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Optical phase conjugation by resonant degenerate four-wave mixing in liquid phase medium

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In this paper, frequency-doubled Nd:YAG laser's phase conjugation has been investigated experimentally using resonant degenerate four-wave mixing (DFWM). The iodine solution was used as resonant medium. In this way, the energy of the DFWM phase conjugation beam arrived at 43μJ/pulse while the total pump beam's energy reached 8mJ/pulse. The relation between the pulse energy of the DFWM phase conjugation beam and that of the pump beam was investigated. We also measured the optical field distributions of pump beam and DFWM phase conjugation beam, from which it can be noticed that the DFWM phase conjugation can improve the laser beam quality. At the same time, we observed the influence of the pump beam's disturbance on the DFWM signal.

Keywords: phase conjugation, DFWM, iodine solution
PACC: 4265

1. Introduction

Optical phase conjugation can generate a wave which retraces the incident wave in a time-reversed way.[1,2] Thereby, it is possible to eliminate phase distortions that occur when a laser beam propagates through the Earth's atmosphere or an optical system. There are two mechanisms that are usually employed to generate a phase conjugation beam: stimulated Brillouin scattering (SBS) and degenerate four-wave mixing (DFWM). The frequency of a phase conjugation beam is strictly equal to that of the incident beam in the DFWM mechanism, while there is a frequency shift in the SBS mechanism. Thus one can obtain an ideal phase conjugation wave using DFWM. At the same time, because its threshold is nearly zero, DFWM can be used for weak optical signals. Because of the advantages described above, DFWM phase conjugation has been widely studied in recent years.[2–5]

From the nonlinear optics theory the intensity of a DFWM signal is proportional to the square of the third-order susceptibility $|\chi^{(3)}|^2$. In order to achieve a higher intensity of the DFWM signal, the medium with a larger value of $|\chi^{(3)}|$ is needed. Unfortunately, the value of $|\chi^{(3)}|$ is small in most cases. To obtain high phase conjugation reflectivity, resonant DFWM is usually applied, which is based on the fact that the intensity of the phase conjugation beam will be greatly enhanced when that of the pump beam is tuned in accord with the resonant frequency of the media. There are many resonant media that can be utilized for DFWM phase conjugation, such as metal vapours, lasing (gain) media and absorbing liquid and solid materials, and so on.[6–11]

In this paper, the resonant DFWM is used to generate the phase conjugation wave of the frequency-doubled Nd:YAG laser. Iodine (I_2) is used as the resonant medium. The laser with wavelength of 532nm is not strictly resonant with I_2, thus the phase conjugation wave of DFWM cannot be enhanced effectively if we use a frequency-doubled Nd:YAG laser to pump I_2 vapour directly. To overcome this problem I_2 is placed in the alcohol solvent. The resonant line of I_2 is broadened by collision in alcohol solvent, thus the DFWM phase conjugation can be enhanced effectively in iodine solution. In this way, the energy of the phase conjugation beam can reach 43μJ/pulse in our experiment.

2. Experimental setup

The experimental setup is shown schematically

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in Fig.1. The laser used in this experiment is a Q-switched Nd:YAG laser working at 1.064μm with its pulse duration of 13ns and repetition rate of 1Hz. The second harmonic of the YAG laser is used as the pump beam of DFWM.

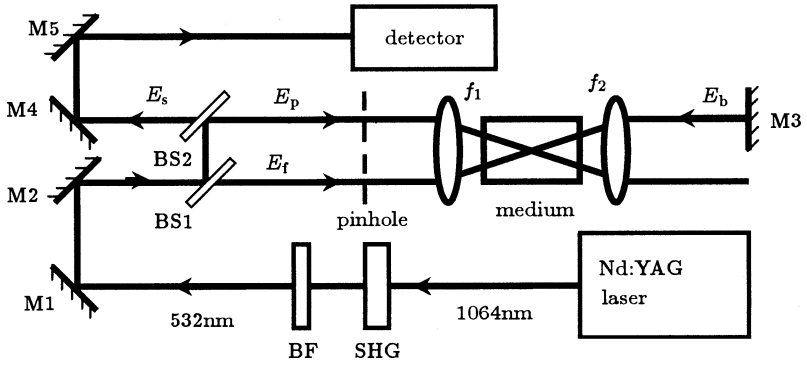


Fig.1. The experimental light path layout of back-DFWM. SHG: second harmonic generator; BF: beam filter; BS1, BS2: beam splitters; $f_1 = f_2$=300mm.

