Simulation of Single Mode Fiber Optics and Optical Communication Components Using VC++

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Abstract:

Single mode optical fibers have already been one of the major transmission media for long distance telecommunication, with very low losses and high bandwidth. The most important properties that affect system performance are fiber attenuation and dispersion. Attenuation limits the maximum distance. While dispersion of the optical pulse as it travels along the fiber limits the information capacity of the fiber. But using of optical amplifiers allows us to eliminate the limiting of the length of section between the transmitter and the receiver. Evaluating the performance of optical fiber communication systems using only analytical techniques is very difficult. In these cases it is important using computer aided techniques, like simulation, to study the performance of these systems. This paper presents a simulation, using VC++, for testing outputs of some of optical communication components like amplifiers, and filters, used in single mode optical fiber systems for compensating the attenuation and dispersion caused by the long distance.

Keywords: Fiber optic systems, Attenuation, Dispersion, Optical communication components.

1- Introduction:

Light wave communication systems, using optical fibers as the communication medium, for transmission networks started at 1980. Because of the low-loss and wide-bandwidth transmission characteristics of optical fibers, they are ideally suited for carrying voice, data, and video signals in a high-information-capacity system, [1]. Fibers that are used for optical communications are wave-guides made of transparent dielectrics whose function is to guide visible and infrared light over long distances, [2]. Signal loss and system bandwidth describe the amount of data transmitted over a specified length of fiber. Many optical fiber properties increase signal loss and reduce system bandwidth, [3,4].

An optical signal will be degraded by attenuation and dispersion as it propagates through the fiber optics. Dispersion can sometime be compensated or eliminated through an excellent design, but attenuation simply leads to a loss of signal, [5,6]. Eventually the energy in the signal becomes weaker and weaker so that it cannot be distinguished with sufficient reliability from the noise always present in the system, an error occurs. Attenuation therefore determines the maximum distance that optical links can be operated without amplification. For longer distance optical amplifiers are needed. In general, when a system has a very high bandwidth used over a long distance, a single-mode fiber is used, [3].

2- Attenuation:

Attenuation is the loss of optical power as light travels along the fiber. This loss or attenuation, in fiber depends on the wavelength of the light propagating within it. There are three main bandwidth 'windows' of interest in the attenuation spectrum of fiber. The 1st window is at 800-900nm, here there is a good source of cheap silicon based sources and detectors. The 2nd window is at 1260-1360nm, here there is low fiber attenuation coupled with zero material dispersion. The 3rd window of interest is at 1430-1580nm where fiber has its attenuation minimum. Typically the telecommunications industry use wavelengths in the 3rd window which coincides with the gain bandwidth of fiber amplifiers. Signal attenuation is defined as the ratio of optical input power (P_i) to the optical output power (P_o). Optical input power is the power injected into the fiber from an optical source. Optical output power is the power received at the fiber end or optical detector. The following equation defines signal attenuation as a unit of length, [7]:

$$attenuation = \frac{10}{L} \, log_{10}\left(\frac{P_i}{P_o}\right)$$

(1)

where (L) is the fiber length expressed in kilometres, and the attenuation is measured in dB/km.. Attenuation is caused by absorption, scattering, and bending losses, [5]. Each mechanism of loss is influenced by fiber-material properties and fiber structure. However, loss is also present at fiber connections. Attenuation increases with the distance through the fiber optic as illustrated in figure (1).
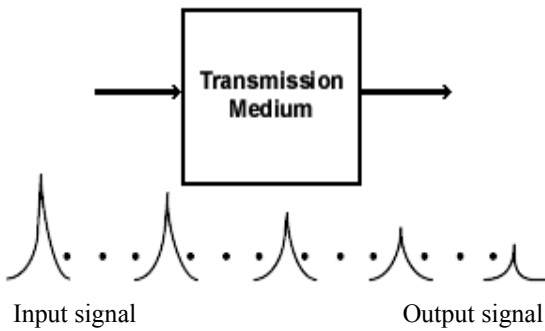

Figure(1): Input data signal attenuating as it propagates down a fiber optic.

