Spectral Phase Conjugation with Cross-Phase Modulation Compensation

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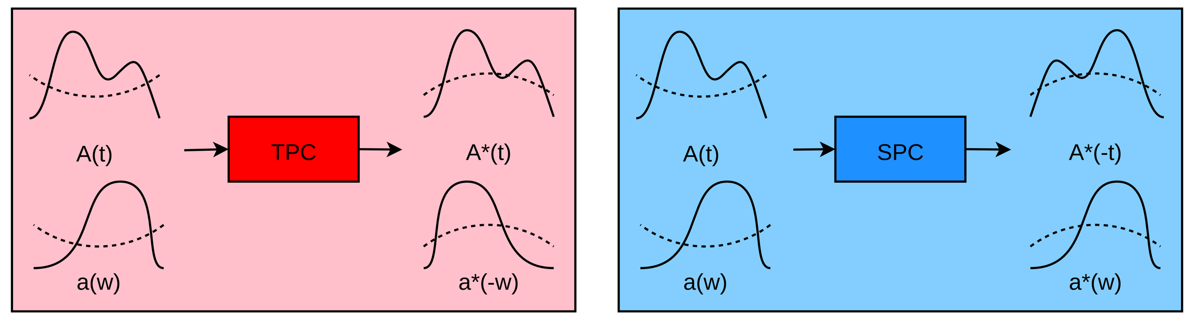
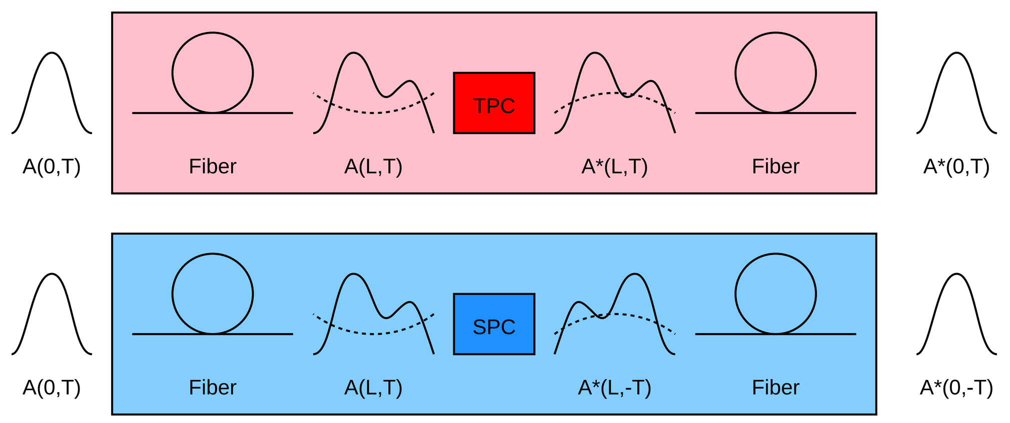
Spectral Phase Conjugation (SPC) vs Temporal Phase Conjugation (TPC)



- Traditional phase conjugation schemes perform phase conjugation of optical envelope in time domain and phase conjugation with **spectral inversion** in frequency domain. This is called Temporal Phase Conjugation (TPC).
- **SPC** performs phase conjugation and **time reversal** of envelope in time domain and phase conjugation in frequency domain [1].

	Time	Frequency
TPC	$A(t) \to A^*(t)$	$a(\omega) \to a^*(\omega_0 - \omega)$
SPC	$A(t) \to A^*(t_0 - t)$	$a(\omega) \to a^*(\omega)$

