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# A study of Soliton Transmission with Wavelength Division Multiplexing and Four Wave Mixing

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**Abstract:-** Soliton waves are those waves which propagate long distance without any distortion of its wave form. The propagations of optical pulses in optical fiber by non-linear Schrodinger (NLS) equation calledsoliton in optical fiber. The optical solitons have been experimentally generated by various research worker using mode-locked lasers and single mode fiber. It is necessary to generate short pulses at wavelength greater than $\Upsilon_0$ which is in the 1.3 to 1.5 µm region of single mode fused silica fibers. Generally color center lasers have been used to create the pulses, although semiconductor diode laser are becoming available which can generate the optical solitons is of the order of 1W. Such peak powers are relatively straight forward to generate.
***Keywords*:** Optical solitons; optical fiber; optical nonlinear; dispersion; WDM and FWM

## 1. Introduction

The optical fiber development much of the effort was devoted to decreasing the loss. These efforts led to the realization of the low-loss single mode silica fiber which has a minimum attenuation at 1.55mm. In single-mode fibers the total dispersion is the sum of material dispersion caused by the dispersive properties of the waveguide material and waveguide dispersion caused by the guidance effects within the fiber structure. The total dispersion can be negative or positive depending on the wavelength. In silica based fiber the total dispersion passes through zero to 1.3mm and it is negative for the wavelength greater than 1.3mm.
In 1973 Hesegawa and Tappert modeled the propagation of coherent optical pulses in optical fiber by nonlinear Schrodinger (NLS) equation which showed theoretically that generation and propagation of shape preserving pulses called soliton in optical fibers. They solved the nonlinear Schrodinger (NLS) equation. This equation has an exact solution for an initial pulses shape of $N_{sech}$ (t), where N is any integer known as order of solitons. The first order solitons is a self-maintaining pulses whereas higher order solitons split and narrow which recovering their initial shape at the end of a period which is P/2 in normalized coordinate axis. This period is known as the solitons period. They showed that the pulses can be convex upward (bright solitons) or Concave upward (dark solitons) depending on the sign of the dispersion. If dispersion is positive 'dark solitons' generated or positive then bright solitons generated. The following properties of solitons make them attractive for optical communication systems.

i. Pulse shape the width and speed are preserved in the absence of loss
ii. Solitons are stable against small perturbations

iii. They collide with each other without changing their shape and speed.

At present solitons propagation is the only method which can be induced broadening of pulses in fiber-optics transmission. This important discovery of Hagegawa and Tappert stimulated extended research towards optical solitons as in high bit-rate optical fiber communication systems.

During the present research work, we have tried to analysis the following cases-

i. Introduction to Soliton Propagation
ii. Types of Soliton
iii. Soliton Transmission
iv. Wavelength Division Multiplexing in Solitons
v. Four Wave Mixing in Solitons
vi. Stability of Solitons
vii. Conclusions

**2. Types of Soliton:**

**2(a) Spatial Solitons :**The nonlinear effect can balance the diffraction. The electromagnetic field can change the refractive index of the medium while propagation thus creating a structure similar to a graded-index fiber. If the field is also a propagating mode of the guide it has created, then it will remain confined and it will propagate without changing its shape.

