Analysis of Self Phase Modulation Fiber nonlinearity in Optical Transmission System with Dispersion

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***Abstract*-- In this paper, self phase modulation fiber nonlinearity, in single mode fiber optical communication system has been investigated with dispersion. The investigation is carried out in terms of Q - factor analysis at optical receiver output of single mode optical fiber communication system by varying the fiber length 10 to 100 Km at different values of fiber dispersion -10 to +10 ps/nm/km. It has been observed from results that at fiber length of 10 km and zero dispersion we obtain maximum Q-factor of 23.73 and it is least affected by SPM. Further we have also analyzed the effect of SPM by varying the input launched optical power from -10 to +12.5 dBm at different values of effective core area of optical fiber 30 to 80 µm^2 in terms of Q-factor. From analysis it has been observed that 60 µm^2 effective fiber core area gives minimum SPM at -10 dBm input launched optical power. Similarly SPM effect is investigated by varying input launched optical power at various values of fiber dispersion from -10 to +10 ps/nm/km and observed that zero fiber dispersion at -10 dBm input launched optical power gives maximum Q-factor. This analysis indicates that 10 km fiber length, -10 dBm optical lunched power and zero fiber dispersion are best suitable parameters for reduction of SPM nonlinearity in these systems.**

***Keywords*—**SPM, Q-factor, EDFA, L_{eff} and A_{eff}

I. INTRODUCTION

In optical fiber communications, with the increasing of transmission distance, the launch power has to be increased. Thus the nonlinear Kerr Effects become one of the most important impairments [4]. Nonlinear effects are weak at low powers but they can become much stronger at high powers. Nonlinear effects which can be readily described by the intensity-dependent refractive index of the fiber. The longer fiber link length, more the light interaction and greater the nonlinear effects. As the optical beam propagates along the link length its power decreases because of power attenuations. The effective length (L_{eff}) is that length, up to which power is assumed to be constant. The optical power at distance *z* along link is given as [10],

$$P(Z) = P_{in}\, exp(-\alpha z)$$

where *Pin* is the input power (power at *z* = 0) and *α* is coefficient ofattenuation. For a actual link length (*L*), effective length is defined as,

$$P_{in}L_{eff} = \int_{Z=0}^{L} P(z)\, dz$$

Using equations (1) and (2), effective link length is obtained as,

$$L_{eff} = \frac{(1 - \exp(-\alpha z)}{\alpha}$$

Since communication fibers are long enough so that $L \gg 1/\alpha$. This result in $L \approx 1/\alpha$

The effect of nonlinearity grows with intensity in fiber and the intensity is inversely proportional to area of the core. Since the power is not uniformly distributed within the cross-section of the fiber, it is reasonable to use effective cross-sectional area (A_{eff}).The A_{eff} is related to the actual area (*A*) and the cross-sectional distribution of intensity I(r, θ) in following way [1],

$$A_{eff} = A \exp(-\rho^2/\omega^2) \exp(\iota\beta z)$$

Where ω is field radius and is known as spot size, ρ is core radius and β is propagation constant in optical fiber. The typical value of A_{eff} is equal to near about 60 µm^2 because the typical value of diameter of single mode fiber is 9 µm. The various non linear effects are self phase modulation (SPM), cross phase modulation (XPM), four wave mixing (FWM). When the power is increased up to certain limit the pulse propagates through the optical fiber change its phase due to its own signal is called self phase modulation (SPM) [2].

Self Phase Modulation

Fiber nonlinearities due to Kerr effect are a limiting factor for optical communication systems. Self-phase modulation (SPM) is a nonlinear optical effect of light-matter interaction. An ultra short pulse of light at high bit rate, when travelling in a medium, will induce a varying refractive index of the medium due to the optical Kerr effects. In SPM a pulse of light when travelling in a medium will induce a varying refractive index of the medium due to the intensity of light.This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum [1]. It results in dispersion and inter symbol interference (ISI) in the optical fiber communication system.

