CHAPTER 1

Overview of Phase Conjugation

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1.1 GENERAL INTRODUCTION

The discovery in the early 1970 by Zel'dovich et al. [1] that a nonlinear process could generate a phase conjugate replica of a complex incident wavefront has opened a wide interest in the laser and optics community. Since the first experiments done with a ruby laser and Brillouin scattering in a gas cell, the field of optical phase conjugation has stimulated a lot of research and development activities that cover both the fundamental and applied parts of the field of laser optics. The important new aspects of optical phase conjugation which are of prime interest are the following: First, phase conjugation is a nonlinear mechanism that reverses both the direction of propagation and the phase of an aberrated wavefront; second, the generation of the conjugate beam can be viewed as a dynamic holographic recording process in a medium that exhibits a third-order nonlinearity. Such an unconventional optical device is now known as a phase conjugator or a nonlinear phase conjugate mirror. The major applications of phase conjugation will rely on these remarkable physical properties, which are illustrated in Fig. 1.1. It shows the now well-known comparison between a classical mirror on Fig. 1.1a which satisfies the conventional reflection law for the incident wavefront, while Fig. 1.1b shows the function of a nonlinear mirror which reverses the sign of the incident wave vector $\vec{k}_i$ at any point of the incident wavefront propagating in the $+z$ direction. In other words, if $\mathbf{E}_i = E_i \exp(i\omega_0 t - ik_i z)$ is the incident scalar optical field expression, the returned conjugate field $\mathbf{E}_c$ due to the nonlinear mirror is expressed by $\mathbf{E}_c = E_i^* \exp(i\omega_0 t + ik_i z)$. This field propagates in the $-z$ direction with complex amplitude E_i^* and at frequency ω_0. We will show later that the intensity of the conjugate field is affected in the general case by a nonlinear reflection coefficient R (R can be larger than one) and in some interactions by a slight frequency shift $\delta \ll \omega_0$. Figure 1.2 illustrates the situation where an incident wavefront is disturbed by an aberrating medium (atmospheric turbulence, passive or active optical components, etc.). Due to phase reversal, a diffraction-

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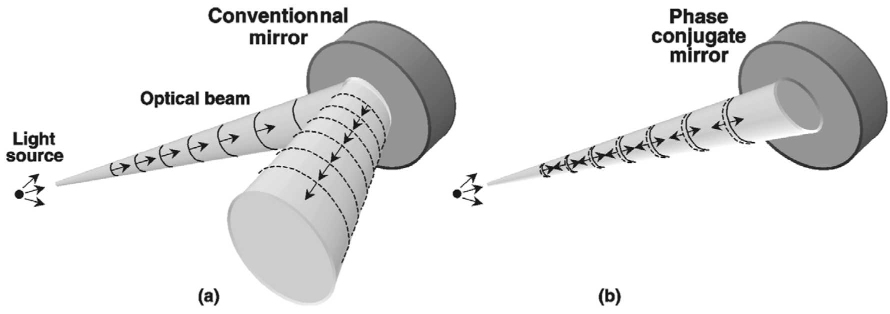

Figure 1.1. Comparison of beam reflection by (a) a conventional mirror and (b) a nonlinear phase conjugate mirror.

limited wave can be recovered after double passing through severely aberrated optical components and beam reflection on the nonlinear mirror. In particular—and this is the main subject treated in this volume—a phase conjugate mirror permits the compensation of any static or dynamic aberrations due to high gain medium in a laser cavity or in a master oscillator power amplifier architecture. These important properties are described in Fig. 1.3. Figure 1.3a shows a laser oscillator whose cavity consists of a classical and a conjugate mirror: A stable oscillation can occur because of the compensation of the thermal lensing effects and aberrations due to the highly pumped gain media. In such conditions a diffraction-limited beam can be extracted from the cavity. The alternative approach is presented in Fig. 1.3b. The oscillator emits a low-energy beam with a diffraction-limited quality. It is then amplified by the gain medium operating in a double-pass configuration. Due to the conjugate mirror, the returned beam is compensated for any aberrations due to the high-gain laser amplifier. A diffraction-limited beam is extracted by 90° polarization rotation. So, according to these remarkable properties, it is expected that we can realize a new class of high-power and high-brightness phase conjugate lasers delivering a beam quality that fits the requirements for scientific and industrial applications. This

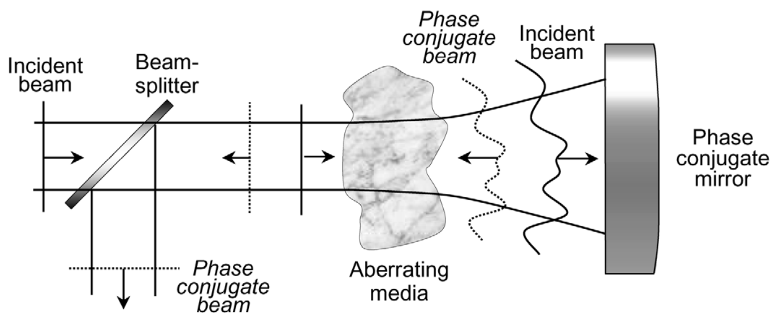

Figure 1.2. Compensation of the aberrations due to a phase distorting media by wavefront reflection on a phase conjugate mirror.

