Phase conjugation and time reversal: techniques and applications

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February 23rd, 2012

Keywords: Phase conjugation, time reversal
Description: Description, history and applications of phase conjugation and time reversal techniques.
Last modification: March 20, 2013

Introduction

Phase conjugation (PC) and time reversal (TR) are a set of techniques for the transformation of a wave field resulting in the reversal of propagation of the waves conserving the initial spatial distribution of amplitudes and phases. [1]

Such a phenomenon is possible when the sign of the time variable in the equation of a wave field can be reversed.

PC was first observed by Zel'dovich et al. in 1972 and then extensively studied in optics. [1]

Time reversal techniques

TR consists in recording the amplitude of the wave field using a line of transducers. The recorded signal is then re-emitted playing the signal backwards. Waiting for the end of the signal before re-emitting it makes it possible to correct or modify in-between. This was technically done by Fink et al. in 1989. [2]

Systems designed in the 1990s use matrix transducers with hundreds of elements, working at a frequency of 5 MHz. However, those systems are expensive, cumbersome and hard to control. [3]

Also, this process only works for relatively low frequency applications (below 1 GHz), such as acoustics, but cannot be used in optics (THz frequencies): recording the phase information at such frequencies is currently impossible. [4]

Multichannel parametric systems are easier to control and can operate in real time. However, the absence of parametric effects results in small amplitudes for the conjugate wave. Such systems were used in a 1D mirror at 300 kHz, but making 2D parametric arrays is extremely complex, especially at higher frequencies. [3]

Phase conjugation techniques

Unlike TR, PC will use physical phenomena to produce the conjugate wave, sometimes allowing amplification. [3]

In holographic pumping, the signal wave interacts with the pump wave of the same frequency. The information on the amplitude-phase distribution in the signal wave is recorded as the spatially inhomogeneous quasi-static perturbation of the medium. A second pump wave propagating toward the recording wave will produce the conjugate wave. [3]

In parametric pumping, counter-propagating pump waves produce a spatially uniform modulation of parameters of the medium at double frequency. The parametric interaction of this perturbation with the incident wave will produce the conjugate wave. [3]

Optical phase conjugation

The holographic method, on fig. 1, is referred as for-wave mixing, because both first and second pump wave will record the incident wave, thus producing the conjugate wave two times and increasing the efficiency of the method. In static holography, the photosensitive layer has to be developed. In dynamic holography, the incident wave will be recorded and read in real time, using nonlinear media in which the permittivity change occurs immediately. [1]

The parametric method, on fig. 2, is referred as three-wave mixing. The reference wave will modulate the permittivity at double frequency. The incident wave has to propagate approximately in the direction of the pump wave. The conjugate wave propagate forwards. A mirror must be used to obtain a backward-propagating conjugate wave. [1]

Ultrasonic phase conjugation

Studies of ultrasonic PC began in the 1980s. Since then, several methods to generate conjugated waves have been proposed. It was also discovered that PC is naturally present in already-existing physical phenomena. [4]

Because the propagation speed of an electro-magnetic wave is 5 orders of magnitude higher than that of an acoustic wave, we write the following relation between the wave vectors k_a and k_{em} of the acoustic and electromagnetic waves

