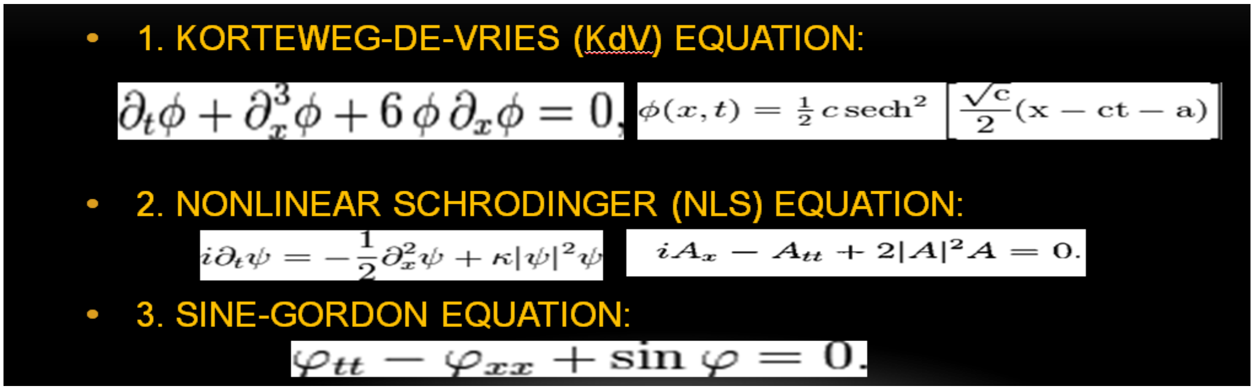
[8] C. C. McAndrew, "Useful numerical techniques for compact modeling," in *Proc. Int. Conf. Microelectron. Test Struct.*, Apr. 8–11, 2002, pp. 121–126.

CHAPTER 4

ELECTRICAL SOLITONS AND THEIR APPLICATION TO COMMUNICATION SYSTEMS

4.1 SOLITONS AND SOLITON EQUATIONS

Solitons are pulses that do not change their shape when propagating through a medium. Solitons can be generated and propagated without distortion if the linearity and nonlinearity of the medium exactly balance each other. Solitons can be described by 3 classical equations, as shown below with conventional notations:



- 1. KORTEWEG-DE-VRIES (KdV) EQUATION:

$$\partial_t\phi + \partial_x^3\phi + 6\,\phi\,\partial_x\phi = 0, \quad \phi(x,t) = \tfrac{1}{2}c\,\mathrm{sech}^2\left[\frac{\sqrt{c}}{2}(x - ct - a)\right]$$

- 2. NONLINEAR SCHRODINGER (NLS) EQUATION:

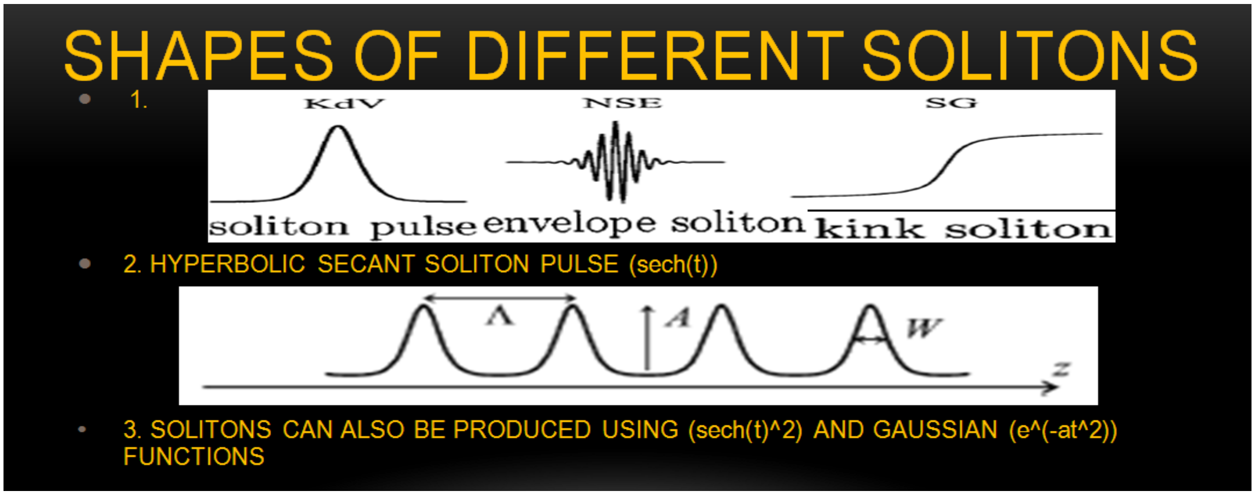
$$i\partial_t\psi = -\frac{1}{2}\partial_x^2\psi + \kappa|\psi|^2\psi \quad iA_x - A_{tt} + 2|A|^2A = 0.$$

- 3. SINE-GORDON EQUATION:

$$\varphi_{tt} - \varphi_{xx} + \sin\varphi = 0.$$

Figure 52 Soliton Equations

The solutions to these equations give rise to the “Solitons”, whose shapes are shown below:



SHAPES OF DIFFERENT SOLITONS

- 1.
- 2. HYPERBOLIC SECANT SOLITON PULSE (sech(t))
- 3. SOLITONS CAN ALSO BE PRODUCED USING (sech(t)^2) AND GAUSSIAN (e^(-at^2)) FUNCTIONS

Figure 53 Shapes of Solitons

Recently, special kinds of solitons were discovered, called the similaritons. Similariton or a “self similar soliton” is a pulse that maintains its shape even when linearity and nonlinearity do not balance each other and hence offers an edge over the conventional solitons. In contrast to the sech soliton, Similaritons are sech^2 functions. This gives a narrower pulse in the similariton which ultimately results in even more distortionless propagation. Solitons maintain their shape, width, and amplitude whereas similaritons maintain their shape but not their width or amplitude.

$$I_B(\chi,\xi) = (\alpha^2/W^2)\mathrm{sech}^2[\alpha(\chi - v\xi)]$$

Figure 54 Equation of Similariton

4.2 BACKGROUND – SOLITONS IN OPTICAL PULSED COMMUNICATIONS

The last couple of decades have witnessed few revolutionary changes in Telecommunications, the most important among them being the use of Solitons in Nonlinear Fiber Optics.

Due to the efforts put forth by Hasegawa, Tappert et al, Solitons have become very popular in optical fibers. Here the linearity is caused by group velocity dispersion which causes spreading of the pulse. Normally anomalous dispersion fibers are chosen. The nonlinearity is brought forth by self phase modulation. As a result of these 2 effects, Solitons have been shown to propagate through long distances (hundreds of kilometers) without change in shape. Using dispersion management techniques, it has been shown that pulse compression is also possible using solitons. Thus solitons form the backbone of ultrafast optical communications.