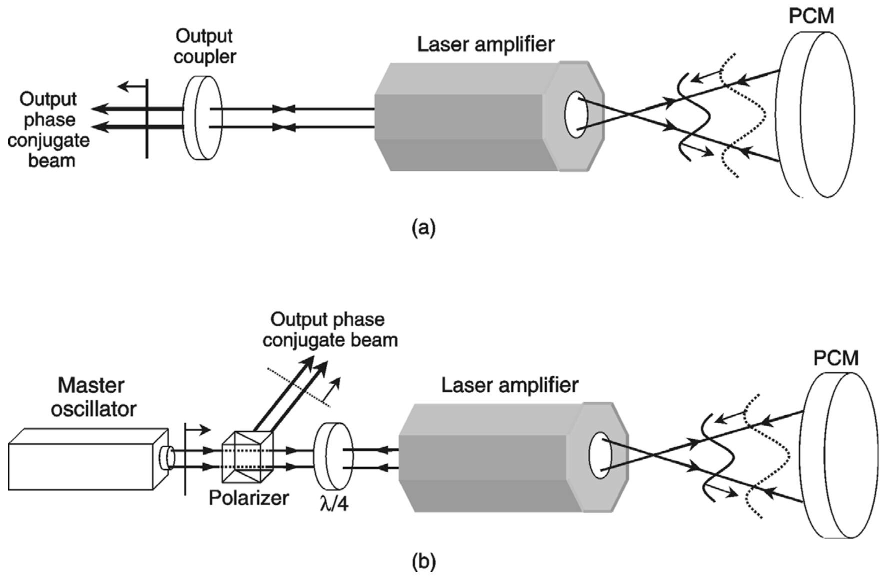

Figure 1.3. The two main laser architectures involving a phase conjugate mirror for correction of the aberrations due to thermal effects in the gain medium. (a) Laser oscillator with intracavity phase conjugate mirror and (b) master-oscillator power amplifier with a phase conjugate mirror.

capability of aberration compensation was also shown in the earliest research works on Fourier optics and holography. Kogelnik [2] had already demonstrated that static aberrations can be compensated by using conventional holographic recording. After processing of the photographic media and proper readout of the hologram, it generated the backward conjugate wave for a clear image restoration through a distorting media. The analogy of phase conjugation with dynamic holography was then outlined by Yariv [3] and in early experiments with photorefractive crystals [4], and it contributed to extend the field of applications, thus including parallel image processing, optical correlation for pattern recognition, holographic interferometry for non destructive testing, incoherent to coherent image conversion, novelty filters for moving object detection [3].

It was then recognized that when doing simultaneous recording and readout of a volume hologram with beams having the same or nearly the same wavelength, the incident or conjugate waves can be amplified [5–8]. This is due to the energy transfer from the pump beams which interfere with the probe beam in the volume of the nonlinear media. These phenomena of mutual coupling of waves interfering in the nonlinear media are of great importance in view of applications and have led to remarkable unified treatments of the fields of nonlinear optics and dynamic holography. These interactions have led to outstanding applications to coherent beam amplification and to amplified phase conjugation. The possibility of amplifying the amplitude of a complex wavefront through a third-order nonlinearity permits (a) the demonstration of novel types of optical resonators, including a nonlinear mirror with gain, or (b) the attainment of high-gain and low-noise image amplification. We must also outline that pioneering experiments on dynamic holography were done in the 1970s in different media allowing the recording of elementary gratings by interfering two beams at the same wavelength. The gratings was due to a change of the absorption or of the index of refraction of the media. In these early experiments, the holographic technique was mainly used to probe the spatiotemporal evolution of the physical mechanisms responsible for grating formation in materials like semiconductors or saturable absorbers [9, 10].

