Phase Conjugation

Polarization Properties of Phase-Conjugate Mirrors

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PACS: 42.65

In degenerate four-wave mixing, the description of the phase-conjugate (PC) emission as "time-reversed" reflection is generally not valid as far as polarizations are concerned: for example, polarization selection rules [1] show that a linearly polarized beam can be reflected with circular polarization. Here, we report on theoretical and experimental studies of PC polarization in low pressure resonant gas media.

In the experiments, a laser beam is divided in two counter-propagating pump beams (f, b) and in an object (probe)beam (o) (angular separation with f is $\theta \sim 2$–$3°$) intersecting inside a Neon discharge. The (linear) polarization of the three beams is monitored individually by three Glan prisms. The PC beam polarization is analyzed with a fourth Glan prism. The laser frequency is scanned across Neon resonant transitions. As is well known, the emission lineshape is a Doppler-free Lorentzian for low incident intensities, but is much more complicated with rather intense fields and in general exhibits a double-peak structure (contribution of high-order susceptibilities $\chi^{(5)}, \chi^{(7)}, \ldots$). We have observed that at high intensities, the lineshape varies with the analyzer angle (Fig. 1); this yields an elegant method to study high-order contributions to PC emission. On the other hand, for sufficiently low intensities, the polarization of the PC wave, mainly generated by $\chi^{(3)}$, becomes independent of the laser frequency.

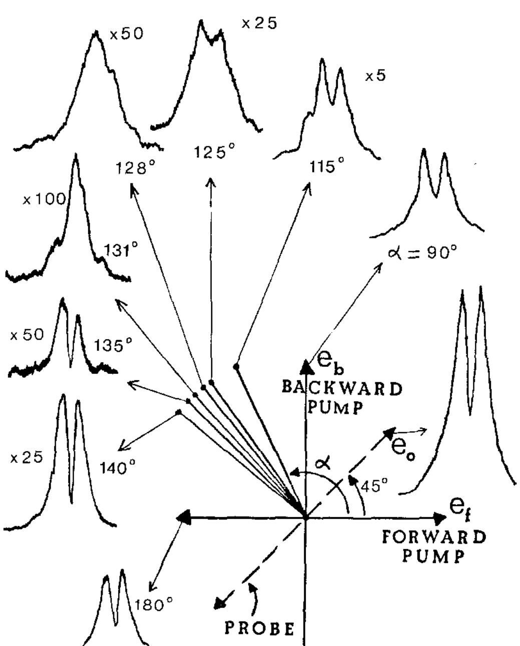

Fig. 1. Lineshape of *saturated* PC emission versus analyser angle, α, for cross-polarized pumps, and probe at $\alpha_o = 45°$ (neon transition $1s_5 \to 2p_9$; $\lambda = 640$ nm; $p = 0.15$ T). Note the lineshape change around near-extinction of the PC field ($\alpha \simeq 131°$)

In these conditions, the PC field depends linearly on each of the three incident fields and two different pump geometries are sufficient to predict the results of all the possible experiments for our set-up: (i) pumps orthogonally polarized [$\mathbf{e}_f$ is π, $\mathbf{e}_b$ is σ]; (ii) pumps co-polarized [$\mathbf{e}_f$ and $\mathbf{e}_b$ are π-polarized]. The PC wave polarization ($\mathbf{e}_r$) is then a function of the probe polarization ($\mathbf{e}_o$). Angular momentum conservation imposes that [2] in the first case, a π (or σ) probe is retroreflected with an orthogonal polarization σ (or π), and in the second case, a π or σ probe is reflected with the same polarization. Hence, if α_o and α_r are the respective angles ($\mathbf{e}_f, \mathbf{e}_o$) and ($\mathbf{e}_f, \mathbf{e}_r$) one obtains [2]:

for cross-polarized pumps $\quad \mathrm{tg}\alpha_o \, \mathrm{tg}\alpha_r = D, \quad (1)$

for co-polarized pumps $\quad \mathrm{tg}\alpha_r = C \, \mathrm{tg}\alpha_o, \quad (2)$

where C and D are two constants related to the respective amplitude reflection efficiencies of π- and σ-polarized probe.

In both configurations, the interaction of the medium with the polarized forward pump beam (f) and the object beam creates population gratings as well as Zeeman coherence gratings. The efficiency of the backward pump (b) diffraction – responsible for the PC emission – is strongly dependent on the lifetime of these gratings. Two processes affect these lifetimes:

(i) The intrinsic relaxation of atomic sublevels populations and Zeeman coherences: since population, orientation and alignment exhibit generally different relaxations, this decay is very sensitive to the discharge conditions (disorienting collisions, cascade effects, ...).

(ii) The grating "scrambling" due to thermal motion: its typical time is $(\mathrm{Ku}\theta)^{-1}$ where Ku is the Doppler width (this is the mean time for an atom to travel across a grating fringe).