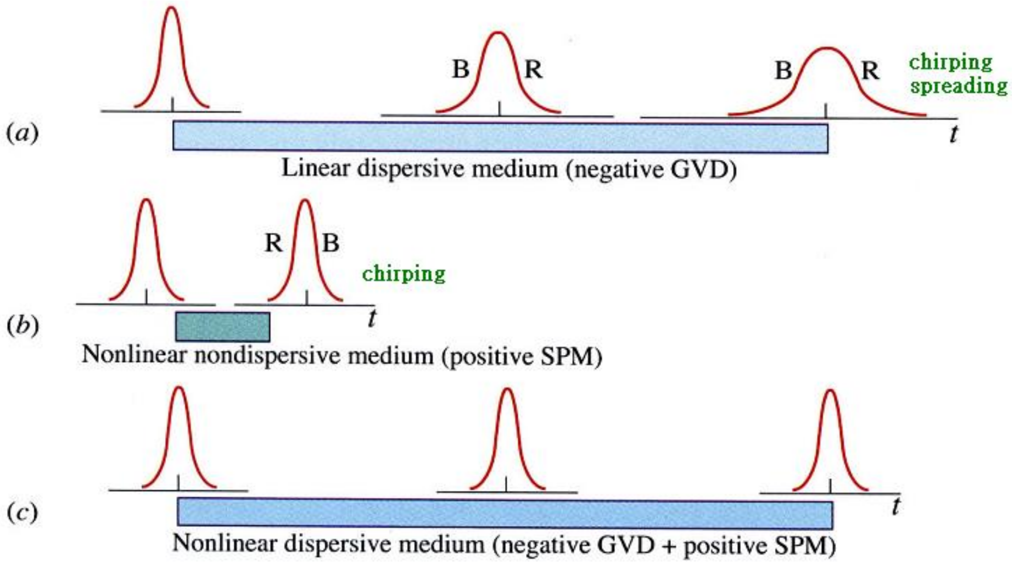


Figure 55 Solitons in Optical Pulsed Communications

4.3 ROBUSTNESS OF ELECTRICAL SOLITONS

The next part of our project is to investigate and study the robustness of electrical solitons/ similaritons in comparison with conventional square pulses, when propagating through various transmission line models. This is done keeping in mind the interconnects used in integrated circuits, as these are modeled using the Microstrip and Coplanar models. Hence these models appropriately represent back end of line (BEOL) interconnects (interconnects between various active and passive components) used in IC's today. In addition long distances involving coaxial and 2 wire transmission line models were also taken into consideration.

Here the equation of a single soliton pulse will be assumed as

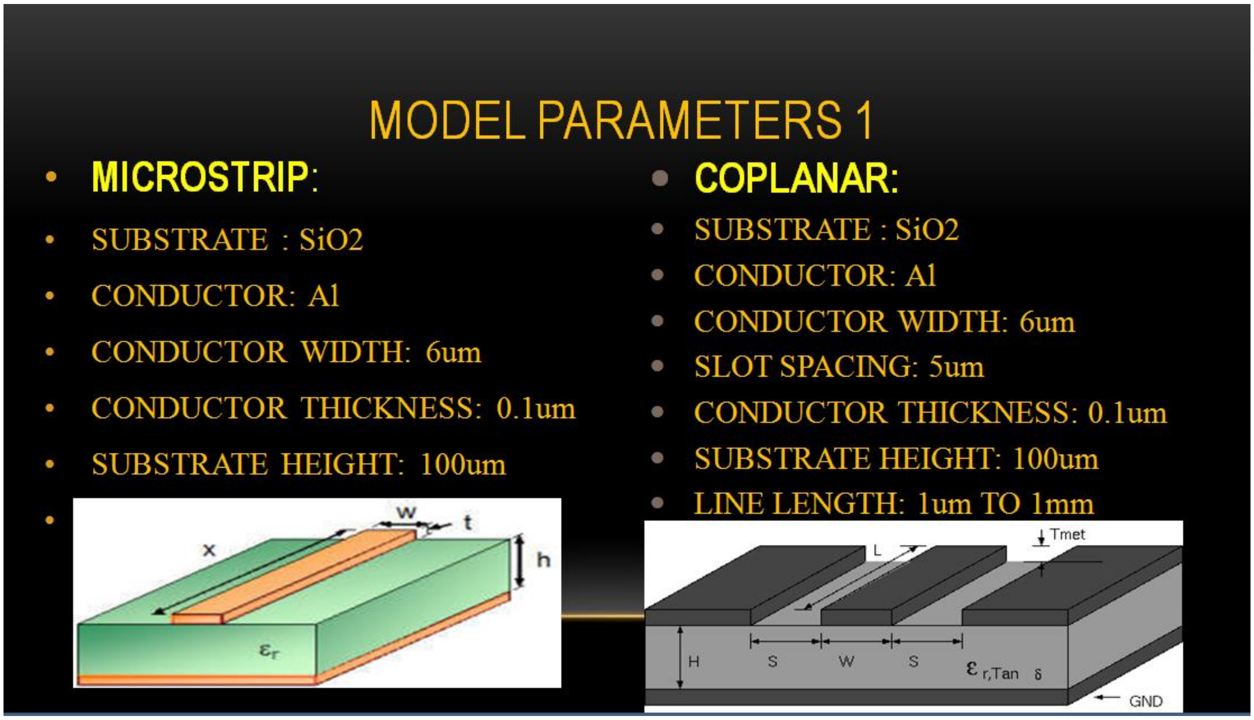
$S(t) = (\operatorname{sech}((t-k)/w))$, where A is the amplitude, K is the shift and W is the pulse width λ

The transmission line models used most commonly to represent interconnects are:

1. The coplanar model (within a metal layer)

2. The microstrip model (between two metal layers of different heights).

The model parameters used for this study is shown below:

