Chapter 2

SYSTEM LEVEL DESIGN OF SSFM COPROCESSOR

SSFM coprocessor design methodology is presented in this chapter at the system level domain. The SSFM coprocessor is a digital, memory intensive unit used in the optical fiber performance parameter estimation. It is capable of computing the dispersion values from the input data and the nonlinearity in terms of the effect on power transmitted. At the RTL level the optimization is done to reduce the computation time. Further data, such as optical fiber specific physical parameters and optical parameters must also be made available as input parameters. For precise system synchronization the control signals and the timing synchronization must be integrated at the hardware design model. In mapping the algorithm to architecture, the test vectors are obtained by simulating the SSFM using high level language. The Matlab™ [6] program has been utilized for functionality testing, parameter selection and input-output test data repository generators. These test vectors are used during hardware modeling of the algorithm. In hardware modeling, the subsystem models are designed to achieve efficiency in terms of speed, area and memory. The memory constraints play a vital role in the hardware design. The performance is measured in
terms of speed, area and memory requirement.

In order to avoid the chaos of changes in one design imparting the entire system performance, subsystem design was first done and integrated to achieve the total functionality. The system level design and analysis done at high level abstraction; provide a complete source of information about the functional flow of the processing modules. Work flow methodology of system level design of SSFM coprocessor is discussed in the next section. We also analyze the effect of dispersion and nonlinearity on the output received power.

2.1 WORK FLOW METHODOLOGY OF THE DESIGN OF SSFM COPROCESSOR

SSFM is used to solve the NLSE equation in wave propagation since it is accurate method to model the real world optical fiber system. Tristan and et.al [7] report the computation time to solve NLSE using SSFM which can be around several days. The reason stated is the long distance optical fibers and large signal bandwidth issues in optical fiber system.

Almost all the profession optical simulators use this popular numerical technique. Several papers report the complexity of the SSFM numerical technique and its software implementation in literature [4, 6]. However, for accurate simulation of SSFM using an FPGA based hardware model with significant reduction in computation time is not found in literature to the best of our knowledge.

This is the first literature where an attempt is made to model it at the
hardware level in this state-of-art semiconductor era. Nevertheless to develop the RTL model domain knowledge of optical communication system, digital signal processing, DSP architecture, VLSI design either ASIC or FPGA based system is a prerequisite. This is due to the fact that SSFM algorithm to architecture mapping is quite complex with various signal processing steps. SSFM [4, 8] is a pseudo-spectral method to solve pulse propagation problem in nonlinear dispersive media.

Figure 2.1 show the work flow methodology to design and develop the SSFM coprocessor. There are four major phases in the design flow are.

1. Performance modelling at system level.
2. Design Deployment Plan (DDP).
3. Architecture Prototyping Phase (APP).
4. Functional Verification (FV).

**2.1.1 Performance modelling at system level**

We investigate the effect of nonlinearity and dispersion performance at high level abstraction using Matlab™. Here we describe the method that is used to obtain the numerical solution of SSFM. The parameters used for this solution are optical fiber physical parameters, time related parameters, frequency domain parameters and a set of parameters to model the input signal appropriately as illustrated in Figure 2.1. The input is modelled as a Gaussian signal, hence a Gaussian signal generator is utilized. The functional model of SSFM [6] is varied for various optical parameters namely the fiber length, chirp is varied for
Figure 2.1: Work flow methodology for the design of SSFM coprocessor
various optical parameters namely the fiber length, chirp parameter and the input frame size to study the behaviour of SSFM.

In this phase there is a whole set of test vectors that are generated which are used at all levels, which eliminate the need of functional difference between the early design phase and post design simulation. The sooner these test plan issues are freezeed in the design mapping flow, the quicker the problem could analyzed, without having to spend more time at the hardware prototype level.

2.1.2 Design Deployment Plan

Evaluation of performance and accuracy of simulation is a requirement in the realization of any system. Therefore, we have a DDP prior to porting the hardware.

SSFM has a compute intensive feature. To study the nonlinear effects and dispersion in the optical fiber NLSE is used. To solve NLSE equation SSFM numeric technique is used. In optical fiber link WDM transmission is utilized. WDM is a large bandwidth transmission system. We need to model the WDM system accurately. This is possible by using large number of Fourier harmonics to cover the entire transmission bandwidth. To analyze these Fourier harmonics in time domain and frequency domain techniques like Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) are used, along with various other complex operations. Hence the SSFM is compute intensive technique.