As propagation continues attenuation increases. Ultimately, the propagating signal is attenuated until it is at some minimal, detectable, level. That is, the signal is attenuated until it can just be sensed by the receiver in the presence of whatever interference is expected. The distance at which the signal reaches this minimal level could be quite significant. The fiber optic has to be able to deliver at least the minimal detectable level of output signal to the receiver. If it cannot, communications between source and receiver really cannot take place. To getting around this, suppose the signal has been attenuated to the minimal detectable level yet it has still not arrived at the receiver. The output signal at this location can then be regenerated, [8]. The signal can be boosted back up to its original energy level using optical amplifiers. It can be repeated and then continue to propagate on its way to the receiver. This is shown in figure (2).
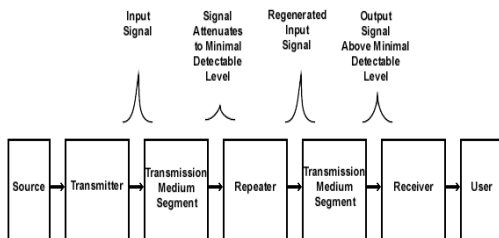

Figure (2): Regenerating and repeating an attenuated signal in order to reach the user.

3- Dispersion:

Light from a typical optical source will contain a finite spectrum. The different wavelength components in this spectrum will propagate at different speeds along the fiber eventually causing the pulse to spread. When the pulses spread to the degree where they 'collide' it causes detection problems at the receiver resulting in errors in transmission. This is called Intersymbol Interference (ISI). Dispersion (sometimes called *chromatic dispersion*) is a limiting factor in fiber bandwidth, since the shorter the pulses the more susceptible they are to ISI, [9].

Dispersion spreads the optical pulse as it transmits along the fiber, as shown in figure (3). This spreading of the signal pulse reduces the system bandwidth or the information-carrying capacity of the fiber. Dispersion limits how fast information is transferred. An error occurs when the receiver is unable to distinguish between input pulses caused by the spreading of each pulse, [10].
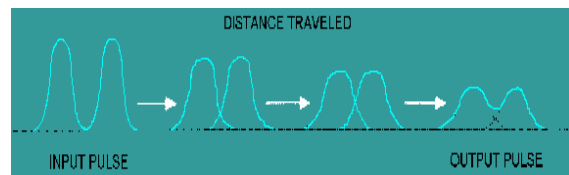

Figure (3): The dispersion along the fiber.

There are two different types of dispersion in optical fibers. The first type is intermodal, or modal, dispersion (β_1) occurs only in multimode fibers. The second type is intramodal, or chromatic, dispersion occurs in all types of fibers. Each type of dispersion mechanism leads to pulse spreading. As a pulse spreads, energy is overlapped, [11]. This condition is shown in figure (4).
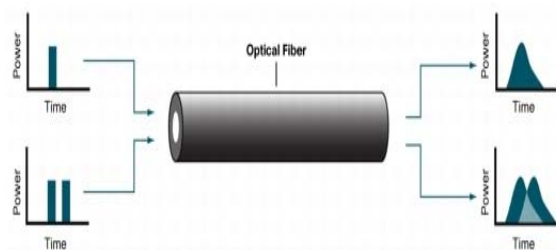

Figure (4): Pulse overlap.

There are two types of intramodal dispersion. The first type is material dispersion (β_2). The second type is waveguide dispersion (β_3).

Intramodal dispersion occurs because different colors of light travel through different materials and different waveguide structures at different speeds. Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Different wavelengths travel at different speeds in the fiber material. Different wavelengths of a light pulse that enter a fiber at one time exit the fiber at different times. Material dispersion is a function of the source spectral width. The spectral width specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths. Waveguide dispersion occurs because the mode propagation constant is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding, [12].