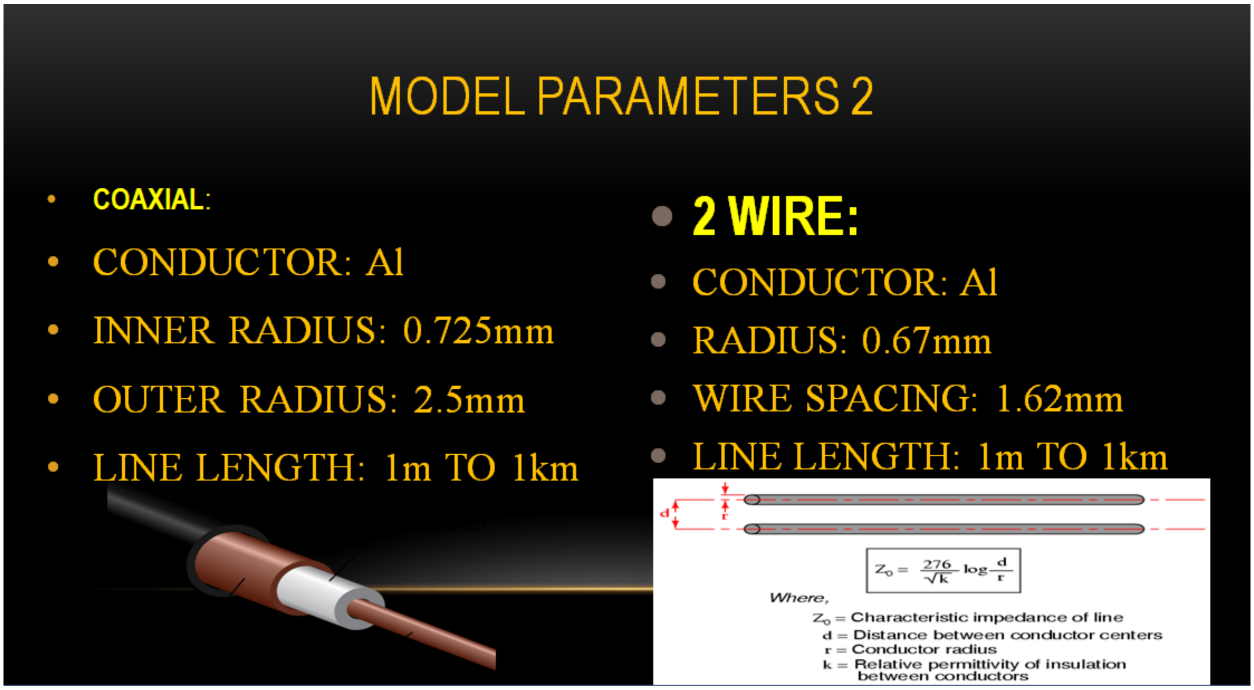


MODEL PARAMETERS 1

- **MICROSTRIP:**
- SUBSTRATE : SiO2
- CONDUCTOR: Al
- CONDUCTOR WIDTH: 6um
- CONDUCTOR THICKNESS: 0.1um
- SUBSTRATE HEIGHT: 100um

- **COPLANAR:**
- SUBSTRATE : SiO2
- CONDUCTOR: Al
- CONDUCTOR WIDTH: 6um
- SLOT SPACING: 5um
- CONDUCTOR THICKNESS: 0.1um
- SUBSTRATE HEIGHT: 100um
- LINE LENGTH: 1um TO 1mm

Figure 56 Microstrip and Coplanar Model Parameters



MODEL PARAMETERS 2

- **COAXIAL:**
- CONDUCTOR: Al
- INNER RADIUS: 0.725mm
- OUTER RADIUS: 2.5mm
- LINE LENGTH: 1m TO 1km

- **2 WIRE:**
- CONDUCTOR: Al
- RADIUS: 0.67mm
- WIRE SPACING: 1.62mm
- LINE LENGTH: 1m TO 1km

$$Z_0 = \frac{276}{\sqrt{k}} \log \frac{d}{r}$$

Where,

Z_0 = Characteristic impedance of line
d = Distance between conductor centers
r = Conductor radius
k = Relative permittivity of insulation between conductors

Figure 57 Coaxial and 2 wire line model parameters

In order to compare solitons and square pulses, we generated the pulses based on their equations at a frequency of 10 GHz. Then we passed them through the built in transmission line blocks of simulink, where we specified the corresponding model parameters. Finally, the outputs were plotted using the scope block. The Block Diagram of this process is as shown below:

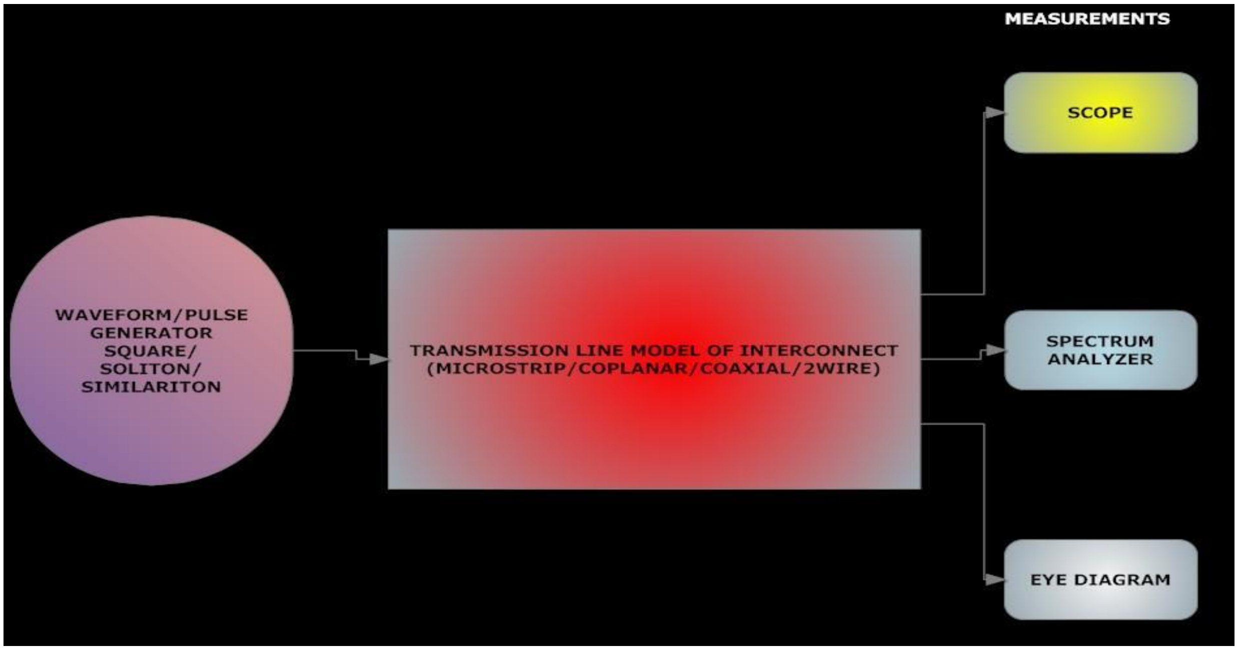


Figure 58 Block Diagram of Robustness study of solitons

4.4 RESULTS OF SIMULINK IMPLEMENTATIONS

Shown below are the results of Simulink implementations of Solitons/Square/Similariton comparisons for the 4 transmission line models with various propagation lengths. The inverted shape seen in some of these are due to polarization changes along transmission line propagations.