In our experimental conditions, this Doppler shortening is predominant and thus allows one to approximate the relaxation of

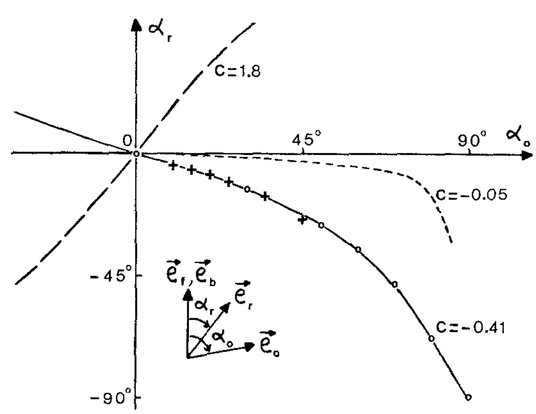

Fig. 2. PC polarization rotation for parallel pump polarizations [Ne $1s_5$ ($J=2$)$\to 2p_9$ ($J=3$)] (+) 0.5 T Ne (○) 0.6 T, 5% Ne–95% He. The plotted curves follow $\mathrm{tg}\alpha_r = C \, \mathrm{tg}\alpha_o$ with $C = -0.05$, 1.8 and -0.41, which are the values respectively predicted for (i) 0.5 T Ne without residual Doppler effect (i.e. $\mathrm{Ku}\theta = 0$), (ii) 0.6 T, 5% Ne–95% He with $\mathrm{Ku}\theta = 0$, (iii) and for Doppler-limited gratings decay time ($\mathrm{Ku}\theta \simeq 37$ MHz)

the atomic system with a single decay time (Fig. 2). In this model, one simply predicts: (i) $D=1$ (with cross-polarized pumps, the medium acts as a $\lambda/2$ "birefringent" mirror), (ii) C depends only on the J values of the transition: the PC mirror is then generally "dichroïc" and "non-reciprocal".

The atomic relaxation introduces a very small change in the D and C constants which can be accurately predicted by a complete theoretical study taking into account multipole relaxation [2].

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Highly Efficient Phase Conjugation of an XeF Laser via Stimulated Brillouin Scattering

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PACS: 42.65

We report the observation of highly efficient, diffraction-limited wavefront reversal (phase conjugation) of an ultraviolet excimer laser beam via backward stimulated Brillouin scattering (BSBS). The laser used was an injection-locked, positive-branch confocal, unstable resonator XeF discharge [1]. About 60% of the inhomogeneously broadened output was locked onto the 1-GHz bandwidth of the Ar-III ion reference oscillator at 3511 Å (which was injected through a small hole in the rear optic of the XeF cavity). The output was ~ 50 mJ in a 30-ns pulse with a beam divergence near the diffraction limit. The locked portion was linearly polarized whereas the remaining 40% (broadband output) was unpolarized.

The laser beam was focused (with f 25 optics) into a variety of liquids and gases. Highly efficient BSBS was observed in liquids such as hexane and propanol and in high pressure (>500 psi) methane. The linearly polarized, reflected beam had the same bandwidth as the reference oscillator and exhibited excellent phase conjugation properties. The reflected power was >70% of the locked fraction of the input power. No BSBS was observed when the XeF laser was not locked (i.e., with the reference oscillator blocked). The threshold focal intensity was ~ 5 GW/cm^2.

The figure shows a combined Fabry-Perot interferogram of both the incident laser light and the reflected light. In addition to the laser line (L) two Brillouin components appear (B_1 and B_2) which correspond to the first and second-Stokes shifted wavelengths.

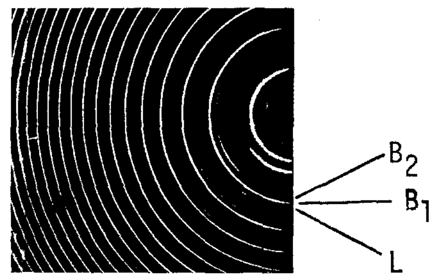

Fig. 1

The second-Stokes shifted light arises in the following manner. The first Stokes reflection returns to the laser cavity and reenters it in a precisely mode-matched manner since it is a phase-conjugate reflection of the output beam. It travels "backwards" in the unstable resonator cavity (until it is diffraction limited in the paraxial region) and then reemerges, slightly amplified since its wavelength is still within the gain linewidth of the XeF medium. It then undergoes BSBS in the liquid to obtain a second shift. If the gain duration in the XeF medium were longer, this process could presumably repeat itself until the Brillouin-shifted frequency was outside the XeF gain bandwidth. Multiple-shift effects were seen as early as 1964 [2] but were not related to phase-conjugate reflection until 1980 [3].

Another interesting feature revealed by the data is that the standing-wave acoustic grating created by the BSBS process acts as a very narrowband filter, reflecting only the 1-GHz-linewidth locked portion of the laser beam. A similar filtering effect has been seen recently for four-wave degenerate mixing [4].

It should also be noted that the BSBS dominated other nonlinear processes and no Raman scattering was observed (expect for very weak scattering in the gaseous methane).