To study the data communication effect in the long distance optical
fiber, it is partitioned into small segments. In each segments the above mentioned compute intensive operations have to be performed. So a large memory is required to store and retrieve the data. It is worthwhile to develop a simulator in the DDP to estimate the memory capacity and number of usable and reusable memory. Memory simulator is developed to do this task.

An empirical memory access model with the knowledge of the memory simulator results is developed. This model gives us a fair idea about the huge memory accesses involved for SSFM. Hence we conclude in DDP that SSFM is memory intensive and is also compute intensive.

Moving on to the task of architecture the understanding of mathematics involved in the computation of the SSFM is required. In DDP focus is on the understanding of the mathematical model analyzing the data flow from input till it appears as the output. The intermediate steps that are to be processed are studied. We also take a look at the input data to be provided and the output that has to be obtained at each sub-processing steps. Thus DDP gives us a clear scenario of what are the basic hardware modules that are required for each and every step in SSFM.

We visualize the total memory capacity that is used in SSFM from the memory simulator. A close look at the number of memory accesses is obtained to the huge memory units. Also the test vectors repository is obtained as ready reckoner for further validation of the system design.
2.1.3 Architecture Prototyping Phase

This phase consists in assigning every computational step of SSFM a hardware module with adequate logic part to properly realize the total functionality together. The input output analysis in applying to each submodule is done to ensure that there are no errors in the data spanning across the SSFM system. Any data path spanning two or more sub-modules may require same data at a given time slot. To ensure accurate data flow the control unit is designed.

The large hardware cost in this algorithm is in designing the modules to perform FFT/IFFT operation. The success of the system design of the hardware prototype is crucially dependent on the data exchange between the various modules in the system. Therefore we investigate the data flow analysis, identifying which are the operations involved in these steps.

We understand the concept of the intermediate data sharing and analyze the entire execution flow where some intermediate data is utilized by modules in the design flow. This information is provided from the DDP stage using the memory accesses and the memory estimator information. This information was the main basis to plug in the memory simulator to obtain the decision of reusable and non-reusable memory. When the memory estimator has identified the memory block as non-reusable the same data output is used somewhere else in the execution flow. This most vital report from DDP ensures a systematic approach in
this prototyping phase to use the synchronous signals in between various sub-modules.

In architecture prototyping phase the timing issues and synchronization issues are addressed, which provide communication among the hardware blocks. In order to inspect the correctness of the design, the test vectors from the DDP report are utilized.

2.1.4 Functional Verification

After the system level phase, Design Deployment Plan phase and the Architecture Prototyping phase, the functional correctness for the results obtained in these phases is verified. For all the simulation verification we have restricted ourselves to 1024 point FFT computations. Result format obtained in the Matlab™ simulation and VHDL simulations are in different form. Hence for proper comparison with VHDL simulation the Matlab™ data is converted to binary. As expected by us we could find that the results at both levels are matching. Due to this good performance reports, we propose our hardware model in the actual optical fiber communication link with suitable modification in the practical parameters employed for the simulation flow. Before mapping this SSFM algorithm to hardware, a mathematical model of the algorithm is required to be developed. The mathematical model helps us to identify the hardware components and the memory requirement to design the hardware model. The next section of this chapter deals with mathematical modeling of NLSE using SSFM.
2.2 MATHEMATICAL MODELLING OF NONLINEAR SCHRODINGER EQUATION USING SPLIT STEP FOURIER METHOD

The fundamental mathematical model for analyzing pulse propagation is NLSE [4]. In general NLSE is a nonlinear partial differential equation. We know that when the optical pulse propagates through the fiber two distinct distortions occur namely dispersion and nonlinearity. The mathematical model i.e NLSE represents the two physical effects dispersion and nonlinearity in the analog domain. The optical pulse which is propagating is a function of two variables

1. Physical length of the optical fiber \( z \)
2. Time along the propagating distance \( \tau \)

The envelop of the optical pulse in the fiber is associated with electric field \( E(z,t) \). Let us represent \( A \) as the envelop of the optical pulse which is modelled as Gaussian in this work and which forms the input in the propagating medium. Since the envelop \( A \) is a function of two variables \( z \) and \( t \), it can be represented as \( A(z,t) \). In the simplest form the NLSE equation is of the form

\[
\frac{\partial A(z,\tau)}{\partial z} = -\frac{j}{2} \beta_2 \frac{\partial^2 A(z,\tau)}{\partial \tau^2} + j \gamma |A(z,\tau)|^2 A(z,\tau) \tag{2.1}
\]

where \( \beta_2 \) is the second order dispersion, \( \gamma \) accounts for the nonlinear effects occurring in the fiber and \( |A(z,t)|^2 \) represents optical power. The analysis of this can be made by considering two ideal cases.
1. Making the nonlinear term $\gamma = 0$, equation 2.1 is written as

$$\frac{\partial A(z, \tau)}{\partial z} = -j \beta_2 \frac{\partial A(z, \tau)}{\partial \tau^2}$$  \hspace{1cm} (2.2)