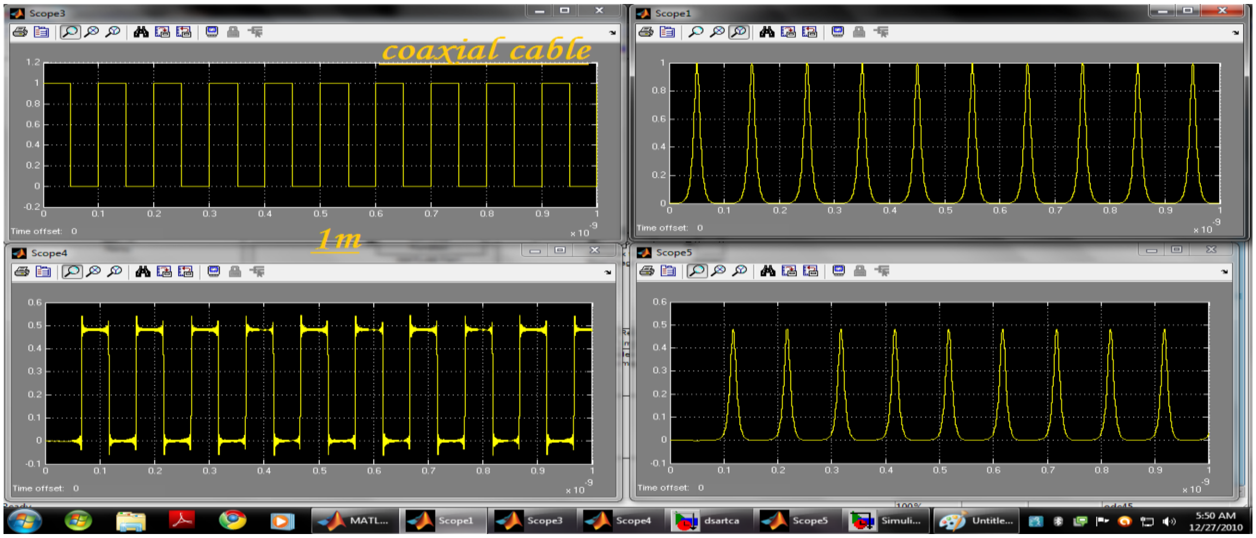


Figure 59 Square and soliton propagation through coaxial cable of 1m, above-input, below-output

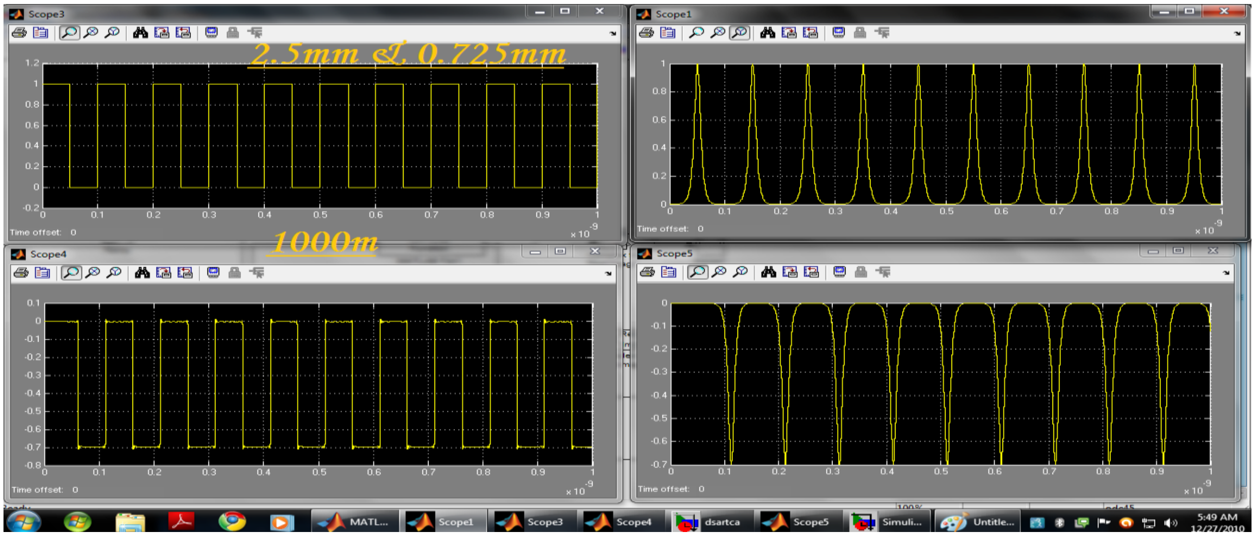


Figure 60 Square and soliton propagation through coaxial cable of 1km, above-input, below-output

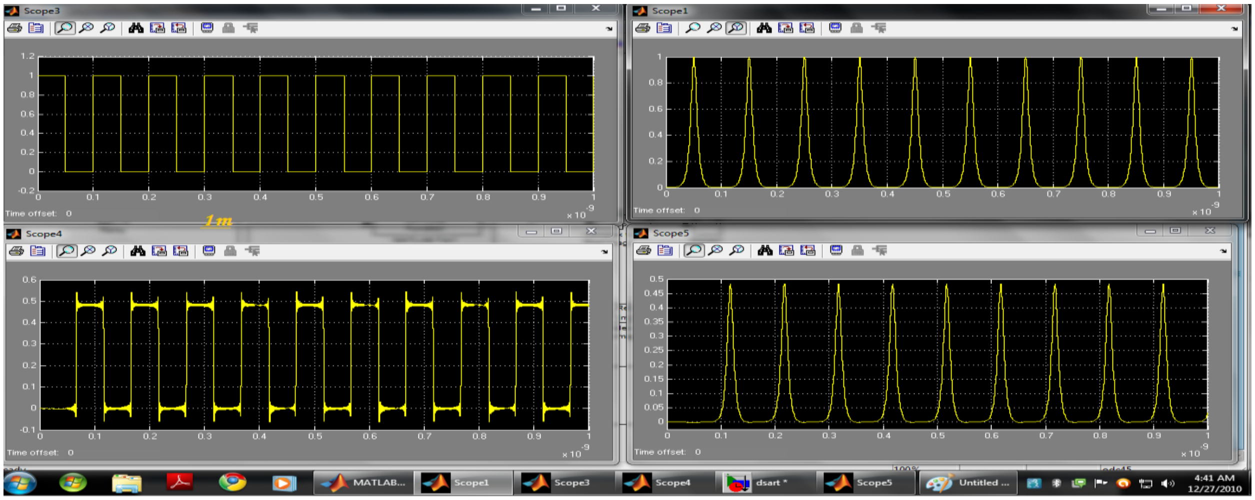


Figure 61 Square and soliton propagation through 2 wire line of 1m, above-input, below-output