II. SIMULATION SETUP

The figure 1 shows a simulation setup for analysis of self-phase modulation in standard single mode optical fiber link having a single channel. The transmitter section consists of Pseudo Random bit Sequence generator having bit rate of 10 Gbps, NRZ pulse generator which converts binary sequence into electrical pulses, continuous wave lorentzian laser of 1552.52 nm wavelength is used to provide input launched power from -10 to 10 dBm, Mach-Zehnder optical modulator has excitation ratio of 30 dB and erbium doped fiber amplifier of gain 40 dB and noise figure of 4 dB. The channel is standard single mode fiber has dispersion varied from -10 to +10 ps/nm/km, dispersion slope of 0.075 $ps/nm^2/km$, has attenuation 0.2 dB/km, β_2 = -20 ps^2/Km and β_3 = 0 ps^3/Km.

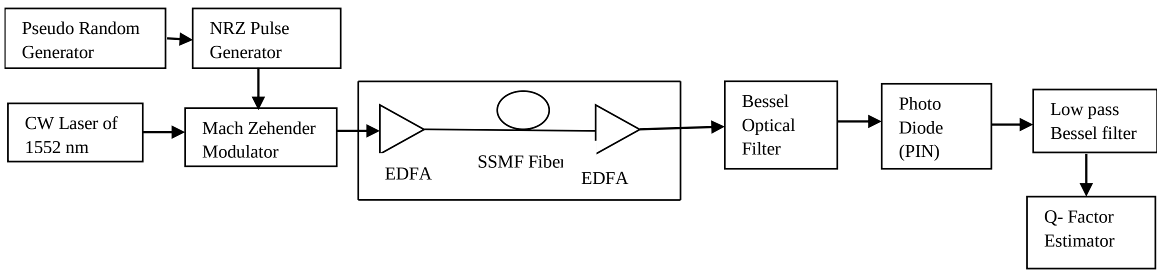

Figure 1.Single Mode Optical Fiber Communication System Set up

The receiver section consists of band pass Bessel optical filter of wavelength 1552.52 nm and bandwidth of 15 GHz, PIN photodiode has responsivity of 1 A/W and dark current of 10 nA for of optical signal into electrical conversion, low pass electrical filter has cut off frequency 0.75 GHz and BER analyzer to estimate the value of Q-factor.

III. RESULTS AND DISCUSSION

To analyze the effect of SPM in terms of Q-factor at various values of optical dispersion with different fiber lengths has been measured as shown in Table 1.

Table 1 Q- Factor at the Output by Varying Fiber Length at Various Values of Dispersion

S. No.	Fiber Length (km)	Q-Factor Dispersion (ps/nm/km) (-10)	(-5)	(0)	(+5)	(+10)
1	10	19.13	21.11	23.73	23.32	22.60
2	20	12.90	16.29	22.24	16.37	15.87
3	30	9.30	12.97	21.31	11.58	8.57
4	40	6.80	10.81	20.81	10.45	10.95
5	50	5.27	9.34	20.51	10.23	10.17
6	60	4.30	8.16	20.29	8.92	8.66
7	70	5.44	7.25	20.15	9.37	9.07
8	80	5.48	6.51	20.06	9.27	9.66
9	90	5.66	5.90	20.00	9.32	9.33
10	100	5.74	5.39	19.96	8.82	8.15

From the figure 2 we have observed that Q-factor value maximum at zero fiber dispersion for the fiber length 10 km without compensating the dispersion. With increase in fiber length the Q-factor value decreases this is due to the fact that SPM effect has been observed at high power and longer distance so at high power and longer distance Q-Factor value is minimum but at the length of 100 km Q-factor value is 20 which is acceptable so that signal can transmit up to 100 km without affected by SPM.