The equation can be solved by Fourier transform. The Fourier transform of equation 2.2 is

$$\frac{\partial A(z, \omega)}{\partial z} = -j \frac{1}{2} \beta_2 A(z, \omega)$$  \hspace{1cm} (2.3)

The solution to the above equation is

$$A(z, \omega) = A(0, \omega) e^{-\frac{j \beta_2 \omega^2 z}{2}}$$  \hspace{1cm} (2.4)

Considering equation 2.4, $|A(z, t)| = |A(0, \omega)|$ for all values of $z$. This indicates that during pulse propagation there is no change in the magnitude of frequency components. $\omega$ is frequency component and related to wavelength by $\lambda \omega = 2\pi c$. In Fourier transform $|f(w)|$ represents the amplitude, which measures the strength of frequency component $\omega$. This refers to the spectral width of $|f(w)|$. From the above we infer that in pure linear case when $\gamma = 0$, function $A(z, t)$ broadens linearly with $z$ in time domain. This is referred to as temporal width, which is pulse width of the function $f(t)$. To summarize, the constant $\beta_2$ is responsible for pulse spreading in time domain, while spectral width is invariant.

2. Making the linear term $\beta_2 = 0$, equation 2.1 takes the form

$$\frac{\partial A(z, \tau)}{\partial z} = j \gamma |A(z, \tau)|^2 A(z, \tau)$$  \hspace{1cm} (2.5)
The solution to equation 2.5 is

\[ A(z, t) = A(0, t)e^{-\gamma |A(0, t)|^2 z} \]  

(2.6)

The absolute value \(|A(z,t)|\), which is a pulse envelop, does not change with \(z\). The exponent of equation 2.6 which is imaginary introduces new frequencies which cause spectral width to spread.

Summarizing the above two cases \(\beta_2\) leads to temporal spreading and \(\gamma\) leads to spectral spreading of the pulse as shown in Figure 2.2.

As the pulse spectrum broadens due to nonlinearity there would be mismatch in velocities of spectral components thus causing temporal pulse broadening. The above analysis shows that when pulse propagation is considered in optical fibers, the performance parameters, nonlinearity and dispersion are considered to act mutually exclusive. One should also notice that the nonlinearity and dispersion should be, computed to validate the performance parameters of the optical fibers. It is now required to solve NLSE to understand various impairments occurring during signal transmission. In general NLSE describes dispersion and nonlinearity which act together in optical waveguide. A numerical approach is necessary to understand these effects in optical fiber. Many numerical methods have been developed [7, 9], out of which there are two broad categories namely finite difference method and pseudo-spectral method [2, 4]. Split step Fourier method (SSFM) [4, 7] is a pseudo-spectral method to solve pulse propagation problem in
nonlinear dispersive media. The central idea in SSFM is to find the approximate solution to NLSE by assuming that nonlinearity and dispersion act independently [4].

### 2.2.1 Split Step Fourier Method

SSFM method consists of two major stages namely linear section and nonlinear section.

- The linear part is solved in frequency domain analytically.
- The nonlinear part is solved in time domain using Fourier Transform.

Figure 2.2: Effect of dispersion and nonlinearity on Gaussian pulse.
SSFM gives an approximate solution as discussed above. This is done by propagating light pulse in the optical fiber for small distance. For this small distance the dispersion and nonlinearity are said to act independently.

To apply SSFM the complete length of the fiber is split into small segments of step size $h$. The step size may be of equal size or different. Each step size $h$ is again divided into three small segments. In the first and the second half segments dispersion alone acts and at the centre of the segment nonlinearity acts. Consider an optical fiber of length 500 Km as shown in the Figure 2.3. This fiber is split into small segments of equal step size of 4 Km. This step size of 4 Km is again divided into three segments. In the first and the third segment dispersion is computed and at the centre the nonlinearity effect is considered.

