Solitons in optical fibers

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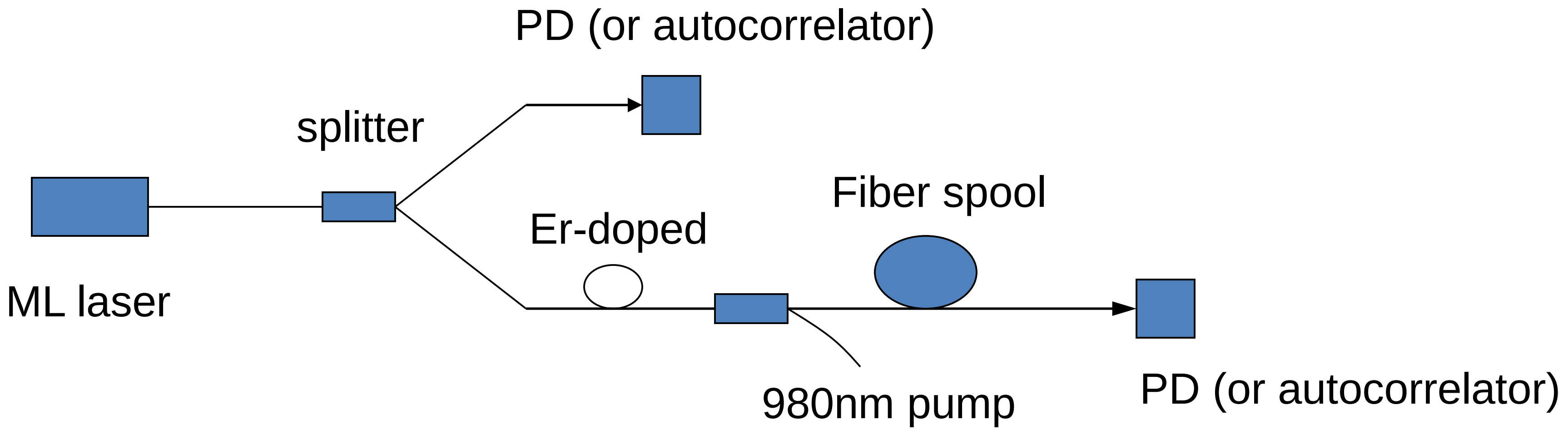
Project 9: Observation of soliton



$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

P_0 is the free parameter

What is a soliton?

The word *soliton* refers to special kinds of wave packets that can propagate undistorted over long distances

John Scott Russell 1834:

I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped—not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it behind, rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon which I have called the Wave of Translation.

What is a soliton?

Recreation of the soliton water wave

What is a optical soliton?

The discovery of Optical Solitons dates back to 1971 when Zhakarov and Sabat solved in 1971 the nonlinear Schrodinger (NLS) equation with the inverse scattering method.

Hasegawa and Tappert realized in 1973 that the same NLS equation governs pulse propagation inside optical fibers. They predicted the formation of both bright and dark solitons.

Bright solitons were first observed in 1980 by Mollenauer et al.

Nonlinear Schrodinger equation (NLS)

From the Maxwell's equations it can be shown that an optical field propagating inside an optical fiber is governed by following equation:

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0$$

Nonlinear Schrodinger equation

β_2 is the GVD of the optical fiber
γ is the nonlinear coefficient of the fiber, $\gamma = \dfrac{n_2\omega_0}{cA_{\text{eff}}}$

G. P. Agrawal, *Nonlinear Fiber Optics,* (Academic Press, 2007)

Influence of dispersion

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0$$ (no nonlinear term)

$$\tau_{out} = \tau_{in} (1 + (\beta_2 . L/\tau^2)^2)^{1/2}$$ (assuming Gaussian pulse shape)

$$\tau_{out} = \tau_{in} (1 + (L/L_D)^2)^{1/2}$$ Where, $L_D = \tau^2 / |\beta_2|$, is the dispersion length

Influence of nonlinearity

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0$$

(no dispersion term)

→ $A(L, t) = A(0, t).\exp(i\varphi_{NL})$; where, $\varphi_{NL} = \gamma . L . |A(0, t)|^2$

Maximum nonlinear phase shift: $\varphi_{max} = \gamma P_0 L = L/L_{NL}$

Nonlinear length: $L_{NL} = (\gamma P_0)^{-1}$

Self-phase modulation (SPM)

For an ultrashort pulse with a Gaussian shape and constant phase, the intensity at time *t* is given by *I*(*t*):

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau^2}\right)$$

Optical Kerr effect:

$$n(I) = n_0 + n_2 \cdot I$$

This variation in refractive index produces a shift in the instantaneous phase of the pulse:

