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Effect of Group Velocity Dispersion (GVD) with and without initial Gaussian Chirp in Enhanced - Large Effective Area Fiber (E-LEAF)

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Abstract—In this work, the effect and mechanism of Group Velocity Dispersion (GVD) in Enhanced- Large effective Area Fiber (E-LEAF) is studied. The mechanism of GVD is noted with chirped and unchirped Gaussian input pulse. Firstly, the effect of pulse broadening is noted with an unchirped pulse for various Dispersion lengths (L_D) in the 20 Gbps system. Secondly, the effect of chirped pulse with an initial chirp (C) of 3 rad/sec is studied for various lengths. It is noted that the minimum pulse broadening for chirped pulse occur at the distance of 13.26 km while the dispersion length of E-LEAF without SPM is 44.21 km. Thus, the power in this case at the distance of 13.26 km, where the initial narrowing occurs is found to be 3.32mW.

Index terms—GVD, SPM, chirp, dispersion length, non-linear length, E-LEAF

1 Introduction

The modern era of optical communication focuses on building up ultra high capacity system. The increase in capacity was made by increasing the bitrate to single channels, but later the concept of transmitting various laser colours (wavelengths) as virtual fibers in a single fiber introduced the concept of Wavelength Division Multiplexing (WDM). The system capacity was increased by increasing number of channels in the system (DWDM)[1]. But the demand of bandwidth from the population side upgraded the optical system to contribute high bitrate to individual channels in multichannel systems. So the contribution of very high bitrate (several Gbps) needs very closed spacing of pulses which is highly pronounced to intra channel impairments. The effect of Inter-symbol Interference (ISI) is deadly high in such system even with small dispersion.

Normally, Conventional Single Mode Fiber (C-SMF) has large dispersion co-efficient around 17ps/nm/Km in 1550 nm transmission window. But the E-LEAF has small dispersion value around 4ps/nm/Km which helps in long distance transmission than the C-SMF does. So, E-LEAF supports high bitrate and long haul transmission for modern optical transmission systems[2][3].

But, even then enormous usage of internet requested more bandwidth which even needs the E-LEAF to be compensated. So, it becomes a major criterion to analyze the effect of dispersion in E-LEAF. In this work, the effect of GVD on Gaussian pulse as an input is noted with and without chirp. Since, the GVD depends on the instantaneous frequency changes (chirp). So, the system is characterized for its performance of chirping in the pulse.

There exists various design issues in fiber design such as, increasing the effective area to reduce non-linearity, low dispersion co-efficient to increase length of transmission, low attenuation loss etc. But the parameters are in reciprocal to each other in design consideration for various telecom fibers.. But E-LEAF provides with low dispersion value, attenuation loss and large effective area which makes it one of the most attracting transmitting fibers [4][5].

2 Theory on Group Velocity Dispersion

. The optical pulse travelling in fiber is governed by Non-Linear Schrödinger's wave equation as,[6]

$$\frac{\partial A(z,t)}{\partial z} = \frac{-\alpha}{2}A(z,t) + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A(z,t)}{\partial t^3} - i\gamma|A(z,t)|^2 A(z,t) \quad (1)$$

where, the first, second, third and fourth terms in the right had side of the equation corresonds to attenuation, first order GVD which is characterized by Dispersion parameter $D = -\frac{2\pi c}{\lambda^2}\beta_2$, second order GVD which is characterized by Dispersion Slope as $S = \frac{dD}{d\lambda} = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 - \frac{2}{\lambda}D$ and non-linearity respectively.

Here the Gaussian pulse is considered for the experimentation with initial power and pulsewidth of P_o and T_o respectively. The Gaussian profile with the amplitude A(z) is represented as follows,

$$A(z=0,t) = \sqrt{P_o}\exp\left(\frac{-t^2}{2T_o^2}\right) \quad (2)$$

The time domain broadening [T(z)] and power [P(z)] of Gaussian shaped electric field envelope in the eqn.(2) at the distance z with the dispersion length as L_D can be given as,

$$T(z) = \left[1 + \left(\frac{z}{L_D}\right)^2\right]^{\frac{1}{2}} T_o \quad (3)$$

$$P(z) = \frac{P_o}{\left[1+\left(\frac{z}{L_D}\right)^2\right]^{\frac{1}{2}}} \quad (4)$$