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Continuouswave Multi-Color Phase Conjugation

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PACS: 42.65

We report the first simultaneous phase-conjugation of cw optical beams of different wavelengths. We employ four-wave mixing in the standard geometry of counter-propagating (multicolor) pump beams. Beam mixing is mediated by the photorefractive effect in a single $2\times3\times3$ mm crystal of barium titanate, having its c-axis parallel to a 3 mm edge. The optical beams originate as five wavelengths λ_i ($i=1, 2, \ldots, 5$) emitted simultaneously by a Lexel Model 95 argon-ion laser. The λ_i are 515, 497, 488, 477, and 458nm respectively. We have observed simultaneous phase-conjugation at all five wavelengths simultaneously, at the longest four wavelengths simultaneously, and at the middle three wavelengths simultaneously. The total power P_t of the pump and image beams in these cases was approximately 40 mW, 6 mW, and 3 mW respectively. The partition of the total power P_t among the component powers P_i varied with laser output power. Operation with equal pump powers gave improved image quality over the case of 2:1 backward-to-forward power ratio. The image-bearing beam was usually oriented near 10 deg to the forward pump beam (inside the crystal). Successful operation required optical isolation of the phase-conjugator from the argon-ion laser which we achieved by a pair of Glan-Thompson polarizers oriented to attenuate the beam by at least a factor of ten in each direction.

Considered as a mirror, the phase-conjugator had different power reflectivities R_i at each wavelength. For given crystal orientation, beam angles, and beam polarizations, the R_i were roughly proportional to $(P_i/P_t)^2$, i.e., to the square of the power fraction at λ_i. This is as is expected from the normal photorefractive effect. We have observed R_i up to 0.5 in multi-color operation before beam self-defocusing limited operation. We believe $R_i > 1$ will be achieved (as has been reported in single-color operation) after self-defocusing is reduced by optimizing beam geometries. We have succeeded in approximately equalizing pump powers in three-color operation so that color balance was perceived in the phase-conjugate of a multi-color image. When pump powers were unbalanced, beam self-defocusing or "fanning" was observed to occur first in the strongest (green) component as the photorefractive grating wavevector was moved away from parallelism with the crystal axis (and the reflectivities increased). Uses of multi-color phase conjugation to probe the electronic properties of barium titanate are described.

Tunable Phase Conjugate Signal Generation Through Two-Frequency Four-Wave Mixing in an Organic Dye

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PACS: 42.65

Organic dyes form a class of resonant materials in which phase conjugate signals have been generated, through degenerate four-wave mixing (DFWM) [1]. Among the many resonances which exist in a dye, the ground-to-first singlet manifold transition ($S_0 \rightarrow S_1$) comprises the primary absorption mechanism, and the gain formation process. The frequency dependence of this transition is characterized by absorption and emission spectra, which are separated in frequency, and which are coupled together through population transfer. Resulting from this is a nonlinearity which can produce "cross talk" in non-degenerate four-wave mixing [2].

We have demonstrated a "dual frequency" four-wave mixing scheme, in which DFWM is performed simultaneously within each spectrum, with separate sets of beams. The situation is shown schematically in the figure. Present are strong counterpropagating pump waves (A_1 and A_2), which are tuned within the absorption spectrum. These excite the dye, producing gain, which exists within the emission spectrum. Within the gain is introduced a second set of counterpropagating pumps (B_1 and B_2), which is collinear with the first set. A single probe wave at one of the frequencies (A_4 for example), results in the creation of backward waves at both frequencies (A_3 and B_3), which are proportional to the phase conjugate of the probe. Additionally, there is generated a forward-propagating wave (B_4), which is a frequency-shifted replica of A_4.

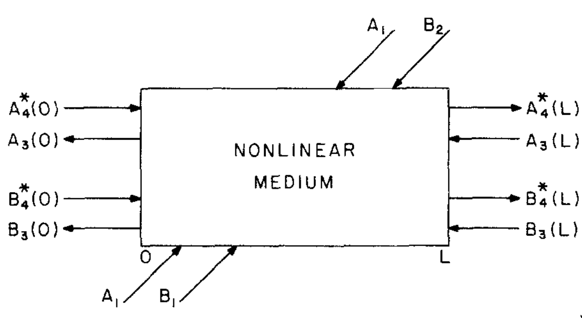

Fig. 1

In the experiment, rhodamine 6G serves as the medium. The primary light source is a doubled YAG laser, whose frequency (530 nm) lies near the center of the dye's absorption spectrum. The YAG simultaneously pumps a dye laser, whose tunable output (560–590 nm) provides the beams that are tuned within the emission spectrum. A small portion of the YAG beam is split off, and is introduced as a probe. With the four pump intensities all at their maximum values (2×10^5 W/cm^2), probe-to-signal conversion efficiencies of about 1% were measured for all outputs. The cross-coupled outputs (B_3 and B_4) change frequency with the dye laser, as the latter is tuned over its entire frequency range. The above efficiencies are nearly optimal for the present system. We feel that they could be improved considerably, however, if higher pump intensities were available, and if a tunable laser, in place of the YAG, could be used as the pump source for the absorption.

