Module 5 : Pulse propagation through third order nonlinear optical medium

Lecture 38 : Long distance soliton transmission system

Objectives

This lecture will outline

- A long distance soliton transmission system.
- Limitations of soliton systems and remedial solutions.

Long distance soliton transmission system

Desirable attributes of a communication system are

1. Large data bit rates
2. Low transmission losses
3. Easy scalability

Since transmission bandwidth or the data bit rate of a communication system is proportional to the carrier wave frequency, light waves being the highest frequency waves are therefore, the best suited candidates as information carrier. Further, the availability of low loss fibers, fiber amplifiers and high speed optical modulators has made the optical communication a reality.

Long distance communication systems like submerged trans-Atlantic communication link require that the integrity definition of the data bits or optical pulses is maintained. However, pulse broadening by group velocity dispersion effect in optical fibers will spoil this definition. This can be managed by using repeater stations at regular periods to recover the data bits and retransmit these. Too frequent use of repeater stations add to the complexity and cost of the system. We have seen in lecture #37 that optical nonlinearity can be exploited to compensate the broadening effects of the group velocity dispersion and generate soliton pulses in optical fibers which maintain their shape with propagation. The long distance soliton communication can, therefore, have great prospects. Nakazawa et-al of NTT(Japan) demonstrated 10Gbits soliton transmission over 1 million kilometer in a land mark paper[1]. Many refinements have been reported since then. The obvious wave length choice for soliton system is 1500nm fiber window as it offers lowest 1.55μm and –ve GVD.

For a typical fiber having $A_{eff} = 50\,\mu m^2$ operating $\lambda_0 = 1500\,nm$ the soliton power, energy and period are given by(see lecture#37).

$$
\begin{aligned}
&P = \frac{1.34D}{(\Delta t)^2} W; E = \frac{1.53D}{(\Delta t)} pJ \text{ and } Z_0 = \frac{0.42(\Delta t)^2}{D} Km \\
&\Delta t - FWHW \text{ in } ps \\
&D - ps/nm/Km \\
&\text{taking } D = 1 ps/nm/km \text{ gives} \\
&P = \frac{1.34D}{(\Delta t)^2} W; E = \frac{1.53}{(\Delta t)} pJ \text{ and } Z_0 = 0.42(\Delta t)^2 Km
\end{aligned}
\tag{38.1}
$$

To achieve high bandwidths, soliton pulse duration should be small. However, it can be seen from equation 38.1 that smaller duration soliton requires large peak powers and energy. The choice of input pulse width then will depend upon the semiconductor laser source. As an example let us consider the duration of soliton pulses $\Delta t = 25ps$

$\Rightarrow P = 2.1mW$ Achievable using semiconductor laser sources

$\Rightarrow Z_0 = 263km$ need amplification for $Z_0 > A_{eff}$

To avoid soliton- soliton interaction of adjacent pulse (e.g. 11000 type pattern) separation between solitons should be several times the soliton width(say times) i.e.

$$5 \times \Delta t = 125\,ps$$

$$data\ \ BW = \frac{1}{125\,ps} = 8GHz$$

There are several factors that affect the performance of the long distance soliton system. In the following we address some of these limitations and remedies to overcome these.

Limitations of soliton systems:

1. **Fiber Loss:**
   Recall from lecture #37 that power requirement of the fundamental soliton of given pulse width is

$$P_1 = \frac{0.776\,\lambda^3\,D\,A_{eff}}{\pi^2\,C\,n_2\,\tau^2} \qquad (38.2)$$

If fiber loss is small over soliton period, Z_0, then pulse will adiabatically adjust its width to conform to power requirement for $N = 1$ Soliton. However, this limits the communication distance. To overcome this limitation, one can use the distributed Raman gain amplification
described in lecture #33.
Taking fiber loss to be 0.2dB/km, 3 dB loss will result after propagation distance L=15 km. Also when input power drops by a factor of 2, the soliton will become a normal dispersive pulse i.e. non-soliton propagation. Hence for long distance it is necessary to amplify the signal periodically. Recall from lecture #37

- Solitons arise as a balance of the phase shifts arising from nonlinearity & dispersion.
- The balance occurs for $Z_0 > L$.