4- Optical Amplifiers

With the demand for longer transmission lengths, optical amplifiers have become an essential component in long-haul fiber optic systems. Semiconductor optical amplifiers (SOAs), erbium doped fiber amplifiers (EDFAs), and Raman optical amplifiers lessen the effects of dispersion and attenuation allowing improved performance of long-haul optical systems. Semiconductor optical amplifiers (SOAs) are essentially laser diodes, without end mirrors, which have fiber attached to both ends, [8,13]. They amplify any optical signal that comes from either fiber and transmit an amplified version of the signal out of the second fiber. SOAs are typically constructed in a small package, and they work for 1310 nm and 1550 nm systems. In addition, they transmit bi-directionally, making the reduced size of the device an advantage over regenerators of EDFAs. However, the drawbacks to SOAs include high-coupling loss, polarization dependence, and a higher noise figure, [14].

The explosion of dense wavelength-division multiplexing (DWDM) applications, make erbium doped fiber amplifiers (EDFAs), an essential fiber optic system building block. EDFAs allow information to be transmitted over longer distances without the need for conventional repeaters, [15]. The fiber is doped with

erbium, a rare earth element, which has the appropriate energy levels in their atomic structures for amplifying light. EDFAs are designed to amplify light at 1550 nm. The device utilizes a 980 nm or 1480nm pump laser to inject energy into the doped fiber. When a weak signal at 1310 nm or 1550 nm enters the fiber, the light stimulates the rare earth atoms to release their stored energy as additional 1550 nm or 1310 nm light. This process continues as the signal passes down the fiber, growing stronger and stronger as it goes. Figure (5) illustrates the first three applications for optical amplifiers.
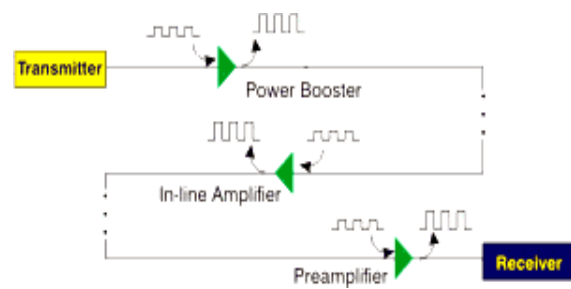

Figure (5) - Three Applications for an EDFA

1- Power amplifiers (also referred to as booster amplifiers) are placed directly after the optical transmitter. This application requires the EDFA to take a large signal input and provide the maximum output level. Small signal response is not as important because the direct transmitter output is usually -10 dBm or higher. The noise added by the amplifier at this point is also not as critical because the incoming signal has a large Signal-to-Noise Ratio (SNR).

2- In-Line Amplifiers: In-line amplifiers or in-line repeaters modify a small input signal and boost it for retransmission down the fiber. Controlling the small signal performance and noise added by the EDFA reduces the risk of limiting a system's length due to the noise produced by the amplifying components.

3- Preamplifiers: Past receiver sensitivity of -30 dBm at 622 Mb/s was acceptable; however, presently, the demands require sensitivity of -40 dBm or -45 dBm. This performance can be achieved by placing an optical amplifier prior to the receiver. Boosting the signal at this point presents a much larger signal into the receiver, thus easing the demands of the receiver design. This application requires careful attention to the noise added by the EDFA; the noise added by the

amplifier must be minimal to maximize the received SNR.

All the amplifiers that used in the fiber optic systems will add noise. In the simulation white Gaussian noise is supposed, and its statistical equation used to expect the amount of random noise in the amplifier.

5- Filters:

There are many types of filters used for removing the noise from the signal transmitted along the fiber. In this simulation two types of filters are used, [16]. The first type is Super Gaussian filter expressed as:

$$F(f) = e^{-\frac{1}{2}\left(\frac{f_{cent} - f_{filter} + df}{\Delta f}\right)^{2n}} \tag{2}$$

The second type is Fabry Perot filter, [17,18] expressed as:

$$F(f) = \sqrt{e^{-\Delta f \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(2\pi \frac{f_{cent} - f_{filter} + df}{T_{filter}}\right)\right)}} \tag{3}$$

where f_{cent} is the center frequency of the filter.