We have analyzed the situation theoretically, modeling the $S_0 \rightarrow S_1$ transition with a four-level system, which we previously used to analyze single-frequency DFWM [3]. Using a modified Abrams-Lind method [4], conversion efficiencies for the direct-coupled and cross-coupled outputs were found, which are in good agreement with our experimental results. Predicted in addition is an increase in all efficiencies (often exceeding unity) as the beams which interact with the absorption are tuned a moderate distance away from line center.

Alternately, the dye itself can be allowed to lase, within a special cavity, thus providing the pump waves within the emission. In performing this experiment, thermal effects were found to comprise the dominant coupling mechanism [5]. The cross-coupled efficiency with this scheme reached 80%. Both conjugate waves exhibited good correction, upon deliberate aberration of the probe.

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A Phase Conjugate Brillouin Mirror for a KrF Laser

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PACS: 42.65

The first observation of phase conjugation (p.c.) of radiation from a rare gas halide laser was recently reported by ourselves [1, 2], as well as by Bigio et al. [3]. In subsequent work on degenerate four-wave mixing of KrF laser radiation, we observed p.c. reflectivities in excess of 300% [4]. In [3] it was reported that stimulated Brillouin scattering had been observed in a variety of liquids using KrF laser radiation. However, the authors of that work concluded that the scattered signal was a relatively poor phase conjugate of the incident pump radiation. Subsequently, the same group reported high reflectivity p.c. signals using XeF laser stimulated Brillouin scattering [5]. In this paper we report observation of high quality phase conjugation of KrF laser radiation using stimulated Brillouin scattering (SBS). We also describe the use of a SBS phase conjugate mirror to compensate for aberrations in a double pass KrF laser amplifier.

The experimental set-up is shown in Fig. 1. The grazing incidence grating type KrF oscillator produced a diffraction limited beam with an energy of $\sim 4\,\mu J$ and a narrowed linewidth of $< 0.2\,cm^{-1}$. This radiation was focused by a 50 cm focal length lens, L_1, so as to enter the amplifier as a diverging beam. After amplification by a factor of $\sim 3 \times 10^3$ it was refocused into the sample cell with a 10 cm focal length lens, L_2. The beam from the amplifier had a divergence of ~ 5 times the diffraction limit. The stimulated Brillouin pulse, which was produced when the pump radiation was focused into the nonlinear medium, returned through the KrF laser amplifier where it experienced a typical saturated gain of ~ 5. Various beamsplitters throughout the system enabled the pulse shapes and energies to be monitored using photodiodes and joulemeters.

In Fig. 2a we show the shape of the oscillator pulse prior to passing through the amplifier, while, using ethanol as the scattering medium, the shape of the SBS pulse after it has returned through the amplifier is shown in Fig. 2b. Figure 2c shows the same SBS pulse after it has passed through a 100 µm pinhole at the focus of a 2.5 m focal length lens. The size of this aperture is such that the transmitted radiation corresponds to a diffraction limited beam. It can be seen that the SBS signal has two components, one of which is the shorter pulse, shown in Fig. 2c, all of which passed through the 100 µm pinhole and was thus diffraction limited. Figure 2b shows this diffraction limited pulse together with the second, more divergent, SBS pulse which has a longer duration. Although the pump radiation at the sample cell had a divergence of ~ 5 times the diffraction limit, after returning through the amplifier the shorter of the two SBS pulses had the same diffraction limited divergence as the original oscillator output pulse at BS_2. This illustrates the phase conjugate nature of this shorter SBS pulse and demonstrates the use of a SBS phase conjugate mirror to compensate for the distortions to the pump wavefront which were produced by the amplifier. At lower pump powers only the longer of the two SBS pulses was observed and this non-p.c. component, shown in Fig. 2d, was found to have a divergence of ~ 10 times the diffraction limit at BS_2 in Fig. 1. It seems likely that this pulse was produced by thermal Brillouin scattering since the absorption coefficient of ethanol at 248 nm was measured to be $\sim 0.4\,cm^{-1}$.

To further test the phase conjugate nature of the shorter SBS pulse, aberrators were placed in the path of the pump wave before it entered the amplifier and good wavefront reconstruction was observed. The maximum p.c. reflectivity observed so far is $\sim 30\%$ and the reflectivity has been measured as a function of pump intensity. The performance of various nonlinear media has been evaluated and the use of a waveguide has been examined. By placing a partially transmitting mirror at M in Fig. 1, diffraction limited oscillation of the KrF laser amplifier module has been observed using this phase conjugate stimulated Brillouin mirror.