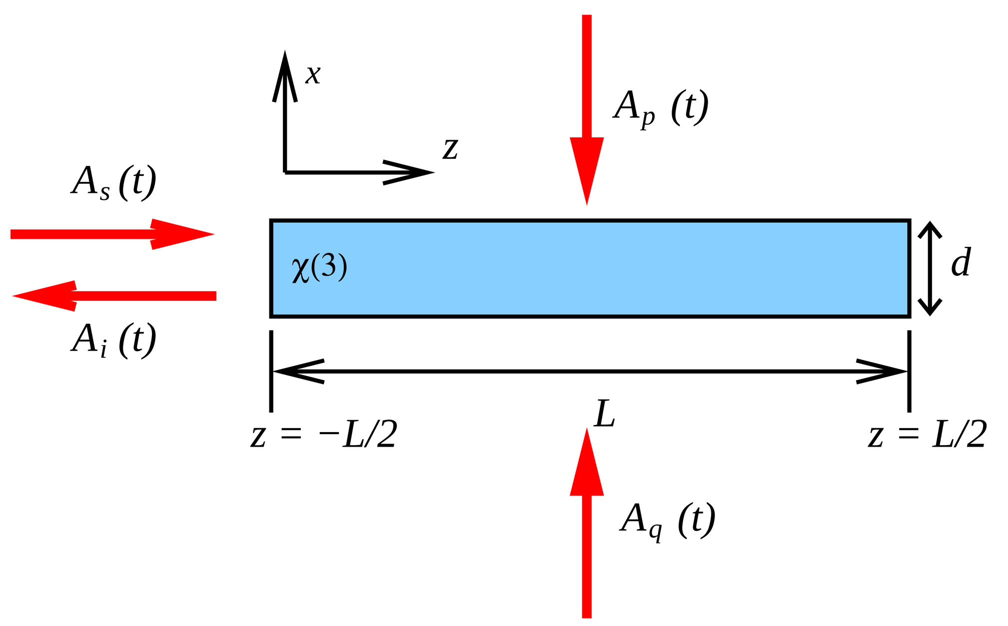
Dispersion and Nonlinearity Compensation



- SPC can compensate for **all chromatic dispersion**, **self-phase modulation (SPM)** and **self-steepening** [2].

	even dispers.	odd dispers.	SPM	steepening	Raman
TPC	√	×	√	×	√
SPC	√	√	√	√	×

Implementation by Four-Wave Mixing (FWM)



Analytic Solutions

- Assumptions: undepleted pump, pump pulses much shorter than signal, long and thin nonlinear medium
- Previous first-order theory predicts that efficiency scales quadratically with pump fluence [1]
- Coupled-mode equations:

$$v\frac{\partial A_s}{\partial z} + \frac{\partial A_s}{\partial t} = jg(t)A_i^* \tag{1}$$

$$-v\frac{\partial A_i}{\partial z} + \frac{\partial A_i}{\partial t} = jg(t)A_s^* \tag{2}$$

$$g(t) = |g(t)|\exp(j\theta) = \frac{3v\omega_0\chi^{(3)}}{4cn_0}A_pA_q \tag{3}$$

A_s = signal, A_i = idler, A_p, A_q = pumps

- Approach: Fourier Transform with respect to z [3]
- Solution:

$$A_i(-\frac{L}{2}, t) = jA_s^*(-\frac{L}{2}, -t)\exp(j\theta)\sinh\left[\int_{-\infty}^{\infty}|g(t')|dt'\right] \tag{4}$$

- **Exponential efficiency** with respect to pump fluence, can be used as a **parametric amplifier**:

$$\eta = \sinh^2\left[\int_{-\infty}^{\infty}|\frac{3v\omega_0\chi^{(3)}}{4cn_0}A_pA_q|dt'\right] \tag{5}$$

- **Accurate time reversal** even beyond the first-order approximation

Cross-Phase Modulation (XPM) Compensation

- XPM detrimental to efficiency and accuracy
- Coupled-mode equations with XPM:

$$v\frac{\partial A_s}{\partial z} + \frac{\partial A_s}{\partial t} = jg(t)A_i^* + jc(t)A_s \tag{6}$$

$$-v\frac{\partial A_i}{\partial z} + \frac{\partial A_i}{\partial t} = jg(t)A_s^* + jc(t)A_i \tag{7}$$

$$c(t) = \frac{3\omega_0\chi^{(3)}}{4n_0^2}\left[|A_p(t)|^2 + |A_q(t)|^2\right]. \tag{8}$$