   F_{filter} is frequency of the filter.

   df is the sampling frequency.

   T_{filter} is the period of the filter.

6- Simulation:

In general, a simulation is a computer model of a part of a real-world system, [19,20]. In this paper the simulation is a computer model of a single mode optical fiber link system, includes attenuation function, dispersion function, nonlinear effective function, and propagation function. The method of propagation is divided the path length of signal propagation in steps to add the effective of attenuation, dispersion, and nonlinear in every step. This method called split-step Fourier, [21], shown in figure (6).
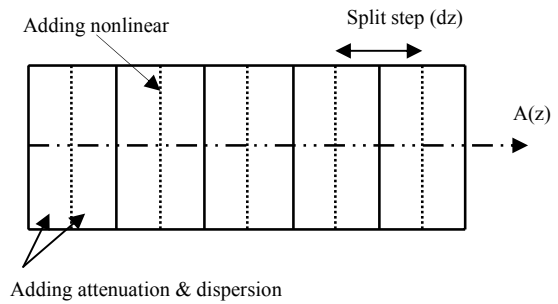

Figure (6): Split-step Fourier method.

The following equations are the attenuation, [22], dispersion, and nonlinear effective, [23] equations, used in the simulation.

$$attenuation = e^{\frac{-\alpha}{2} \times \frac{dz}{2}} \tag{4}$$

where: α is the attenuation factor.

dz is split-step distance as shown in the figure (5).

$$dispersion = e^{i\left(\beta_1 \frac{\omega}{2} + \beta_2 \frac{\omega^2}{2} + \beta_3 \frac{\omega^3}{2}\right) \times \frac{dz}{2}} \tag{5}$$

For single mode fiber intermodal, or modal, dispersion equal to zero ($\beta_1 = 0$),

$$\beta_2 = \frac{\lambda^2 \times D_1}{-2\pi c} \tag{6}$$

$$\beta_3 = -\frac{1}{(2\pi c)^2}\left(D_3 + \frac{2D_2}{\lambda_{ref}}\right)\lambda_{ref}^4 \tag{7}$$

where C is the velocity of light free space.

   D_2 is the second order dispersion.

   D_3 is the third order dispersion.

$$nonlinear = e^{\frac{2\pi N_{ref} J}{\lambda A_{eff}} \times dz} \tag{8}$$

where I = |signal|^2

n$_2$ is the nonlinear factor.

A$_{eff}$ is the effective cross-section area of the fiber's core.

The propagation of the light signal in the fiber optic system is given by the flow chart, [24,25], shown in figure (7). The attenuation effect can be added either in time domain or in frequency domain. In the simulation the attenuation has been added in time domain. But when the dispersion effect is added, it must be add in frequency domain. While the nonlinear effect is add in time domain. The signal transform from domain to another domain can made using Fast Fourier Transform (FFT), [26].

7- The input signal:

The input signals are the signals that will transmit through the fiber link, or, the output signals of the light sources. These signals are converted in to a shape that the computer can deal with it. So, the input signal must first be represented in the form of a numeric array. The array contains samples of the amplitude profile at N equally spaced points. The sampling resolution must be fine enough to resolve all spatial features of the amplitude profile, at the same time it must sparse enough to allow reasonable processing speed on a computer. The type of pulses that used in the simulation is Gaussian pulse, [27]:

$$A(t) = A_0 exp\left\{-\frac{(t-t_0)^2}{2\sigma^2}\right\} \qquad (9)$$

With full width at half amplitude:

$$\tau = \sqrt{ln2}\tau_e = 0.833\tau_e \qquad (10)$$

and with root-mean-square pulse width:

