Optical solitons

Module PS407: Quantum Electronics
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1. Introduction

The nineties have seen the birth of a new era, with a major development of Internet, fax, and phone: the information highway’s era. Nowadays, more and more data travel each day with emergence of dataphyles applications such as numeric videos or pictures. This, associated with a globalization of exchanges, requires the actual network to be extended and to increase its debit: which was successfully done until now. However the systems seems to haven reached its physical and technological limits. From few years, a (maybe the) solution would be a new kind of optical pulses, called solitons. Indeed, using basically the same network, it has been demonstrated that solitons can carry more information to further distance. Knowing that these pulses travel in the actual fibers, but in all optical transmission’s system, a financial interest and a real confidentiality of communications make this technology attractive.

Nevertheless, this discovery being so young (end of the twentieth century) it’s not superfluous to remind the different steps, which bring it to the optical fibers, and to explain the physical properties of such a different pulse. Then, after a brief explanation on the limits of the actual communication link, we’ll describe an all-optical technique, trying to discuss the advantages provided.
2. from the soliton’s discovery to its optical development.

2.1. Historical review

Scott Russell observed the first soliton on the Edinburgh-Glasgow canal in 1834. He observed a wave, which guided through the canal seemed to travel as he could see without loosing its shape. “He jumped on a horse, the story goes, and followed the wave for miles along the canal” (cf. [1]).

Re-creation of John Scott Russell’s soliton

It was only, about one century later, in 1964 that the first mathematical solution of a soliton wave was found from the KdV equation by Zabusky and Kruskal. And in 1973 Hasegawa and Tappert solved the non-linear Shrödinger (NLS) equation and introduced the term and theory of optical soliton. But only seven years after, Mollenauer succeeded the first experiment of soliton propagation in optical fibers, this being due to the unexistence of adapted fibers (low loss) at the time. Try now to understand this principle.

2.2. Optical fiber and its non-linearity.

It is important to understand that an optical soliton cannot be propagated anywhere except in mater like optical fibers which possess two main properties such as:
- the group velocity dispersion (GVD)
- the Kerr effect
What is the GVD? A little bit of physics:

\[ V_g = \frac{d\omega}{dk} \]

\[ \frac{1}{V_g} = \frac{dk}{d\omega} = \frac{d}{d\omega} \left( \frac{n\omega}{c} \right) = \frac{n}{c} + \frac{\omega}{c} \frac{dn}{d\omega} = \frac{1}{c} \left( n + \omega \frac{dn}{d\omega} \right) \]

\[ \frac{dn}{d\omega} = \frac{dn}{d\lambda} \frac{d\lambda}{d\omega} = -\frac{\lambda}{\omega} \frac{dn}{d\lambda} \]  
(Because \( k = \frac{2\pi}{\lambda} = \frac{n\omega}{c} \Rightarrow \lambda = 2c\pi/n\omega \))

\[ \frac{1}{V_g} = \frac{1}{c} \left( n - \lambda \frac{dn}{d\lambda} \right) \Rightarrow \frac{1}{V_g} = \frac{N_\lambda}{c} \]  
Where \( N_\lambda = n - \lambda \frac{dn}{d\lambda} \) = group index

\[ t_\lambda = \frac{L}{V_g(\lambda)} t_{\lambda + d\lambda} = \frac{LN(\lambda)}{c} \]

So \( \frac{dt}{d\lambda} = \frac{L}{c} \frac{dN}{d\lambda} \)  

\[ D_\lambda = \frac{1}{L} \frac{dt}{d\lambda} = \text{Chromatic scattering} \]

This formula is not very clear. So let see what happens with classical pulse knowing that optical fiber, actually used, has a positive chromatic scattering because \( \lambda_{\text{use}} = 1.55 \mu\text{m} \).

\( D_\lambda \geq 0 \Rightarrow \frac{dt}{d\lambda} \geq 0 \) thus for \( d\lambda \geq 0 \) (\( \lambda_{\text{red}} \geq \lambda_{\text{blue}} \)) we have \( dt \geq 0 \Rightarrow t_{\text{red}} \geq t_{\text{blue}} \)

The pulse broadens because they are composed of a spread of wavelength that all travel at different speeds. This effect is called dispersion. The shorter (blue) wavelength of the pulse travel faster than the longer (red) wavelength.

![A trivial example of the broadening effect](image)

But it is different with soliton. They experience the effect of GVD; their width of only few picoseconds associated with their high peak power induces a non-linear (Kerr) effect.

What is exactly the Kerr effect?
It is a physical property that means that the refractive index of the medium depends on the square of light’s amplitude.
Which gives us \( n = n_0 + n_2 |E|^2 \)

2.3 NLS equation.

These two properties give us the non-linear Schrödinger equation:

\[
i \frac{\partial q}{\partial z} + \frac{1}{2} \frac{\partial^2 q}{\partial t^2} + |q|^2 q = 0
\]

Where \( q \) is the complex amplitude of the pulse, \( z \) represents the distance along the direction of propagation, \( t \) the time.

