of 2000 z-steps for a fiber length of up to 12 m. We used shorter time windows and more z-steps in certain cases to avoid spectral aliasing problems. The signal pulse was taken to have a flat amplitude and constant phase, initially. The pump pulse was modeled as a superposition of spectral modes of uniformly random phase, with mode amplitudes following a Gaussian shape. For more realism, the mode amplitudes in some cases were required to satisfy Rayleigh statistics, while maintaining an overall Gaussian envelope. The spectral-shape resulting from cross-phase-modulation is not Gaussian, and is typically very noisy. So to obtain the spectral width from the simulations, we first calculate the centroid of the distribution, $\omega_c = (\int \omega v(\omega)^2 d\omega) / (\int v(\omega)^2 d\omega)$, where $v(\omega)$ is the Fourier transform of the electric field envelope of the signal pulse (or pump pulse), and then the square-root of the variance of the spectral power about the centroid position, that is $\sigma_\omega = [(\int \omega^2 v(\omega)^2 d\omega) / (\int v(\omega)^2 d\omega) - \omega_c^2]^{1/2}$. We then define the spectral bandwidth as $\delta\omega_{fwhm} = 2\sqrt{2\ln(2)}\sigma_\omega = 2.355\sigma_\omega$, which is exactly the full-width at half-maximum for a Gaussian power spectrum. This number will be somewhat larger than we would estimate as the experimental full-width at half-maximum for an XPM-induced spectral shape.

The results of one representative simulation are shown in Fig. 6, and were obtained with a beam area of $66.7 \mu\text{m}^2$, which is very close to the estimate given in Section 2. As the pump and signal pulses move down the fiber and interact via the nonlinear refractive index, their spectral widths broaden linearly with fiber length up to a length of about ~ 1.5 -m. The signal pulse develops $\sim 20 \text{ \AA}$ width and the pump pulse spectrum increases from $16.7 \text{ \AA}$ to $\sim 40 \text{ \AA}$. Beyond 2-m length, the signal pulse broadens at a slower rate with distance and tends towards a limiting value of $\sim 40 \text{ \AA}$ at 8-10 m. The intensity noise (as quantified by the normalized root-variance) appears to initially grow quadratically with distance, but then grows linearly with distance from 2 to 5 m, and finally flattens out to a σ value of ~ 0.65 at 12 m. Interestingly, the pump pulse, beginning with $\sigma \sim 0.94$ (ideal statistics gives $\sigma = 1$), gets less noisy with distance and reaches an asymptotic level of $\sigma \sim 0.56$ at a fiber length of 6-m. As the pump pulse noise decreases, its spectral width becomes limited to a value of $\sim 68 \text{ \AA}$, which is an increase of 4 times over the initial bandwidth. Fig. 7 shows representative pump and signal pulseshapes and spectra at a fiber length of 6-m, where the signal has broadened to twice the initial pump spectral width, and where the σ values are approximately equal. In practice, however, we have never seen the pump spectrum broaden by this amount. Examination of the frequency centroids shows that the pump pulse should develop a "red" shift of $\sim 19 \text{ GHz}$ at 6-m and $\sim 75 \text{ GHz}$ at 12-m length, for propagation down the "slow" fiber axis; and the signal pulse should "blue" shift by $\sim 39 \text{ GHz}$ at 6-m and $\sim 151 \text{ GHz}$ at 12-m, for propagation down the "fast" axis. When the axes are reversed the pulses shift in the opposite sense. As with the soliton propagation in birefringent fibers, the spectral centroids shift apart because the two polarizations are bound together through cross-phase-modulation. The frequency centroids shift in opposite directions using the group-velocity-dispersion to eliminate the polarization velocity difference.