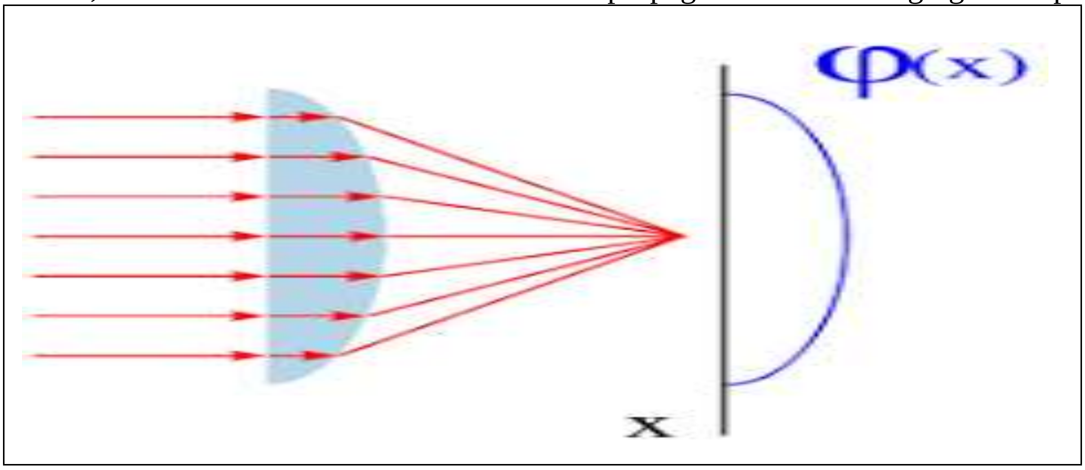


Fig- Optical field approaches the lens and focused

In order to understand how a spatial soliton can exist, we have to make some considerations about a simple convex lens. As shown in picture on the right an optical field approaches the lens and then it is focused. The effect of the lens is to introduce a non-uniform phase change that causes focusing. This phase change is a function of the space can be representing with a Ψ(x), whose shape is approximately represented in picture.

The phase change can be expressed as the product of the phase constant and the width of the path in field has covered can be written as

$$\Psi(x)= k_0 n L(x) \qquad \ldots\ldots\ldots\ldots 1.1$$

Where L(x) is the width of the lens changing in each point with a shape that is the same of Ψ(x) because $k_0$ and 'n' are constants. In other words, in order to get a focusing effect we just have to introduce a phase change of such a shape but we change the value of the refractive index n(x) we will get exactly the same effect, but with the completely different approach.

That's the way graded-index fiber work; the change in the refractive index introduces a focusing effect that can balance the natural diffraction of the field. If the two effects balance each other perfectly, then we have a confined field propagating within the fiber. Spatial solitons are based on the same principal: Kerr effect introduce a self-phase modulation that changes the refractive index according to the intensity

$$\Psi(x) = k_0(x)L = k_0L[n+n_2I(x)] \qquad \text{............1.2}$$

If I(x) have a shape similar to the one shown in the figure, then we have created the phase behavior we wanted and the field will show a self-focusing effect. In other words the field creates a fiber like guiding structure while propagating. If the field creates a fiber and it is the mode of such a fiber at the same time. It means that the focusing non-linear and diffractive linear effects are perfectly balanced and the field will propagate forever without changing its shape (as long as the medium does not change and if we can neglect losses. In order to have a self-focusing effect, we must have a positive $n_2$, otherwise we will get the opposite effect and we will not notice any non-linear behavior.

**2(b) Temporal Solitons:**If the electromagnetic field is already spatially confined, it is possible to send pulses that will not change their shape because the non-linear effects will balance the dispersion. Those solitons were discovered first and they are often simply referred as "solitons" in optics. The main problem that limits transmission bit rate in optical fibers is group velocity dispersion. It is due to the fact that generated impulses have a non-zero wide bandwidth and the medium they are propagating through have a refractive index that depends on the frequency or wavelength. This effect is represented by the group delay dispersion parameter D; using it it's possible to calculate exactly how much the pulse will widen

$$\Delta\tau \sim DL\Delta\lambda \qquad \text{.................................1.3}$$

Where L is the length of the fiber and $\Delta\lambda$ is the bandwidth in terms of wavelength. The approach in modern communication systems is to balance such dispersion with other fiber having D with difference signs in different parts of the fiber: this way pulses keep on broadening and shrinking while propagating anyway with temporal solitons. It is possible to remove such a problem completely.