The second term is originated from the GVD and the third is due to the Kerr effect.

Hasegawa in 1973 was the first to show that a pulse of light in a fiber suit exactly to the NLS, to solve this equation and to introduced the optical soliton as solution (cf. [2]).

We will not describe the way to solve the NLS equation, based on the inverse scattering method. (cf. [3])

The soliton comes from the exact cancellation between the GVD and the non-linear effect. As a result, a soliton can travel without spreading its shape, through a fiber over thousands kilometers.

3. Comparison between actual transmission system and soliton transmission.

3.1 Limits of actual system.

First, whatever is the bits’ format to send, it is important to precise that different wavelengths (colors) travel at the same time in the same fiber (with approximately the same speed), the multiplexing, more or less dense (DWDM), is made to send more data at the same time.

Actually most of transmission use NRZ and RZ method (cf. [4] and [5]).

Both NRZ and RZ system are limited by the spreading of their shape, which requires a large pulses separation and fiber spans of limited length. This also imply to use electronic components at the end of each span (to combat the deformation of the bits), to receive the signal, to analyze it, then to rebuild it and to send it in the new span.
But nowadays, recent applications use more data such as videoconference, Internet etc…which imply an increasing request in higher rate system and what are the physical solutions?

First of all, a physical approach is to increase the frequency (data rate) in a channel. For that we send pulses with less separation between them. A problem occurs: the broadening which gets worse as data rate increase (GVD).

Secondly, another way should be to increase the multiplexing in one band (add new colors). If we move away from 1550 nm, we are in the area where the losses of the fiber are more important so we have to add more power at the injection, and problems of NLS appear.

Finally, a conceivable solution should be to add another band (L band at longer wavelength) to increase the data rate, but a new problem occurs: the Raman effect which should distort the actual C band transmission (the L band pump the energy of the C band).

As a conclusion of actual system, to go from 2.5 Gbit/s to 10 (or even to 40 Gbit/s we need more sensitive receivers and spans less long. But it is too expensive!
3.2. The soliton solution.

The soliton transmission system is a RZ transmission and the time of the pulse is in order to picosecond. This kind of transmission is characterized by two main advantages. First there is a slow rate of change of the pulse, so there is no need of transmitters and receivers but only optical amplifiers. Thus the cost of the installation is less expensive than a classical communication link (cf. [6]). Moreover, the fact that there is not use of electronic components eliminates the problem relative to different kind of encoding between countries.

Secondly, we know that soliton travel in non-linear medium, this is important too because it allows higher power to be injected into the fiber.

These two advantages induce in 8 dB of extra power margin (5 dB due to better signal over noise and 3 dB from higher power injection). Thus, the span can be longer and we can broaden the width of multiplexing (to move away from 1550 nm, in area where the losses of the fiber are a little bit more important).

3.3. The soliton transmission system.

With the first experiments, researchers conclude that solitons were suitable at higher bit rate only on submarine links but not for DWDM system (dense wavelength division multiplexing) on terrestrial link because of four-wave mixing (FWM). The FWM results from interaction between different wavelength (multiplexing). That interaction generates additional optical carriers and is proportional to the spacing of the channel in DWDM system.

To combat the FWM, we need a high dispersion when to avoid pulse broadening, a low average dispersion is required (cf. [7]). Technically we will have to use spans with more of 20 ps/nm.km of dispersion but with a total average of a few ps/nm/Km.

A usual assembly looks like that:

- Classical fiber: 17 ps/km.nm
- DSM: -100 ps/km.nm
- Amplifier span: EDFA
- 100 km x 17 km
- 50-60 times

Recently, Mollenauer (in May 2000) succeeded to transmit soliton at a rate of 270 Gbit/s along 9000 km staying in the error free domain (less than 1 error for $10^9$ bits). (cf. [8]) For that, he has used DSM (Dispersion Shift Management) fibers, filter sliding system, a channel spacing of 75 GHz and 27 channels (range from 1542.5 nm to 1558.1 nm). The amplification was realized with erbium doped fibers and Raman gain control system. Despite the fact that the optical amplification is still a problem, this test is a great success for solitons that have really broken the rules of the actual other techniques’ limits.
Furthermore, Mollenauer soon expects to send information at 1 THz with the same range but only 0.4 nm spacing, underlying that last experiment was only limited by technical problems.

4. Conclusion.

First of all, a limitation in the developments of all optical transmission system with soliton is the difficulties met to realize average dispersion sufficiently low over all the range of multiplexing. And to use an equal optical amplification with either EDFA (erbium doped fiber) or Raman amplification for all this range.

On the one hand it is because of the youth of this technology and on the other hand due to the problem of choice between different amplification that it is still in labs except for some tries (Germany, France, Spain…). Only one or two questions have to be solved, like the problem of jitters between pulses, but new answers are found every day and we should soon see the first industrial applications.

Now researchers are already working on performs the soliton transmission with a new kind of soliton: dark soliton, which should be a new step in optical fibers, travelling in a band of communication actually unused.
REFERENCES