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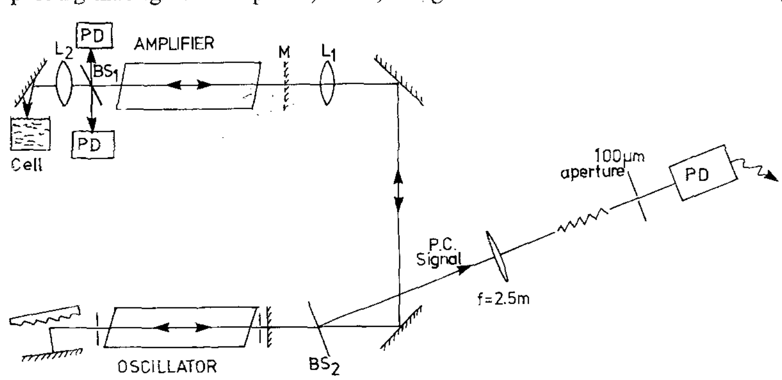

Fig. 1. Experimental setup for stimulated Brillouin phase conjugation of KrF radiation

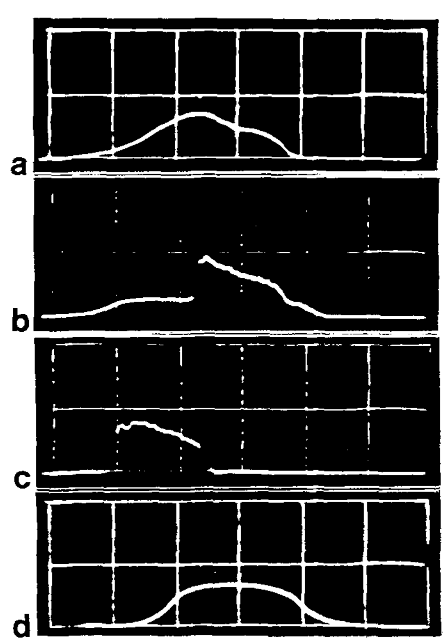

Fig. 2. (a) Oscillator, (b) total stimulated Brillouin signal, (c) p.c. stimulated Brillouin signal (through spatial filter), (d) as (b) at lower intensity. (Increasing time to right at 5 ns/div)

A Study of Laser Pulse Compression and Phase Conjugation by SBS

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PACS: 42.65

An experimental and numerical study of the compression of laser pulses by stimulated Brillouin scattering (SBS) is undertaken. The interaction geometry utilised to produce compression by backward-wave amplification involves the use of a convergently tapering waveguide [1] which contains a Brillouin-active medium. A backward-travelling Stokes pulse of short duration is spontaneously generated from a region near the exit of the waveguide where the laser intensity is greatest. Once generated it propagates down the waveguide receiving amplification by the incoming laser pulse which is correspondingly depleted. Furthermore, the Stokes pulse is a phase conjugate of the input laser pulse.

We demonstrate the compression of ruby and dye laser pulses in high-pressure gases, such as methane, which exhibit long damping times producing scattering in the transient regime, and in Brillouin-active liquids such as CS_2 with shorter acoustic lifetimes.

The interaction has been modelled by solving the coupled travelling wave equations for the laser and Stokes electric fields and the amplitude of the acoustic wave. Figure 1 shows the depleted laser pulse and compressed Stokes pulse when a 20 ns pulse of ruby laser radiation is passed into a tapered waveguide filled with methane at a pressure of 130 bar. The laser intensity at the exit of the waveguide is 350 MW/cm^2. It is notable that pulses of

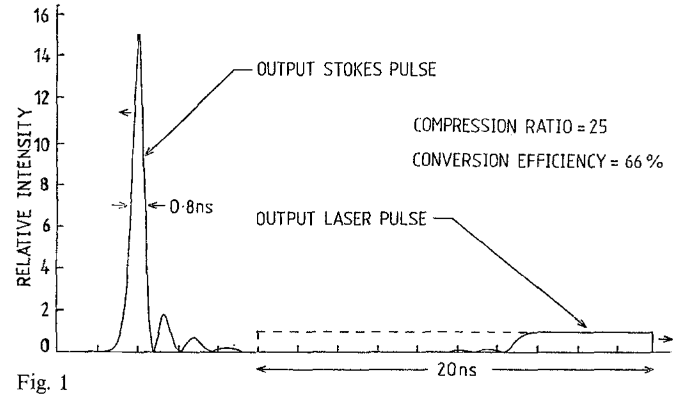

Fig. 1

durations substantially less than the acoustic phonon decay time. ($\tau_B \simeq 8$ ns in this case [2]) can be produced. This has been confirmed experimentally by the production of Stokes pulses as short as 1 ns in duration. The important parameters of the process, the compression ratio and conversion efficiency, are determined as a function of laser intensity, pulse shape and waveguide geometry. The efficiency of Stokes wave generation is predicted to be $\gtrsim 70\%$ under favourable circumstances and backscattering efficiencies of $\sim 70\%$ have been measured. The experimental results are compared to the numerical code developed to model the backward SBS interaction in tapered geometries.

Finally, the experimental evidence for phase conjugation will be presented and the implications for the development of higher power lasers will be discussed.

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Degenerate Four-Wave Mixing in a XeCl Amplifier

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PACS: 42.65

Degenerate four wave mixing in saturable amplifiers for the purpose of generating phase-conjugated waves has the attractive feature that extremely high conjugate reflectivity can be obtained. The high reflectivity results from amplification in both the interaction region [1] and the gain length before the probe overlaps with the pump. DFWM in amplifiers has been demonstrated in Nd:YAG[2] and CO_2^3 laser amplifiers with conjugate reflectivities of 0.1% and 250% respectively. We have recently succeeded in obtaining conjugate reflection from a XeCl amplifier with reflectivity in the range of 10^4%.