The mechanisms of dynamic holography and phase conjugation have stimulated a great interest in the research laboratories for nearly two decades. First, it was important to analyze and to characterize with details the physics of the third-order nonlinearities $\chi^{(3)}$ when the material is illuminated by interference of a pump and probe beams. It induces a spatial modulation of the material complex dielectric constant which generates an amplitude or a phase volume grating. Third-order effects occur in isotropic transparent media, and there is no restriction to material that exhibits an inversion symmetry center as for the second-order nonlinearities. In particular, the most established $\chi^{(3)}$ nonlinear mechanisms for phase conjugation are Kerr effects, Brillouin scattering, and Raman scattering. However, other effects that may also provide an efficient index or amplitude modulation through mechanisms with a response time ranging several nanoseconds to seconds are of great interest for phase conjugation [11]. This is the situation encountered with photorefractive effects, free carrier generation in semiconductors, laser gain media, and so on; several chapters of this book will present laser architectures and system performances based on these nonlinearities used to realize an efficient phase conjugate mirror. Another aspect of the field which has been intensively covered in the research labs is the capability of the dynamic hologram to exchange energy between the incident and conjugate waves that interfere in the dynamic media. First observed and analyzed by holographic self-diffraction phenomena in photorefractive crystals like $LiNbO_3$, [12, 13], these effects were subjects to intense research activities either using the formalism of wave propagation in the nonlinear media, or based on the point of view of holography and self-diffraction that can reinforce (or reduce) the intensity of one of the interfering probe (or pump) beams. Both approaches complement each other with regard to the understanding of the physical phenomena involved for the generation of a phase conjugate wavefront. They permit the prediction of novel beam interactions and applications and also enable us to compare materials and mechanisms through the calculation and experimental measurements of the two-wave or four-wave mixing gain coefficients per unit of length of the nonlinear media. This parameter, as well as the required laser characteristics such as wavelength, continuous or pulsed operation, and incident energy or power levels, will contribute to our making the right choice of the nonlinear mechanism and materials for a reliable operation of the laser including a phase conjugator [14, 15]. Hereafter, we will detail the main optical configurations as well as the physical mechanisms and materials that have been proposed and studied during the early stages of the field [16–18]. They are now at the origin of the current developments of optical phase conjugation for novel laser cavities and architectures which are treated in this book.

1.2 PHASE CONJUGATION THROUGH FOUR-WAVE MIXING

1.2.1 Phase conjugation and holography

It is now well established from previous works that the basic geometry for phase conjugation consists of two counterpropagating plane waves that are the pump beams of amplitudes E_1 and E_2 and that interfere with a probe beam of amplitude E_p. In general, the beams have the same polarization state, and the probe is incident at an arbitrary angle on the recording medium having a third-order nonlinearity. A clear interpretation of conjugate beam generation shown in Fig. 1.4 is the following: The probe and signal beam interfere in the nonlinear material and create an interference periodic pattern that modulates the properties of the media. The resulting grating wave vector amplitude is $k = 2\pi/\Lambda$. The fringe period Λ is given by the formula $\Lambda = \lambda/2\sin\theta$, where λ is the laser wavelength, and $\pm\theta$ is the pump and probe beam incident angles with respect to the normal to the nonlinear media; it results in a complex volume hologram due to a spatial distribution of the refractive index (Kerr-like media), of the absorption (saturable absorbers), or of the gain when the conjugator is the laser medium itself. The second antiparallel pump beam is then diffracted under Bragg conditions by the dynamic volume hologram; following the classical formalism of holography, it generates a backward conjugate wavefront whose complex amplitude can written as $E_c = E_p^* E_1 E_2$. It is named the conjugate image beam in holography, and its amplitude is proportional to E_p^*. Since this geometry involves waves E_1, E_2, E_p, and E_c which are simultaneously present in the material, it is known as four-wave mixing (4WM). The reflectivity of the nonlinear mirror is thus defined as $R = |E_c(0)/E_p(0)|^2$. Considering that ω_1, ω_2, and ω_p are the respective frequencies of the pump and probe beams, the conjugate beam exhibits a frequency $\omega_c = \omega_1 + \omega_2 - \omega_p$. However, starting from this general formula, two particular situations are of interest: the degenerate four-wave mixing where all frequencies are equal to ω_0 (Fig. 1.4a) and the nearly degenerate four-wave mixing case (Fig. 1.4b) where $\omega_c = \omega_0 - \delta$, $\delta \ll \omega_0$ when the probe and pump frequencies are respectively $\omega_0 + \delta$ and ω_0. This last situation is com-monly encountered in several types of efficient nonlinearities (Brillouin scattering, photorefractives, etc.) where the frequency detuning δ range respectively from several gigahertz to few hertz. It is viewed as a nonlinear interaction involving a moving holographic grating. The formalism describing the coupling of the interfering optical fields via a given material nonlinearity is another important aspect of the work done on phase conjugation. The analysis must identify the conditions for efficient interactions between the beams for energy transfer from the pump to the incident and conjugate beams. In particular, it will be shown that interactions involving nearly degenerate four-wave mixing or a nonlocal spatial response of the material (phase-shifted volume grating) permit the attainment of high gain coefficients. It will result in

