Optical Communication Networks

Prof. Fabio Baronio
e-mail: fabio.baronio@unibs.it

The main goal of my lectures is the investigation of the evolution of optical pulses propagating in an optical fiber.

I will consider the propagation of pulses from i) a theoretical point of view, and ii) i will confirm the theoretical results exploiting numerical simulations.

Thus,

- × Theoretical investigation
- × Numerical investigation

P.S. As to numerics i will use MaTlab, but you can use different tools C, C++, etc.

I will show to you different optical effects / regimes :

- Group Velocity Dispersion (linear effect)
- Self-Phase Modulation (nonlinear effect)

- Optical self-Trapped waves, Solitons
- Abnormal, Extreme Waves
- Optical shocks

As to the final exam: you will do a homework on the numerical dynamics of pulses propagating under different linear and nonlinear effects.

I will personally discuss the work with each of you at the end.

You will have different jobs, but I invite you to collaborate. An attempt, groups of 2-3 persons.

One suggested book: Nonlinear Fiber Optics, G.P. Agrawal (however, as to me, the lectures will be enough).

At first i recall the scenario of the optical investigation, that is the propagation of optical pulses in a fiber, thus a nonlinear dispersive medium.

I recall the fundamental and universal model of optical wave dynamics: the nonlinear Schrödinger equation (NLSE)

The NLSE can be studied analytically (Prof. Costantino De Angelis has shown to you the properties...). I will show to you, during the lectures different regimes, from a theoretical point of view.

Moreover, a numerical investigation of the NLSE model can be of help for understanding of the nonlinear and linear effects of the pulses.

Thus, i will show to you a method, a numerical method that has been used extensively to solve the pulse propagation problem, i.e. the NLSE.

• NONLINEAR SCHRÖDINGER EQUATION (NLSE)

$$j\frac{\partial A(r,t)}{\partial z} + \frac{1}{2\beta}\frac{\partial^2 A(r,t)}{\partial x^2} + \frac{1}{2\beta}\frac{\partial^2 A(r,t)}{\partial y^2} - \frac{\beta''}{2}\frac{\partial^2 A(r,t)}{\partial t^2} + \chi^{(3)}\left|A(r,t)\right|^2 A(r,t) = 0$$