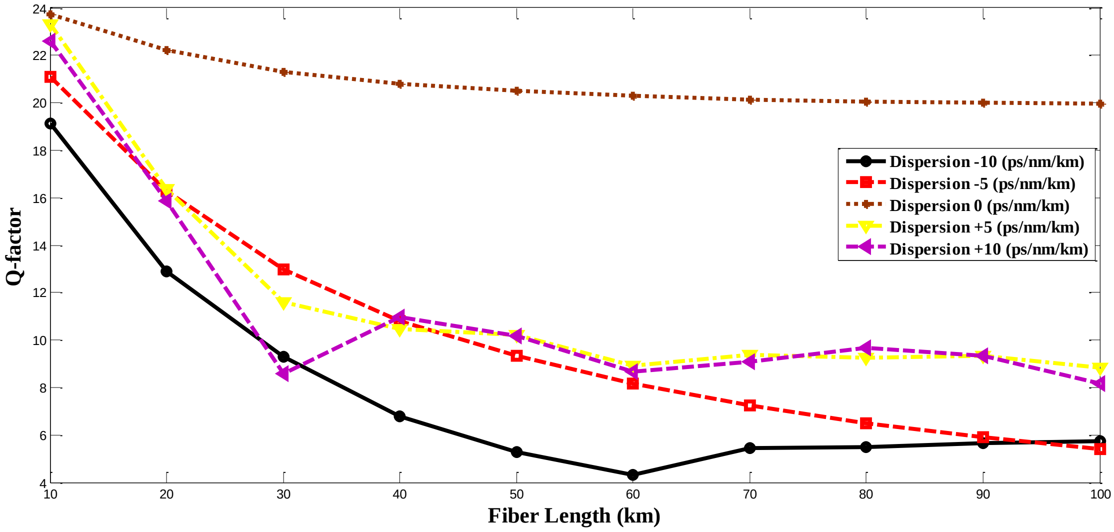

Figure 2.Q-Factor Vs Fiber Length at Various Values of Dispersion -10 To +10 ps/nm/Km

Similarly, we have analyzed the effect of SPM in terms of Q-Factor by varying the input launched power varying from -10 to +12.5 dBm with effective core area ranging from 30 to 80 μm^2 in Table 2.

Table 2 Q-Factor at output by Varying Input Launched Power for Different Fiber Effective Core Area

S.No.	Q-Factor						
	Input launched Power (dBm)	**Effective Core area (μm^2)**					
1.	-10	24.22	24.21	24.19	24.17	24.16	24.15
2.	-7.5	24.10	24.30	24.37	24.39	24.40	24.40
3.	-5	22.83	23.65	24.04	24.24	24.35	24.42
4.	-2.5	20.45	21.56	22.51	23.16	23.58	23.86
5.	0	19.83	20.20	20.30	20.81	21.44	22.02
6.	2.5	7.27	16.31	19.40	20.24	20.25	20.21
7.	5	5.91	6.20	6.38	12.65	16.05	18.16
8.	7.5	5.20	6.15	6.89	7.20	1.87	2.87
9.	10	4.23	5.30	5.72	6.28	2.64	0
10.	12.5	3.46	3.94	4.16	4.26	0	0

By varying the input power at different values of effective core area we have seen that Q-factor values drastically decreases with increase in the input power as shown in figure 3. The maximum core area of the single mode fiber acceptable is near about 60 um^2 because the typical value of the diameter of the single mode fiber is 9 μm. By increasing the effective core area of the fiber we have reduced the effect of SPM but we increase the effective core area up to certain limit due to value of core diameter of single mode fiber is in range of 8.5 to 9.5 μm and if we increase the core diameter beyond this limit the value of Q-factor becomes zero at power 12.5 dBm. The power dependence of nonlinear phase constant (ϕ_{nl}) is responsible for SPM impact on communication systems.To reduce this impact, it is necessary to have ϕ_{nl} <<1. If we use ϕ_{nl} = 0.1 as the maximum tolerable value then nonlinear phase constant (ϕ_{nl}) can be written as

$$\emptyset_{nl} = \gamma P_{in} L_{eff}$$

where nonlinear propagation constant,

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}$$

So, with $L_{eff} \approx \frac{1}{\alpha}$ one may obtain, $P_{in} < \frac{0.1\,\alpha}{\gamma}$

Typically α = 0.2 dB/km at λ = 1552.52 nm, $\gamma = 1.75\times10^{-3}$ mW and $n_2 = 2.6 \times 10^{-20}$ m^2/W and the value of L_{eff} = 21.7 km calculated from equation 3. So the input power should be kept below 10.57 dBm as we increase the input launched power above 10.57 dBm the value of Q-factor becomes zero.