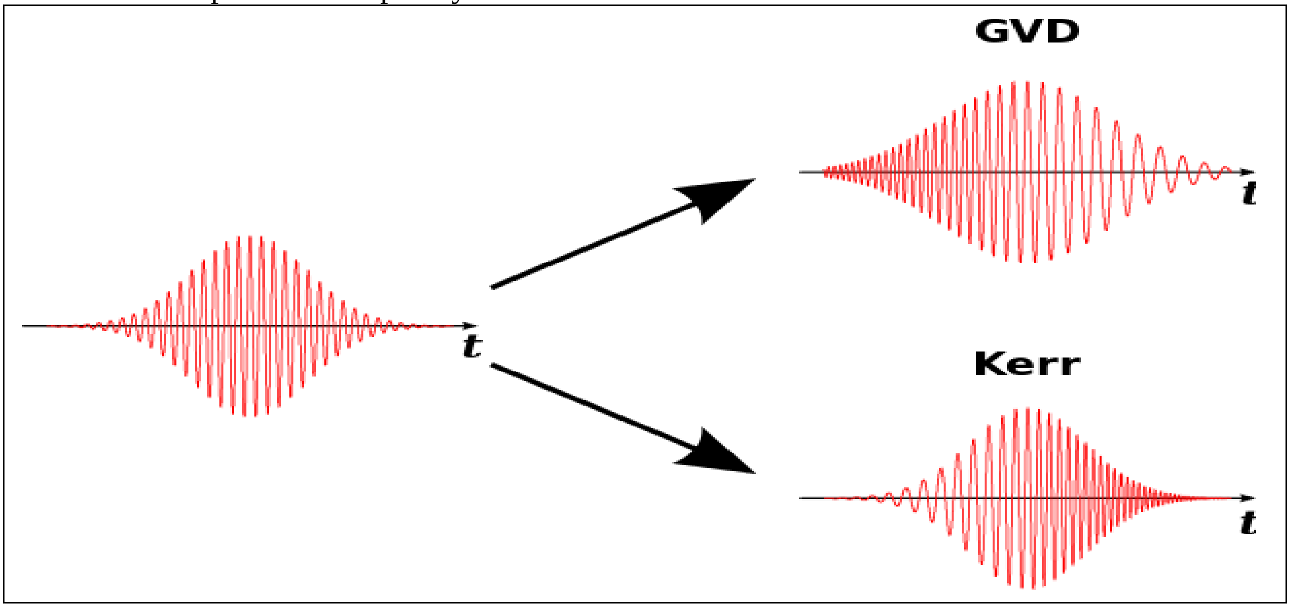


*Fig:- Linear and Non-linear effects on Gaussian pulses*

In above picture left side is a standard Gaussian pulse which is the envelope of the field oscillating at a defined frequency. We assume that the frequency remains perfectly constant during then pulse.

Now we let this pulse propagate through a fiber with D>0, it will be affected by group velocity dispersion. The higher frequency components will propagate a little bit faster than the lower frequencies, thus arriving before at the end of fiber. The overall signal we get is a wider chirped pulse shown in the upper right of the picture.

Now let us assume we have a medium that shows only non-linear Kerr effect but its refractive index does not depend on frequency- such a medium does not exists, but it's worth considering it to understand the different effects.
The phase of the field is given by:

$$\Psi(t) = \omega_0 t - kz = \omega_0 t - k_0 z[n+n_2 I(t)] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.4$$

The frequency (according to its definition) is given by

$$\omega(y) = \partial\Psi(t)/\partial t = \omega_0 - k_0 z n_2 \partial I(t)/\partial t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.5$$

This situation is represented in the picture on the left shows in beginning of the pulse the frequency is lower and at the end is higher. After the propagation through our ideal medium, we will get a chirped pulse with no broadening because we have neglected dispersion.
Coming back to the first picture, we see that the two effects introduce a change in frequency in two different opposite directions. It is possible to make a pulse so that the two effects will balance each other. Considering higher frequencies, linear dispersion will tends to let them propagate faster, while non-linear Kerr effect will slow them down. The overall effect will be that the pulses do not change while propagating: such pulses are called temporalsolitons. An electric field is propagating in a medium showing optical Kerr effect through a guiding structure (as an optical fiber) that limits the power on x-y plane.
**2(c) Dark Solitons:-** In the analysis of both types of solitons we have assumed particular conditions about the medium