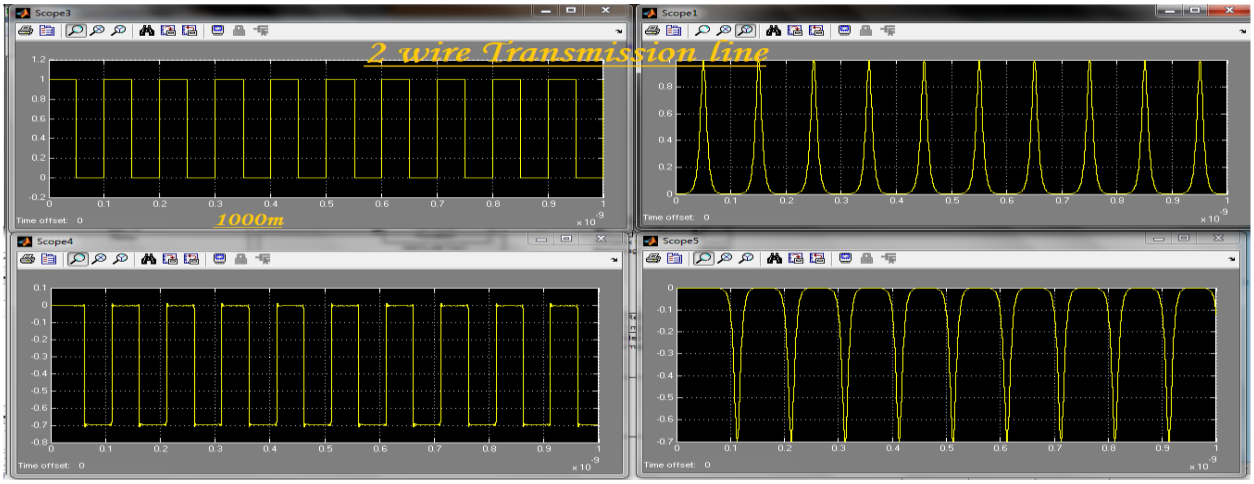


Figure 62 Square and soliton propagation through 2 wire line of 1km, above-input, below-output

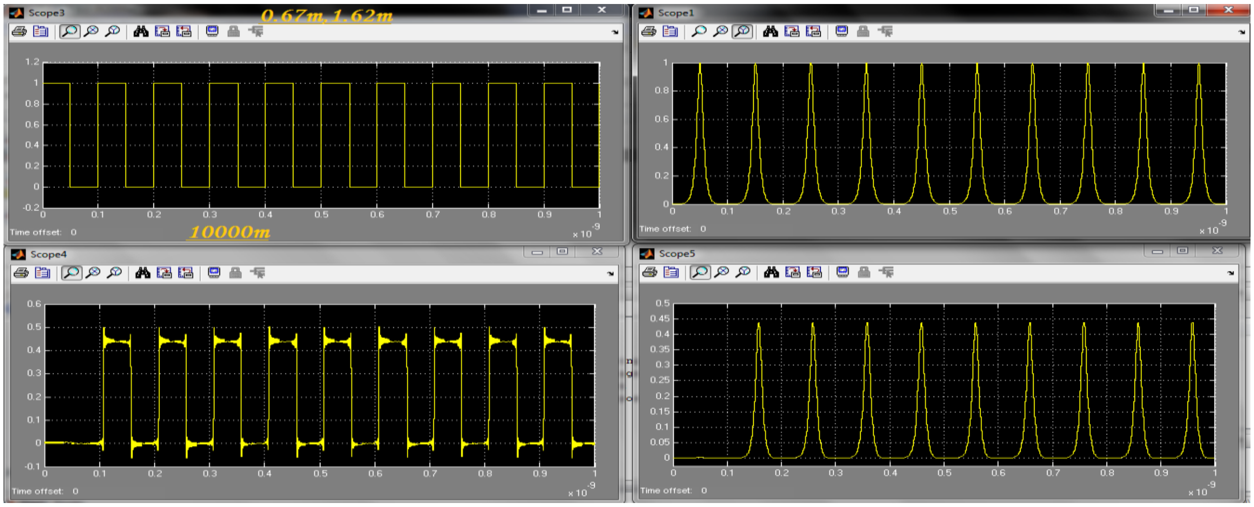
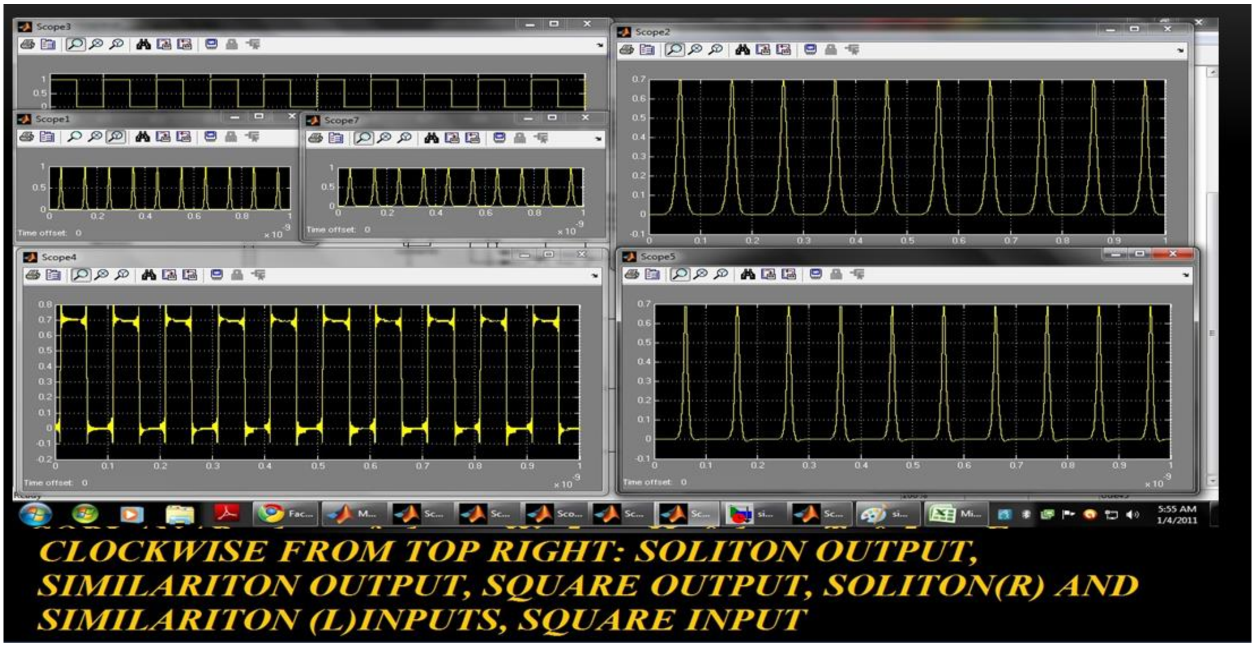


Figure 63 Square and soliton propagation through 2 wire line of 10km, above-input, below-output



CLOCKWISE FROM TOP RIGHT: SOLITON OUTPUT, SIMILARITON OUTPUT, SQUARE OUTPUT, SOLITON(R) AND SIMILARITON (L)INPUTS, SQUARE INPUT