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Such that from eqn. (3) and (4), it is easily understood that at the distance of dispersion length($z=L_D$), the broadening increases and power decreases by a factor of $\sqrt{2}$. Since, we are dealing with the focussed experimentation of GVD, the eqn. (1) can be given as follows by neglecting the attenuation, Kerr non-linearity and second order GVD as,

$$i\frac{\partial A(z,t)}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} \tag{5}$$

where, $\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2}$ (GVD parameter) is the relation of second order derivative of fiber mode propagation constant to the frequency. The GVD is characterized by a main parameter called Dispersion length and is given by,

$$L_D = \frac{T_O^2}{|\beta_2|} \tag{6}$$

where, $\beta_2 = -D\frac{\lambda^2}{2\pi c}$ and T_o as initial pulse width. Now, on considering the chirped Gausian input, the profile of envelope of the electric field is given as,

$$A(0,T) = exp\left[-\frac{(1+iC)}{2}\frac{T^2}{T_O^2}\right] \tag{7}$$

The spectral half width is noted as,

$$\Delta\omega = \left(\frac{2\pi T_O^2}{1+iC}\right)^{1/2} exp\left[\frac{\omega^2 T_O^2}{2(1+iC)}\right] \tag{8}$$

The pulse broadening propagating through a distance z is given by,

$$\frac{T_1}{T_O} = \left[\left(1+\frac{C\beta_2 z}{T_O^2}\right)^2 + \left(\frac{\beta_2 z}{T_O^2}\right)^2\right]^{1/2} \tag{9}$$

The chirp parameter (C) changes for various values and the minimum distance of transmission without broadening (or initial narrowing) can be calculated from the following equation as,

$$z = \frac{C}{1+C^2}L_D \tag{10}$$

while the pulse width along the distance and power in this case is given in eqn. (11) and eqn. (12) respectively,

$$T(z_{min}) = \frac{T_O}{(1+C^2)^{1/2}} \tag{11}$$

$$P(z_{min}) = P_o(1+C^2)^{1/2} \tag{12}$$

3 Simulation Parameter for E-LEAF:

The characteristic parameters used for E-LEAF in the simulation is tabulated in table.1.[7]

S.no	Parameters	Values	Units
1.	Reference wavelength(λ)	1550	nm
2.	Dispersion Coefficient(D)	4	ps/nm.Km
3.	Dispersion Slope(S)	0.085	ps/nm²/Km
4.	Attenuation(α)	0.2	dB/Km
5.	Effective Area(A_{eff})	72	μm²
6.	Non-linear index(n_2)	2×10^{-20}	m²/W
7.	Mode field diameter(MFD)	9-10	μm
8.	Polarization Mode Dispersion(P)	0.1	ps/√km
9.	Non-linear co-efficient(γ)	1.4638	$W^{-1}Km^{-1}$

Table.1. Parameters of E-LEAF used in simulation.

4 Brief Description of the System

The system is operated with the bitrate of 20Gbps. The bit width is the inverse of bitrate, so T becomes 50ps (1/bitrate). The default value is 0.5 bit. So, T becomes 25ps. The initial pulse width and T_{FWHM} is related by $T_o \sim T_{FWHM}/1.665$. Now, the initial pulse width is calculated as 15.02ps. The Dispersion length (L_D) is calculated from eqn.6 by considering β_2=-5.1 ps²/km as 44.21km.

When considering chirped Gaussian pulse the broadening is given by the eqn.9. In case of the chirped pulse the initial narrowing is calculated from the eqn.10 which gives the minimum distance. By substituting the Chirp parameter (C) as 3rad/sec. in the eq.10, the value of z becomes 13.26km. At this case the peak power is found to be 3.32mW which can be seen from fig.1.

5 Results and Discussions

In this section, firstly, the unchirped pulse is simulated at various dispersion lengths (L_D) and the broadening of the pulse with respect to the distance in noted in fig.2(c). The concept of broadening can be clearly understood from fig.2(a) and fig.2(b), where the fig.2(a) shows the chirpless input pulse with 1mW input power in 20Gbps system.

But, the pulse received after the dispersion length of 44.21 km shows the presence of chirping across the pulse that can be pictured in fig.2(b). The chirping constantly decreases from the leading edge to the trailing edge depicts the presence of higher frequency in the leading edge and lower frequency in the trailing edge.