- In spatial solitons, $n_{2 > 0,}$ that means the self-phase modulations causes self-focusing
- In temporal solitons$\beta_2 < 0$ or $D > 0$, anomalous dispersion

Is it possible to obtain solitons if those conditions are not verified or if we assumed $n_2 > 0$ or $\beta_2 < 0$ we get the following differential equation ( it has the same form in both cases we will use only the notation of the temporal solitons ).

$$-1/2\partial^2 a/\partial\tau + \partial a/\partial^{\zeta} + N^2 |a|^2 a = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.6$$

This equationhas soliton like solution . For the first order (N=1):

$$a(T,\zeta) = \tanh(T)e^{i\zeta} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.7$$

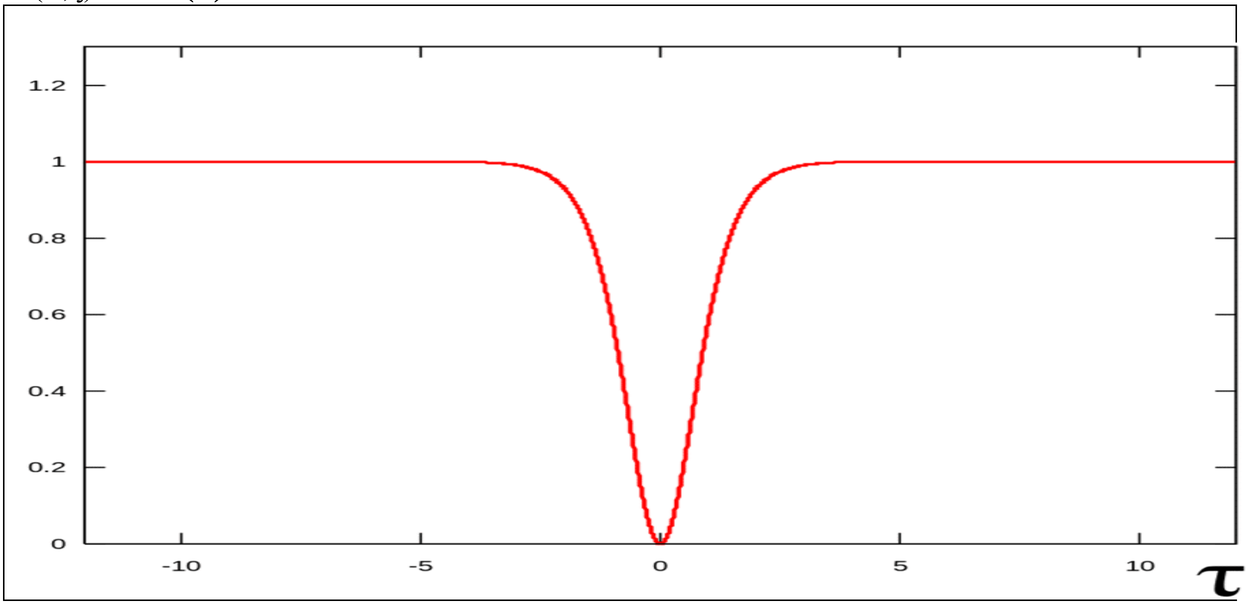


*Fig:- power of a dark soliton*

Power of darksoliton shown in figure. For highest order soliton (N>1) we can use the following closedform expression.It is a soliton, in the sense that it propagates without changing its shape, but it is not made by a normal pulse, but it is a lack of energy in a continuous time beam. The intensity is always constant, but for a short time it becomes zero and then back to the constant value again , thus generating a "dark pulse", from which the name dark solitonthose soliton can actually be generated introducing short dark pulses in much longer standard pulses. Dark solitonsare GeO2and $P_2O_5$ compositional fluctuations can occurs .These two effect give rise to refractive index variations which occurs within the glass over distances that are small compared with he wavelength. These index variations cause a Rayleigh-type scattering of light. Rayleigh scattering in glass is the same phenomenon that scatters light from the sun in the atmosphere, thereby giving rise to a blue sky.

