PHASE CONJUGATION OF KrF LASER RADIATION

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Résumé - Nous rendons compte de réflexions conjuguées en phase de radiation d'un laser KrF en utilisant un mélange à quatre ondes dégénérées (DFWM) ou une diffusion Brillouin stimulée (SBS). En utilisant DFWM nous avons mesuré des réflectivités de ~ 300% et les résultats sont en bon accord avec une théorie pour un mécanisme déclenché thermiquement dans le milieu. Le miroir conjugué en phase utilisant la diffusion Brillouin stimulée a été employé dans une variété d'applications qui sont d'un grand intérêt pour le développement des lasers de forte puissance se servant des halogénures de gaz rares.

Abstract - We report observations of phase conjugate reflection of KrF laser radiation using both degenerate four-wave mixing (DFWM) and stimulated Brillouin scattering (SBS). Using DFWM we have measured reflectivities of ~ 300% and the results are in good agreement with a theory for a thermally induced mechanism in the medium. The SBS phase conjugate mirror has been used in a variety of applications which are of interest to the development of high energy rare-gas halide lasers.

I EXPERIMENTAL

Since normal unarrowed KrF lasers have a coherence length of only ~ 170 μm, for the majority of phase conjugation experiments which achieve high reflectivity using these lasers it is necessary to further line-narrow their output. Our KrF laser source /1/ consisted of a line-narrowed oscillator and, for the DFWM experiments, a slaved unstable resonator oscillator as shown in Fig. 1. The two discharge lasers were synchronised by using a common spark gap switch. This system produced ~ 5 MW, 10 - 20 nsec pulses of radiation at 249 nm with a linewidth of ~ 0.3 cm⁻¹ and in a near diffraction limited beam. For the SBS work the slaved unstable resonator oscillator was replaced by a single pass amplifier which produced ~ 1 MW, 7 nsec pulses at 249 nm.

Fig. 1. Line narrowed, diffraction limited beam quality slaved oscillator setup.

Fig. 2. DFWM setup. M₁ is a 100% reflecting mirror and BS are beam-splitters. The telescope compressed the beam by x 5.
II DEGENERATE FOUR-WAVE MIXING (DFWM)

For the DFWM experiments we have used the standard retro-reflecting geometry as shown in Fig. 2 and described in detail elsewhere /2,3/. The probe wave, $I_3$, was focused by a 1.75 m focal length lens, $L$, and intersected the pump waves, $I_1$ and $I_2$, at an angle of $\approx 4^\circ$ at the 0.5 cm long sample cell. For the majority of the DFWM work discussed here Rhodamine 6G (Rh6G) dissolved in various solvents was used as the active medium.

In the regime where the reflected intensity $I_4$ becomes comparable to that of the pump waves, saturation of the PC reflectivity (PCR) due to pump depletion and competing nonlinear effects is to be expected. In Fig. 3 we show measurements of the reflectivity as a function of the probe intensity $I_3$, for fixed pump intensities. The phase conjugate reflectivity is observed to begin to decrease from its maximum value of 300% for $I_3/I_1 \gtrsim 10^{-2}$.

In Fig. 4 we show the observed phase conjugate (PC) signals for $I_1 \sim 12 \text{ MW/cm}^2$ and the laser pulse shape shown in Fig. 4(a). A relatively slow buildup of the PCR is observed in Fig. 4(b) for which $I_3/I_1 \sim 10^{-2}$. In contrast, for $I_3/I_1 \sim 1$, as shown in Fig. 4(c) the PCR rises much more rapidly and exhibits saturation early on in the pulse as pump depletion and competing processes occur. This type of behaviour is characteristic of a process for which the medium has a relatively long relaxation time compared to the laser pulse duration. Further evidence for a slow relaxation, time integrating type of mechanism is shown in Fig. 5 where the PCR was measured as a function of the delay between $I_1$ and $I_3$.