NLSE (3+1) D

where

$r = (x,y,z)$ spatial coordinates

t temporal coordinate

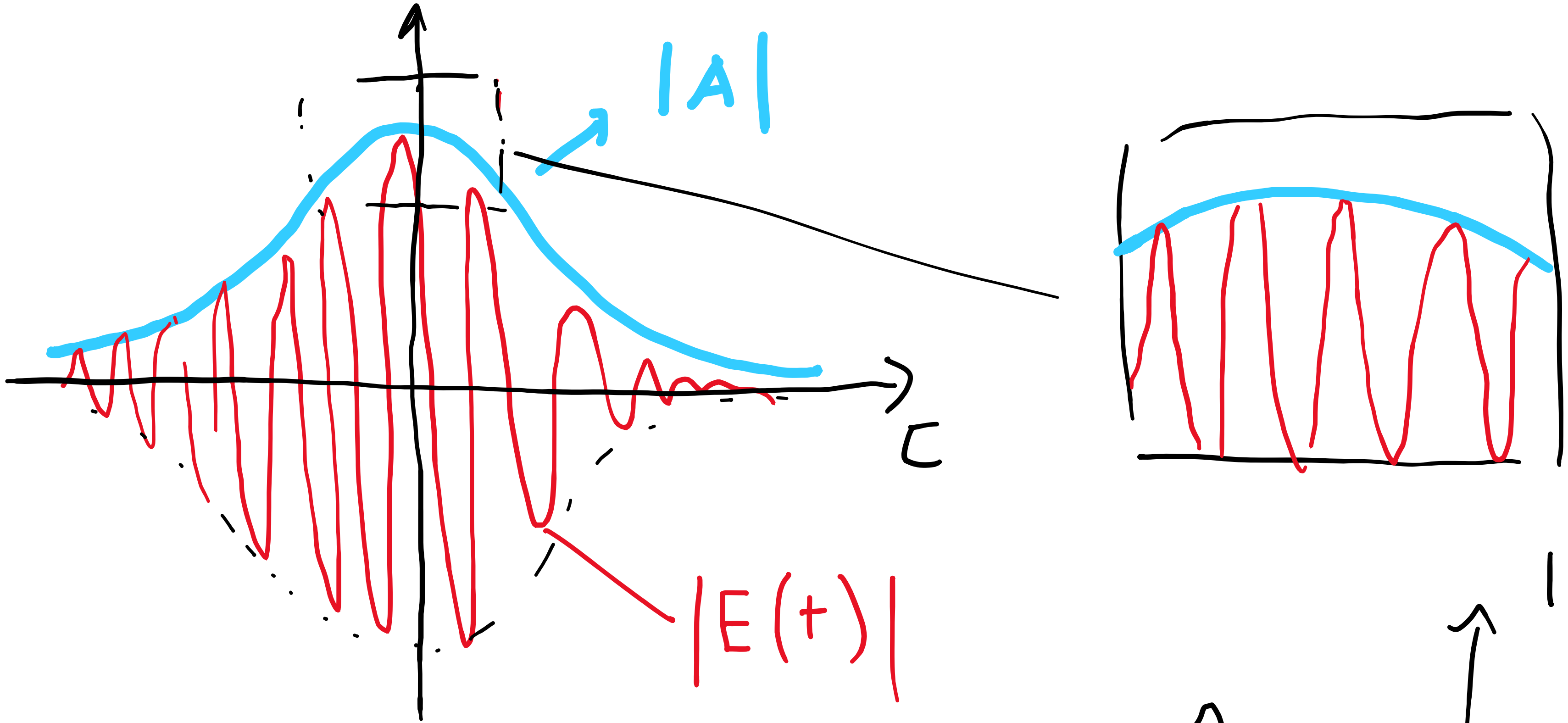
$$E(r,t) = \mathrm{Re}\left[A(r,t)\, e^{i(\omega_0 t + \beta_0 z)}\right]$$

