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Complete Compensation of Self-Phase Modulation in Cesium Vapor at 1.06μ

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Laser Plasma Branch
Plasma Physics Division

May 1977

Work performed at the Naval Research Laboratory under the auspices of the
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We have observed a complete cancellation of self-phase modulation at 1.06 μ pulses propagating through cesium vapor. The negative nonlinear refractive index responsible for this is measured as $n_2/N = -(2.5 \pm .5) \times 10^{-30}$ esu, in good agreement with the theoretical value -2.62×10^{-30} esu.

10 to the -30th power

COMPLETE COMPENSATION OF SELF-PHASE MODULATION IN CESIUM VAPOR AT 1.06 μ

Recently, we reported the observation of self-defocusing of mode-locked pulses at 1.06 μ in cesium vapor, and attributed the effect primarily to a nearby two-photon resonace with the $6s\ ^2S_{\frac{1}{2}}$ - $7s\ ^2S_{\frac{1}{2}}$ levels.[1,2] From these measurements, we inferred a negative nonlinear refractive index $n_2 \simeq -1.5 \times 10^{-30}$ N esu, in reasonable agreement with the theoretical value -2.62×10^{-30} N esu.[2] Thus, the magnitude of n_2 at cesium vapor densities of approximately 10^{17} cm^{-3} will be comparable to that of typical laser glass[3,4], giving rise to the possibility of compensation for the whole beam self-focusing and self-phase modulation in the amplifier chains of large glass lasers. The recent use of spatial filters to suppress small-scale self focusing has allowed operation of lasers at peak nonlinear phase retardations up to 3π,[5] where these effects are appreciable.[6]

Initial studies of the compensation process were reported at the IXth IQEC.[7] Here, we report the complete compensation of self-phase modulation (and, therefore, whole beam self focusing) induced by YAG amplifiers and CS_2 on mode-locked pulses from a Nd:YAG laser by propagating the pulses through a cesium vapor cell. From the variation of nonlinear phase compensation with Cs number density we have determined a value of $n_2/N = -(2.5 \pm .5) \times 10^{-30}$ esu, which is in excellent agreement with the theoretical value. Finally, the degree of compensation that we have been able to achieve indicates that the nonlinear refraction in Cs is instantaneous (i.e., $\delta n(t) \sim n_2 I(t)$; therefore, this process should be useful for compensating the self-phase modulation introduced by other rapidly responding media.

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A pulse propagating through such a medium develops an intensity dependent phase shift:

$$B(t) = \frac{8\pi^2}{n_o \lambda_o c} \int_0^L n_2 I(z,t) dz. \qquad (1)$$

where I(z,t) is the intensity, and L is the path length. The instantaneous frequency shift of the pulse $\delta\omega(t) = - \dot{B}(t)$ results in spectral broadening with a Bessel function modulation that is characteristic of self-phase modulation (SPM). Typical calculated spectra are shown in Fig. 1 for temporally Gaussian pulses with various values of peak nonlinear phase shift B. The FWHM spectral width $\Delta\lambda_{pp}$ between the outermost peaks (normalized to the unchirped FWHM width $\Delta\lambda_o$) are shown as a function of B in Fig. 2. It is evident from this figure that $\Delta\lambda$ is approximately equal to the maximum instantaneous wavelength excursion due to the chirp $\delta\lambda_{max} - \delta\lambda_{min} = (\lambda_o^2/\pi c) \dot{B}(max) = 1.03 B\Delta\lambda_o$ for $B \gg 1$.

If a pulse with this type of phase structure is subsequently propagated through a second medium with n_2 of opposite sign to that of the first, the nonlinear phase structure can be cancelled. This cancellation should occur at all times during the pulse and at all positions across the beam profile if the spatial changes due to self focusing and defocusing are negligible within or between the two media i.e., if the nonlinear refraction affects only the phase of the pulse.[8]

In order to investigate these concepts, we performed the experiment indicated schematically in Fig. 3. Single mode-locked pulses from a Nd:YAG laser were self phase modulated in a positive sense by propagation through the YAG amplifiers and 2 mm of CS_2. The pulses incident on the CS_2 cell contained nominally 40 mj of energy with a 35 ps pulse width, as determined by a 5 psec resolution streak camera. The spatial profile, as determined by a silicon diode array, was an Airy pattern with a 4.0 mm 1/e diameter, which was truncated at its first minimum by aperture A_1. After a 2.1:1 expansion by a Galilean telescope to minimize the spatial effects of self defocusing, the pulses were propagated through a 1 m long, two-temperature cesium cell, which has been described elsewhere.[2] The pulse energy was monitored before and after the cell with a calibrated photodiode. The peak on-axis intensity at the entrance was approximately 1 GW/cm^2, and the insertion loss (due to cesium dimers[2,9]) was less than 20% under optimum compensation conditions.

Time-integrated spectra of the on-axis portion of the pulse were recorded both before and after the cell by a 1 m normal incidence grating monochromator and a streak camera. The streak camera was operated with a time resolution of 350 psec, thereby providing time-integrated spectra of each pulse, while allowing the incident and transmitted pulses to be separated in time. The spectral resolution was 0.18 Å.