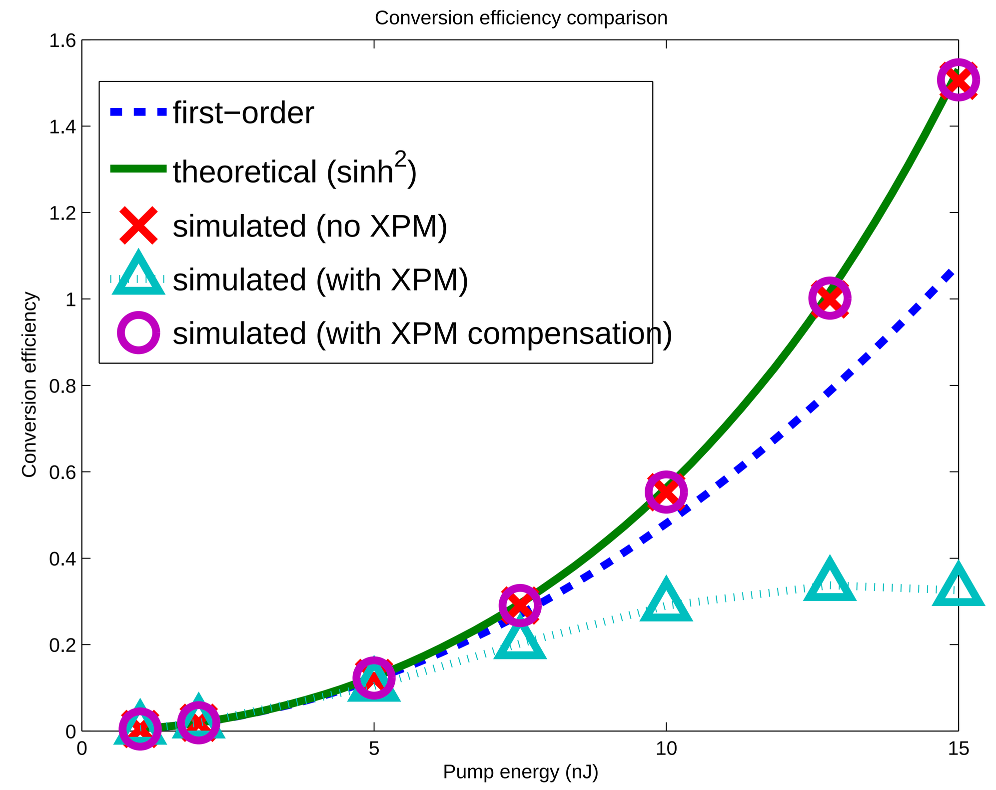
- **Eliminate XPM** by *pump pulse shaping* [3]:

$$\theta(t) = \theta_0 + 2\int_{-\infty}^{t} c(t')dt' \tag{9}$$

- Phase acquired from pump via FWM can exactly cancel XPM
- **Efficiency** and **accuracy** are **restored**:

$$A_i(-\frac{L}{2}, t) = jA_s^*(-\frac{L}{2}, -t)\exp\left[j\theta_0 + j\int_{-\infty}^{\infty}c(t')dt'\right]\sinh\left[\int_{-\infty}^{\infty}|g(t')|dt'\right] \tag{10}$$

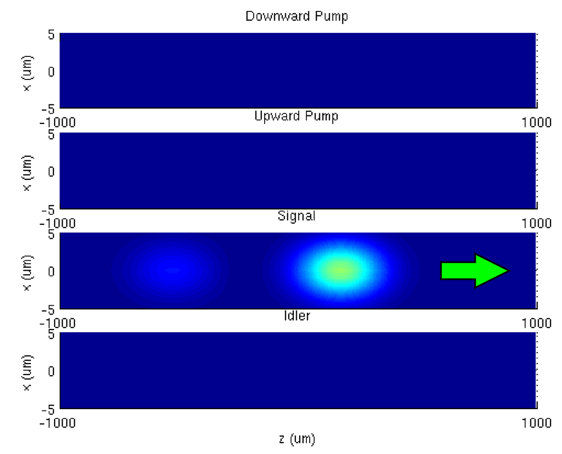
Numerical Analysis of Efficiency



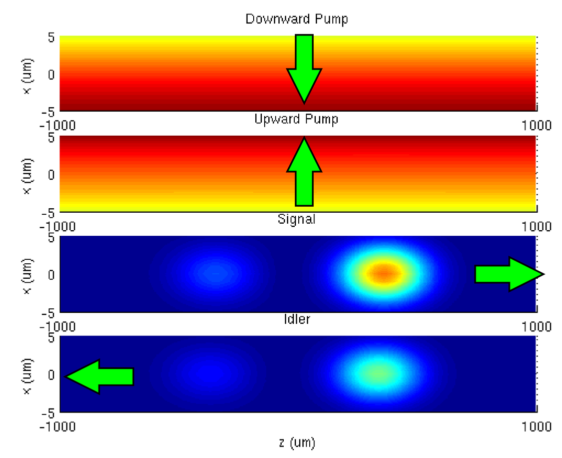
- Numerical results confirm theory
- XPM reduces efficiency
- XPM compensation restores optimum efficiency