By making length of fiber amplifier $L_a < Z_0$ so that the phase change in each amplifier segment is small, average dispersion can be cancelled by the average nonlinear phase shift. Hence Soliton System can even be realized with lumped amplification which can be easily realized using Erbium doped fiber amplifiers arranged periodically in a chain.

The significance of Er doped fiber amplifier is that

- It can provide amplification for signal in the low loss region of 1520-1580 nm range.
- Pump power are modest ~tens of mw.
- Pumping possible with 1480 nm In Ga As/ in gap MQW Lasers.
- Gain of up to 25dB.

The gain factor of the amplifier has to be such that the gain $g = e^{\alpha z_a}$ exactly compensates the loss.

For a fiber having loss of $0.2\ {}^{dB}\!/_{km} \;\Rightarrow\; \alpha = 0.046\ {}^{}\!/_{km}$

Let

$$z_a = 0.1 \times Z_0 = 0.1 \times 263km$$

$$= 25\,km$$

$$\Rightarrow g = 3.16$$

To compensate for the loss we need to launch power greater than necessary for exciting $N = 1$ soliton.
Thus to have “average $N = 1$” soliton it can be shown that we require

$$N=\left[\frac{\ln g}{1-\frac{1}{g}}\right]^{1/2} \tag{38.3}$$

$$\Rightarrow N=1.3$$

For the example of 25ps fundamental soliton $(N=1)$ in a lossless system, one requires

$$P_1=2.1\,mW$$

Therefore power required for $N=1.3$ soliton is

$$P_N=N^2P_1=(1.3)^2\times 2.1\,mW=3.55\,mW$$

Hence in Average Soliton Model the launched Soliton is $N=1.3$ but it shows dynamics of pure "$N=1$". Dynamics of the signal in a lumped amplifier chain is shown in figure 38.1

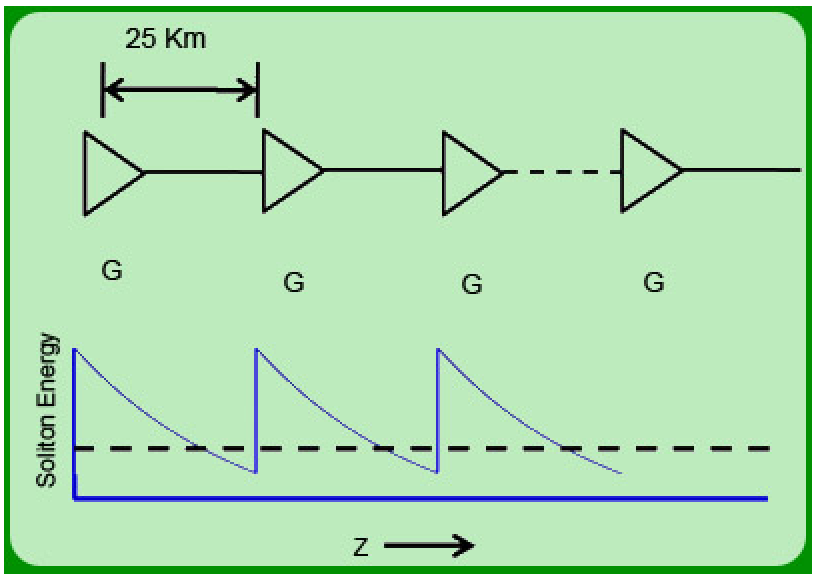

Figure 38.1

2. **Amplifier induced pulse jitter:**
   A penalty of having amplification in any system is that amplification invariably introduces Noise. Fiber Amplifier output is accompanied by Amplified Spontaneous Emission(ASE).

   ASE results in random frequency shift after each amplifier and this frequency "Jitter" is translated into timing jitter via dispersion --"Gordon-Haus" Effect. This happens because the stable soliton wants to keep its shape and reacts on perturbation with frequency shift via GVD, the group velocity change statistically and due to statistically shifted times of arrival, a timing jitter occurs. The perturbing Gordon-Haus effect can be reduced considerably by adopting the following measures

   - Use narrow-band frequency-guiding filters periodically distributed along the transmission line. Key is that the filters are opaque to noise but transparent to solitons.
   - Use post- transmission dispersion compensation. This can reduce jitter up to a factor of 2.
3. **Soliton- Soliton Interactions**

   Maximum data rate is determined by how close two adjacent pulse/bits can be packed. To determine how close two solitons can propagate without interacting one needs to solve nonlinear Schrödinger equation numerically with initial condition

$$u(z=0,t)=\operatorname{sech}(t-\Delta)+\operatorname{sech}(t+\Delta)e^{i\theta}$$

where Δ is their initial separation and θ is their relative phase.