When Raman scattering was included in these simulations, the results were changed only slightly because the spectral broadening in the first few meters was much less than the 13.2 THz Raman shift. Simulations showed that a small fraction of power was transferred from the fast axis (signal) which has a higher central frequency, to the slow axis (pump) as expected for Raman scattering. We also observed additional "red" shifts on both polarizations, with the pump beam seeing the larger shift - an additional red shift of 17 GHz at 6-m and 70 GHz at 12-m, with the signal beam only red shifting by 16 GHz at 12-m for a total "blue" shift of 135 GHz . At twice the pump energy per pulse, $10 \mu\text{J}$ in 15-ns, at an estimated pump intensity in the fiber of 1 GW/cm^2 , simulations (Fig. 8) show more noticeable Raman effects, particularly on the pump pulse (upper left). Over a 6-m fiber length, the "red" shift on the pump beam is large, $\sim 1 \text{ THz}$, due to the development of a long "red" wing, and $\sim 72\%$ additional spectral broadening is predicted. In contrast to the previous simulations, the signal spectrum (upper right) is pushed even further to the "blue" with SRS - 97 GHz compared to 46 GHz without SRS, and the signal spectrum also shows a 30% increase in broadening. A small percentage ($\sim 2.3\%$) of signal power is also transferred from the signal to the pump pulse. As discussed in Section 2, the stimulated threshold for Raman scattering should occur at a pump intensity of $\sim 3.3 \text{ GW/cm}^2$. However, a noisy pulse can exceed 3 times the average intensity 5% of the time, and these intensity peaks can contain up to $\sim 20\%$ of the total power, so it is not surprising that we predict noticeable Raman effects at below threshold.

Optimization of the XPM process is illustrated with the simulation results shown in Fig. 9. In order to examine the effects of polarization walk-off (fiber birefringence) and group-velocity dispersion on XPM, a matrix of runs was performed

with the "standard" pump and signal input conditions described earlier, where the dispersion was varied from $D = 5$ to 40 ps/nm-km and the birefringence Δn was varied from 5×10^{-6} to 8×10^{-5} . Not surprisingly, large spectral broadening can be induced on the signal pulse, up to $\sim 80 \text{ \AA}$, with a simultaneously low fiber dispersion and low birefringence. Results of two runs are shown in Fig. 9 where $D = 5$ or 10 ps/nm-km and $\Delta n = 2 \times 10^{-5}$. Notice that with 4 times lower dispersion and 3 times lower birefringence (curves denoted by notation 10/2), at fiber lengths greater than about 4–5 m, a significant amount of intensity noise grows on the signal pulse and the spectral broadening begins to saturate – as we observed with more typical fiber parameters. In the 10/2 case, 40 $\text{\AA}$ of broadening can be obtained on the signal at a fiber length of ~ 4 -m, with induced noise of less than 10%. Lowering the dispersion to 5 ps/nm-km (curves denoted by 5/2) increases the spectral width only slightly, while reducing intensity noise in half. Low birefringence can be engineered into specialty fibers, but the difficulty then is to maintain a high extinction ratio between fiber polarizations, so as to avoid scattering of noisy pump light into the signal polarization. Theoretically, the ratio can be arbitrarily high if there are no material defects or bends and twists in the fiber. Since the fiber lengths required are only a few meters, this might be practical. The reduction in group-velocity dispersion from 40 to 10 ps/nm-km, by modifying the fiber mode guiding properties at 1053-nm wavelength will require significant engineering effort, but might be possible.

5. Summary

We have numerically examined the spectral broadening of single-frequency laser pulses by using cross-phase-modulation with a noisy broadband laser pulse in a linearly birefringent optical fiber. The simulations have been normalized to experimental data obtained at LLNL during development of this technique for the generation of wide-bandwidth pulses for use in smoothing the target irradiance of high power solid state Nd:glass lasers used for inertial confinement fusion research. Large bandwidths can be achieved by this technique, but the intensity modulation might be as high as 60%, measured in a root-rms sense, using commercially available fibers. Large bandwidths and low noise might be achieved with specialty fibers that possess both reduced birefringence (by 3 times) and lower chromatic dispersion (by 4 times).