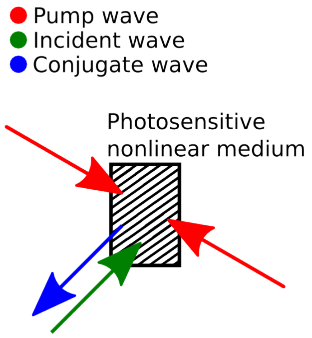

Fig. 1: Diagram of a four-wave mixing interaction

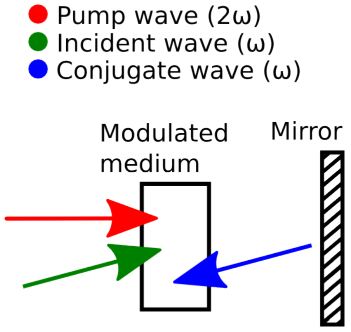

Fig. 2: Diagram of a three-wave mixing interaction

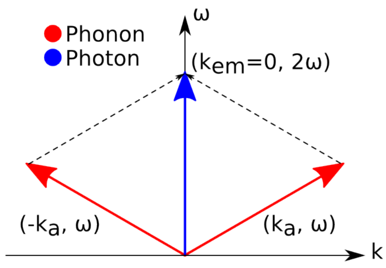

Fig. 3: Vector diagram of a phonon-photon interaction

respectively: $k_a \gg k_{em} \sim 0$. Fig. 3 illustrates the laws of conservation of energy and momentum that allow the counter-propagating wave to exist. [3]

Active materials will be used to create an electromagnetic pump, excited by an electromagnetic field that will modulate the sound velocity in the medium. In piezoelectric crystals, the electro-acoustic modulation only reaches fractions of a percent. In magnetic crystals, the magneto-acoustic coupling can reach dozens of percent, by using the magnetoacoustic resonance or by combining the magnetostriction and spin reorientation transition effects. [3]
An alternative to active materials is semiconductors, in which a phonon-plasmon parametric interaction can be produced by an alternative electric field or a modulated optical pump. [3]
In liquids, PC can be enhanced by introducing air bubbles, which will add dispersion and increase nonlinearity. [3]
In solids, tuning the acoustic parameters through collective excitation can increase the efficiency of PC. [3]

In the conditions of parametric PC beyond the threshold of the absolute instability of phonons in magnetoacoustic media, one can obtain a giant amplification, up to 80 dB, which uses the nonlinear properties of the media. [5]

In dispersion-free nonlinear acoustic media, PC auto-focusing and auto-compensation of phase distortion can still be observed, even if the nonlinear properties partially violate the time reversibility of the propagation law. [5]

Applications

The main interest of PC and TR is the auto-compensation of phase distortion, which allows the self-targeting of the re-emitted wave: when the incident wave crosses a phase-nonuniform medium, then, the wave re-emitted by a PC mirror will auto-focus itself on its initial source, even a moving object. [3]

This allows acoustic PC to be used in non-destructive testing and in medical therapy for tumor destruction, like lithotripsy and hyperthermia, using the supercritical amplification. [3]

In acoustic microscopy, PC can improve the image quality and permits a control on contrast and brightness. [3]
Applying selective PC of some harmonics of the incident wave can improve the image resolution and allows mapping the nonlinear parameters of the media. [5]
For example, PC can result in the generation of the fourth (and possibly higher) harmonic without increasing the order of nonlinearity of the interaction, thus narrowing the focal distribution of those harmonics and reducting the sidelobes and reverberation noise. [6]

PC on moving scatterers produces a Doppler shift one order of magnitude higher than the usual one, allowing better contactless velocity measurement. [5]

References

[1] B. Y. Zel'dovich, N. F. Pilipetsky, and V. V. Shkunov, *Principles of Phase Conjugation.* Springer-Verlag, 1985. 1

[2] M. Fink, C. Prada, and D. Cassereau, "Self-focusing with time reversal mirror in inhomogeneous media," *Proc. IEEE Ultrason. Symp.*, pp. 681–686, 1989. 1

[3] A. Brysev, L. Krutyansky, and V. Preobrazhensky, "Wave phase conjugation of ultrasonic beams," *Physics-Uspekhi*, pp. 793–805, 1998. 1, 2

[4] M. Ohno, K. Yamamoto, A. Kobuko, K. Sakai, and K. Takagi, "Acoustic phase conjugation by nonlinear piezo-electricity. i. principle and basic experiments," *J. Acoust. Soc. Am.*, pp. 1330–1338, 1999. 1

[5] V. L. Preobrazhensky, "Parametrically phase-conjugate waves: application in nonlinear acoustic imaging and diagnostics," *Physics-Uspekhi*, 2006. 2

[6] A. Brysev, L. Krutyansky, P. Pernod, and V. Preobrazhensky, "Nonlinear ultrasonic phase-conjugate beams and their application in ultrasonic imaging," *Acoustical Physics*, pp. 623–640, 2004. 2