Figure 64 Square, soliton and similariton propagation through coplanar waveguide, 1mm

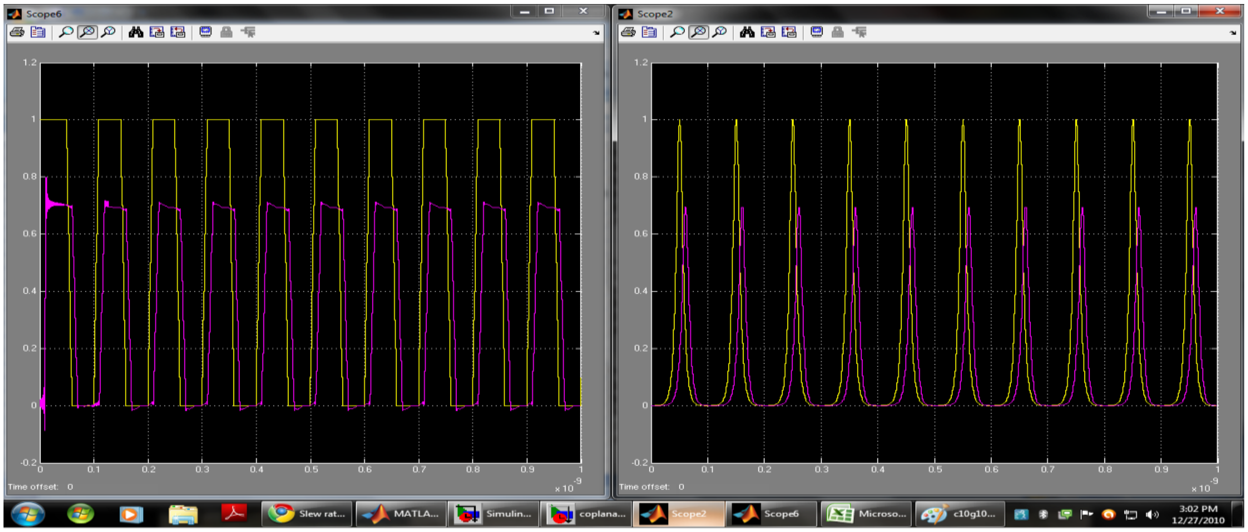


Figure 65 Soliton and square propagation through coplanar waveguide, 1mm with slew

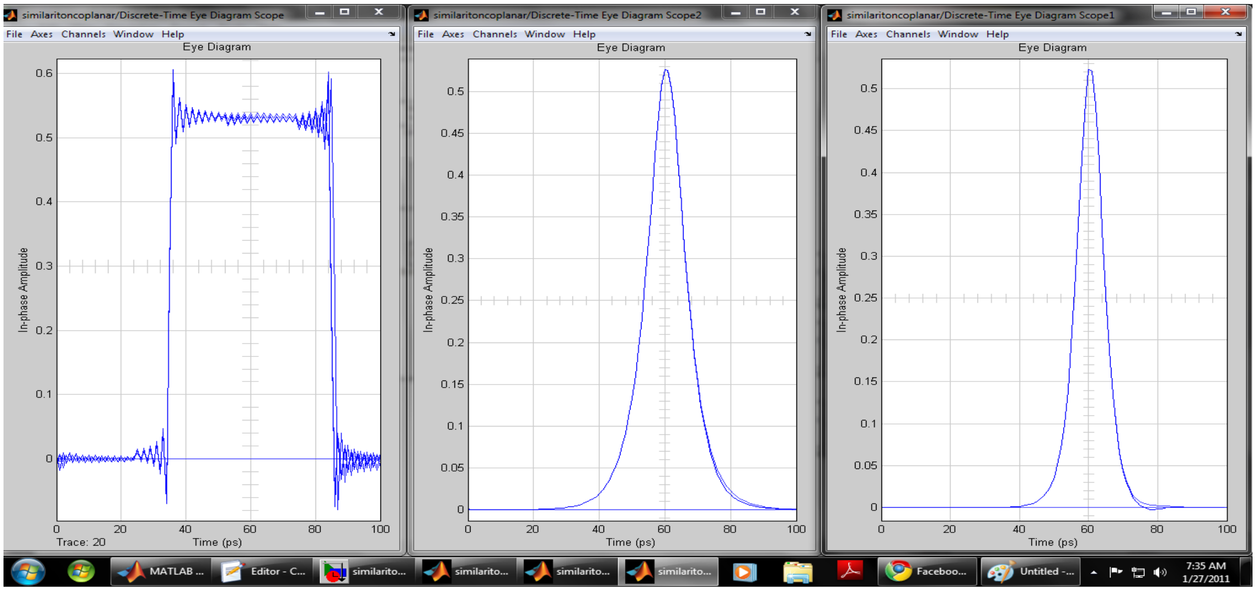
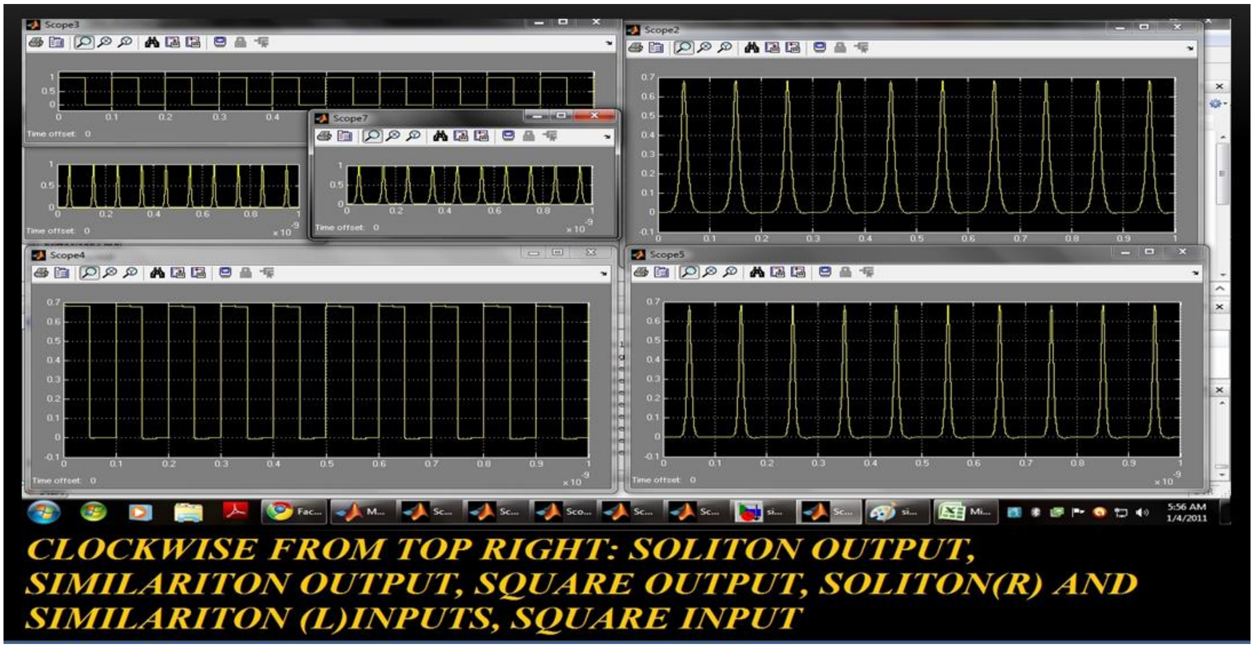