6. Acknowledgments

One of us (M. A. Henesian) would like to thank co-inventors P. H. Chaffee and F. G. Patterson for their collaboration at LLNL in developing the technique of cross-phase-modulating noisy broadband pulses with single-frequency pulses for the purpose of obtaining temporally smooth wide-band pulses for ICF applications, and we also thank Professor Robert W. Hellwarth of University of Southern California for stimulating discussions on this subject. We (M. A. Henesian and S. N. Dixit) also thank D. F. Browning, T. L. Weiland, and R. B. Wilcox at LLNL for engineering the cross-phase-modulation technique into operational hardware for the Nova laser, used routinely today for target irradiance experiments with temporally and spatially incoherent beams. We also thank H. T. Powell at LLNL for his encouragement in the present work, and D. M. Pennington and M. Webb at LLNL for their support on recent broadband development work. We (C.-J. Chen, P. K. A. Wai, and C. R. Menyuk) particularly thank M. N. Islam and R. H. Stolen of AT&T Bell Laboratories for informative discussions on propagation effects in birefringent optical fibers and fiber-optic technology. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

7. References

- 1.) M. N. Islam, L. F. Mollenauer, R. H. Stolen, J. R. Simpson, and H. T. Shang, Opt. Lett. 12, 625-627 (1987).
- 2.) P. H. Chaffee, F. G. Patterson, and M. A. Henesian, Technical Digest, Conference on Lasers and Electro-Optics 10, paper WD3 (1989, Optical Society of America, Baltimore, Maryland), and U. S. Patent No. 5,015,054 (May 14, 1991).
- 3.) H. T. Powell, S. N. Dixit, and M. A. Henesian, ICF Quarterly Report, Lawrence Livermore National Laboratory, Livermore, California, UCRL-LR-105821-91-1, 28 (1991), and M. A. Henesian, S. N. Dixit, H. T. Powell, C. E. Thompson, P. J. Wegner, and T. L. Weiland, Technical Digest, International Quantum Electronics Conference 9, paper TuE3 (1992, XVIII International Quantum Electronics Conference, Vienna, Austria).
- 4.) D. M. Pennington, M. A. Henesian, H. T. Powell, C. E. Thompson, and T. L. Weiland, Technical Digest, Conference on Lasers and Electro-Optics 11, paper CTuC4 (1993, Optical Society of America, Baltimore, Maryland).

- 5.) S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, and J. M. Soures, J. Appl. Phys. 66, 3456 (1989).
- 6.) R. H. Lehmberg, A. J. Schmitt, and S. E. Bodner, J. Appl. Phys. 62, 2680 (1987).
- 7.) D. Veron, H. Ayrat, C. Guedard, D. Husson, J. Lauriou, O. Martin, B. Meyer, M. Rostaing, and C. Sauteret, Opt. Commun. 65, 42-44 (1988).
- 8.) H. T. Powell, M. A. Henesian, F. G. Patterson, M. D. Perry, and P. J. Wegner, Technical Digest, Conference on Lasers and Electro-Optics 12, paper CFA4 (1992, Optical Society of America, Anaheim, California).
- 9.) J. W. Goodman, Statistical Optics, John Wiley & Sons, c. 1985.
- 10.) C. R. Menyuk, IEEE J. Quantum Electron. QE-25, 2674-2682 (1989).
- 11.) J. T. Manassah, Opt. Lett. 16, 1379-1381 (1991).
- 12.) R. H. Stolen, C. Lee, and R. K. Jain, J. Opt. Soc. Am. B 1, 652-657 (1984).
- 13.) C. R. Menyuk, Opt. Lett. 12, 614-616 (1987).
- 14.) C.-J. Chen, C. R. Menyuk, M. N. Islam, and R. H. Stolen, Opt. Lett. 16, 1647-1649 (1991).
- 15.) Newport Corp. Catalog, page J-4, 1992.
- 16.) T. R. Taha, and M. J. Ablowitz, J. Comp. Phys. 55, 203-230 (1984).
- 17.) C. R. Menyuk, J. Opt. Soc. Am. B 5, 392-402 (1988).

8. Figures

Fig. 1. Optical layout for cross-phase-modulation (XPM) of single-frequency and broadband laser pulses in a single-mode polarization preserving optical fiber for generation of wide bandwidth pulses.

Fig. 2. Layout of components for 'noisy' broadband Nd:Glass laser oscillator. Typical performance is 10 mJ output energy in a 150-ns Q-switched pulse at 1054-nm wavelength in a TEM_{00} spatial mode.