Now, it becomes more important to describe the different dispersion regime. In anomalous regime (β_2<0 or D>0), the blue frequencies (higher) travels faster than the red frequencies (lower). Conversely in normal dispersion regime (β_2>0, D<0), the red frequencies travel faster than blue frequencies. So, in the E-LEAF with anomalous regime, blue frequencies in the trailing edge travel faster than the red frequencies in the leading edge causing broadening of pulse[8][9].

In case of chirped pulse the broadening is not constant as in unchirped Gaussian pulse. Fig.1 and fig.2 gives the clear picture on the concept of GVD with chirped pulse with chirp parameter of C=3 rad/sec.

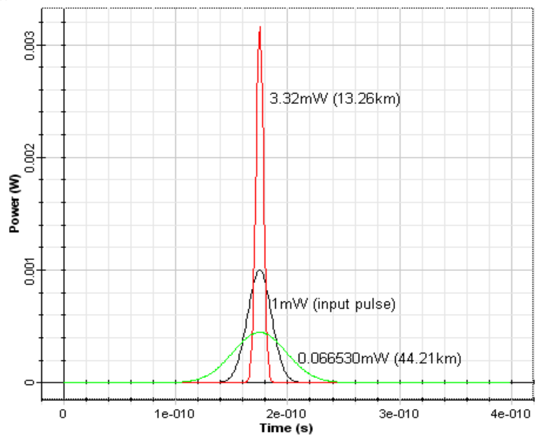

Fig.1. Comparative study of chirped pulse before and after fiber

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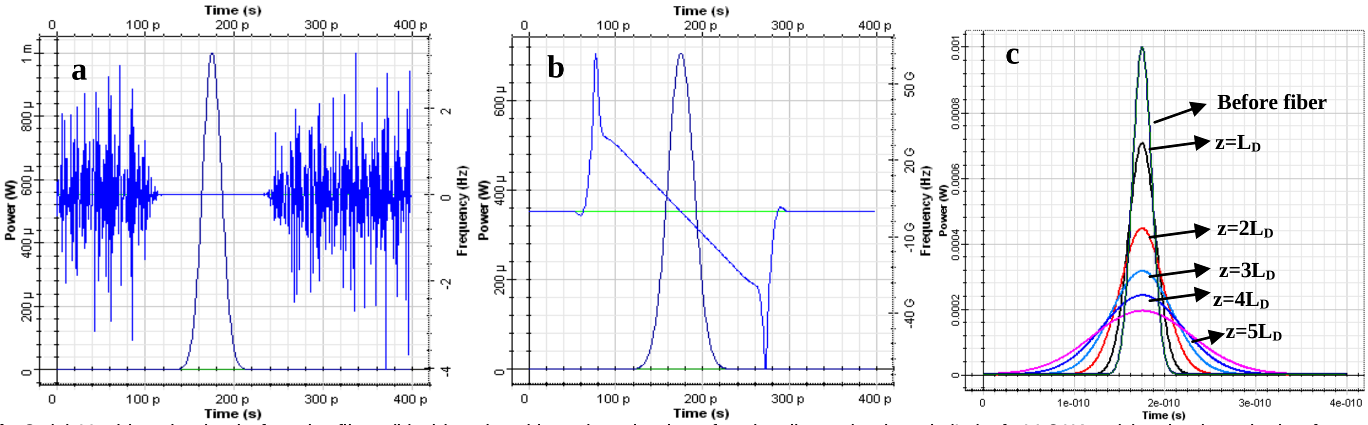

Fig.2. (a) Unchirped pulse before the fiber, (b) chirped and broadened pulse after the dispersion length (L_D) of 44.21Km, (c) pulse broadening for various dispersion lengths in E-LEAF.