$$\sigma = \frac{\tau_e}{2\sqrt{2}} = 0.354\tau_e = 0.425\tau \qquad (11)$$
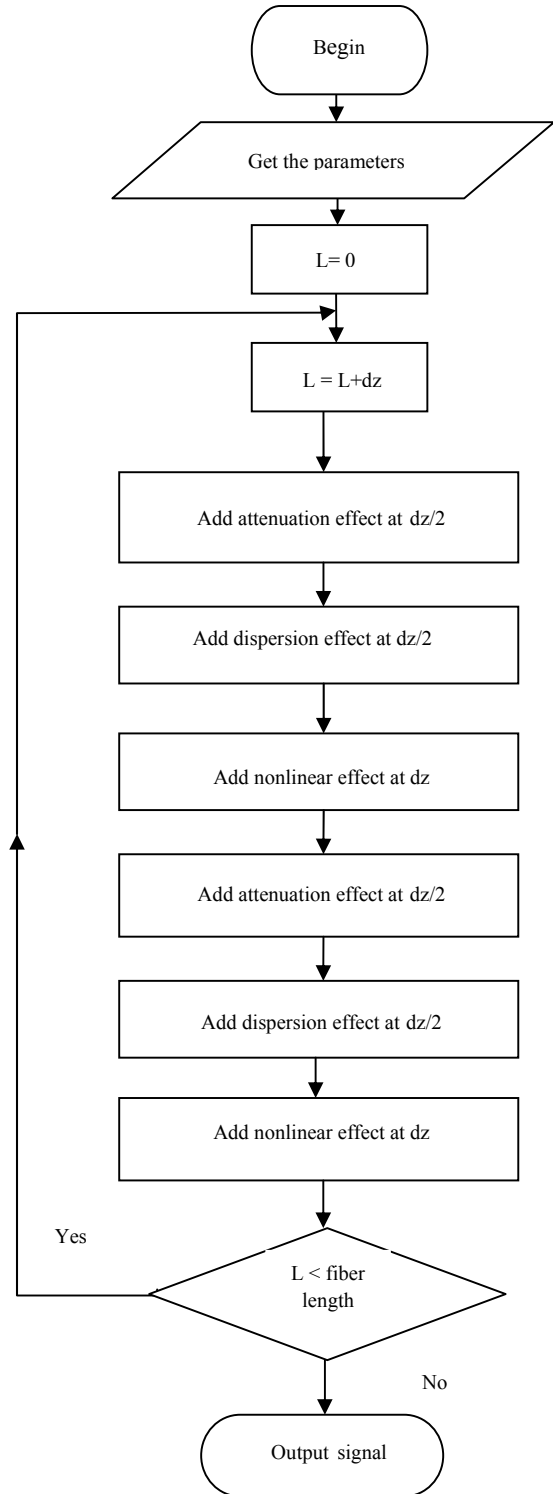

Figure (7): Flow chart of light propagation in the fiber.

The Gaussian pulse is used because the optical sources have a distribution of power with wavelength that is approximately Gaussian distribution in form, as shown in figure (8).
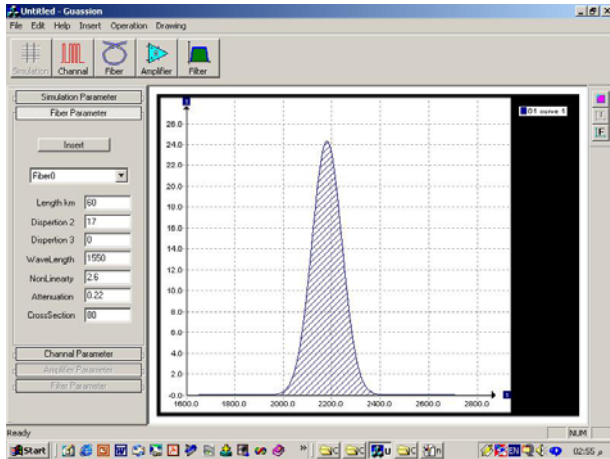

Figure (8): Gaussian pulse.