Figure 66 Eye Diagram of square soliton and similariton after propagating through coplanar waveguide, 1mm



CLOCKWISE FROM TOP RIGHT: SOLITON OUTPUT, SIMILARITON OUTPUT, SQUARE OUTPUT, SOLITON(R) AND SIMILARITON (L)INPUTS, SQUARE INPUT

Figure 67 Square, soliton and similariton propagation through coplanar waveguide, 1um

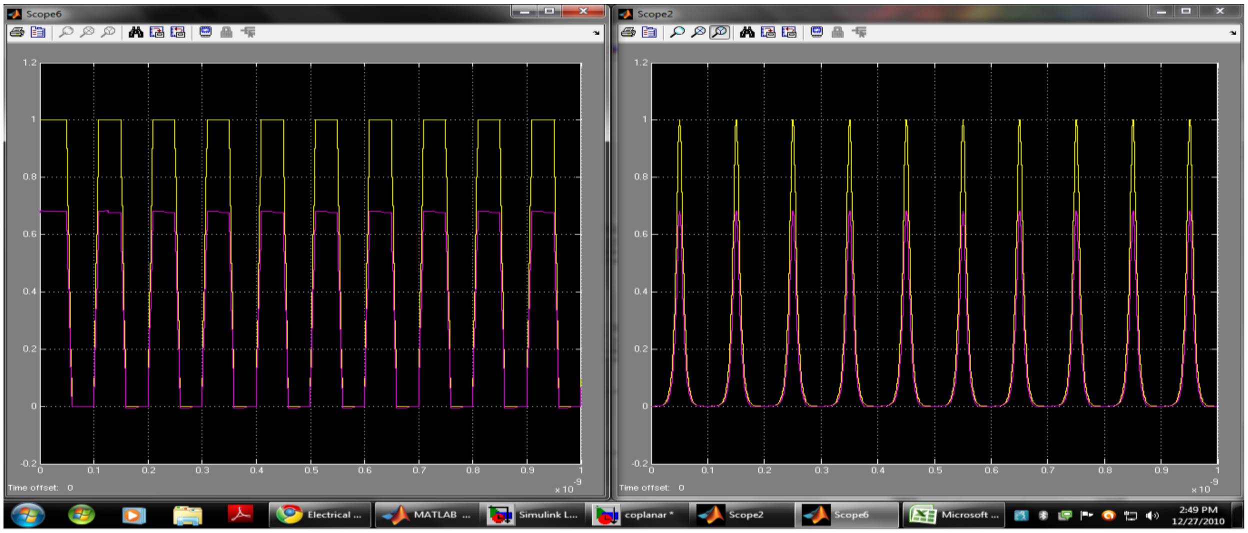


Figure 68 Soliton and square propagation through coplanar waveguide, 1um with slew

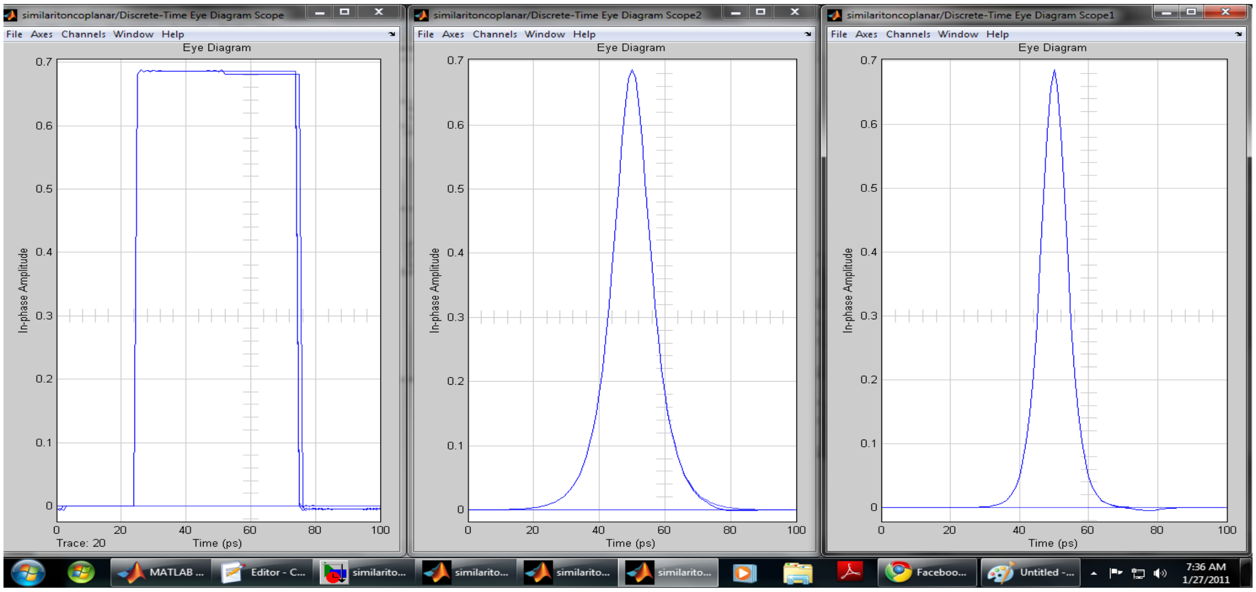
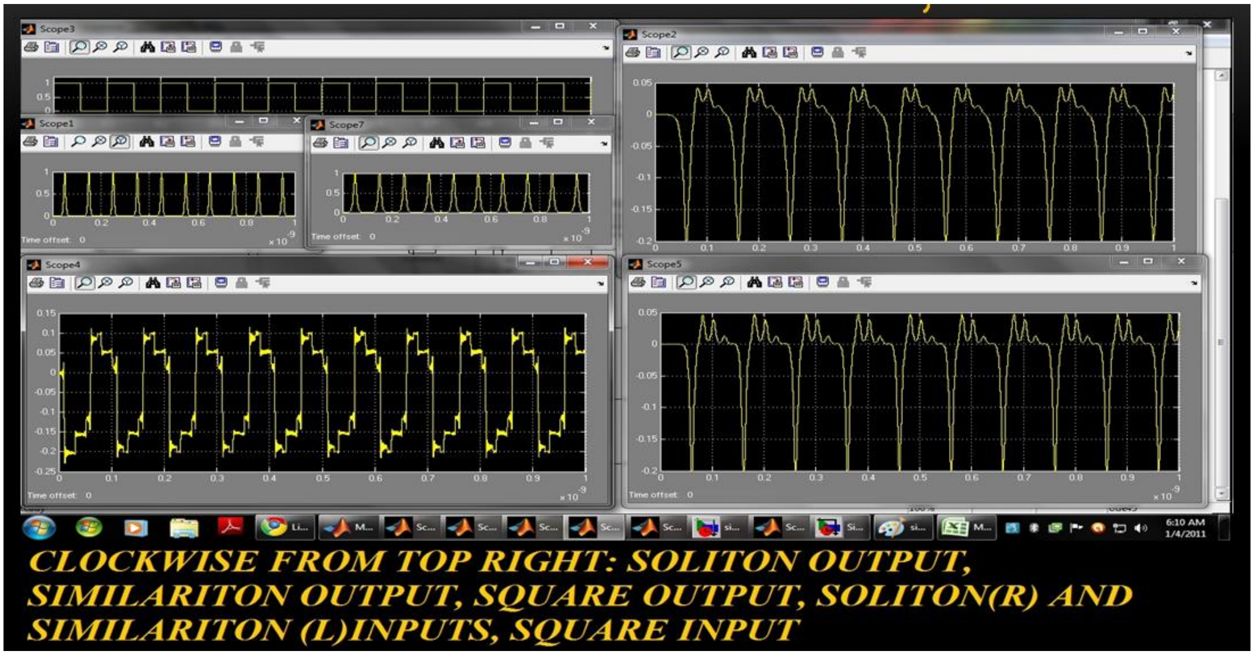