![Fig. 3. DFWM PCR as a function of probe intensity for constant pump intensity $I_1 \sim 20 \text{ MW/cm}^2$. $2 \times 10^{-5} \text{ M Rh6G in EtOH.}$.](image1)

![Fig. 4. Oscilloscope traces of (a) the laser pulse, (b) PCR with $I_3/I_1 \sim 10^{-2}$, (c) PCR with $I_3/I_1 \sim 1$ where $I_1 = 12 \text{ MW/cm}^2$, $2 \times 10^{-5} \text{ M Rh6G in EtOH.}$. 10 nsec/div.](image2)

![Fig. 5. DFWM PCR as a function of delay between $I_1$ and $I_3$. $I_1 \sim 12 \text{ MW/cm}^2$, $I_3 \sim 0.2 \text{ MW/cm}^2$, $3 \times 10^{-5} \text{ M Rh6G in EtOH.}$.](image3)
between the time of arrival of the pump and probe waves at the cell. It can be seen that at times greater than the 0.1 nsec coherence time of the laser, the PCR drops significantly. This behaviour suggests that the degree of mutual coherence between the probe, \(I_3\), and the pump, \(I_1\), waves must be high if large PCR's are to be observed with this mechanism. In view of this behaviour and in the light of further evidence which we shall present below, we conclude that the mechanism responsible for the refractive index non-linearity in the medium is of a thermal nature.

Since most non-linear media are absorbing in the ultraviolet, we have used \(^4\) a coupled-wave analysis and included the effects of absorption of the pump and probe waves by the medium to obtain an expression for the PCR:

\[
R = \left| \frac{20 \sin(Hd/2)}{H \cos(Hd/2) + \alpha \sin(Hd/2)} \right|^2
\]  
(1)

where \(H = (4 \, q^2 - \alpha^2)^{1/2}\) and for a thermally-induced nonlinearity

\[
q^2 = [Df_1 \alpha e^{-md}]^2, \quad f = \text{fraction of absorbed energy converted to heat},
\]

\(\tau = \text{laser pulse duration}, \alpha = \text{absorption coefficient of the medium}, \text{and } d = \text{the cell length. The thermodynamic parameter } D = \left( -\frac{\omega}{\rho C_p} \right) \left( \frac{dn}{dT} \right)_p \text{ in a medium which has density } \rho, \text{ and specific heat and refractive index temperature coefficient, at constant pressure, } C_p \text{ and } \left( \frac{dn}{dT} \right)_p \text{ respectively. In the low reflectivity regime } (R \ll 1\%) \text{ Eq. (1) reduces to:}

\[
R \approx [Df_1 \alpha e^{-md} (1 - e^{-md})]^2
\]  
(2)

an equation which was first derived by Martin and Hellwarth \(^5\). As shown in Fig. 6, and in accordance with Eq. (2), we observe a quadratic dependence of the PCR on \(I_1^2\). However, for high reflectivities \((R >> 1\%) \text{ as is apparent from Fig. 7, an } I_1^2 \text{ dependence of } R \text{ is no longer observed. Although a cubic dependence seems to be more appropriate in the regime of these data, curves A and B in Fig. 7 show plots of Eq. (1) for values of } f = 0.3 \text{ and } 0.7 \text{ respectively (curve } B \text{ has been multiplied by a scaling factor of } 0.1). \text{ Although the choice of value for } f \text{ is somewhat arbitrary since exact values are unknown, it can be seen that good agreement can be obtained between the theory and the experimental results.}

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Fig. 6. PCR power as a function of input laser power. \(5 \times 10^{-5} \text{ M Rh6G in EtOH.}\)

Fig. 7. DFWM PCR as a function of pump intensity. \(2 \times 10^{-5} \text{ M Rh6G in EtOH. A and B are plots of Eq. (1) with } f = 0.3 \text{ and } 0.7 \text{ respectively. B has been multiplied by a scaling factor of } 0.1\)
Fig. 8 shows the effect of varying the concentration of Rh6G with either EtOH or H2O as solvents. It is immediately apparent from these data that much lower PC reflectivities are obtained when H2O, rather than EtOH, is used as the solvent. We believe that this provides further evidence that the mechanism producing the refractive index non-linearity is a thermal one, since, in Eqs. (1) and (2), the value of the thermodynamic parameter, D, for H2O is approximately a factor of 5 less than that for EtOH (10^-3 and 5 x 10^-3 m^2/J, respectively). Other possible mechanisms which could produce PC signals in Rh6G are not expected to be as solvent sensitive as the thermal effect. Curve A in Fig. 8 shows a plot of Eq. (1) for water as the solvent and using f = 0.3. Again there appears to be good agreement between our theoretical expression (Eq. 1) and the experimental data.