Through beam splitters BS1 and BS2 and mirror M2, the pump beam is divided into three beams: the forward pump beam E_f, backward pump beam E_b and probe beam E_p with the energy proportion of $E_f : E_b : E_p \approx 3 : 3 : 1$. E_f and E_b pass through the nonlinear medium in a counter-propagating way, while the probe beam E_p is incident upon the nonlinear medium with a crossing angle to E_f. To achieve a high local intensity, two lenses f_1 and f_2 are used. The generated phase conjugation wave, the DFWM signal beam E_s, propagating backward along the probe beam E_p, passes through the BS_2 and is reflected to the detectors.

3. The phase conjugation reflectivity versus the intensity of the pump beam

Abrams *et al*[12] have presented a nondegenerate two-level model for the resonant DFWM, which shows good agreement with experiments. The reflectivity R, the ratio of the phase conjugate signal I_s to the input probe intensity I_p, is given by

$$R = \frac{I_s}{I_p} = \left| \frac{\beta \sinh(\Gamma L)}{\Gamma \cosh(\Gamma L) + \alpha \sinh(\Gamma L)} \right|^2, \quad (1)$$

where the linear coupling coefficient α is expressed as

$$\alpha = -\alpha_0 \frac{(1 - i\delta)[1 + 2(I/I_{sat})]}{(1 + \delta^2)[1 + 4(I/I_{sat})]^{3/2}}. \quad (2)$$

The nonlinear coupling coefficient β is represented by

$$\beta = \alpha_0 \frac{(i + \delta)(2I/I_{sat})}{(1 + \delta^2)[1 + 4(I/I_{sat})]^{3/2}}. \quad (3)$$

In Eq.(1) $\Gamma = (|\beta|^2 - \alpha^2)^{1/2}$ is a measure of the degree at which nonlinearity exceeds linear absorption.

In most cases, $\Gamma L \ll 1$, thus we have

$$\sinh(\Gamma L) \approx \Gamma L, \quad (4)$$

$$\Gamma \cosh(\Gamma L) + \alpha \sinh(\Gamma L) \approx \Gamma. \quad (5)$$

Using Eqs.(4) and (5), we can simplify Eq.(1) as

$$R = \frac{I_s}{I_p} \approx |\beta L|^2 \propto \frac{4(I/I_{sat})^2}{(1 + 4I/I_{sat})^3}, \quad (6)$$

where $I = I_f = I_b$ is the pump-beam intensity, I_p is the intensity of probe beam and I_{sat} is the saturation intensity that is defined by Abrams and Lind.

4. Results and discussion

Adjusting BS_1, BS_2 and M_3, signals could be obtained in front of the detector. Blocking off either the pump beam E_f or probe beam E_p, the signals disappeared, indicating that the signals we observed were not the back-scattered signals such as SBS, the reflection of the window of the media cell and so on, but the DFWM signals. Keeping the optical layout identical and replacing the solution by pure alcohol, the signals could not be observed by the naked eye. This proved that the intensity of DFWM signals could be greatly enhanced because of the resonant effect of I_2. Iodine vapour has also been used as a nonlinear medium, but the signal was too weak to be detected by the energy detector. The frequency-doubled Nd:YAG laser is not strictly resonant with I_2 so that in iodine vapour the

DFWM signals cannot be enhanced effectively. This can be improved by placing I_2 in alcohol solvent because of the collisional broadening of the I_2 spectral line in the solvent.

(1) The DFWM phase conjugation pulse energy versus the pump pulse energy

The energy of the DFWM phase conjugation pulse E_s is detected as a function of that of the pump pulse.

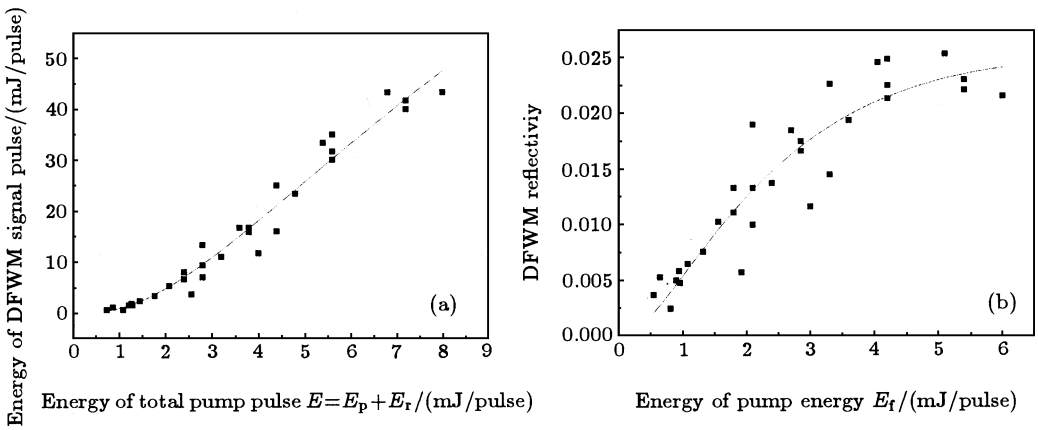


Fig.2. (a) DFWM signal pulse energy as a function of the total pump pulse energy and (b) DFWM phase conjugation reflectivity as a function of the forward pulse energy. Here the solid line is the theoretical fitting line.