Fig. 3. Typical spectra: single-frequency pulse before entering optical fiber (linewidth $< 0.5 \text{ \AA}$) (upper left), Single-frequency pulse after XPM in fiber (linewidth $\sim 22.7 \text{ \AA}$) (upper right), broadband pulse before entering fiber (linewidth $\sim 14.3 \text{ \AA}$) (lower left), broadband pulse after XPM in fiber (linewidth $\sim 23.5 \text{ \AA}$) (lower right). Experimental conditions: broadband (pump) energy $\sim 5 \mu\text{J/pulse}$ in 15-ns, single-frequency (signal) energy $\sim 1 \mu\text{J/pulse}$ in 10-ns, fiber length = 12.2 m, fiber core = $4.2 \times 7.4 \mu\text{m}$. Spectrometer dispersion = $5.6 \text{ \AA/division}$.

**Broadband Spectrum
(w/XPM and Raman in fiber)**

red ← → blue

**Single-Mode Spectrum
(w/XPM in fiber)**

red ← → blue

Fig. 4. Typical spectra at high broadband pulse energy: single-frequency pulse spectra (right) shifted towards blue wavelengths (linewidth $\sim 35 \text{ \AA}$), Broadband pulse spectra (left) shifted towards red wavelengths. Experimental conditions: broadband (pump) energy $\sim 10 \text{ \mu J/pulse}$ in 15-ns, single-frequency (signal) energy $\sim 1 \text{ \mu J/pulse}$ in 10-ns, fiber length = 12.2 m, fiber core = $4.2 \times 7.4 \text{ \mu m}$. Spectrometer dispersion = $5.6 \text{ \AA/division}$.

Fig. 5. Measurements of XPM spectral broadening of single-frequency pulse as function of broadband (pump) pulse energy measured at fiber output at fiber lengths of 2, 10, and 20 m. Same fiber type as results shown in Figs. 3 and 4.

Fig. 6. Simulation results for best experimental case: pump energy = 5 μJ in 15-ns pulse, signal energy = 1 μJ in 10-ns pulse, initial pump linewidth ~ 450 GHz (16.6 $\text{\AA}$), fiber parameters: $D = 40$ ps/nm-km, $\Delta n = 6 \times 10^{-5}$, effective beam area $\sim 66.7 \mu\text{m}^2$. Plot of spectral broadening of pump and signal pulses with fiber length (left), plot of normalized root-variance σ of intensity for pump and signal pulses with fiber length (right).

Fig. 7. Pump and signal pulses and spectra at 6-m of fiber from simulations in Fig. 6 above. Pump pulse (upper left) has $\sigma=0.554$ with average intensity of 1.0 a.u., signal pulse (upper right) has $\sigma = 0.506$ and average intensity of 0.3 a.u. Pump spectra (lower left) has 68.4 $\text{\AA}$ fwhm, and signal spectra (lower right) has 34.8 $\text{\AA}$ fwhm.

Fig. 8. Particular simulation showing Raman scattering (SRS) effect on pump and signal pulses: pump energy = 10 μ J in 15-ns pulse, signal energy = 1 μ J in 10-ns pulse, initial pump linewidth $\sim$ 450 GHz (16.6 $\text{\AA}$), fiber parameters: length = 6 m, $D = 40$ ps/nm-km, $\Delta n = 6 \times 10^{-5}$, effective beam area $\sim$ 66.7 μm^2 . Spectrum of pump pulse with SRS (upper left), spectrum of signal pulse with SRS (upper right), spectrum of pump pulse without SRS (lower left), spectrum of signal pulse without SRS (lower right).

Fig. 9. Simulation results with special low dispersion, low birefringence optical fibers with laser parameters from Fig. 6. Two fiber types are shown, labeled 5/2: $D = 5$ ps/nm-km, $\Delta n = 2 \times 10^{-5}$, and labeled 10/2: $D = 10$ ps/nm-km, $\Delta n = 2 \times 10^{-5}$. Plot of spectral broadening of pump and signal pulses with fiber length (left), plot of normalized root-variance σ of intensity for pump and signal pulses with fiber length (right).

END

DATE
FILMED

11 / 16 / 93