Similar concentration data is also shown in Fig. 9 for the case of CS2, with fractional concentration \( \psi \), diluted in hexane. The dilution of CS2 in hexane reduces the CS2 absorption cross-section at 249 nm /6/. Our previous observations in CS2 /2/ are also consistent with a thermal mechanism producing the PC signal. In Fig. 9, the maximum reflectivity of \( \sim 300\% \) is comparable in magnitude to the amplified PC signals previously reported using Rh6G as the medium /3/. The curve, which again is in good agreement with the data, is a plot of Eq. /1/ with f = 0.5 and D = \( \psi_{CS^2} + (1-\psi)D_{Hexane} \) (\( D_{CS^2} = 4 \times 10^{-2} m^2/J \) and \( D_{Hexane} = 8 \times 10^{-3} m^2/J \)).

III STIMULATED BRILLOUIN SCATTERING (SBS)

The experimental set up used for our KrF laser SBS work uses an oscillator/amplifier configuration as shown in Fig. 10. In order to better fill the amplifier volume the line-narrowed pulse was focused by a 50 cm focal length lens, \( L_1 \), and the resulting diverging beam was passed through the amplifier which had a new gain of \( \sim 3 \times 10^3 \). The radiation emergent from the amplifier had the area of the discharge \( (2 \times 0.5 \text{ cm}^2) \), and a beam divergence measured to be \( \sim 5 \) times the diffraction limit at BS1. Spectroscopic grade hexane (BDH, Spectrosol, absorption < 2\% cm^-1 at 249 nm) was used as the Brillouin medium in the work described here. The SBS PC signal was monitored from BS1 before passing through the amplifier and monitored at BS2.

Using different focal-length lenses to focus the radiation emergent from the amplifier into the scattering cell, in Fig. 11 we show measurements that characterize the PC reflectivity of the Brillouin mirror as a function of the product If^2, where I is the intensity at focus. As described in Ref. 7 spatial
Fig. 10. Setup for SBS PC experiments. Lens L1 was 1.1 m in front of the amplifier entrance plane. The distance between the oscillator and amplifier was 3.2 m. BS and PD are beam splitters and photodiodes respectively.

filtering was used to detect only the PC component of the SBS return. It can be seen that the maximum observed PC reflectivity was \( \sim 80\% \) and decreases somewhat at higher intensities for a given focal length lens. Also in Fig. 1, as expected, one can see that the reflectivity is independent of the focal length of the lens (if \( n \) is the interaction length, then the SBS signal depends on the product \( n^2 \alpha \frac{f}{f} \), which is independent of \( f \)).

Although the pump radiation at the sample cell had a divergence of \( \sim \times 5 \) the diffraction limit, after the SBS signal returned through the amplifier it had the same beam divergence as the oscillator pulse. Thus the PC mirror has compensated for the distortions induced by the amplifier on the pump wavefront.

Applications

Because of the inability of rare-gas-halide (RGH) molecules to store energy for times longer than a few nanoseconds, it is necessary to use various pulse-compression schemes for efficient short-pulse extraction from high-energy RGH amplifiers. One such scheme is angular multiplexing, whereby the available energy in the amplifier is extracted by a sequence of angle-encoded pulses. A scheme for angular multiplexing using a phase conjugate mirror in a double-pass amplifier arrangement is shown in Fig 12. Use of a PC SBS mirror in this configuration could have several advantages over use of a conventional mirror. As well as being simple and not requiring high-quality optical components, the PC mirror also compensates for aberrations induced on the wave front by the KrF amplifier itself. In addition, since PC mirrors automatically retroreflect beams incident upon them they should also help to reduce cross talk between beams. As we will show later, because this type of PC mirror acts as a narrow-bandwidth reflector, it also increases optical isolation of the system from broadband KrF amplified spontaneous emission (ASE). Since this type of PC SBS mirror produces a polarization state of the reflected beam similar to that obtained from a conventional mirror, i.e., the polarization is not conjugated /3/, switch-out of the pulses returning from the amplifier to optical delay lines may be achieved by using a combination of polarizers and quarter-wave plates.