**3. Soliton Transmission:-** The solutions a pulse able to keep its shape and width steady as a result of mutual compensation of dispersion broadening and self-phase modulations narrowing processes has been discussed above. The Wavelength Division Multiplexing system is based on solitons transmission. System of 128 channels with each channel carrying capable of 109 bit/sec. Its pulse is able to travel upto6,000KM without regeneration. Since solitons can be transmitted over a very long fiber link without amplifications and dispersion compensation. They look like the most promising transmission technology. The urgent need of solitons stems from the necessity to cope the most limiting effects in today's fiber. The major challenge in the development of commercial solitons transmission is already installed multimillion networks of standard fibers. Solitons are used to produce a pulse train suitable for solitons transmission.

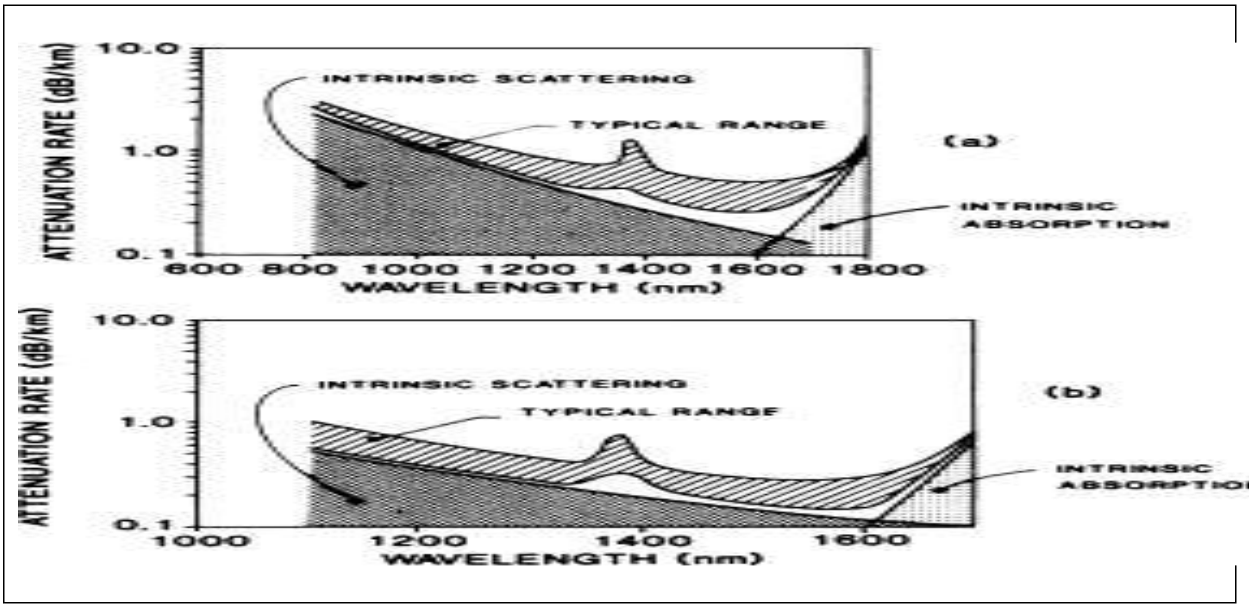


*Fig- Semiconductor of the device for a hybrid pulse source*

Our research goal is to realize long distance large capacity optical transmission by taking advantage of optical nonlinear effects, including optical solitons and nonlinear techniques for generating ultra-short optical pulses. Thus soliton is a wave that exists in nature which can propagate over long distances without any distortion in its waveform. Another interesting property of solitons is the durability, which means that once generated and launched into the fiber they retain their shape over long distances.