$E(r,t)$ is the electrical field of pulses

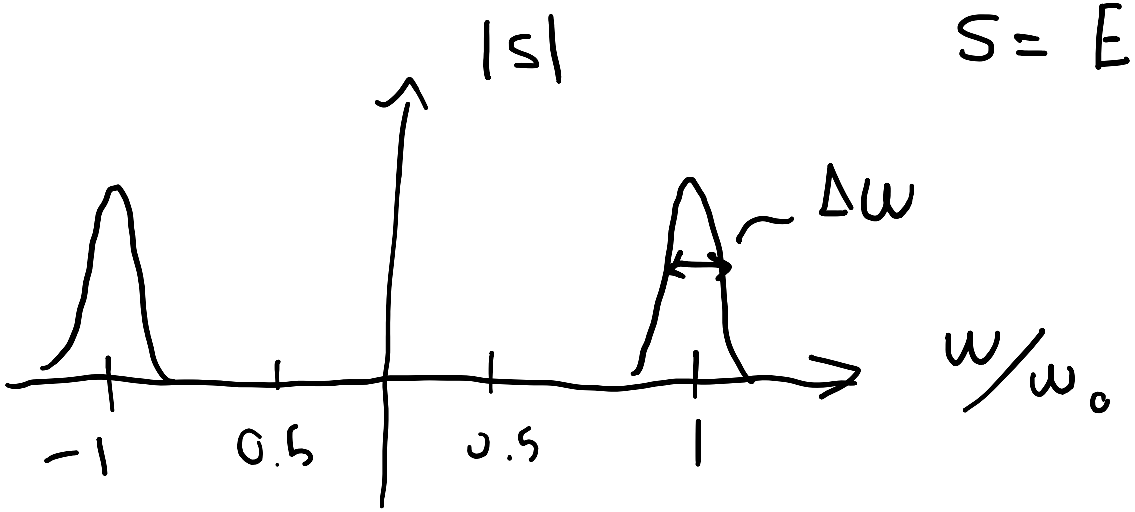
$A(r,t)$ is the slowly varying envelope

$e^{i(\omega_c t + \beta_c z)}$ stands for the optical carrier at the frequency ω_c and wavenumber β_c

$z=0$, $x=0$, $y=0$; $E(z=0,t) = E(t)$; $A(0,t) = A(t)$



$S = \hat{E}$



$\Delta\omega \ll \omega_0$

$j \dfrac{\partial A(r,t)}{\partial z}$ takes into account the propagation along the coordinate z

$\dfrac{1}{2\beta} \dfrac{\partial^2 A(r,t)}{\partial x^2}$ The diffraction term, along the coordinate x

$\dfrac{1}{2\beta} \dfrac{\partial^2 A(r,t)}{\partial y^2}$ The diffraction term, along the coordinate y

$-\dfrac{\beta''}{2} \dfrac{\partial^2 A(r,t)}{\partial t^2}$ The dispersion term, along the coordinate t

$\chi^{(2)} |A(r,t)|^2 A(r,t)$ is the nonlinear term

β is the propagation constant

β'' is the group velocity dispersion

$\chi^{(3)}$ accounts for nonlinear cubic response of the medium

In general the NLSE is a $(3+1)$ D model

(x, y, z, t)

which describes the evolution of an optical light bullet in space and time

In optical fibers, the envelope $A(r,t)$ can be expressed, exploiting the separation of variables, as:

$$A(r,t) = A(x,y,z,t) = F(z,t) \cdot M(x,y)\, e^{i\partial\beta z}$$

where $M(x,y)$ defines the mode profiles, and $\partial\beta$ is the correction of the propagation constant (thus $\beta = \beta_0 + \delta\beta$). $M(x,y)\, e^{i\partial\beta z}$ describes the modal distribution in the plane (x,y).