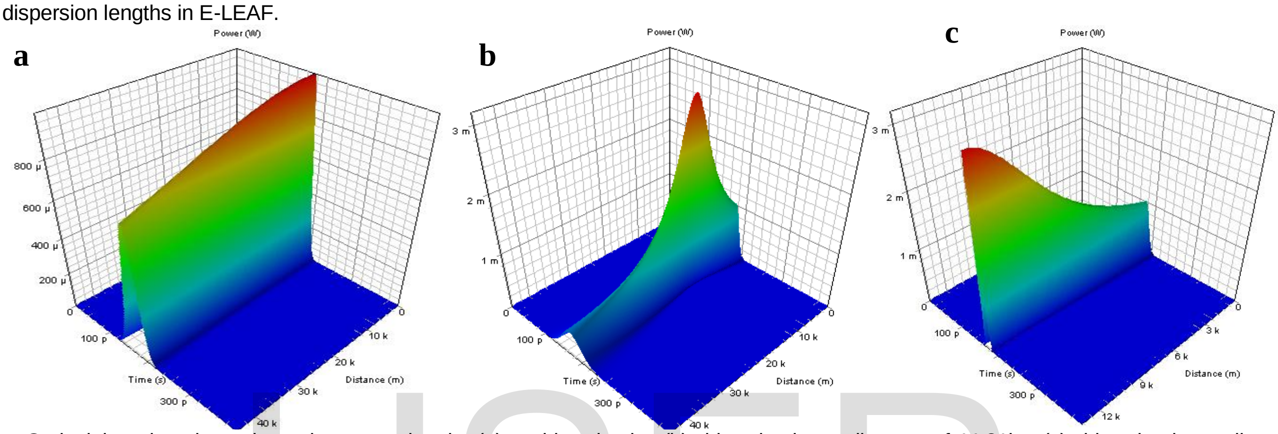

Fig.3. The Optical time domain analyzer demonstrating the (a) unchirped pulse (b) chirped pulse at distance of 44.21km (c) chirped pulse at distance of 13.26 km

In anomalous regime, the impact of chirped pulse leads to initial narrowing at first and broadens with further distance. Fig.3(a) gives the picture of broadening of unchirped pulse with respect to time for the distance of z=44.21km which is the dispersion length of E-LEAF. In fig.3(b), the chirped pulse with C=3, pulse becomes narrower and then broadens with the increase in the distance. Fig.3(c) gives the minimum distance (z=13.26km) at which the perfect compensation occurs between SPM and GVD, so that the pulse has minimum width.

Fig.1 gives the clear picture on chirped pulse where the power increase to 3.32mW (refer eqn.12) at the minimum distance z=13.26km where the broadening is minimum. Thus, the chirped pulse broadens gradually and reaches with the power of ~0.07mW at the distance of dispersion length, L_D=44.26km.

Fig.5 shows the mechanism of pulse broadening, where in an unchirped pulse the chirping is seen to be decreasing from the leading edge to trailing edge (blue frequencies in the leading edge and red frequencies in the trailing edge) which is the characteristic feature of GVD in anomalous regime at the dispersion length.

But, with an initial chirp, it travelling at 10Km length. This proves that initially the red frequencies are present in the leading edge and blue frequencies are preseint in the trailing edge for initially chirped Gaussian pulse.

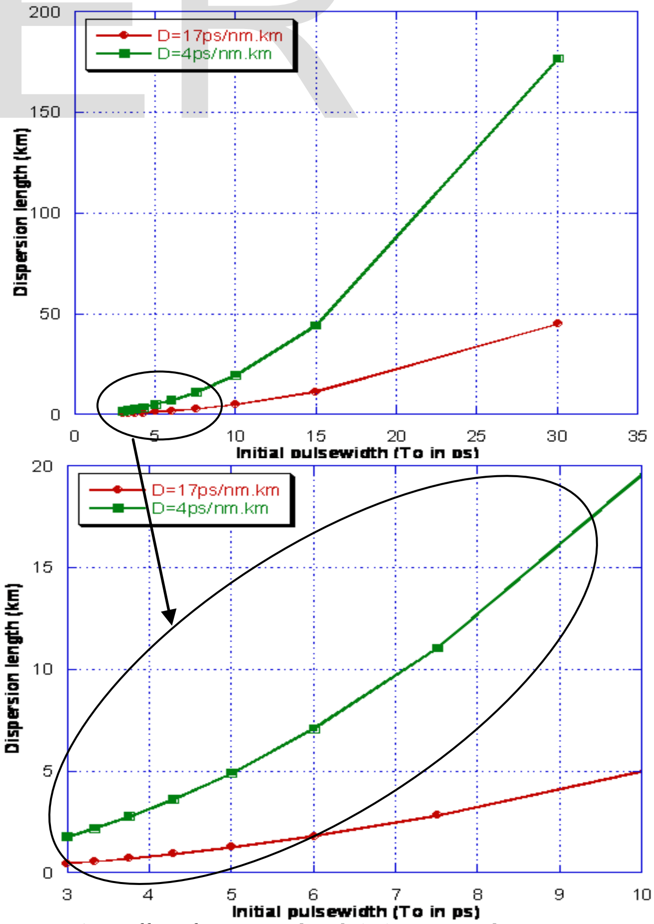

Fig.4. Effect of Dispersion length (L_D) in SMF and E-LEAF.