In Figs. 12(a) - (e) we show oscilloscope traces of the pulses using this scheme in a 3 x multiplexing arrangement (without switch-out). The oscillator pulse shown in Fig. 12(a) is angle encoded [Fig. 12(b)] and passed through the amplifier [Fig. 12(c)] with a net gain of \( \sim 10^3 \). The reflections from the PC SBS mirror [Fig. 12(d)] repass through the amplifier, and the diffraction-limited return from
the three delay lines is shown in Fig. 12(e). By measuring the energy obtained from the amplifier when it is operated as a superradiant oscillator with an 80% plane reflecting mirror of equivalent aperture in place of the PC mirror, we were able to assess the efficiency of this multiplexing arrangement. We found that > 70% of the energy obtained from this long-pulse oscillator could be extracted in the short-pulse multiplexed mode of operation.

Another application of PC mirrors that we have investigated is for their use as reflectors in a KrF regenerative amplifier. Regenerative amplifiers can be used to provide synchronized short diagnostic probe pulses in laser-fusion experiments. There are several advantages of using PC mirrors instead of conventional mirrors in such amplifiers. Not only are PC mirrors capable of producing an unaberrated beam, but we have found that no optical isolation of the mirrors, in the form of a Q-switch, is necessary in the cavity. Also, the mirrors themselves produce pulse shortening. To demonstrate the operation of a KrF regenerative amplifier with PC mirrors, we used the setup shown in Fig. 13. The low-intensity injected oscillator pulse was passed through the first Brillouin cell (M₂) into the regenerative amplifier. The output pulses obtained from the intracavity beam splitter are shown in Fig. 13(a). It can be seen that the gain in the amplifier persists for three round trips of the injected pulse. In contrast, in Fig. 13(b) we show the output when the PC mirror, M₂, is replaced by a 10% reflecting plane mirror aligned with the centre of the discharge. The second pulse in Fig. 13(b) is much longer than that obtained using two PC mirrors because of an additional contribution produced by SBS of the broadband double-pass ASE radiation reflected from the real mirror at M₂. The observation that this additional component to the output was of a much poorer beam quality than the PC component further supports this explanation. Thus the presence of the second PC mirror optically isolated the system from broad-bandwidth ASE. Since Brillouin shifts are \( \approx 0.1 \text{ cm}^{-1} \), and provided that the gain duration is long enough, many cavity round trips are possible with the radiation still remaining within the \( \approx 300 \text{ cm}^{-1} \) gain bandwidth of KrF.

Another application of PC mirrors that has been suggested is for use in the automatic alignment of targets /10/. An example of such a scheme is shown in Fig. 14, whereby the reflection, or glint, of the low-powered oscillator from the target is sent through the amplifier and automatically retroreflected at a much higher intensity back onto the target by the PC mirror. To demonstrate this
capability (see Fig. 14), using a 50 cm lens to focus the oscillator pulse onto a 500 \( \mu \text{m} \) diameter plane aluminium lollipop target, which was placed 1.5 cm inside and 0.2 cm to one side of the focus of a 5 cm lens, \( L_1 \), we were able to destroy the target with the double-pass output from the amplifier by using the PC SBS mirror retroreflector. When the PC mirror was replaced by an aligned plane 80\% reflector, both the reflected amplified glint and the ASE from the amplifier, which were focused by \( L_1 \), completely missed the target and left it undamaged. Furthermore, when the target was placed at the focus of \( L_1 \), it was destroyed by the focused broadband ASE from the amplifier. It is possible therefore that, as well as for automatic alignment of targets, this type of arrangement could be used to isolate the target from prepulse ASE arising from the final amplifier stages of a KrF fusion driver system.

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