8- Results and discussion:

In the simulation Gaussian pulse has taken as an input signal and studies all effects that change its shape due to attenuation, dispersion and nonlinearly. In the first example the output taken at a distance 25 km, while in the second example the output is taken at a distance 60 km. Figures (9)-(16), illustrate the effects of attenuation, dispersion, and nonlinearity of the fiber for the two examples.

It is clear from the comparison between the results of the two examples that the attenuation, the dispersion and the nonlinearly effects increase when the distance of communication through the fiber optics is increase. Therefore, repeaters are necessary for long-distances fiber optic systems when the signals be very weak. Optical in-line amplifiers must be used as repeaters for compensating the attenuation affects. The amplifiers add noise, so it is necessary to use filters after the amplification of the signal. The filter removes the effects of the noise, as shown in figure (18) and figure (19).
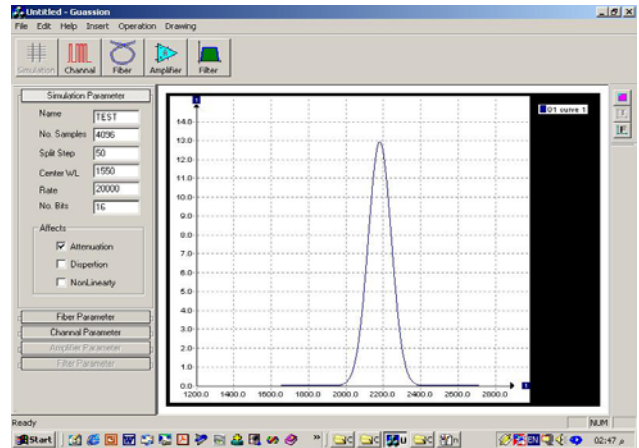

Figure (9): Attenuation effects at 25 km distance.
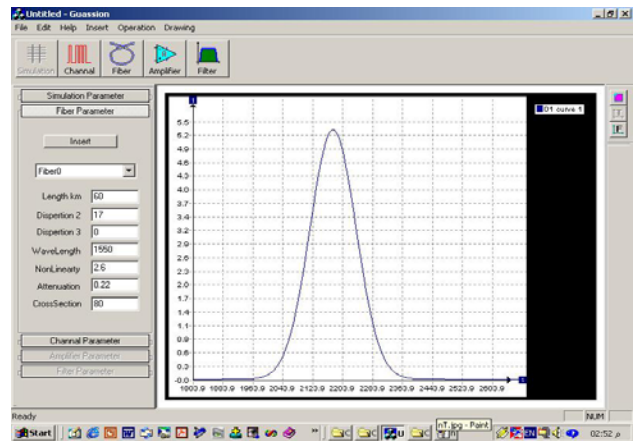

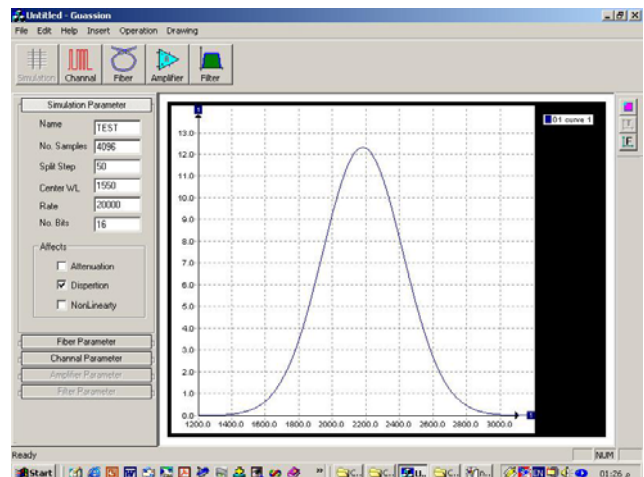Figure (10): Attenuation effects at 60 km distance.