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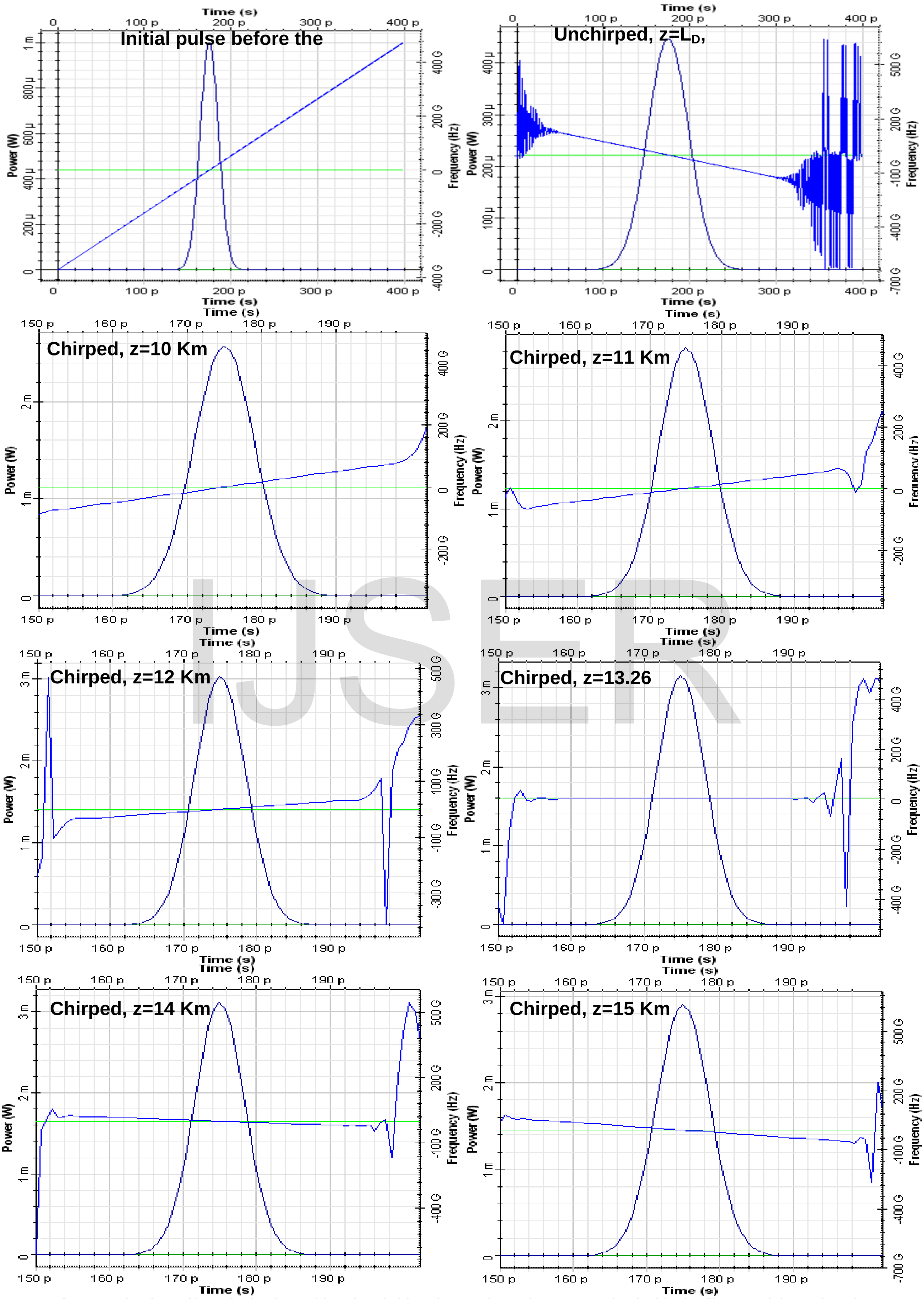

Fig.5. Mechanism of broadening in unchirped and chirped Gaussian pulse propagating inside the fiber at minimum length.