From the Table 2 we have observed that at 10 dBm input launched optical power the Q-factor value is near about 1 due to SPM effect. Therefore to increase the transmission distance, more power must be launched into each fiber. This increased power increases SPM effect on lightwave systems, which results in pulse spreading so the use of large-effective area fibers reduces intensity inside the fiber and hence SPM impact on the system.

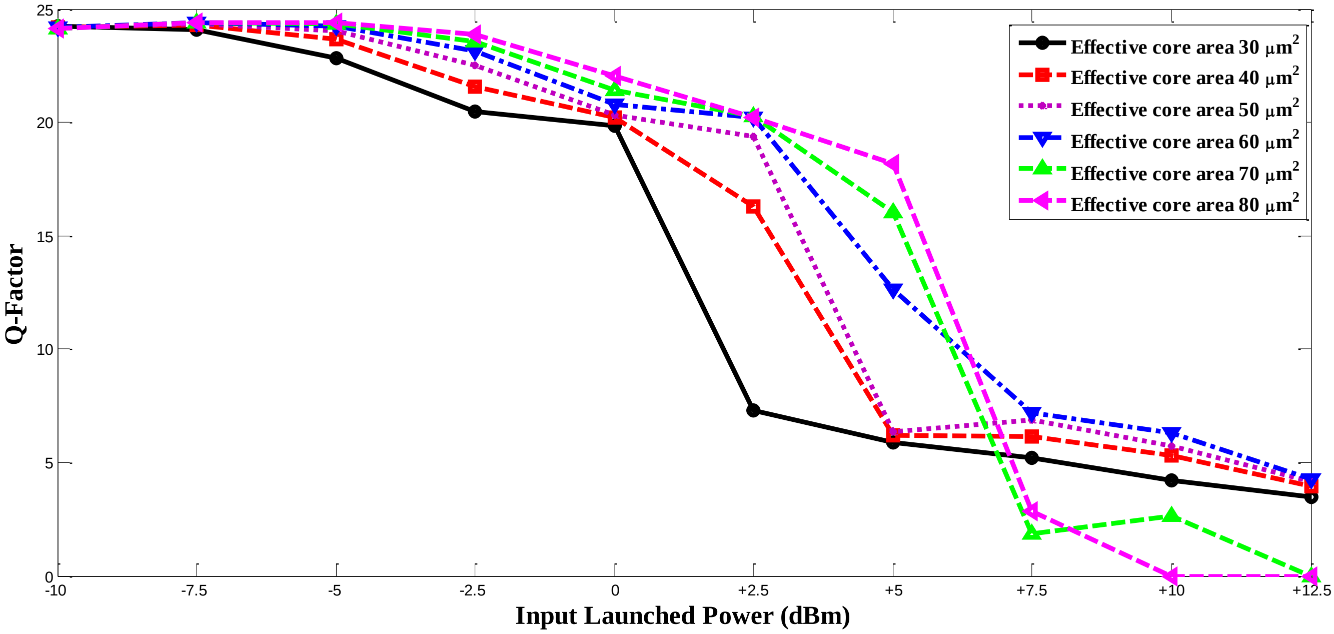

Figure 3.Q-Factor Vs Input Power at Various Values of Effective Core Area Varied from 30 to 80μm²

Now we have also analyzed the effect of SPM by varying the input launched power ranging from -10 to +10 dBm at different values of dispersion ranging from -10 to +10 ps/nm/km with fiber length of 40 km and effective core area of 60 μm² in Table 3.

Table 3 Q-Factor at the Output by Varying Input Power for Different Fiber Dispersion

S.No.	Q-Factor					
	Input Launched Power (dBm)	Fiber Dispersion (ps/nm/km) (-10) (-5) (0) (+5) (+10)				
1	-10	19.08	20.98	24.78	22.37	21.17
2	-7.5	18.52	20.74	24.51	23.09	22.18
3	-5	17.23	19.97	24.37	22.94	23.59
4	-2.5	14.87	18.29	24.36	24.66	23.44
5	0	11.41	15.41	23.45	23.75	23.68
6	2.5	7.51	11.61	21.25	13.42	14.12
7	5	4.55	7.81	20.30	6.38	6.22
8	7.5	6.62	4.51	15.45	4.54	4.24
9	10	7.66	3.44	12.70	2.38	2.20

From the figure 4 we have observed that when the input power increases Q-factor value decreases at different values of fiber dispersion but when the dispersion of fiber is 0 ps/nm/km and input power is -10 dBm we get the maximum value of Q-factor is 24.78 so the effect of SPM in the system is less.