In our experiment, the laser source was a small, narrow band XeCl oscillator. The output was amplified, collimated and spatially filtered. One percent of the beam was split off to be used as the probe wave, while the remaining pump wave was directed into the amplifier-conjugator cell and reflected back on itself with a flat total reflector. The probe beam was directed into the cell at a small angle so that the beams crossed very near the far end of the conjugator. The laser line width was 0.1 cm^{-1}, the $1/e$ beam diameter 0.16 cm, and the peak power of the pump 5–10 kW. The interaction length is calculated to be 7 cm, slightly less than the 10 cm coherence length of the laser. The amplifier-conjugator was an x-ray preionized discharge laser cell with a 3.5 × 3.5 cm aperture, 80 cm gain length and 60 ns pulse length [4]. The cell was filled with a HCl/Xe/He mixture and the small signal gain measured to be ~ 10%/cm. This device was used because of its long pulse length and stable, homogeneous discharge characteristics. The crossing point was set 74 cm from the beginning of the gain length to insure that the conjugate signal would be greater than the amplified spontaneous emission.

When the experiment was performed a strong reflected beam was visible. The peak intensity of this signal was measured to be 50–100 times that measured when the probe beam was reflected into the signal detector with the pump retro-reflector (with the amplifier off). Because of the long exponential gain length traversed by the probe and conjugate beams, it is difficult to extract an exact value for the conjugate reflectivity of the interaction region. Using measurements of the single pass gain as a function of probe intensity for the gain of the probe and conjugate beams, we can set a conservative value of 0.01% for the actual conjugate reflectivity of the interaction region. The reflectivity was also measured as the pump beam was attenuated. We found that the reflectivity decreased slowly with pump intensity, by a factor of 5 when the pump intensity was decreased by two orders of magnitude. A decrease in the reflected signal by a factor of 4 was observed when the back mirror was replaced by a 4% reflector.

At the present time the theoretical model we have developed assumes a probe beam power which is negligible compared to the saturation intensity. Because of the long gain length this was not the case in our experiment, but the experimental value is within a factor of 2 of the present calculated value. The model is being modified to include finite probe amplitudes.

DFWM in excimer laser amplifiers offers the promise of high reflectivity and large aperture conjugators. We are presently improving and extending our experiments to a longer interaction length using a narrower linewidth source, and significantly larger beam diameter.

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Pressure Induced Effects on cw Degenerate and Nearly Degenerate Four-Wave Mixing

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PACS: 42.65

We report experimental and theoretical studies on the effect of buffer gas collisions with sodium atoms using nearly degenerate four-wave mixing (NDFWM) as well as degenerate four-wave mixing (DFWM) using the $3s^2S_{1/2}-3p^2P_{3/2}$ transition. Our work demonstrates collisional narrowing of the pump-probe detuning bandwidth in NDFWM and collisional enhancement of certain optically pumped hyperfine components in DFWM.

The first set of experiments we describe involve NDFWM using two cw tunable stabilized dye lasers tuned to the 5890 Å transition. In the experiments, the backward pump (E_b) and forward pump (E_f) are supplied by the same laser and are arranged to be exactly counterpropagating. The probe is supplied by a second dye laser and is nearly collinear with the forward pump ($\theta < 1°$). In an earlier paper, we reported the multiresonant complex spectral structure observed in Doppler-broadened media when the probe frequency is tuned with respect to the pump frequency [1]. If the pump frequency is detuned from the atomic resonance by an amount Δ and δ is the pump-probe detuning, then we find two resonances as the probe frequency is adjusted occurring at $\delta=0$ and $\delta=2\Delta$. The first resonance has a width determined by T_1 while the width of the second resonance is determined by T_2 as shown in Fig. 1a. Hence, it is expected that collisions should affect these two resonances quite differently. Indeed, as buffer gas is added, we observe that the width and relative amplitude of the second resonance changes as expected due to dephasing collisions (Fig. 1b). However, the first resonance is actually observed to experience narrowing. In fact, at high buffer gas pressures when $\Delta=0$, we observe that the pump-probe detuning bandwidth decreases from roughly 20 MHz to less than 10 MHz (Fig. 1c).

The theoretical work to describe these collisional effects in NDFWM uses a collision model which includes phase interrupting collisions affecting the optical coherence and velocity changing collisions (vcc) which affect the populations [2]. The phase interrupting collisions give rise to pressure broadening and a pressure induced shift in the resonance frequency. vcc lead to a thermalization of the velocity distribution in the limit of the strong vcc approximation. As indicated above there are two components to the phase conjugate signal. The first one (arising from the $v=0$ velocity class) is strongly affected by vcc while the second component (arising from the $\omega_{\text{forward}}-\omega_0-\mathbf{k}_f\cdot\mathbf{v}=0$ velocity class) is not affected by vcc but undergoes pressure broadening due to phase interrupting collisions. In addition, fine structure (fs) changing collisions (i.e., $3P_{3/2}\leftrightarrow 3P_{1/2}$) are included along with hyperfine structure (hfs) changing collisions in order to enable quantitative comparison between theory and experiment [3].

