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Cross-Phase Modulation: A New Technique for Controlling the Spectral, Temporal, and Spatial Properties of Ultrashort Pulses

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1. Introduction

Self-phase modulation (SPM) is the principal mechanism responsible for the generation of picosecond and femtosecond white-light supercontinua. When an intense ultrashort pulse propagates through a medium, it distorts the atomic configuration of the material, which changes the refractive index. The pulse phase is time modulated, which causes the generation of new frequencies. This phase modulation originates from the pulse itself (self-phase modulation). It can also be generated by a copropagating pulse (cross-phase modulation).

Several schemes of nonlinear interaction between optical pulses can lead to cross-phase modulation (XPM). For example, XPM is intrinsic to the generation processes of stimulated Raman scattering (SRS) pulses, second harmonic generation (SHG) pulses, and stimulated four-photon mixing (SFPM) pulses. More important, the XPM generated by pump pulses can be used to control, with femtosecond time response, the spectral, temporal, and spatial properties of ultrashort probe pulses.

Early studies on XPM characterized induced polarization effects (optical Kerr effect) and induced phase changes, but did not investigate spectral, temporal and spatial effects on the properties of ultrashort pulses. In 1980, Gersten, Alfano, and Belic predicted that Raman spectra of ultrashort pulses would be broadened by XPM (Gersten et al., 1980). The first experimental observation of XPM spectral effects dates to early 1986, when it was reported that intense picosecond pulses could be used to enhance the spectral broadening of weaker pulses copropagating in bulk glasses (Alfano et al., 1986). Since then, several groups have been studying XPM effects generated by ultrashort pump pulses on copropagating Raman pulses (Schadt et al., 1986; Schadt and Jaskorzynska, 1987a; Islam et al., 1987a; Alfano et al., 1987b; Baldeck et al., 1987b–d; Manassah, 1987a, b; Hook et al., 1988), second harmonic pulses (Alfano et al., 1987a; Manassah, 1987c; Manassah and Cockings, 1987; Ho et al., 1988), stimulated four-photon mixing pulses (Baldeck and Alfano, 1987), and probe pulses (Manassah et al., 1985;
Agrawal et al., 1989a; Baldeck et al., 1988a, c). Recently, it has been shown that XPM leads to the generation of modulation instability (Agrawal, 1987; Agrawal et al., 1989b; Schadt and Jaskorzynska, 1987b; Baldeck et al., 1988b, 1988d; Gouveia-Neto et al., 1988a, b), solitary waves (Islam et al., 1987b; Trillo et al., 1988), and pulse compression (Jaskorzynska and Schadt, 1988; Manassah, 1988; Agrawal et al., 1988). Finally, XPM effects on ultrashort pulses have been proposed to tune the frequency of probe pulses (Baldeck et al., 1988a), to eliminate the soliton self-frequency shift effect (Schadt and Jaskorzynska, 1988), and to control the spatial distribution of light in large core optical fibers (Baldeck et al., 1987a).

This chapter reviews some of the key theoretical and experimental works that have predicted and described spectral, temporal, and spatial effects attributed to XPM. In Section 2, the basis of the XPM theory is outlined. The nonlinear polarizations, XPM phases, and spectral distributions of copropagating pulses are computed. The effects of pulse walk-off, input time delay, and group velocity dispersion broadening are particularly discussed. (Additional work on XPM and on SPM theories can be found in Manassah (Chapter 5) and Agrawal (Chapter 3).) Experimental evidence for spectral broadening enhancement, induced-frequency shift, and XPM-induced optical amplification is presented in Section 3. Sections 4, 5, and 6 consider the effects of XPM on Raman pulses, second harmonic pulses, and stimulated four-photon mixing pulses, respectively. Section 7 shows how induced focusing can be initiated by XPM in optical fibers. Section 8 presents measurements of modulation instability induced by cross-phase modulation in the normal dispersion region of optical fibers. Section 9 describes XPM-based devices that could be developed for the optical processing of ultrashort pulses with terahertz repetition rates. Finally, Section 10 summarizes the chapter and highlights future trends.

2. Cross-Phase Modulation Theory

2.1 Coupled Nonlinear Equations of Copropagating Pulses

The methods of multiple scales and slowly varying amplitude (SVA) are the two independent approximations used to derive the coupled nonlinear equations of copropagating pulses. The multiple scale method, which has been used for the first theoretical study on induced-phase modulation, is described in Manassah (Chapter 5). The following derivation is based on the SVA approximation.

The optical electromagnetic field of two copropagating pulses must ultimately satisfy Maxwell’s vector equation:

$$\nabla \times \nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{D}}{\partial t} \tag{1a}$$

and