The Q-Factor value decreases with increase in input power due to SPM effect because the effect of SPM has been observed at high power.

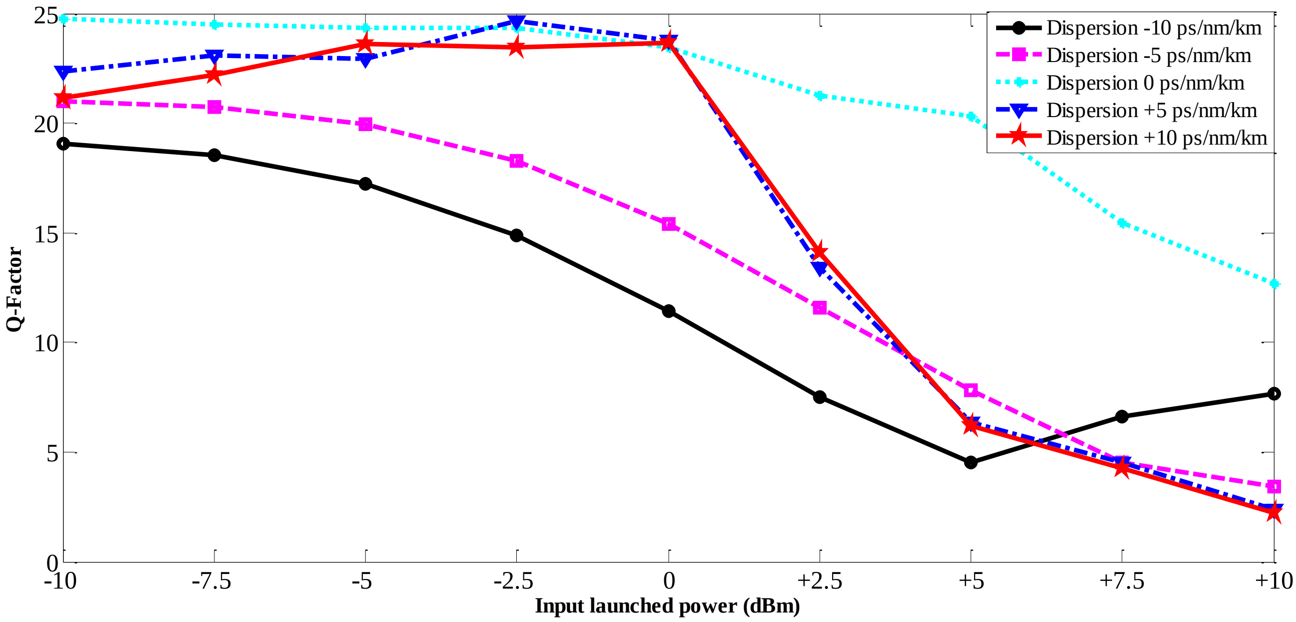

Figure 4.Q-Factor Vs Input Power (dBm) at Various Values of Fiber Dispersion Varied From -10 To +10 (ps/nm/Km)

IV. CONCLUSIONS

We have analyzed the effect of Self Phase Modulation in single mode optical fiber communication system in terms of Quality Factor by varying the optical dispersion at different fiber lengths. From the results presented here in this work, it has been observed that when the fiber length and dispersion increases the Quality factor decreases due to the SPM effect. So it can be seen that system operated at 10 km fiber length with zero fiber dispersion is best values to minimize the effect of SPM. Further we have analyzed the SPM effect by varying input launched optical power at various effective core area of the fiber and observed that Q-factor drastically decreases with increase in input launched power but we get the maximum value of Q-factor of 24 when the system launched with -10 dBm optical power and effective core area of 60 μm^2. These are the typical values of fiber dispersion, fiber length, input launched power and effective core area of the fiber to minimize the effect of SPM without compensating the dispersion.

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