Adiabatic Frequency Conversion

Ady Arie
Dept. of Physical Electronics
Tel-Aviv University
Tel-Aviv, Israel
ady@eng.tau.ac.il

Abstract—Adiabatic frequency conversion is a nonlinear process in which the coupling between the interacting waves changes slowly with respect to the internal system dynamics. It enables efficient (near 100%) scalable broadband frequency conversion using a single adiabatic process, as well as complete frequency conversion through an opaque intermediate level by multiple adiabatic processes.

Keywords—Nonlinear optics, quasi phase matching, adiabatic following, STIRAP.

Adiabatic processes in a dynamical system occur when the system is varied slowly compared to its internal dynamics, allowing it to adapt to the external changes. Under this condition, the system can remain at one of its eigenmodes throughout the entire dynamical evolution. These processes were investigated in many subfields in physics and engineering, such as adiabatic evolution in nuclear magnetic resonance, coherently excited quantum atomic systems, optical switching, waveguide arrays, etc. Recently it was realized that adiabatic dynamical processes can be useful for optical frequency conversion, thereby opening new schemes for efficient optical frequency conversion.

In quadratic nonlinear optical crystals, two optical light waves can be coupled by a third pump wave. The coupling strength relies on the pump intensity and on the phase mismatch between the interacting waves. Quasi phase matching provides a convenient way to control this coupling, by varying the modulation period of the nonlinear coefficient, and thereby determining the phase mismatch of the process. It is therefore possible to adapt in nonlinear optics concepts of adiabatic processes that were previously developed in other physical systems.

Adiabatic frequency conversion opens new possibilities for nonlinear optical interactions. Specifically, by using a crystal whose second order nonlinearity is modulated with a spatial frequency that slowly increases (or decreases) along the interaction region and by using sufficiently strong pump intensity, highly efficient, broadband and robust frequency conversion is possible. This concept was first realized for sum frequency generation (SFG) from the near-IR into the visible. It was verified experimentally that the conversion process is robust – it was insensitive to small changes in parameters of the crystal or pump light. The concept was then applied successfully to the up-conversion and down-conversion of ultrashort pulses, where conversion of Ti:Sapphire oscillator pulses with near-100% efficiency for ultra-broadband spectrum has been obtained, allowing the generation of high-energy, multi-octave-spanning IR pulsed sources.

The concept of adiabatic evolution has been extended beyond this adiabatic following mechanism by adapting adiabatic dynamics schemes of coherently excited multi-level quantum systems in frequency conversion, predicting and demonstrating new and unique phenomena. Two such novel schemes are adiabatic elimination mechanisms and the introduction of a scheme analogous to Stimulated Raman Adiabatic Passage (STIRAP) from three level atomic dynamics, providing complete frequency conversion through a highly absorptive frequency band. In the case of adiabatic elimination, it was shown that in addition to the material dispersion, phase matching also depends on the pump intensities, in analogy to the Stark shift in atomic systems. Another method directly extends the basic approach, facilitating efficient broadband multi-process frequency conversion between very far or near frequencies by using chirp-periodic modulation of the nonlinear coefficient.

Recently, the restriction of the undepleted pump assumption in the analysis was removed, thereby allowing the exploration of adiabatic processes in the fully nonlinear dynamics regime of nonlinear optics, in which all the interacting waves may be depleted or amplified. The analysis is expected to further expand the use of the method to other nonlinear processes such as optical parametric amplification, second harmonic generation and four-wave mixing.