The NLSE equation
\[
\frac{\partial A(z, \tau)}{\partial z} = -\frac{j}{2} \beta_z \frac{\partial^2 A(z, \tau)}{\partial \tau^2} + j \gamma |A(z, \tau)|^2 A(z, \tau) \quad (2.7)
\]

Which can be written as
\[
\frac{\partial A(z, \tau)}{\partial z} = (L + N)A(z, \tau) \quad (2.8)
\]

where \(L\) and \(N\) are linear and nonlinear operators. The propagation of the pulse from \(z\) to \(z + h\) is made in three steps. To estimate the accuracy of SSFM the exact solution to equation 2.8 is
\[
A(z + h, t) = \exp \left(h(L + N)\right)A(z, t) \quad (2.9)
\]
To obtain better accuracy the solution can be further written as
\[
A(z + h, t) = \exp \left(\frac{h}{2} L\right) \exp \left(\int^h_{-h} N(z)dz\right) \exp \left(\frac{h}{2} L\right) \quad (2.10)
\]

here the nonlinearity effect is included at the centre of the segment.

### 2.2.1.1 Optical fiber parameters

Optical fibers used in the communication system are connected in between long distances. Suitable parameters are a pre-requisite to compute the performance of pulse propagation using SSFM. We can classify the parameters as those related to optical fiber link, input pulse modelling and performance analysis parameters. For our simulation we use the parameters that are specified in [6] for a single channel transmission link. Table 2.1[6] lists the optical fiber link parameters as centre wavelength \(\gamma\) is \(1.55 \times 10^{-9}\) km, speed of light \(c\) is \(3 \times 10^5\) km s\(^{-1}\). Since we are finding the effects of non-linearity on pulse propagation in optical fibers an initial value to start with namely non-linear factor \(\gamma\) is taken as
0.0024 km mw$^{-1}$. We also access the effect of dispersion in the optical fiber along the complete optical fiber length. We start with an initial value of dispersion parameter $\beta_2$ as $2.5491e^{-24}$ sec$^2$ km$^{-1}$.

We need to access the non-linearity and the dispersion for an input Gaussian pulse. For this input pulse which is Gaussian the initial peak power $P_0$ is taken as 1 mW with a chirping parameter $C_0$ as 0, with a super Gaussian parameter $m$ as 1. The effect of output power for a given input peak power is to be observed and hence an initial pulse width $t_0$ as $5 \times 10^{-12}$ sec is taken. These parameters [6] are shown in Table 2.2. To compute the non-linearity and dispersion in the optical link performance analysis parameters are required. The optical fiber length is taken as

<table>
<thead>
<tr>
<th>Centre wavelength $\lambda$</th>
<th>1.55 e$^{-9}$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of light $c$</td>
<td>$3 \times 10^5$ km s$^{-1}$</td>
</tr>
<tr>
<td>Nonlinear factor $\gamma$</td>
<td>0.0024 km mw$^{-1}$</td>
</tr>
<tr>
<td>Dispersion parameter $\beta_2$</td>
<td>$2.5491e^{-24}$ sec$^2$ km$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial peak power $P_0$</th>
<th>1 mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chirping parameter $C_0$</td>
<td>0</td>
</tr>
<tr>
<td>Super-Gaussian parameter $m$</td>
<td>1</td>
</tr>
<tr>
<td>Initial pulse width $t_0$</td>
<td>$5 \times 10^{-12}$ sec</td>
</tr>
</tbody>
</table>
500 Km segmented into M with each segment of 4 Km. To model the pulse propagation we have earlier presented that the transmission consists of Fourier harmonics. These Fourier harmonics can be analyzed in the digital domain using FFT and IFFT. Therefore we should freeze the length N of the FFT to be used. We used 1024 point FFT in the design simulation of the SSFM unit. These parameters are shown in Table 2.3.

**2.2.1.2 Computational steps in segmented SSFM**

Figure 2.4 show the optical fiber of length 500 Km segmented into 125 partitions each of 4 Km. The computations in SSFM are done in each segment. Hence SSFM is computed for 125 times to cover a fiber length of 500 Km. For example in the $z^{th}$ segment of 4 Km the effect of dispersion is studied for the first $(z + 2)$ Km, at the centre the effect of non-linearity is observed and for the next $(z + 2)$ Km dispersion is again observed. The details of each segment computation are presented below.