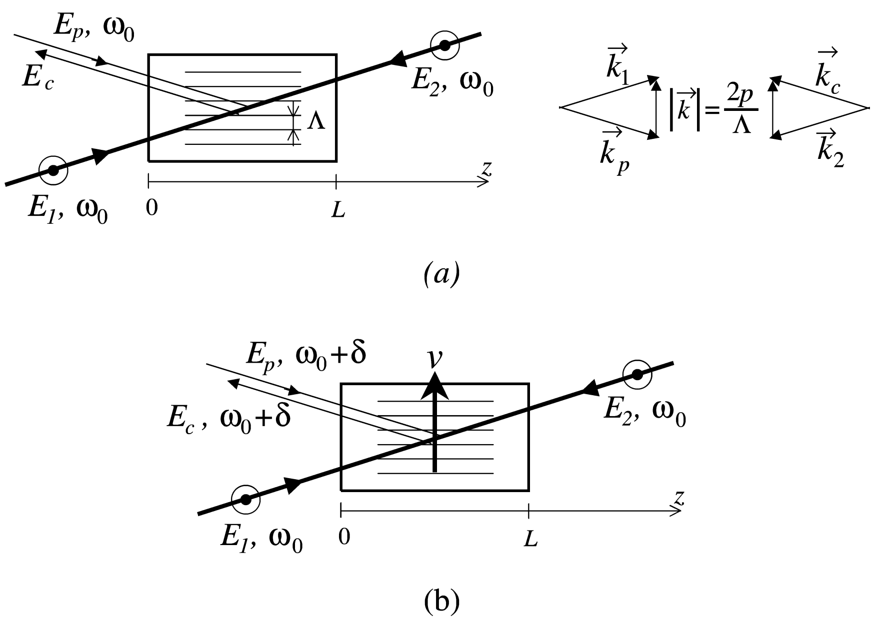

Figure 1.4. Generation of a phase conjugate wavefront by four-wave mixing interaction. The pump and probe beams interfere to create a dynamic hologram in the nonlinear medium. (a) Degenerate four-wave mixing and (b) nearly degenerate four-wave mixing.

amplification (or depletion) of the probe or amplified conjugate beam reflectivity. These unique properties make the 4WM interactions extremely useful for the applications developed in this book. Hereafter, we give some of the major relations that govern the amplitudes of the transmitted E_p ($z = L$) and conjugate E_c ($z = 0$) waves, thus allowing us to calculate the reflectivity of the nonlinear mirror.

1.2.2 The basic formalism of four-wave mixing

The original equations of degenerate (or nearly degenerate) 4WM were first derived independently by Yariv and Pepper [5] and Bloom and Bjorklund [8] by considering a set of coupling wave equations which will describe the space and time evolution of the waves that interact all together in the nonlinear media. The equations relate the fact that the hologram is dynamic: It adapts in real time (with an inertia due to a finite response time) to the interference pattern due to mutual interference of the beams in the gratings that they are writing and reading. Note that with all beams having the same or nearly the same frequency ($\delta \ll \omega_0$), we consider that there is a perfect phase matching of the $\vec{k}$ vectors $\vec{k}_c = \vec{k}_1 + \vec{k}_2 - \vec{k}_p$, where $\vec{k}_i$ is the optical wave vector. In the hypothesis of nondepleted pump beam and equal frequencies, we have from Refs. [5–9] the following set of coupled equations for the steady-state amplitudes of the optical fields E_c and E_p:

$$\frac{dE_c}{dz} = i\frac{\omega_0}{2}\sqrt{\frac{\mu}{\varepsilon}}\chi^{(3)}E_p^*E_1E_2 \tag{1}$$

$$\frac{dE_p}{dz} = -i\frac{\omega_0}{2}\sqrt{\frac{\mu}{\varepsilon}}\chi^{(3)}E_c^*E_1E_2 \tag{2}$$

where ω_0 the optical frequency of the beams, $\chi^{(3)}$ is the third-order nonlinearity in SI units, and μ and ε are the susceptibility and permittivity of the media. From these general expressions we can derive more simple formulas when introducing a coupling constant K that will be proportional to the pump beam amplitudes E_1 and E_2 and to the third-order nonlinear coefficient of the media χ^3:

$$\frac{dE_p}{dz} = -iK^*E_c^* \tag{3}$$

$$\frac{dE_c}{dz} = -iK^*E_P^* \tag{4}$$

where $K^* = i(\omega_0/2)\sqrt{\mu/\varepsilon}\chi^{(3)}E_1E_2$. Solving these equations leads to the following expressions for the transmitted and reflected fields for a material interaction length L:

$$E_c(0) = -iE_p^*(0)\frac{K^*}{|K|}\tan|K|L \tag{5}$$

$$E_p(L) = E_p(0)\frac{1}{\cos|K|L} \tag{6}$$

Two parameters will be of interest in view of applications of degenerate four-wave mixing: first, the reflectivity $R = |E_c(0)/E_p(0)|^2$ of the nonlinear phase conjugate mirror; and second, the gain $G = |E_p(L)/E_p(0)|^2$, which characterizes probe beam amplification. According to the above relations, the parameters R and G which are characteristic of the degenerate 4WM interaction are expressed by the following expressions:

$$R = \tan^2|K|L \tag{7}$$

$$G = \frac{1}{\cos^2|K|L} \tag{8}$$

These formula clearly show that amplified reflection and transmission can occur for $|KL|$ satisfying $\pi/4 < |K|L < 3\pi/4$. In these conditions, the nonlinear interaction can be seen as a parametric amplifier for both the reflected and transmitted waves due to efficient energy transfer from the pump beams. Also an important consequence is the existence of self-oscillation when $|K|L = \pi/2$. It physically corresponds to an optical oscillation without mirror feedback for zero intensity probe beam.