**4. Wavelength Division Multiplexing (WDM) with solitons-**

The wavelength division multiplexing is the potentially an effective way to increase the capacity of ultra-long distance date transmission. For most transmission modes, however nonlinear interaction tend to cause server in inter channel interference. On the other hand in losses, constant dispersion fiber, solitons of different wavelength are transparent to each other. The transparency means that each solitons emerges from a mutual collision with wavelength energy and shape. In particular FWM components that make a temporary appearance during the collisions are reabsorbed by solitons. This transparency can be maintain in the system by use of a chain of lumped amplifiers as long as the collision length (

the distance that the solitons travel down the fiber while passing through each other) is two or more times the amplifier spacing. Nevertheless the effect of cross-phase modulation between colliding solitons and their generation of the FWM components was assumed to be similar to that in the lossless case. In the recent experimented study of soliton WDM transmission at 10 G bits per channel, however we observed serious penalties, particulars the distance for error free transmission. Thus it is clear that the above analysis has an important effect.

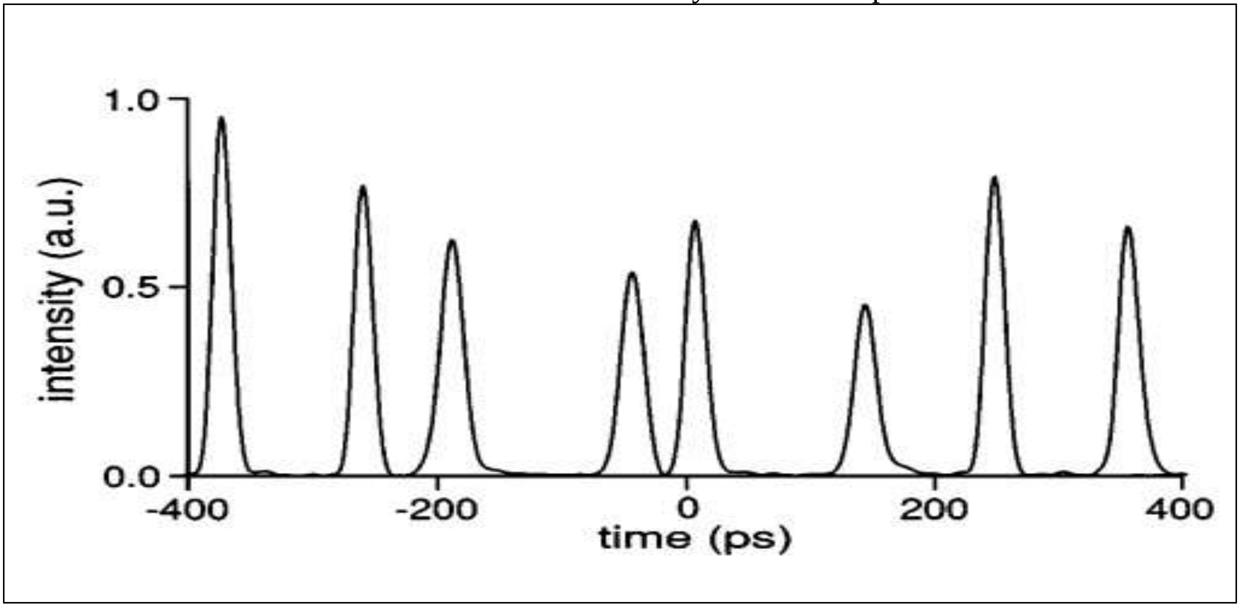


***Fig-*** *Intensity(a.u.) with respect to Time(p.sec)*

The net results in that WDM solitons system behave quite differently from conventional WDM system e.g. channel spacing $\Delta\lambda$ in conventional WDM system must be longer than a certain critic value or satisfactory performance. But soliton system impose an additional requirement $\Delta\lambda$ must be smaller than another critical value. The growth of FWM products can be effectively eliminated through proper dispersion management. The elimination is complete when the fiber decreases exponentially with distance exactly as does the single energy. Although such dispersion tapered fiber is not yet commercially available e.g. just a twosteps approximation almost completely eliminated the timing and amplitude jitter.