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It is already known that the blue frequencies travel faster than the red frequencies in anomalous dispersion regime. So, in case of initially the pulse narrowing occurs due to this concept, where the faster blue components in the trailing edge overtakes the slower red components in the leading edge till the minimum distance limit of 13.26Km.

The time domain analyzer view shown in the fig.5 for the distance 10 and 20Km shows the effect of increase in frequency components from the leading edge to trailing edge. At, 13.26Km, there is a complete balance between the chirping induced by GVD and initial chirp of the pulse. This is referred to the minimum distance where the pulse has minimum width (refer eqn.10 & 11).

Thus, the initial narrowing comes to an end till this minimum distance and the propagation distance of 14km and 15km in fig.5 shows that the pulse broadens after this minimum distance (z). At the distance of 14km and 15km, it is seen the blue frequencies are in the leading edge and red frequencies in the trailing edge resulting in broadening of pulse as in the case of unchirped pulse in anomalous dispersion regime. Thus the slow and faster components separate with the time leading to initial narrowing and broadening.

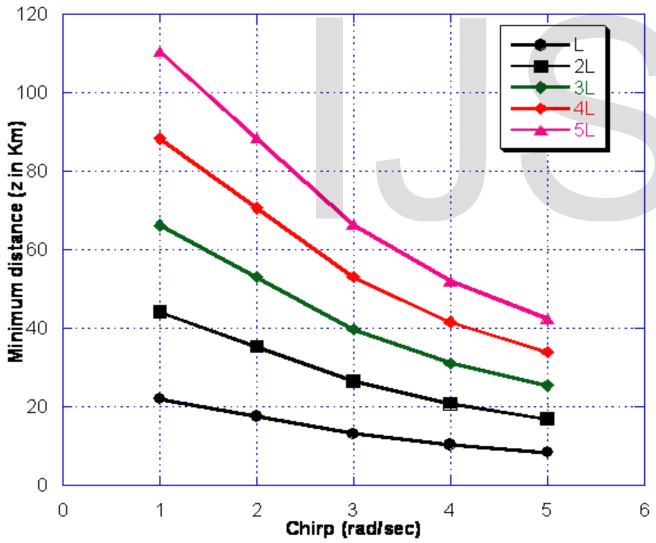

Fig.6. Effect of minimum pulse width at minimum distance (z) during initial narrowing with respect to initial Gaussian chirp parameter (C).

Fig.4. gives the clear picture on the effect of C-SMF with Dispersion co-efficient of 17ps/nm.km and E-LEAF with the dispersion co-efficient of 4ps/nm.km in maximum propagation length without any dispersion compensation. The low dispersion co-efficient of E-LEAF helps in maximum transmission length than the C-SMF for the given initial pulse width. Even, in case of very short pulse width, E-LEAF has long transmission length.

Fig.5 gives the effect of chirp parameter of the Gaussian pulse transmitted inside the fiber for various dispersion lengths. The chirp parameter initially present in the pulse determines the initial narrowing and broadening of the pulse. From the figure it is seen that the increase in chirp parameter decreases the minimum length where complete compensation occurs between the chirp induced by GVD and chirp in the initial pulse. Also, it is seen that the minimum distance increases for the longer dispersion lengths. Thus, the chirping parameters for the initial Gaussian pulse can be selected for the required transmission length in order to reduce the pulse broadening with respect to the dispersion parameter of the fiber.

6 Conclusion

The effect of E-LEAF with respect to the Conventional Single Mode Fiber is demonstrated by numerical simulations. The effect of GVD has less impact on E-LEAF than C-SMF which can be proved by the Dispersion length for various bitrates. Thus, E-LEAF forms an effective transmission with its attracting low dispersion co-efficient and large effective area. It can be also noted that the large effective area can decrease the non-linearity in optical telecommunication systems where other practical telecom fibers with less dispersion constant has small effective area.

The effect of GVD with and without initial Gaussian chirping helps to understand that E-LEAF transmission without Dispersion Compensation Fiber (DCF) for long distance than C-SMF as DCF is more pronounced to non-linearity due to smaller effective area of 16-21 μm^2.

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