In the absence of buffer gas, DFWM experiments in sodium on the 5890 Å transition have shown the importance of hfs optical pumping [4]. There are six dipole allowed hf transitions at 5890 Å. The ground state ($^2S_{1/2}$) is split into two hf levels with $F=2$ and 1 (where F is the total angular momentum quantum number). The upper level ($^2P_{3/2}$) is split into four hf levels ($F=0-3$). Because of optical pumping usually only the $^2S_{1/2}(F=2)-{}^2P_{3/2}(F=3)$ and the $^2S_{1/2}(F=0)-{}^2P_{3/2}(F=1)$ transitions are observed. The remaining four transitions are weak since optical pumping removes the ground state population from the desired F level to the remaining F level where the atoms are no longer resonant with the laser frequency. The two strong transitions (denoted 2–3 and 0–1, respectively) are not optically pumped since decay from $F=3$ to $F=1$ and $F=0$ to $F=2$ are dipole forbidden. However, in the presence of buffer gas, the above behavior is dramatically affected due to fs and hfs changing collisions and vcc. Our measurements show that at very low buffer gas pressures (a few tens of millitorr), the strength of the 2–3 transition is significantly reduced while the normally very weak signal on $^2S_{1/2}(F=1)-{}^2P_{3/2}(F=2)$ transition is enhanced. We presently believe that in the first case, diffusion coupled with fs and hfs changing collisions provides a strong optical pumping effect resulting in a significant depopulation of the $F=2$ ground state. As indicated above in the second case, normal optical pumping depletes the $F=1$ ground state. However, in the presence of buffer gas vcc are believed to play an important role in effectively increasing the steady-state population of the depleted ground state. Experimental data to support these explanations are presented for various buffer gases.

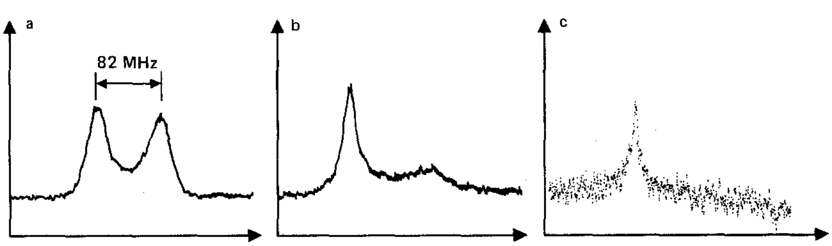

Fig. 1a–c. Pump-probe detuning response (a) $\Delta \simeq 82$ MHz with no buffer gas; (b) $\Delta \simeq 82$ MHz with 2 Torr of neon buffer gas; (c) $\Delta=0$ with 33 Torr of neon buffer gas

The analysis of these effects in DFWM is based on both a simple rate equation model and a more detailed density matrix calculation. In the first case, both diffusion, fs and hfs changing collisions, and vcc are included but standing wave effects are ignored. A density matrix calculation is also described where standing wave effects are included.

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Double Degenerate Four-Wave Mixing in $LiNbO_3$ Waveguides

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PACS: 42.65

TM-mode to TE-mode conversion is observed in $LiNbO_3$ waveguides excited at $\lambda = 6328$ Å. The converse TE to TM conversion does not take place. A theory is presented. The phenomenon can be used to gauge quantitatively the optical damage effect.

We observed the complete conversion of a TM-mode to a TE-mode in a single mode optical waveguide fabricated by Ti indiffusion into X-cut and Y-propagating $LiNbO_3$. The effect builds up on a time scale of several seconds for power levels of $50–10^3$ w/cm^2. The TE-mode does not get converted into TM. The Te- and TM-modes are strongly phase mismatched and thus conversion is not expected. Figure 1 shows an experimentally observed dependence of the TE and TM output as a function of time.