Densitometer traces of typical spectra are shown in Fig. 4. The incident spectra (lower traces) were broadened to widths of 2-4 Å, with approximately equal contributions from the CS_2 cells and the YAG laser amplifiers. They have the double-peaked appearance characteristic of their phase modulation depths B_{in} between 1.5 π and 1.7 π. The spectral asymmetry is due to a temporal asymmetry of the laser pulse that arises from gain saturation in the final YAG amplifier. For an empty cell (Fig. 4a), the output spectrum is actually broadened slightly due to additional positive self-phase modulation in the lenses and cell windows. At intermediate cesium densities (4b), partial compensation is evident, with the spectrum narrowing and becoming single-peaked. At a density $N \simeq .76 \times 10^{17}$ cm^{-3} (4c), compensation is complete, and the spectrum of the initially phase-modulated pulse narrows to its time-bandwidth limit. Higher densities (4d) result in overcompensation; i.e., the pulse becomes self phase modulated in a negative sense, with its spectrum broadened and the spectral asymmetry reversed. Further studies showed that optimal compensation could be achieved for the largest values of B_{in} that we were able to produce without beam breakup (~ 3 π).

The numerical value of n_2/N was obtained from Eq. (1) with $B = B_{out} - B_{in}$, using nine shots of known peak intensities and cesium pressures. B_{in}, which ranged from $1.5\ \pi$ to $2.5\ \pi$, was estimated by measuring the peak-to-peak spacing of the input spectra, calculating $\Delta\lambda_{pp}/\Delta\lambda_o$, and using Fig. 2.[10] For a pulsewidth $\Delta t = 35$ psec, $\Delta\lambda_o = (2\ell n2)\ \lambda_o^2/\pi c\Delta t = 0.48$ Å. At the output, where B_{out} ranged from $.55\ \pi$ to $1.0\ \pi$, the spectra were single-peaked in most of the cases chosen. B_{out} was estimated by measuring the FWHM spectral widths relative to those of time-limited pulses of similar intensity and film exposure. No shots in which $|B_{out}| < .5\ \pi$ or $1.0\ \pi < B_{in} < 1.5\ \pi$ were used, because of the difficulty of estimating accurate B values from spectra in these ranges. (See Fig. 2.) In all of the shots that were used, the calculated B values matched closely with values inferred from theoretical spectra of similar qualitative appearance. (See Fig. 1.)

Although the value $n_2/N = -(2.5 \pm .5) \times 10^{-30}$ esu determined in the present work agrees with the theory, the precision is somewhat poorer than in our earlier measurement because of the difficulty in evaluating accurate B values of the input and output pulses from the spectra. The inaccuracy of our earlier value of n_2/N probably arose from inaccuracy in measuring N. In the present experiment, we allowed a significantly longer time for the two-temperature cesium oven to reach thermal equilibrium at each new density, and this appears to have remedied the problem.

In summary, we have demonstrated that the negative nonlinear refractive index of Cs vapor at $1.06\ \mu$ can be used to compensate for the self-phase modulation introduced on laser pulses by propagation through media with positive n_2 values. The value of n_2/N determined in these measurements is in excellent agreement with that obtained from ab-initio calculations. Although the major thrust of the current work was to observe compensation of self-phase modulation artifically introduced in CS_2, some of the phase modulation that was compensated arose in the amplifier stages of the laser. In addition, virtually complete compensation was observed for our maximum modulated pulses up to 3π which is comparable to the phase modulation found in some lasers currently being built for fusion research.[5] Our work, therefore, indicates the feasibility of using cesium to compensate self-phase modulation, and hence whole beam self focusing, in large Nd:Glass laser systems.

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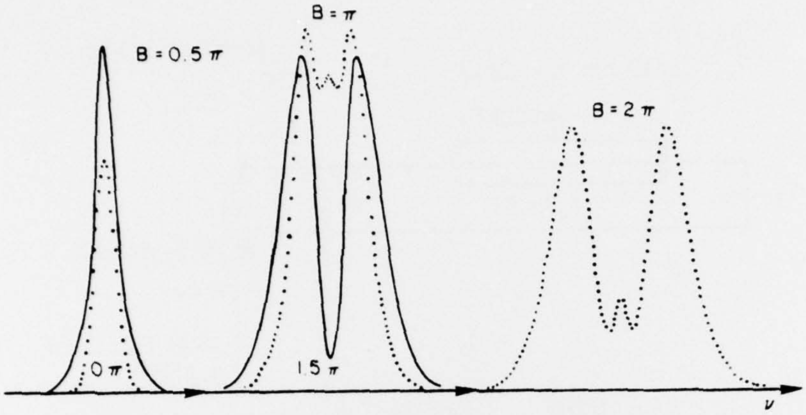

Fig. 1 — Calculated spectra of self phase modulated Gaussian pulses with peak nonlinear phase shifts B = 0, 0.5 π, 1.0 π, 1.5 π and 2.0 π