**Figure 2.4: Schematic for one step SSFM**
1. **Studying the propagation of the pulse in the first half of the dispersive region from** $z$ to $z + \frac{h}{2}$

This requires solving the linear part. The solution to this part is obtained in frequency domain. The Gaussian pulse which is generated in time domain has to be converted to frequency domain. This helps us to know the amount of the frequency component $\omega$ affected due to dispersion. To convert Gaussian pulse from time domain to frequency domain, a Digital Signal Processing (DSP) tool Fourier Transform (FT) is used. Taking FT on the Gaussian pulse $A(z, t)$ in discrete domain.

$$A(j\omega) = \sum_{n=0}^{N-1} A(n)e^{j\omega n} \quad (2.11)$$

To analyze the effect of dispersion, a dispersion exponent operator $D_h$ is defined considering the effect of dispersion factor $\beta_2$ and the first half propagation distance $\frac{h}{2}$. This operator is single dimension complex operator computed to the FT-length. To study the effect, it is superimposed with the complex input field. Each complex element of dispersion operator is to be multiplied with the corresponding complex
input element. This operation is performed using a dot vector multiplier. This is an element by element multiplication. The \(i^{th}\) element of dispersion operator is multiplied with the \(i^{th}\) element of the discrete Gaussian pulse.

\[
H_f = D_h \cdot A(j\omega)(i) \quad i \in (0, N-1)
\]

(2.12)

The propagated signal \(H_f\) thus obtained describes the propagation of the pulse affected by dispersion for the first half step i.e. \(z\) to \(z + \frac{h}{2}\).

2. **Studying the effect of nonlinearity at the centre of the step** \(z + \frac{h}{2}\).

In SSFM the effect of nonlinearity is studied at the centre of the simulation step. To estimate the effect of nonlinearity the dispersed pulse which is in frequency domain is to be converted to time domain. This conversion can be done by using IFFT as a Fourier tool in DSP domain.

\[
h_n = \frac{1}{N} \sum_{n=0}^{N-1} H_f e^{jn\omega}
\]

(2.13)

The nonlinear effects are observed at various light intensities. These are associated with electric field or energy of the incident radiation. Energy spectral density describes the distribution of energy with frequency. If energy in a signal is calculated then its complex amplitude has to be multiplied by the conjugate of the complex value. For an \(i^{th}\) signal value
h_{nl}(i) represents the energy or signal intensities in a signal and this is given by equation 2.14.

\[ h_{nl}(i) = (h_{real}(i) + \text{i} h_{img}(i)) \cdot (h_{real}(i) - \text{i} h_{img}(i)) \quad i \in (0, N-1) \]  

(2.14)

To mitigate the effects of optical non-linearities in fiber the signal intensity of time signal is multiplied with nonlinearity factor $\gamma$ and is represented as $h_{ng}(i)$ for the $i^{th}$ signal value.

\[ h_{ng}(i) = h_{nl}(i) \times \gamma \quad i \in (0, N-1) \]  

(2.15)

Equation 2.15 can be written in terms of real and imaginary parts to superimpose the effect of $\gamma$ on the time signal. This is obtained by first taking exponent and performing the dot vector multiplication.

\[ h_{nl}(i) = h_{nl}(i) \cdot e^{h_{nl}(i)} \quad i \in (0, N-1) \]  

(2.16)

Equation 2.16 thus obtained, depicts the effect of nonlinearity at the centre of the step $z + \frac{h}{2}$.

3. **Studying the propagation of the pulse in the second half of the dispersive region** $z + \frac{h}{2}$ **to** $z + h$.

The third step in SSFM is to study the effect of dispersion during second half of the dispersive region. This is a linear part whose solution is obtained in frequency domain. To convert the time domain pulse $h_{nl}$ to frequency domain FFT is used. The signal is represented as $h(j\omega)_{sec}$.
To analyze the effect of dispersion from $z + \frac{h}{2}$ to $z + h$, a dispersion exponent operator $D_h$ is defined considering the effect of dispersion factor $\beta_2$ and the second half propagation distance $\frac{h}{2}$. This operator is single dimension complex operator equal to the FT-length. To study the effect this, it is superimposed with $h(j\omega)_{sec}$. Each complex element of $D_h$ is multiplied with the corresponding element $h(j\omega)_{sec}$. This operation is performed using a dot vector multiplier. The output thus obtained is represented as $h_{fsec}$.

$$h_{fsec}(i) = D_h(i)^* h(j\omega)_{sec}(i) \quad i \in (0, N-1)$$  \hfill (2.18)