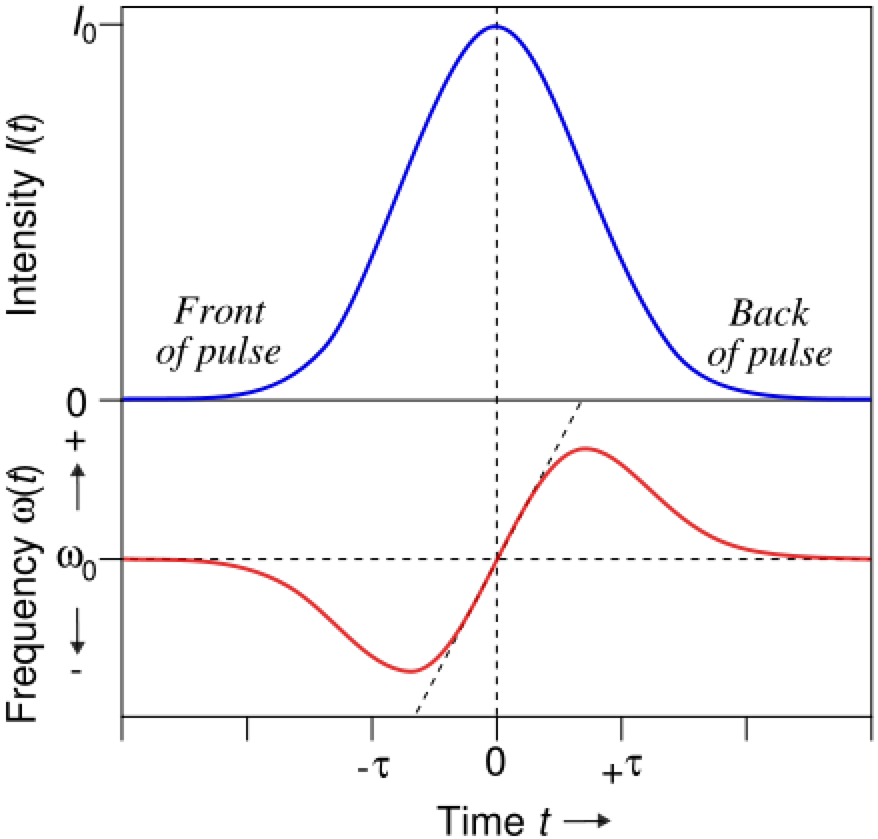
$$\phi(t) = \omega_0 t - kx = \omega_0 t - \frac{2\pi}{\lambda_0} \cdot n(I)L$$

The phase shift results in a frequency shift of the pulse. The instantaneous frequency ω(*t*) is given by:

$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 - \frac{2\pi L}{\lambda_0}\frac{dn(I)}{dt},$$

$$\omega(t) = \omega_0 + \frac{4\pi L n_2 I_0}{\lambda_0 \tau^2} \cdot t \cdot \exp\left(\frac{-t^2}{\tau^2}\right).$$

Self-phase modulation (SPM)



Soliton propagation

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0$$

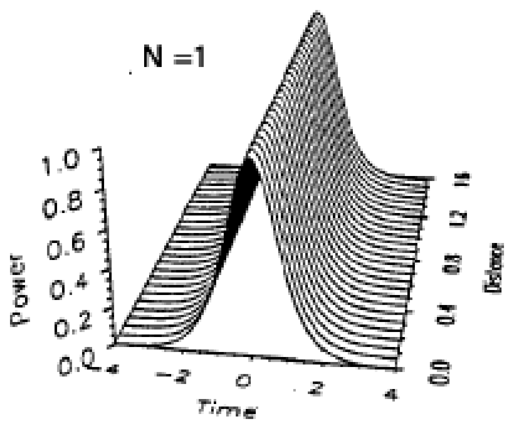
Solution depends on a single parameter:

$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

N is the soliton number

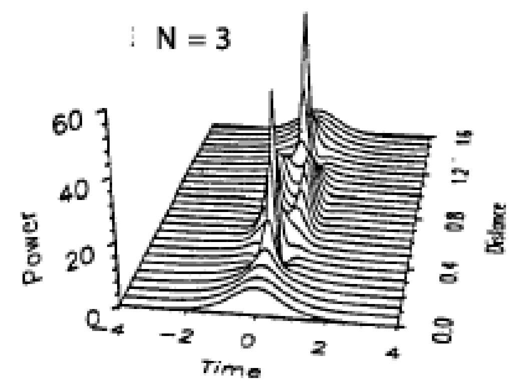
Since n_2 is positive need β_2 to be negative

Fundamental soliton



(a)