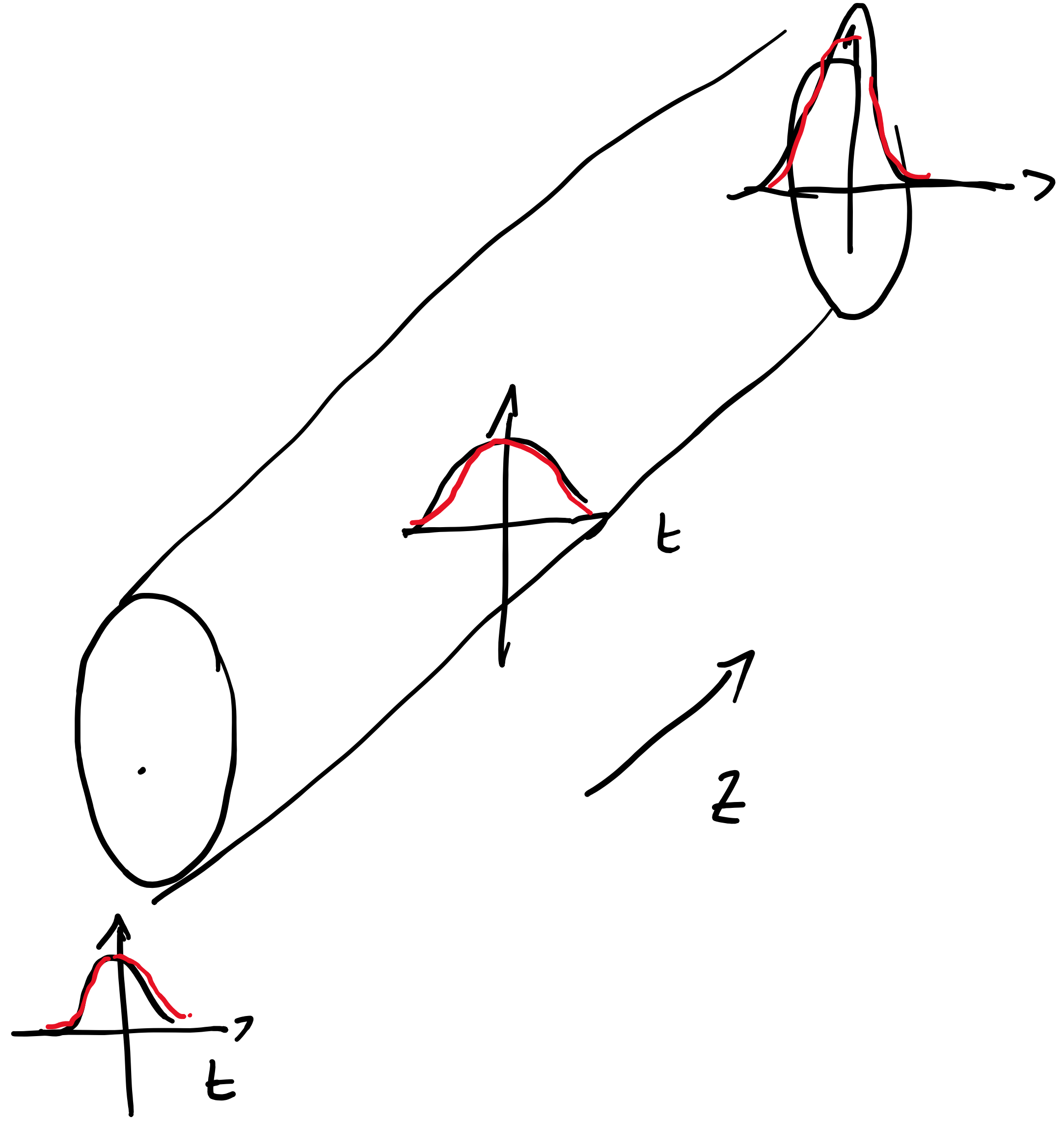
$F(z,t)$ describes the slowly varying pulse envelope in the plane (z,t).

The focus, my focus, is on the spatio-temporal evolution of $F(z,t)$.

From the NLSE (3+1)D one can derive the model for $F(z,t)$, and obtain the NLSE (1+1)D:

$$\boxed{j\frac{\partial F(z,t)}{\partial z} - \frac{\beta''}{2}\frac{\partial^2 F(z,t)}{\partial t^2} + \gamma |F(z,t)|^2 F(z,t) = 0}$$

z is the propagation / evolution coordinate
t is the temporal coordinate
β'' is the group velocity dispersion inside the fiber
γ is the effective nonlinear term (related to $\chi^{(3)}$)


t
t
z

I want To observe That The NLSE (3+1) D, and also The NLSE (1+1) D, is a nonlinear partial differential equation That does not generally lend itself To analytic solutions, except For some specific cases.

On one hand, it's interesting and useful The study, The analytical study of the NLSE (1+1) D. The study of The NLSE (3+1) D is very difficult.

On the other hand, a numerical approach can be of helf for an understanding of the nonlinear - linear effects in optical fibers.

A large number of numerical methods can be used for this purpose. These can be classified in two broad categories known as:

- o) The finete - difference methods
- oo) the pseudospectral methods

Generally speaking, pseudospectral methods are faster by up to an order of magnitude to achieve the same accuracy.

The one method that has been used extensively to solve the pulse propagation problem in nonlinear dispersive media is the split-step Fourier method.

N.B. The relative speed of this method compared with finite difference schemes can be attributed in part to the use of the Finite Fourier Transform FFT algorithm.

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