The propagated signal $h_{fsec}$ thus obtained describes the propagation of the pulse affected by dispersion for the second half step i.e, $z + \frac{h}{2}$ to $z + h$. These three steps are repeated for the entire length of the fiber of 500Km as shown in Figure 2.4. The input Gaussian pulse is made to propagate through a fiber of length $z$. This length is split into step size $h$. The above mentioned three steps are depicted in the Figure 2.4. The output pulse is Gaussian pulse, affected by dispersion and nonlinearity. The output pulse $A(z,t)$ has undergone temporal spreading and spectral boarding. Upto now we have seen the details of the computational steps.
in a single optical segment during SSFM execution. We have also illustrated the design methodology used in our approach with various phases. In the next section we present the simulation results of the system level design phase where the modeling is done using Matlab™.

2.3 SYSTEM LEVEL SIMULATION

The input Gaussian pulse is made to propagate through a fiber. The effects of dispersion and nonlinearity are superimposed on the Gaussian pulse. This pulse is first exposed to dispersion only neglecting the effect of nonlinearity. Further the pulse is exposed to nonlinearity neglecting the effect of dispersion.

2.3.1 Experimental set up

The simulation set up used to obtain the results is the Matlab™ model [46]. The input parameters are taken from Table 2.1, Table 2.2 and Table 2.3 from previous section. These input parameters and input signal parameters are used to generate a Gaussian input pulse which propagates along the optical fiber length. The functional model of the SSFM does all the signal processing steps in SSFM. The main objective of this experimental set up are

- To study the behaviour of the system and its effects on dispersion and non-linearity on the received power for a given length of optical fiber.
- To study the effect of varying chirp parameter for various length of optical fiber.
• To vary the length of the optical fiber and observe the effect on received power when the effect of dispersion and non-linearity are assessed.

• To generate the test vector repository which will be used to validate the behaviour of SSFM at the system level and the hardware prototyping level.

These results obtained at both the levels are functionally validated during the last phase of our design process.

In the experimental results presented by various researchers for SSFM simulator [10, 11] we have not come across the study on the received power varying chirp parameter. In our experimental results we present the results for the variation in chirp parameter also.

2.3.2 Effect of propagation distance on received power

The change of received power as the propagation distance varies is depicted in Figure 2.5. To study the effect of propagation distance on the received power the propagation distance is varied for fixed chirp of $C = 0$. As shown in the figure 2.5 for a propagation distance of 300 Km the received Gaussian pulse shows a power is $1 \text{mW}$. As the propagation distance increases to 350 Km the Gaussian pulse shows a power $0.35 \text{mW}$. A reduction of 65% of received power is observed as the propagation distance increases by 50 Km. Hence propagation distance becomes the key parameter in the estimating the effect of dispersion and nonlinearity on pulse.
2.3.3 Effect of chirp

A pulse can acquire a chirp during propagation in a transparent medium due to the effects of chromatic dispersion and nonlinearities (e.g. self-phase modulation arising from the Kerr effect). The effect of chirp on the received power is shown in Figure 2.6 and Figure 2.7. For the propagation distance of 200 Km, chirping factor $C = 0$ the received power is $80\text{mw}$ and the width of the pulse is $1.5 \times 10^{-9}$ ns.
Figure 2.6: Variation of chirp on the received power

As the chirping factor increases to $C = 5$, the power received is 38 mw and the width of the received pulse is $3 \times 10^{-9}$ ns. The experimental results show that as the chirping factor increases the pulse broadens. This is depicted in Figure 2.6. This broadening of pulse results in reduction of received power at the output. With increase in chirping factor the output
Figure 2.7: Effect of chirp on received power

power reduces by 79.52%. Hence another key parameter in the estimation of effect of dispersion and nonlinearity on pulse is chirp.

2.4 SUMMARY

Considering the key parameters the split step Fourier algorithm is mapped to hardware architecture. The system design approach that we have adopted in this design flow facilities developing test benches/test vectors and provides a quick reference to verify the functionality of the subsystem that are designed. The system level approach gave us an inside into the complexity of the design modules at an early stage in the
design cycle. Critical design issues like

1. Memory intensive models.
2. Compute intensive subsystem.

were recognized in the beginning of the design phase even before mapping the entire system into hardware model. Major decisions like total memory capacity of the entire design created interest and was a major motivation to develop our memory estimator to depict the memory requirement. The memory estimator is discussed in the next chapter.