Numerical Simulations

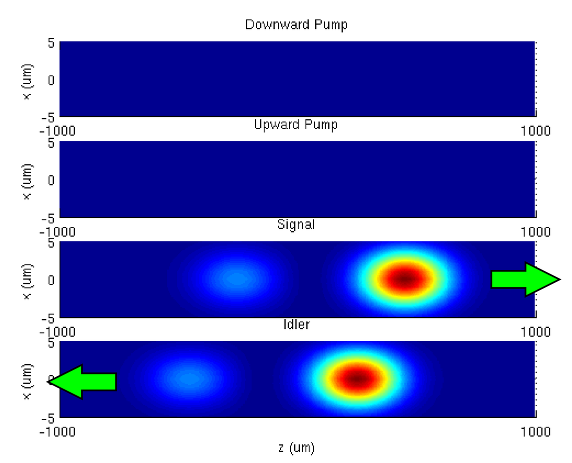
- Signal comes in



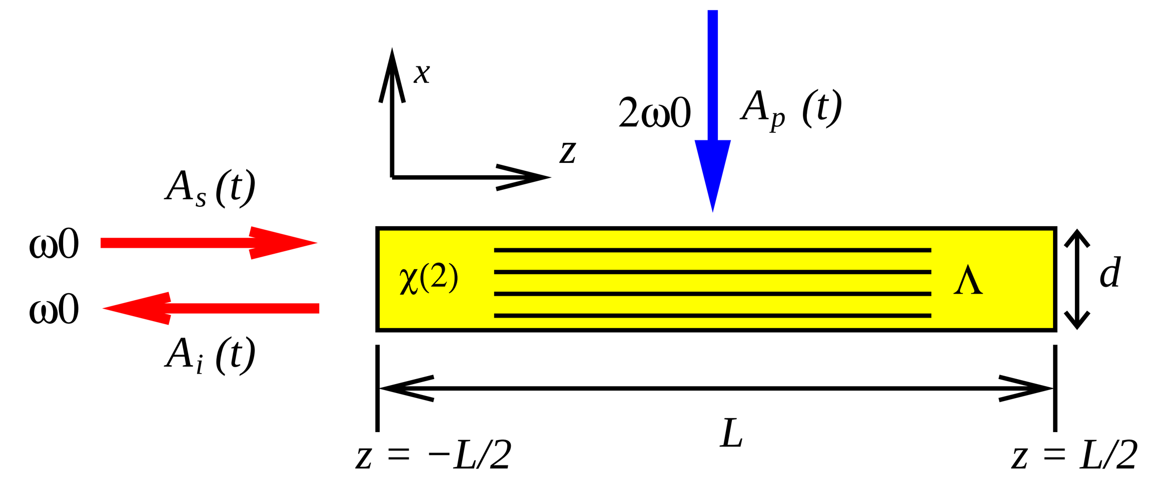
- Pump pulses take **"snapshot"** of signal



- time-reversed and phase-conjugated signal propagates back as idler



Implementation by Quasi-Phase-Matched Three-Wave Mixing



- Quasi-phase matching cancels the carrier pump wave vector
- Same formalism as FWM, parametric amplification and time reversal can be achieved [4]
- Competing third-order nonlinearity can be eliminated using XPM compensation

Quantum Theory of SPC

- Conventional spontaneous parametric down conversion creates frequency anti-correlated photon pairs
- Spontaneous SPC can generate **entanglement with time anti-correlation and frequency correlation** [5]
- FWM in $\chi^{(3)}$ medium or quasi-phase matching in $\chi^{(2)}$ medium provides **improvement in efficiency** over previous proposals

Acknowledgements

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References

[1] D. A. B. Miller, "Time reversal of optical pulses by four-wave mixing," Opt. Lett. **5,** 300 (1980).

[2] M. Tsang, D. Psaltis, "Dispersion and nonlinearity compensation by spectral phase conjugation," Opt. Lett. **28,** 1558 (2003).

[3] M. Tsang, D. Psaltis, "Spectral phase conjugation with cross-phase modulation compensation," Opt. Express **12,** 2207 (2004).

[4] M. Tsang, D. Psaltis, "Spectral phase conjugation by quasi-phase-matched three-wave mixing," Opt. Commun. , in press

[5] M. Tsang, "Quantum theory of spectral phase conjugation," in preparation.