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Phase Conjugate Lasers using Simulated Brillouin Scattering

1. Introduction

A phase conjugate mirror has the remarkable property of correcting wavefront distortion created by an aberrating medium. If a plane wavefront is distorted as it passes through a medium, then reflects off an ideal phase conjugate mirror, the light will travel exactly backwards along its incident route, removing its aberration, and emerge again as a plane wave. This effect has the potential to be used with a high-power laser resonator to remove aberration created by the gain medium and restore diffraction limited beam quality. Because of this possibility, much research has been done since Zel'dovich *et al.* (1972) first demonstrated phase conjugation due to Stimulated Brillouin Scattering (SBS).

2. Stimulated Brillouin Scattering (SBS)

Most high-power phase conjugate resonators utilize Stimulated Brillouin Scattering (SBS). This effect is due to the interaction between incident light, scattered light, and acoustic phonons induced by electrostriction. Incident light is scattered while propagating through a medium. If the intensity is sufficiently high, the incident and scattered wave fields beat against each other producing a significant variation in the electric field strength. Electrostriction is the physical compression of a medium due to large electric fields. The beating of incident and scattered light produce oscillating electrostriction, which then creates a phonon. The light scattered by the acoustic wave is called the Stokes wave, and it is Doppler shifted in frequency. The Stokes wave and the acoustic wave propagate opposite the incident light and promote each other's growth. This can cause the SBS medium to act as a high reflectivity mirror with a frequency shifted reflection. The reason for the frequency shift is apparent in the nonlinear energy level diagram of SBS shown in Figure 1. However, it should be noted that SBS is considered to be a χ^3 nonlinearity since it is created by electrostriction, $\chi^3(\omega=\omega+\omega-\omega)$.

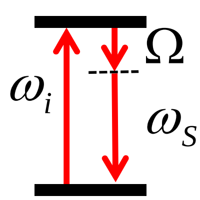

Figure 1

ω_i is the incident frequency, ω_S is the Stokes frequency, Ω is the phonon frequecy

3. Phase Conjugation due to SBS

Phase conjugation was discovered experimentally by Zel'dovich *et al.* (1972) in high pressure methane gas. The concept behind its occurrence in a SBS medium is not intuitive. When light with strong aberration is focused, it creates a highly nonuniform intensity distribution. Since SBS is intensity dependent, when aberrated light is focused into a nonlinear medium it causes nonuniform SBS generation. The phase conjugate Stokes wave has the highest overlap with the incident intensity and receives the highest gain as it builds up from noise. The Stokes wave is the phase conjugate of the incident light because of its generation from a nonuniform intensity distribution, as displayed in Figure 2. In *Nonlinear Optics* (Boyd, 2008), Boyd mentions that for normal operating conditions of SBS phase conjugation, the phase conjugate component of the Stokes wave can receive linear gain exp(15) times larger than any other component.

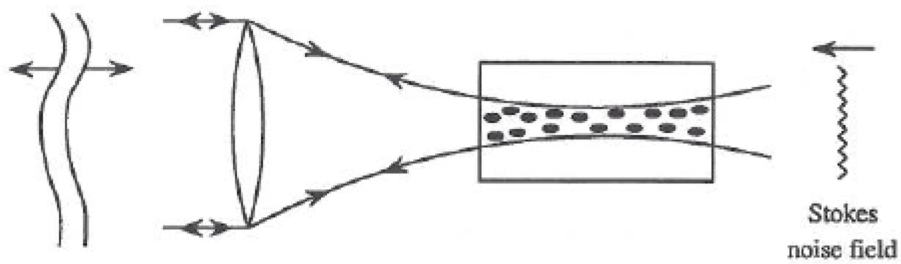

Figure 2

Image from (Boyd, 2008). Aberrated incident light creates a nonuniform intensity distribution which gives the highest gain to the phase conjugate Stokes wave.

4. Reasons Why SBS Phase Conjugate Resonators must be Pulsed

There are three aspects of phase conjugate mirrors that require pulsed operation. (1) The SBS threshold is often high, (2) an SBS phase conjugate mirror also exhibits behavior similar to a saturable absorber, and (3) the Stokes frequency shift causes each mode to "lock" a mode of lower frequency. All three effects occur simultaneously, causing most SBS phase conjugate resonators to be both Q-switched and modelocked.

4.1. SBS Threshold

The SBS power threshold is defined as the input power required to create a certain reflectivity of the Stokes wave. For the nonlinear medium CS_2, with a 1.06μm incident Gaussian beam, the SBS threshold to create 1% reflectivity is 9 kW (Boyd, 2008). Since CS_2 has a large χ^3, the threshold for other media is often much higher. Studying SBS using lasers with 9 kW average power or higher is undesirable due to high cost and difficult operation. Also the SBS threshold may exceed the damage threshold of the nonlinear medium. In this case, the SBS threshold cannot be reached with a CW laser. However, SBS is dependent upon power over a small time scale, so a pulsed laser (with high peak power) can satisfy the SBS threshold without having a large average power.