Since amplification appears to be independent of the pump-probe beam angle in the above formula, 4WM interaction could permit to amplify complex incident and conjugate wavefront carrying spatial informations. However, it will be shown that with real materials there often exist an optimum range of pump-probe beam angles due to the physical mechanisms involved for the generation of the photoinduced grating index modulation. This angular bandpass will limit the number of transverse modes that can be amplified or conjugated, and it determines the space bandwidth product of this new type of image amplifier.

As an example, stimulated Brillouin scattering and photorefractive phenomena at zero applied field are more efficient for high spatial frequency gratings arising from interference of contrapropagating beams. On the other hand, other effects will require large grating periods due a low beam angle between probe and pump.

An important consequence of the 4WM interaction is its capability of realizing a laser cavity including a phase conjugate mirror having a continuous gain as demonstrated first by Feinberg and Hellwarth [19] with $BaTiO_3$ crystal and shown in Fig. 1.5. A classical mirror of amplitude reflectivity r is introduced on the path of the incident probe; and due to the phase conjugate properties of the nonlinear mirror whose reflectivity can be higher than unity, there can be a stable oscillation buildup in the cavity. The beam oscillating in the cavity starts from the coherent noise due to the pump beams E_1 and E_2. Its frequency is equal to the pump frequencies ω_0 in the case of a degenerate interaction and is independent of the distance between the mirror and the nonlinear medium. This experiment is generally realized with interfering pump and probe beams having the same state of polarization. If this condition is not satisfied due to the optical components that introduce both spatial aberrations and depolarizations, a special experimental arrangement is required to process the two polarization states for obtaining vectorial phase conjugation.

1.2.3 Self-pumped phase conjugation

Another important configuration for conjugation shown in Fig. 1.6 consists only of an aberrated signal beam that is reflected back by the nonlinear medium as a conjugate wavefront. This particular interaction, called self-pumped phase conjugation [20], does not require external contrapropagative pump beams, which

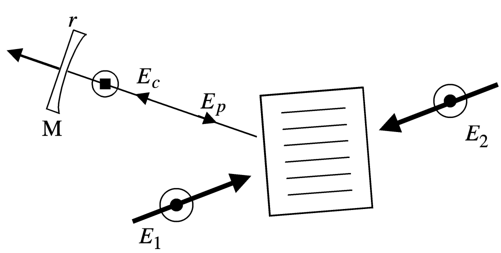

Figure 1.5. Phase conjugate oscillator. The oscillation is due to the nonlinear phase conjugate mirror that exhibits a reflectivity higher than unity.

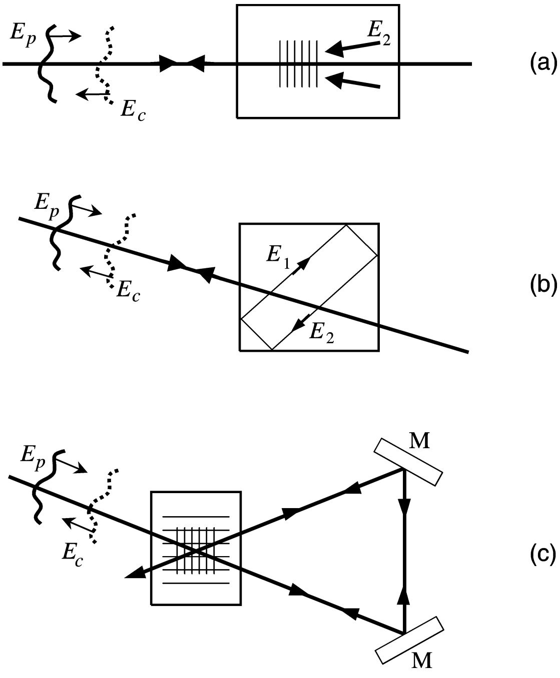

Figure 1.6. Self-pumped phase conjugate (SPPC) configurations. (a) SPPC by nonlinear backscattering, (b) SPPC due to self-induced internal feedback loop inside the nonlinear material, and (c) SPPC due to an external feedback loop.