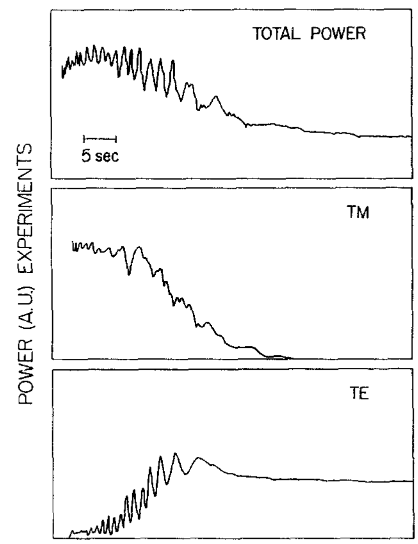

Fig. 1. Experimental traces of output power for a TM excitation

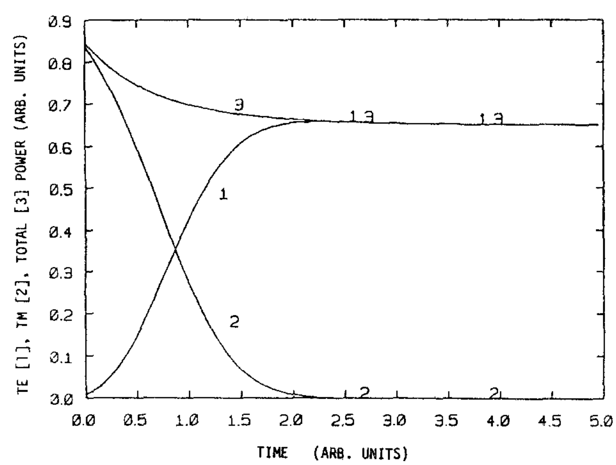

Fig. 2. Predicted output for TM excitation

We have constructed a theoretical model which predicts the asymmetry of conversion (TM to TE, but not the reverse) and the time evolution of the conversion. The build-up part of the process, in the "small signal" approximation permits a closed-form solution. The effect is attributed to optically induced refractive index inhomogeneities, a phenomenon usually called optical damage. The conversion starts from random scattering, or imperfect excitation of the TM wave. The photoionization of electrons is a function of the square of the optical field. The subsequent drift of the carriers establishes a field and an index change, via the linear electrooptic effect, of spatial dependence along the waveguide: $\exp \pm j(K_{TE} - K_{TM})y$. This grating scatters TM to TE, and itself builds up from the increased TE field. The effect gets stronger with increased scattering, hence the runaway effect. Figure 2 shows the predicted TE, TM output as a function of time. The "wiggles" observed in the experimental traces are a consequence of the damage induced index changes for the TE and TM waves and is not included in the numerical model of Fig. 2. Since the process involves fields of equal ω and pairwise equal $\bar{K}$, we call it Doubly Degenerate Four Wave Mixing. The spatial phase of the grating determines whether the phenomenon is symmetric in TE and TM, or one way, as observed experimentally. From symmetry considerations we can determine that the transverse component of the TM mode couples to the longitudinal component of the TE mode via the electrooptic coefficient r_{61} and the damage field along the x direction caused by the drift of the photoexcited carriers.

We have applied a low frequency RF field to electrodes deposited along the waveguides, and we have observed that the coupling does not occur for a high enough field. This external oscillating field clearly disturbs the distribution of the carriers, and can make the damage grating disappear.

We have also observed, in multimode waveguides, a coupling between the first and second order mode, which we also attribute to optical damage. We will discuss its time and polarization dependence, and the damage fields that produce it.

Theory and Experiments of Optical Oscillators and Phase Conjugate Mirrors with Gain Based on Four-Wave Mixing in Photorefractive Media

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PACS: 42.65

We describe here several new optical oscillator configurations including a unidirectional ring resonator and a self-pumped phase conjugate mirror. These oscillators operate on the basis of two and four-wave mixing in photorefractive media. Original demonstrations in our laboratory involved the ferroelectric perovskite $BaTiO_3$ as the nonlinear holographic medium. Subsequently we found that another ferroelectric perovskite $Ba_xSr_{1-x}Nb_2O_6$ (SBN) was also good enough to construct phase conjugate mirrors with gain, and to employ in these oscillators. Both $BaTiO_3$ and SBN are distinguished by their high electrooptic coefficients, and the availability of samples with impurities appropriate for the excitation of charge carriers by the interacting beams. Because the mechanism for beam interaction involves diffusion of these charge carriers, the nonlinear response of the photorefractive materials is nonlocal. We have generalized the electromagnetic formulation of four-wave interactions in materials with local nonlinearities to include the effects of the nonlocal response characteristic of photorefractive media. This generalized theory yields expressions for amplified phase conjugate reflection, amplified transmission, and mirrorless self-oscillation. We find that in general maximum phase conjugate reflectivity occurs with pumps of unequal intensity, a result which is related to the lack of inversion symmetry in photorefractive media. We apply this theory to the phase conjugate resonator of Fig. 1a as well as to the new optical oscillator configuration we have demonstrated in our laboratory, namely,

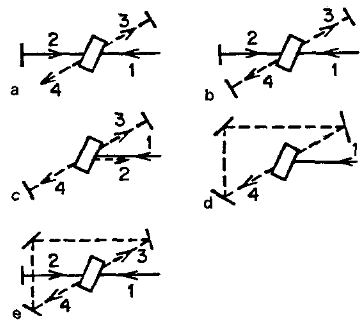

Fig. 1a–e. Arrangement of the photorefractive crystal (rectangle) mirrors and light beams of the oscillators (a)–(e) as described in the text. Pump beams are shown solid, oscillation beams are shown dashed

i) An oscillator using two conventional mirrors in which gain is provided by two pumping beams (Fig. 1b).

ii) The self-pumped phase conjugate mirror (Fig. 1c). This oscillator can be viewed as a "black box" which reflects a phase conjugate of an input wave without using a separate coherent pump source.

iii) An unidirectional ring oscillator pumped by a single beam (Fig. 1d).

iv) A bidirectional ring oscillator pumped with two counterpropagating beams (Fig. 1e).