According to the theoretical fitting (shown as solid line in Fig.2) based on Eq.(6), the intensity of the DFWM signal E_s and the reflectivity R of the DFWM rise up with the increase of the pump-pulse intensity. But the increase of R becomes slower at larger values of the pump-pulse intensity. In our experiment, the DFWM signal with an energy of 43μJ is obtained when the total pump energy E $(= E_f + E_p)$ reaches about 8mJ. The value of the reflectivity R of DFWM is the largest (about 2.5%) when the pump-pulse energy E_f arrives at about 5mJ.

(2) The transverse distribution of the laser beam.

The transverse distribution of the DFWM signal beam was detected with a CCD camera. Figure 3 shows the spot of DFWM phase conjugation pulse under the best condition of the optical layout.

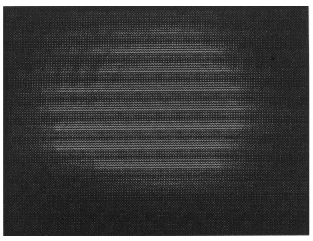


Fig.3. The DFWM signal spot in the best condition.

The interval from M3 to the beam splitters of BS1 and BS2 in Fig.1 is about 4m, so that the overlapped spot of E_f, E_b and E_p is sensitive to the pump-beam excursion. This causes the spots of the DFWM signals to be distorted. Figure 4 shows some of the distorted spots of the DFWM signal beam.

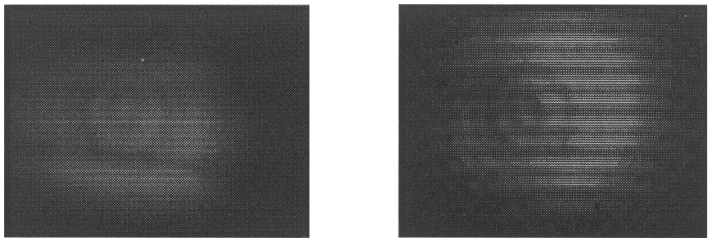


Fig.4. The distorted DFWM signal beam spots caused by pump-beam excursion.

In order to compare the beam qualities between the DFWM phase conjugation beam and the pump beam, the distribution of intensity at the focal spot is observed after the lens transform. This is shown in Fig.5, with (a) the pump beam and (b) the DFWM signal beam. It can be noticed that the optical field distribution of the phase-conjugation beam is more uniform than that of the pump beam, indicating that the beam quality has been improved by the DFWM phase conjugation.

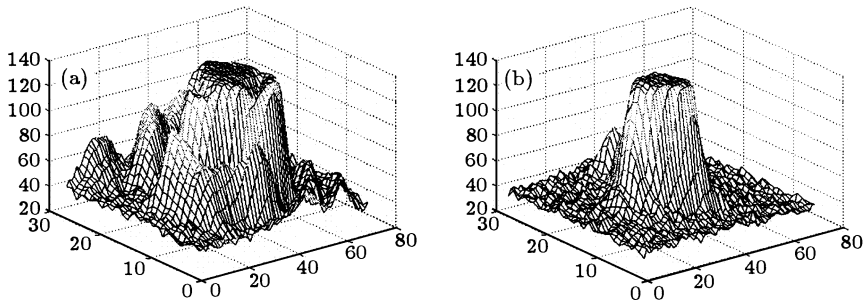


Fig.5. The distributions of intensity at the focus spots, (a) pump beam and (b) DFWM signal beam.

5. Conclusion

In this paper, the resonant DFWM of frequency-doubled Nd:YAG laser has been experimentally investigated in iodine solution. The results demonstrated that (1) the intensity of the DFWM phase conjugation beam is greatly enhanced by the resonant effect of I_2 when the phase conjugation beam energy reaches 43μJ/pulse, (2) the DFWM phase conjugation beam's transverse distribution is obtained by using a CCD camera and we notice that the phase conjugation spots are influenced by the pump beam distortion, and (3) from the distribution of intensity at the focal spot after the lens transform, we also notice that the phase conjugation beam of DFWM can improve the beam quality of the laser.

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