Third order soliton

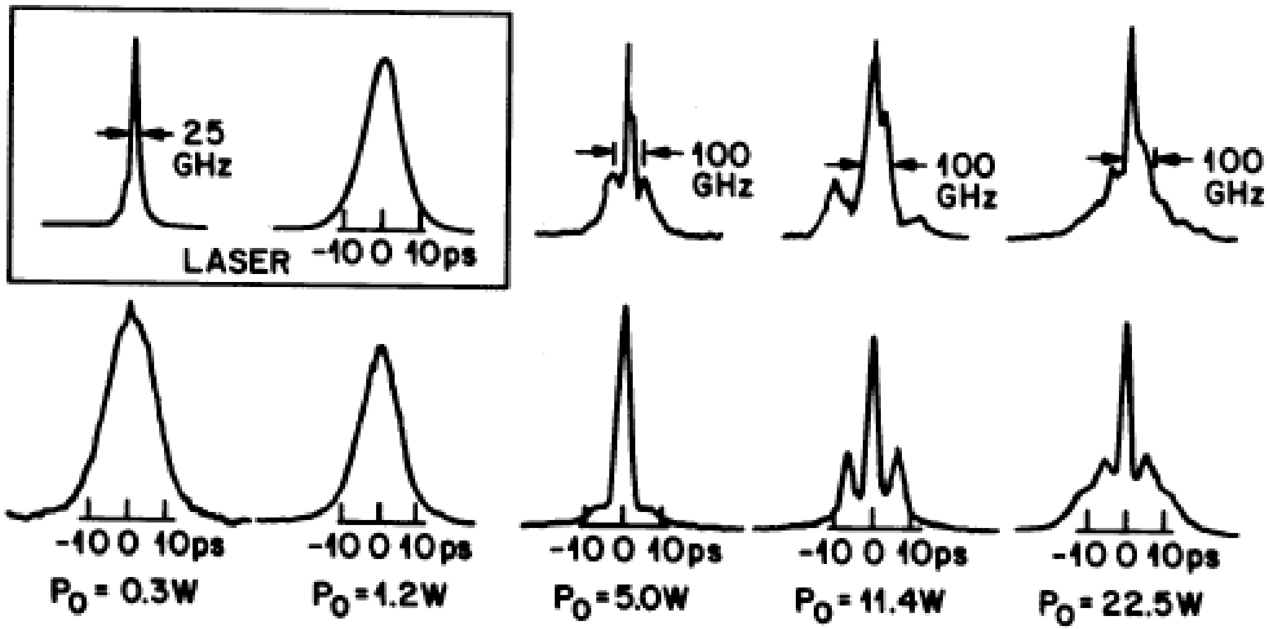


(b)

$$L_{NL} = (\gamma P_0)^{-1} = L_D = T_0^2/|\beta_2|$$

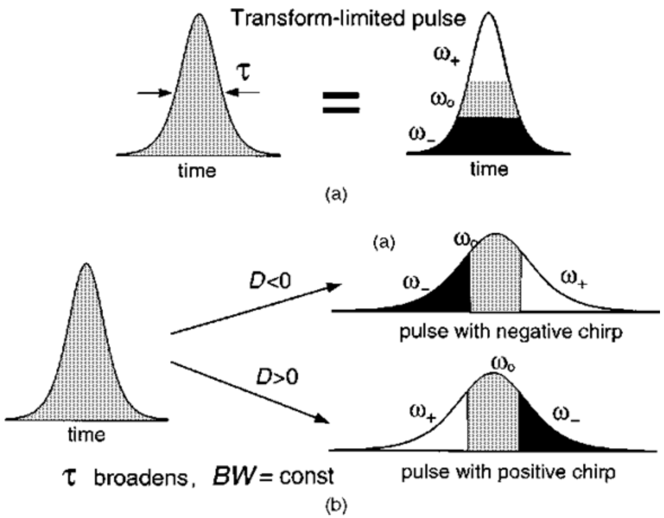
G. P. Agrawal, *Nonlinear Fiber Optics,* (Academic Press, 2007)