interfere with the signal wave as shown in the Fig. 1.4a. In view of applications, it thus appears very convenient to use this interaction whose main characteristics are thus the following: The maximum conjugate beam reflectivity is equal to unity since there is no gain is due to energy transfer from a pump beam as is achieved in the conventional 4WM geometry; the phase conjugate beam originates from the coherent noise due to the signal beam. As shown in the Fig. 1.6a, it generates in the nonlinear medium complex reflection (or transmission) types of holographic volume gratings which are due to the interference of the signal with scattered plane waves components that propagate in the same or in opposite directions. It thus results in regions in the nonlinear medium where there is the equivalent of a 4WM interaction that self-generates the conjugate wave of the incident one. Also, the beams inside the volume of the media may form a loop (Fig. 1.6b), but the interaction can also be reinforced by using and external ring cavity geometry [21] to perform self-pumped phase conjugation with higher reflectivity (Fig. 1.6c). This geometry is very simple to use in experiments, and it has a great potential for improving the brightness of laser sources. However, this self-pumped interaction is not encountered in all nonlinear mechanisms. Self-pumped phase conjugation is very well suited in interactions involving stimulated Brillouin scattering or photorefractive backscattering phenomena and in particular several chapters of this book will illustrate applications showing the great potential of these mechanisms for beam quality control in laser cavities or in master oscillator power amplifier laser architectures.

1.3 THE NONLINEAR MATERIALS

There is potentially a wide variety of nonlinear physical mechanisms that can be used for optical phase conjugation of coherent laser beams. The generation of a phase conjugate wavefront arises from the third-order material nonlinearity; moreover, analogy with holography introduced above affords the opportunity of using materials allowing the recording of phase or amplitude dynamic volume of the holograms. Therefore, the mechanisms presented hereafter have been the subject of extensive research activities during the last two decades—both on the basic material properties and in depth analysis of interactions between beams that interfere in the volume of the nonlinear media.

1.3.1 Optical Kerr effects

This mechanism is a basic third-order nonlinearity that appears in isotropic materials such as gases, liquids, or solids in the presence of a strong electric field due to an intense optical beam or to an external applied voltage. On the microscopic scale it corresponds to a reorientation of dipoles in the presence of the high field. In such conditions the material refractive index n becomes a function of the light intensity according to the relation of the form $n = n_0 + n_2 I$, where I is the intensity of the optical beam and n_2 is the nonlinear refractive index, which is related to the electro-optic Kerr coefficient of the material. Kerr nonlinearity may exhibit an extremely short response time (picosecond range), but it generally requires high peak intensities ($>10\,\mathrm{GW \cdot cm^{-2}}$) to induce efficient index nonlinearity for phase conjugation or ultrafast optical switching. Main materials used for experiments in wave mixing are liquids such as carbone disulfide (CS_2), nitrobenzene, acetone, and benzene or solids like quartz, silica, and glass (bulk or fibers).

1.3.2 Stimulated Brillouin scattering

The stimulated Brillouin scattering (SBS) effect originates from the electrostrictive effect in the transparent dielectric media such as liquids, gases or solids. The interference patterns due to the incident and spontaneous scattered optical fields generate a traveling acoustic wave that modulates the material refractive index through the elasto-optic effect. It thus results from the interaction the equivalent of a coherent moving phase grating that propagates at the sound velocity and that diffracts in the backward direction a phase conjugate replica of the incident high-intensity laser beam. SBS is a phenomena that exhibits a threshold, and its typical response time ranges in the nanosecond due to the phonon lifetime. Also, because of the moving grating the retro-reflected Stokes wave is frequency-shifted by the

Doppler effect corresponding to the sound velocity by several gigahertz. As will be shown in several chapters of this book, SBS is a very well suited interaction for self-pumped phase conjugation and most efficient materials are high-pressure gases (SF_6, N_2, Xe, etc.), liquids (CS_2, CCl_4, $GeCl_4$, $SiCl_4$, $TiCl_4$, freon, acetone, etc.), or solids (silica fibers or bulk, quartz, organic crystals such as LAP, DLAP, etc.).

1.3.3 Photorefraction

Photorefraction is a particular type of nonlinearity which arises in materials that exhibit linear (or quadratic) electro-optic (EO) effects. The illumination of the material by a two-beam interference pattern generates a photoinduced charge distribution. The photo-generated carriers (electrons or holes) are trapped, and thus it results in a space-charge field in the volume of the material which modulates the refractive index through the electro-optics coefficient. Microscopic phenomena for space-charge buildup involves electrons charge diffusion or drift under an external applied electric field. There are several specific characteristics of the photorefractive effect which differ from other known nonlinear mechanisms. First, there is no threshold effect and the material responds to the incident energy. In such conditions the material response time can be easily controlled from a fraction of a microsecond to several seconds; second, the amplitude of the photoinduced index modulation is mainly determined by the value of the electro-optic coefficient and by the trapping center density. Also, photorefractive materials have a dark storage time constant, equivalent to memory effect. Photorefractive materials have already demonstrated their great importance in experiments based on the recording and erasure of holograms for optical information processing, high-gain wave mixing, and phase conjugation with low-power visible or near-infrared laser beams. Most of the experiments were performed with different types of EO materials such as $LiNbO_3$, $BaTiO_3$, and $Bi_{12}(Si,Ge,Ti)O_{20}$; semiconductors such as GaAs, InP, and CdTe; PLZT ceramics; and, more recently, doped EO polymers or liquid crystals.