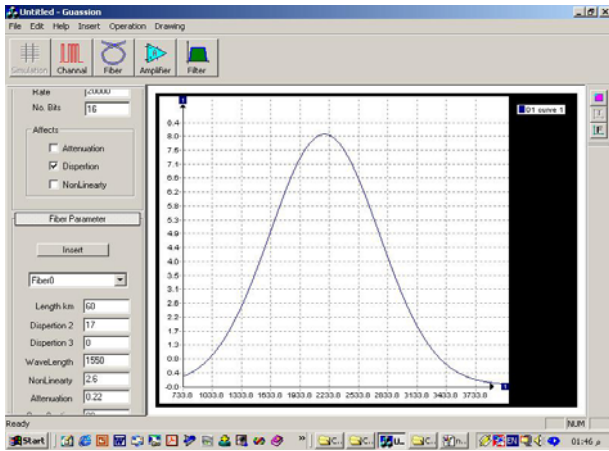Figure (11): Dispersion effects at 25 km distance.

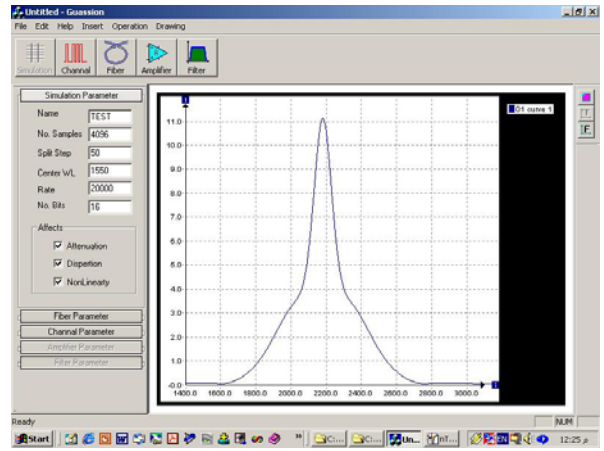Figure (12): Dispersion effects at 60 km distance.

Figure (15): All effects at 25 km distance.
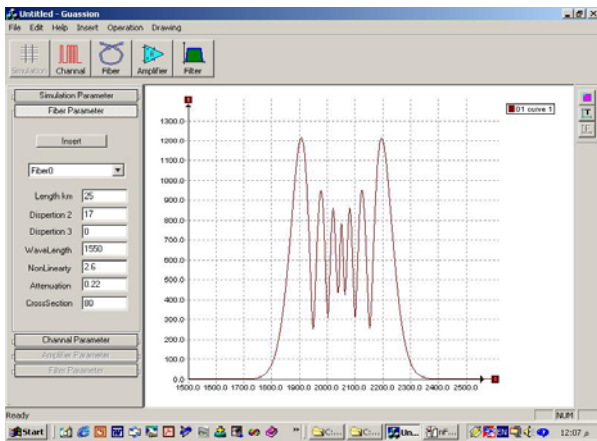

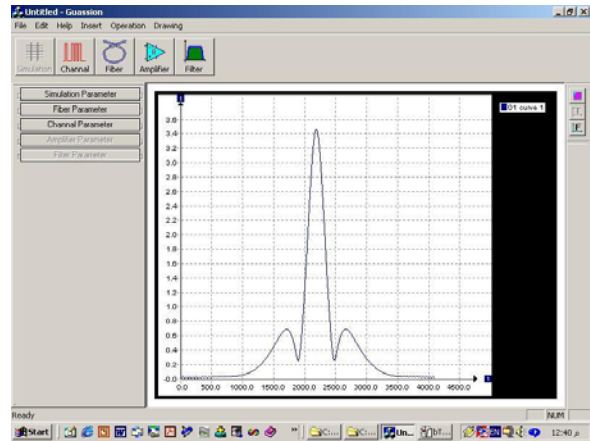Figure (13): Nonlinear effects at 25 km distance.