4.2. Using an SBS Phase Conjugate Mirror as a Saturable Absorber

Due to its threshold properties, an SBS phase conjugate mirror exhibits behavior similar to a saturable absorber, except that it is a reflective optic rather than transmissive. Because of this, both SBS phase conjugate mirrors and saturable absorbers can be used in similar ways to create passively Q-switched or modelocked lasers. When the resonant power is below threshold, an SBS phase conjugate mirror has low reflectivity, which can cause low cavity Q-factor. While this occurs, energy builds up in the gain medium. Once the power of the lasing light is above the SBS threshold, the phase conjugate mirror becomes highly reflective, the Q-factor rapidly increases, and a burst of energy exits the resonator. In this manner, an SBS phase conjugate mirror is used to Q-switch a laser, and a similar situation can be used to modelock.

Since the reflectivity of an SBS phase conjugate mirror is nearly zero below threshold, a start mirror is necessary to create oscillation. If the Q-switch process described above causes the Q-factor to drop to zero, then no amount of energy build up in the gain medium can cause the resonant power to exceed the SBS threshold and no laser pulse can be released. A start mirror is used to provide an alternative pathway for resonance to occur, such that when the SBS phase conjugate mirror has essentially zero reflectivity, the cavity Q-factor maintains a small, but non-zero, value. The reflectivity of the start mirror can be varied in order to change the minimum value of the Q-switch and tune the pulse duration and frequency. A phase conjugate resonator with a start mirror (M_{start}) is shown in Figure 3. The resonator design shown allows for additional tuning of the Q-switch by rotation of the quarter-wave plate (λ/4). (Brignon & Huignard, 2004)

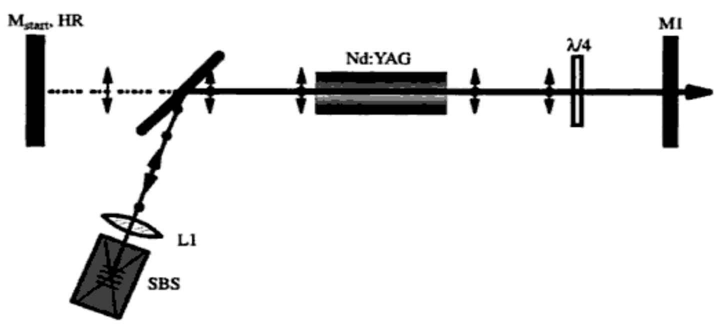

Figure 3

Phase conjugate resonator with start mirror

4.3. Harmonic Modelocking due to SBS Phase Shift

The Stokes wave is the phase conjugate of the incident light, except that it is phase shifted by the acoustic wave. The mode structure of the resonator must be designed so that the Stokes frequency shift does not cause loss, but only energy transfer between resonances. Longitudinal modes occur when the cavity length is an integral number of wavelengths. So, in a phase conjugate resonator, the cavity length must be tuned so that the Stokes frequency shift corresponds to the frequency shift between modes. A side effect of this process is that the modes “seed” each other, creating a fixed phase relationship called modelocking, and causing the modes to oscillate together as a laser pulse. Most SBS phase conjugate resonators are both Q-switched and modelocked, since even in the short duration of a

Q-switched pulse, enough mode structure can develop to cause simultaneous modelocking. (Kappe, 2006)

5. Recent Achievements in High Power Phase Conjugate Lasers

A phase conjugate mirror can be used in a high power laser either inside the resonator or externally as an amplifier. The highest power achieved, to my knowledge, was in a Maser Oscillator Power Amplifier (MOPA) system, using multiple, parallel phase conjugate mirrors and multiple gain cell amplifiers. An average output power of 875W was accomplished. (St. Pierre, et al., 1997) From a single phase conjugate power amplifier, using a Nd:glass zigzag design, an average power output was achieved of 213W. (Yasuhara, et al., 2008) Using an internal phase conjugate mirror, an average power output of 27W has been demonstrated. (Ostermeyer, Heuer, & Menzel, 1998) Since phase conjugate mirrors cause all resonant modes to be stable, to achieve good beam quality, apertures were used to only allow oscillation of the fundamental TEM_{00} mode. Apertures or other mode discrimination techniques have diminished the power output capability of intracavity phase conjugation. It should be noted that all phase conjugate resonators mentioned also achieved nearly diffraction limited beam quality.

6. Conclusion

Phase conjugate mirrors have the unique capability of actively correcting aberration with high fidelity. As such, phase conjugate resonators are capable of producing near diffraction limited beam quality regardless of gain medium aberration. Phase conjugation due to SBS has been demonstrated in pulsed laser systems at increasingly high powers and is capable of being scaled further.

Works Cited

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