1.3.4 Free carriers in semiconductors

Semiconductors are excellent candidates for nonlinear optics experiments since they possess a large variety of physical mechanisms that can provide efficient and fast spatial index or absorption modulation under continuous-wave (CW) or pulsed laser illumination. The first 4WM experiments were based on electron–hole generation under pulsed laser for transient gratings recording at a wavelength for which photon energy is larger than the bandgap energy. The generated plasma induces a large modification of the semiconductor dielectric constant, thus leading to the recording of both phase and amplitude gratings. However, the index modulation will, in general, be the dominant contribution in efficient 4WM interactions involving large period gratings ($\Lambda > 10\ \mu m$). Due to spatial plasma diffusion, small period gratings are washed out and their contribution to the diffraction is very much reduced. Temporal dynamics in semiconductors ranges from picoseconds to several 10 ns, depending of the material and laser wavelength used in the experiments.

Microcrystallites of a semiconductor can also be included in a glass matrix. It results in a bulk and isotropic material that may exhibit relatively efficient 4WM even for small period gratings as was demonstrated in CdSe-doped glasses in the green–red spectral region. Also, major advances in the semiconductor technology now permit the confinement of electron–hole pairs in potential walls called multiquantum wells. It permits an increase in the electronic density of states, thus leading to enhanced optical nonlinearities as already demonstrated in wave mixing experiments done on multiquantum well structures with GaAlAs–GaInAs on GaAs substrates. These materials may operate efficiently at semiconductor laser wavelength with low incident power.

1.3.5 Saturable amplification

The laser gain media itself is also of great interest for its capabilities of performing real-time holography and phase conjugation through saturable amplification. When two beams interfere in a flash lamp of diode pumped gain media, they create a spatial modulation of the beam amplitudes due to gain saturation effect. In other words, in bright region of the fringes, the amplification is reduced due to the gain saturation, while dark regions of the fringes receive a higher gain. It thus results in a spatial gain grating that diffracts the incident waves and generates a phase conjugate of the incident probe wave through a 4WM configuration. We note that in this interaction the amplitude grating is shifted by π with respect to the incident interference fringes. Also, the beams that interfere in the gain media will be amplified through the laser gain, and energy transfer will also occur through self-diffraction phenomena. Therefore, four-wave mixing in the laser media offers very attractive features: Highly efficient diffraction can be obtained for transmission- or reflection-type gratings, fast response time, and self-matching nonlinearity with respect to the laser wavelength. This interaction can operate in different temporal regimes and does not require high optical powers. Conjugate beams with high reflectivities can be obtained after optimizing the pump beam fluences with respect to (a) the saturation fluence of the laser media and (b) pump-to-probe beam ratios. With such conditions, self-pumped phase conjugate loop resonators using four-wave mixing in the gain media are demonstrated; they can be injected or self-starting. It will be shown that this interaction is well suited in laser media having a high gain length product, and experiments have been performed in solid-state saturable amplifiers such as ruby, Nd:YAG, Nd:YVO_4, Nd:glass, Nd:YLF, Ti:sapphire, liquid rhodamine dyes, or CO_2 and Cu vapor gas lasers.

1.3.6 Saturable absorption

The saturable absorption was recognized early as an efficient mechanism for efficient phase conjugation. It is based on the dependence of the absorption and refractive index of a two-level system as a function of the incident average intensity due to pump and probe beams. It is expected that transitions with a large cross section and a long relaxation time are more easily saturable. Also another important parameter is the frequency detuning off the transition line center. The effect of detuning the laser permits to have a dominant contribution of the phase grating, thus leading to a significant increase of the conjugate beam reflectivity. After optimizing the conditions of interactions—in particular, using large grating periods—amplified reflections by four-wave mixing was observed in atomic sodium vapor. However, for applications, it may be more attractive to use solid-state saturable absorbers such as Cr^{3+}-doped, Nd^{3+}-doped, and color-center crystals. More recently it was also shown that Cr^{4+}-doped GSGG and Cr^{4+}:YAG possess a broad absorption band around 1 μm and can be used for phase conjugation at 1.06 μm. Such characteristics are well suited for further applications on laser beam control, dynamic holography performed at this important wavelength.