Residual Four Wave Mixing energy following a single collisions of 20-ps solitons in channels spaced 0.6 nm apart in a chain of fiber spans with D=0.5ps/(nm km). For constant D and for the optical two, three, four step approximation to the ideal exponential taper. The Four Wave Mixing energy for a single sideband and is normalized to the soliton pulse energy. No noise seed was used in these simulations. Channel spaced ‘n’ times the adjacent channel spacing the Four Wave Mixing intensity should scale as n-5. The apparently rapid full of in Four Wave Mixing effect is tempered somewhat by the facts that the no of collisions tends to increase as ‘n’ and that is really the vector addition of residual field quantum from at least several successive collisions that is to be referred here. Also note that the no of steps require for total suppression of the FWM intensity increasing channel spacing just two steps are required for lamp. In the neighborhood of 30km. Whereas our steps are required for same in fig. Finally note that because of the finite nature of the pulse width and collision length are responses.

**5. Four Wave Mixing in Solitons-**

The power dependence of refractive index has its origin in the third order non-linear susceptibility denoted by $\chi^{(3)}$. The non-linear phenomenon known as the Four Wave Mixing also originates from $\chi^{(3)}$. If three optical fields with carrier frequencies $\omega_1$, $\omega_2$ and $\omega_3$ co-propagate inside the fiber simultaneously $\chi^{(3)}$ generate four field whose frequency is $\omega_4$ related to other frequencies by a relation $\omega_4=\omega_1\pm\omega_2 \pm \omega_3$several frequencies corresponding to different pulse and minus signs combinations are possible in principal. In practice most of these combinations do not build up because of the phase matching requirement. Frequency combination of the form $\omega_4= \omega_1+\omega_2-\omega_3$ are often troublesome for multichannel communication systems. Since they can become nearly phase matched when channel wavelength lie close to the zero dispersion wavelength. In fact the degenerate Four Wave Mixing process for which $\omega_1=\omega_2$is often the dominate process and impulse the system performance most. On the fundamental level, a four wave mixing process can be viewed as a scattering process and impacts the system performance most. The four wave mixing process may also be interpreted between four photons. A photon of frequency $\omega_3$ combines with a photon of frequency $\omega_4$ will produce a proton of frequency $\omega_1$ and $\omega_2$ shown in fig.

$$\Delta=\beta(\omega_3)+ \beta(\omega_4)- \beta(\omega_1)- \beta(\omega_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.8$$

Where $\beta(\omega)$ is propagation constant for an optical field with frequency $\omega$.in degenerate case $\omega_2=\omega_1$, $\omega_3=\omega_1+\Omega$ and $\omega_3=\omega_1-\Omega$ where $\Omega$ represents the channel spacing. This process can still occur and transfer power from each channel to nearest neighbors. Such a power transfer not only results in the power loss for a channel but also induced inter-channel cross tall that degrades.