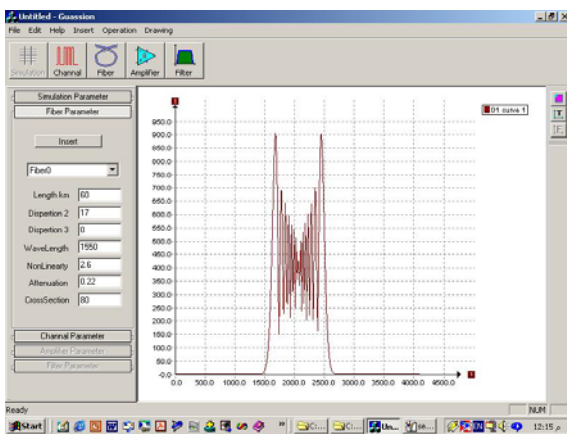Figure (16): All effects at 60 km distance.

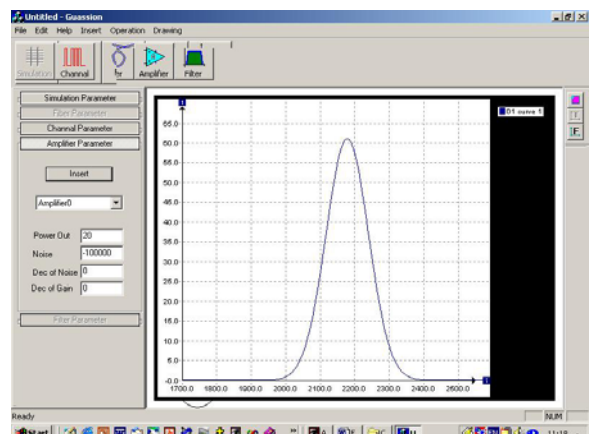Figure (14): Nonlinear effects at 60 km distance.

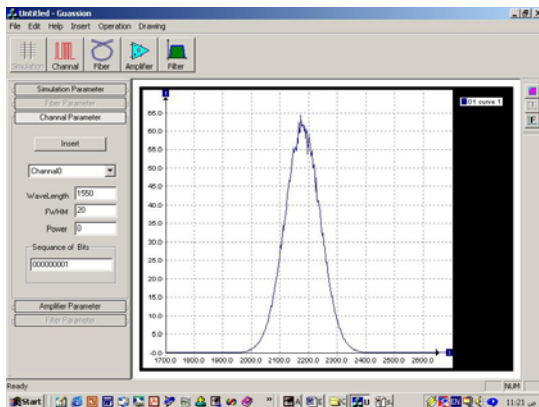Figure (17): The output using ideal amplifier.
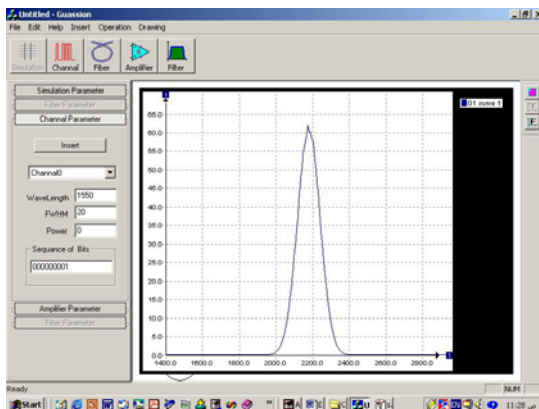
Figure (18): The output using practical amplifier.

Figure (19): The output using amplifier and filter.

9- Conclusion:

In this paper, simulation methods are presented on a single mode optical fiber link system, using VC++. The signal with wavelength of 1550 micrometer was used, to study the effects of attenuation, dispersion, and nonlinear through the fiber optic length by numerical simulations. The results indicate that these effects increase with increasing the distance through the fiber optic length. As propagation continues attenuation increases. Ultimately, the propagating signal is attenuated until it is at some minimal, detectable, level. At this distance we used amplifiers to regenerate the optical signal and to eliminate the effects of the attenuation. We supposed this distance at 25 km in the first example, and 60 km in the second example.

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