1.3.7 Molecular reorientation in liquid crystals

Organics may offer very attractive properties when used in wave-mixing and dynamic holographic experiments: Large-size materials can be fabricated; and due to the large diversity of chemical compounds for material synthesis, it is expected that their nonlinearities can be optimized for a given application. The most promising media are based on polymers, liquid crystal, or a mixture of polymer-dispersed liquid crystal. In these materials the photoinduced index anisotropic called the Fredericks transition arises from molecular reorientation due to the electric field. It results in an index spatial modulation that gives rise to a dynamic grating or to self-phase modulation. Due to the large birefringence of liquid crystal, quite efficient photoinduced nonlinearities can be obtained in the visible or near-IR wavelengths. Typically, a nonlinear response in liquid crystal requires an equivalent electric field of 1 to 10 $\mathrm{V} \cdot \mu\mathrm{m}^{-1}$, while other polymer materials require more than 100 $\mathrm{V} \cdot \mu\mathrm{m}^{-1}$. Another remarkable property is that the nonlinear response can be further increased by doping with a dye such as dispersed red or orange. Although large gain coefficients have been measured in wave mixing experiments, the detailed mechanisms for molecular reorientation at low power levels in dye-doped liquid crystals are not yet fully explained. Several mechanisms with different time constants may be present: space-charge field at the interfaces, photomolecular alignment, and photoisomerization, thus leading to the recording of dynamic or nearly permanent holograms. Also, a different structure can be made: It consists of a liquid crystal layer deposited on a photoconductive film. In wave-mixing experiments, this hybrid structure behaves as a nonlinear media for dynamic phase holography. Liquid crystals thus provide the opportunity of new types of third-order nonlinearities; moreover, their physical and chemical properties continue to progress due to the development of the display market.

1.3.8 Thermal gratings

The energy or incident power absorbed by a media at a given wavelength in wave-mixing interactions also induces spatial index modulation through the contribution of the thermal coefficient $\partial n/\partial T$. This intensity-dependent change of the refractive index in liquids or solids may result in very significant self-diffraction effects for phase conjugate beam generation. From early works on these mechanisms, it is well established from heat equations that the steady-state index modulation varies as the square of the grating period and is inversely proportional to the thermal conductivity of the material. Therefore, for small grating periods, thermal diffusion tends to reduce both the photoinduced index modulation amplitude and the diffraction efficiency of thermal holograms. For that reason, wave-mixing experiments based on thermal nonlinearities will benefit from using a small pump-probe beam angle or a longer wavelength up to 10 μm. Also, in the pulse regime, if the pulse duration is short compared to the thermal relaxation time, the induced index nonlinearity is reduced. To perform efficient wave mixing, phase conjugation materials that display high thermal coefficient must be used, and this condition can be achieved in semiconductors like HgCdTe where $\partial n/\partial T = 10^{-3}$ at $\lambda = 10.6$ μm, or in liquid crystals where $\partial n/\partial T = 10^{-3}$ at room temperature and $\partial n/\partial T = 10^{-2}$ near the transition temperature.

1.4 THE CRITERIA FOR THE CHOICE OF MATERIALS

This review (which summarizes the main physical mechanisms) and nonlinear media highlight the great diversity and the intense research activities that have been pursued in the field of phase conjugation. Both the fundamental and applied aspects of the field have stimulated remarkable innovative concepts and subsequent new applications. To identify the most convenient mechanism is now an important task since each material exhibits very specific properties and the choice will result from a compromise with respect to the requirements due to the applica-tions. To illustrate this complex situation, we outline in the following list the main parameters which will contribute to identify the most suitable nonlinearity and material:

- Operating mode of the source: pulsed, CW, wavelength
- Required conjugate beam reflectivity and beam interactions (4WM or self-pumped)
- Required response time of the nonlinearity (can range from seconds to nanoseconds or even shorter).
- Good optical quality and stability, high damage threshold and compactness.

Beside these most important parameters, other characteristics such as low speckle noise wavefront generation, conjugate beam fidelity, and material reliability may also contribute to the selection of the good material for an optimum operation of the nonlinear mirror in a full-scale laser system. Nonlinear optical phase conjugation undoubtedly offers a great potential for energy scaling of laser sources, and several comprehensive books or review papers exist on this subject, on both the basic and applied aspects of this field [22–33].

1.5 CONCLUSION

Optical phase conjugation is now established as a domain of nonlinear optics, and further noticeable advances are expected due to the interest in the development of high-energy or high average power laser sources. The concept of phase conjugation permits the restoration of a beam whose quality is close to the diffraction limit whatever the phase aberrations present on the optical path of the laser beam. Moreover, this property is maintained even when changing the laser pulse energy or pulse repetition rate. This permits the attainment of a great flexibility in the operating conditions of the source for adjusting its characteristics to the requirements of the applications. Also, another very important property of phase conjugation is the capability of combining and phase locking of several laser sources, thus leading to an improvement of power and brightness of the emitted beam. For that purpose the concept of phase conjugation permits to overpass the limitations of classical laser architectures for power or energy scaling. To demonstrate and to integrate these concepts in laser systems require efficient third-order nonlinear materials for conjugate beam generation through a dynamic hologram. The main objective of this book is therefore to highlight the most suitable class of nonlinear mechanisms such as Brillouin scattering, photorefraction, saturable amplification, or thermal index modulation. Beside these established effects, there is still a great potential for optimizing the properties of existing media or for the discovery of new fundamental mechanisms or laser architectures based on the remarkable properties of nonlinear optical phase conjugation.

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