Pulse Propagation Modeling

Definition: working with physical models describing the propagation of ultrashort pulses e.g. in lasers or optical fibers

German: Modellierung der Pulsausbreitung

Categories: methods, physical foundations, light pulses

How to cite the article; suggest additional literature

When propagating in transparent optical media, the properties of ultrashort pulses can undergo complicated changes. Typical physical effects influencing pulses are:

- *Chromatic dispersion* can lead to dispersive pulse broadening, but also to pulse compression, generation of a chirp, etc.
- Various *nonlinearities* can become relevant at high peak powers. For example, the Kerr effect can cause self-phase modulation, and Raman scattering may e.g. induce Raman gain within the pulse spectrum (*Raman self-frequency shift*).
- Optical *gain* and *losses* can modify the pulse energy and the spectral shape.
- The spatial properties can change due to linear effects such as *diffraction* and *waveguiding*, but also due to nonlinear effects such as *self-focusing*. In highly nonlinear interactions, *filamentation* may occur.

Of course, different effects can act simultaneously, and often interact in surprising ways. For example, chromatic dispersion and Kerr nonlinearity can lead to soliton effects.

– Relevance of Pulse Propagation Effects

Pulse propagation effects as mentioned above are relevant in various kinds of situations. Some examples are:

- Details of the propagation of ultrashort pulses in a mode-locked laser determine the steady-state pulse properties such as pulse duration, bandwidth and chirp, or the stability of pulse generation, multiple pulsing, etc.
- The propagation in fibers is relevant e.g. for pulse amplification, pulse compression and supercontinuum generation, and in optical fiber communications.
- Nonlinear frequency conversion of ultrashort pulses can lead to complicated changes of pulse shapes. In addition to the nonlinear interaction, there can be influences from effects such as temporal spatial walk-off and dispersive broadening.

– Techniques for Modeling of Pulse Propagation

Depending on the situation, different kinds of physical modeling techniques are required. Some of the most important ones are shortly described in the following:

- The *Haus Master equation* is an analytical tool mainly for calculating the steady-state pulse properties obtained in mode-locked lasers. It can be seen as a generalization of the *nonlinear Schrödinger equation*.
- *Soliton perturbation theory* describes the propagation of soliton pulses which can be subject to gain or loss, spectral filtering, etc. A number of dynamic equations describe the evolution of the basic parameters of solitons under the influence of various effects. Also, the so-called *continuum* is included, i.e. a temporally broad background radiation with which a soliton can interact. Soliton perturbation theory can be used, e.g., to describe the generation of Kelly sidebands.
- Models based on second-order moments of the complex electric field of a pulse [5] can also greatly reduce the number of dynamic variables. However, they are applicable only as long as the pulse shapes remain relatively simple. A difficulty is that it is not always obvious where the parameter region with a reasonable accuracy ends. The advantage of a significantly faster computation (compared with a full numerical simulation) becomes less important as the power of computers is increasing.
- Numerical techniques are available for simulating pulse propagation in more general cases. A straightforward approach applicable e.g. to mode-locked lasers describes a short pulse with an array of complex amplitudes in the time or frequency domain. Linear effects such as dispersion are easily treated in the frequency domain, whereas nonlinear interactions are often (but not always) more conveniently handled in the time domain. As required, switching between both domains can be done with a fast Fourier transform algorithm (*FFT techniques*).
- A special case is the *symmetrized split-step Fourier method*, used particularly for pulse propagation in fibers [9]. The (weak) dispersive and nonlinear effects corresponding to short fiber pieces are alternately applied. The numerical errors associated with the finite longitudinal step size can be minimized with a special symmetrization technique, which allows for higher accuracies without excessively increased computation times. Automatic step size control can be very important for computational efficiency.
- Still more refined techniques take into account the transverse spatial variation as well. They can be used, e.g., to investigate Kerr lens mode locking or filamentation phenomena.
- For propagation in multimode waveguides, it is often advantageous to describe the optical field as a superposition of propagation modes, which can be coupled e.g. via nonlinearities.

By applying statistical techniques, pulse propagation models can also be used to investigate noise phenomena [7].

– Bibliography

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(Suggest additional literature!)

See also: dispersion, nonlinearities, nonlinear pulse distortion, pulse compression, double pulses, parabolic pulses, supercontinuum generation, Haus Master equation
and other articles in the categories methods, physical foundations, light pulses

A Quiz Question

taken from the **Photonics Quiz**:

The use of quasi-phase matching (QPM) in a nonlinear frequency conversion device

- (a) leads to a reduced effective nonlinear coefficient
- (b) is less practical in cases with high phase mismatch
- (c) can be applied with nearly all nonlinear crystal materials
- (d) allows for an increased phase-matching bandwidth

Get your answer checked