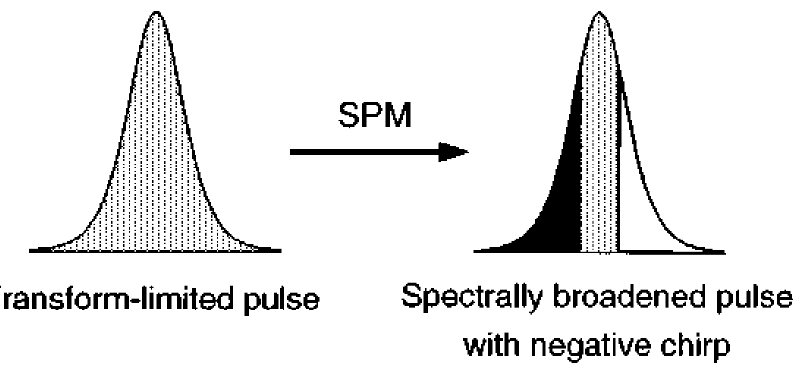
First experimental observation

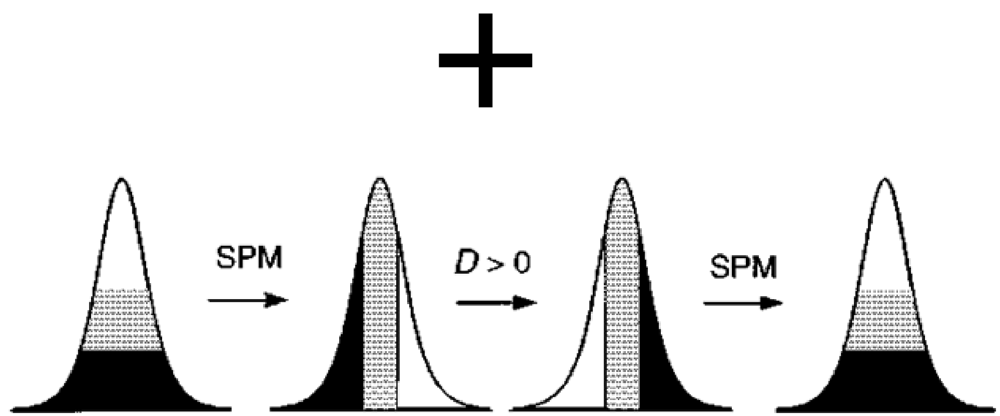


L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, *Phys. Rev. Lett.* **45**, 1095 (1980)

Explain soliton







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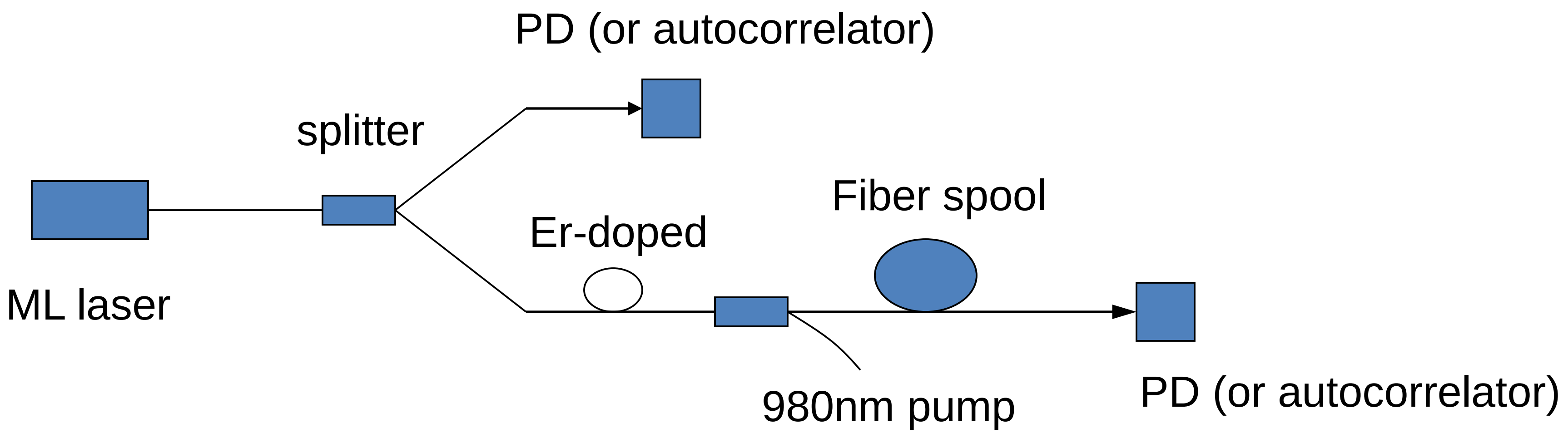

$$N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

P_0 is the free parameter

Other types of solitons

Dark soliton

Higher order solitons

Dispersion managed soliton

Spatial soliton

Spatiotemporal soliton: light “bullet”

Applications of solitons

Telecommunication

Pulse compression

ML laser design

Interesting scientifically

What’s else?

Books to read

G. Agrawal: Nonlinear fiber optics

A. Hasegawa: Solitons in fibers

J. Taylor: Optical solitons: Theory and experiment

Questions for thoughts

Why soliton transmission is still not widely used today?

What are the main challenges?

Why does nature tend to modify/distort wave packets?