Note that $\Delta=0$ gives $N=2$ bound soliton while $\Delta=\infty$ will correspond to two independent single solitons. Evolution of two co propagating solitons with $\Delta=3.5$ is shown in figure 38.2. It can be seen that these collapse and separate with an oscillation period $z_0 e^{\Delta}$.

This process is referred as "Breather Soliton".

If the relative phase "θ" between adjacent solitons is such that $\theta \neq 0$ then they experience repulsive force.

Propagation over Length $L_c=\frac{\pi}{2}e^{\Delta}$ results in collapse of two in-phase soliton and distance Δ apart at input. By choosing the soliton travel length $L_T < L_C$ soliton collapse can be avoided.

In practice soliton separation has to be 5-10 X soliton width.

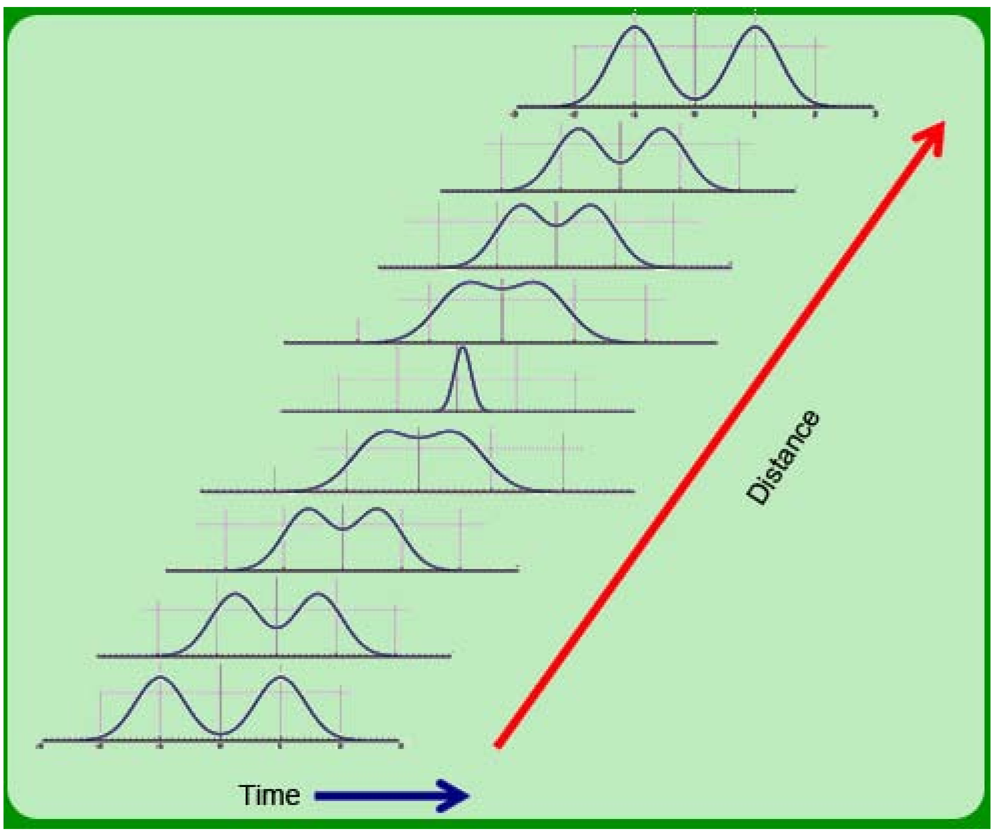

Figure 38.2

Hence using 1 ps soliton data transmission rates ~100-200 G bits /s can be realized. 10 ps soliton will provide data rates of 10-20 Gbits/s and 25ps soliton will enable only 4-8Gbits/s data rates.

References:

1. M. Nakazawa, E. Yamada, H. Kubota and K. Suzuki, Electronics Letters, **27,**1270(1991)

Recap

In this lecture you have learnt the following

- The long distance soliton transmission system.
- Limitations of soliton systems and remedial solutions.