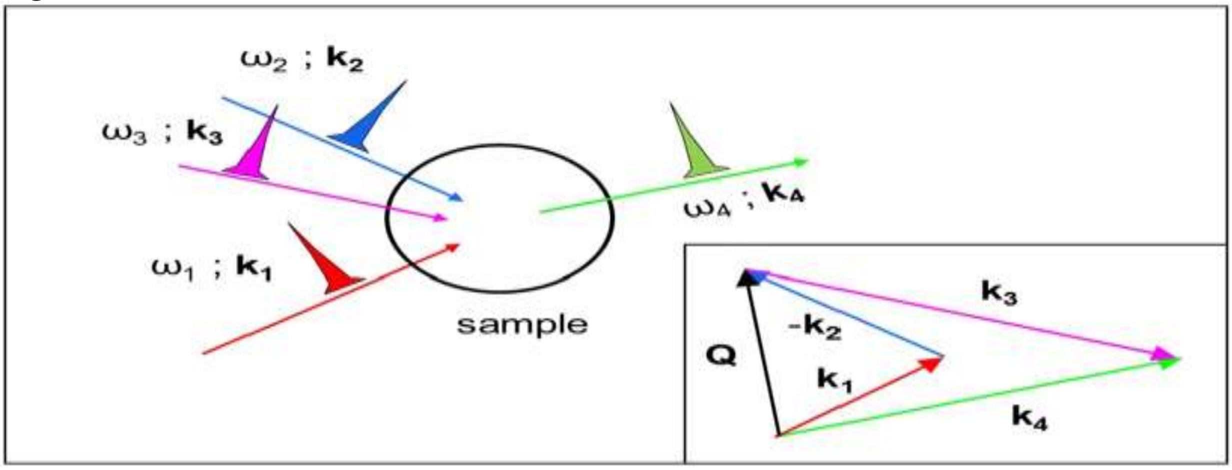


***Fig****-Interaction of four photons in Four Wave Mixing*

Modern Wavelength Division Multiplexing system avoid Four Wave Mixing by using the technique of dispersion management I which Group Velocity Dispersion is kept locally high in each fiber section en through it is low on average. Four Wave Mixing, can also be useful in designing light wave system. It is also used for de-multiplexing individual channels when time division multiplexing is used in the optical domain. It is also used for wavelength conversion. Four Wave Mixing in optical fiber, is some time used for generating for a spectrally inverted signal through the process of optical phase conjugate. This technique is useful for dispersion compensation.

**6. Stability of Solitons-**We have describe what optical solitons are to creat a field with a particular shape with a particular power related to theduration of the impulses. But what if we are a bit wrong in creating such impulses then adding small perturbations to the equations and solving them numerically, it is impossible to show that memo-dimensional solitions are stable. They often referred as (1+1)Dsolitions meaning that they are limited in one dimension and propagate in another one say z.

If we create such a soliton using slightly wrong power or shape then it will adjust itself until it reaches the standard such shape with the right power. Unfortunately this is achieved at the expense of some power loss that can cause problems because it can generate another non-soliton field propagation together as we want. On the other hand (2+1)D spatial solitons are unstable so any small perturbation can cause the soliton to different as a field in a linear medium or to collapse damaging the materials. So working close this saturation level makes it possible to create a stable soliton in a three dimensional space.

**7. Conclusions-** The propagation of first order solitons with different pulse widths indicates that shorter initial pulse spread more than longer once although the loss coefficient in the non linear Schrodinger equations is smaller. These solitons are basically used in optical communications, optical switching, high energy physics and in solid state physics.

- **In optical communications-** The most use of solitons are in optical communications. In these cases information is encoded in light pulses and transmitted through optical fiber over a long distance in 1977. With the help of solitons theory optical cables has been developed which transmit 40,000 telephone conversations simultaneously which have been experimentally observed and theoretically confirmed. In addition we have shown that the uses of the DM soliton improve the power margin and the dispersion tolerance of long distance transmission systems without any distortion.
- **In optical switching-** The optical switching as the controlling of the gain from very low values to very high value or vice-versa. The solitons pulse having very narrow band width and highly intense so we obtain optical switching using solitons system.
- **In high energy physics-**High energy physics means the particle physics where size of the particle is very small having high kinetic energies. Ideal solitons, which propagate without waveform distortion, can exist only in a transmission line with no energy loss and no fluctuation of the group velocity dispersion along the line. For achieving soliton transmission in a real optical fiber, it has been necessary to extend the concept of the soliton.
- **In Solid State Physics-** In this case we used to measure the high energy of any object. If we want to measure the length of a person with having a box of height of several hundred meters so there is no matching of size of person and the box. It can be easily measured the height of a person accurately with the help of box. We have developed sereral novel soliton transmission techniques, such as the use of dispersion managed solitons, a pulse reshaping technique which we call soliton control and also wavelength division multiplexed (WDM) soliton transmission. By adopting these techniques, we can increase transmission capacity and upgrade installed terrestrial or submarine cables. As enabling technologies for these transmission techniques for ultra-short optical pulses; fiber gratings for the dispersion compensation and equalization and the application of ultra-fast optical pulses to optical signal processing. So we used the solitons system in solid state physics.

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