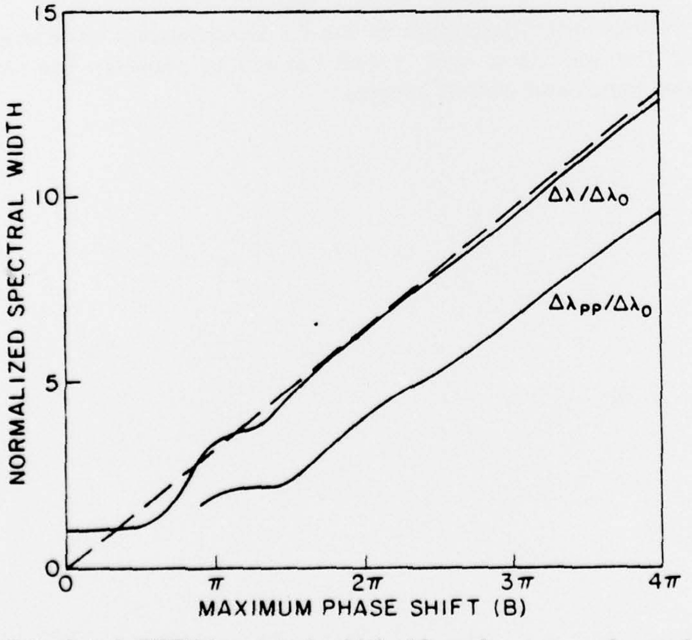

Fig. 2 — Calculated FWHM spectral width $\Delta\lambda$ and outer peak spacing $\Delta\lambda_{pp}$ (normalized to the time-bandwidth limited width $\Delta\lambda_o$) of self phase modulated Gaussian pulses of peak nonlinear phase shift B. The dashed line is the normalized maximum instantaneous wavelength excursion due to the chirp.

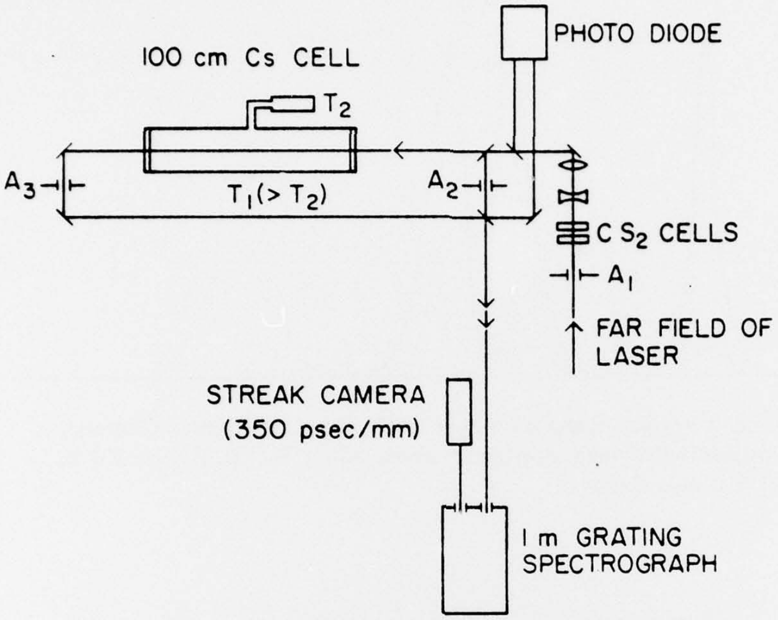

Fig. 3 — Schematic illustration of the Cs compensation experiment, showing the use of a slow streak camera to separate the time-integrated input and output spectra

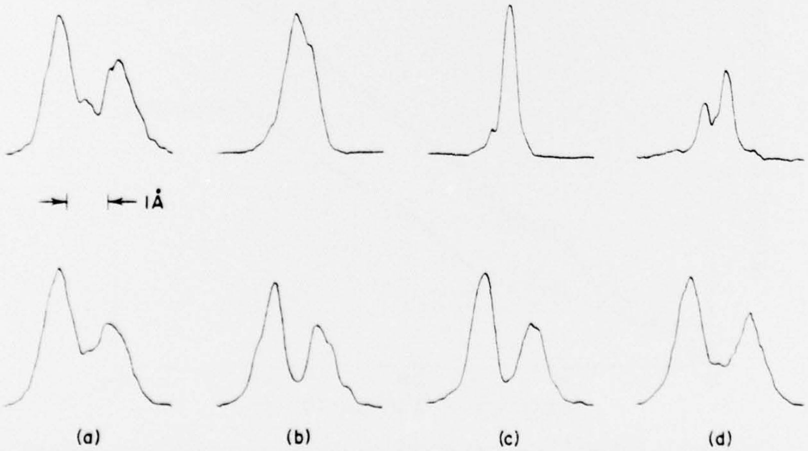

Fig. 4 — Densitometer traces of the incident spectra (lower) and transmitted spectra (upper) for cesium densities of (a) N = 0, (b) 4.6×10^{16} cm^{-3}, (c) 7.6×10^{16} cm^{-3}, and (d) 1.13×10^{17} cm^{-3}