Figure 69 Eye Diagram of square soliton and similariton after propagating through coplanar waveguide, 1um



CLOCKWISE FROM TOP RIGHT: SOLITON OUTPUT, SIMILARITON OUTPUT, SQUARE OUTPUT, SOLITON(R) AND SIMILARITON (L)INPUTS, SQUARE INPUT

Figure 70 Square, soliton and similariton propagation through microstrip, 1mm

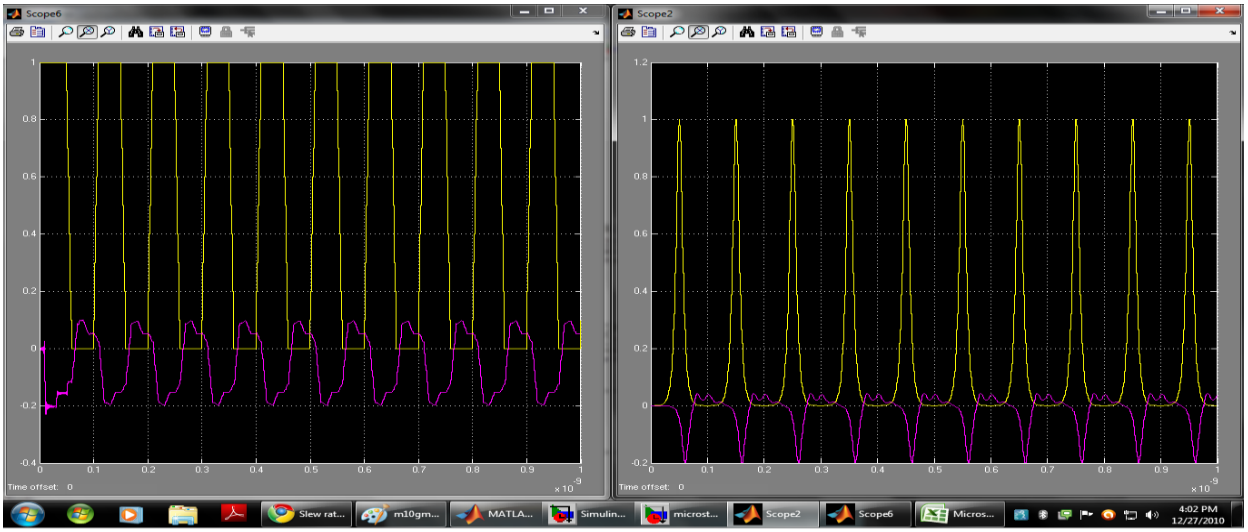


Figure 71 Soliton and square propagation through microstrip, 1mm with slew

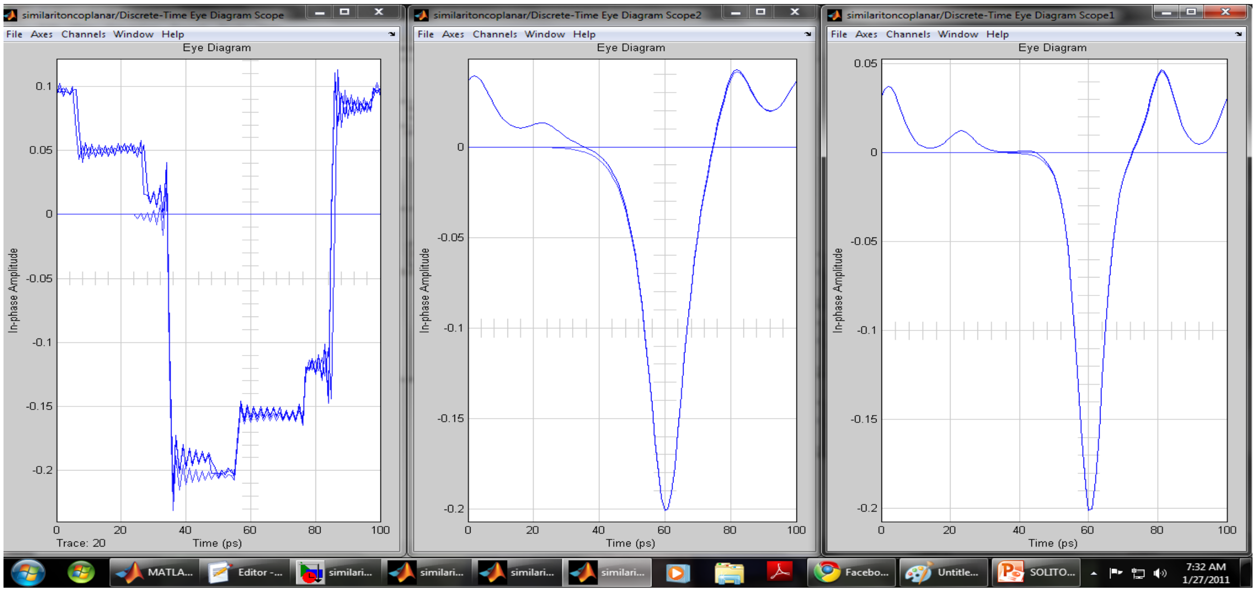
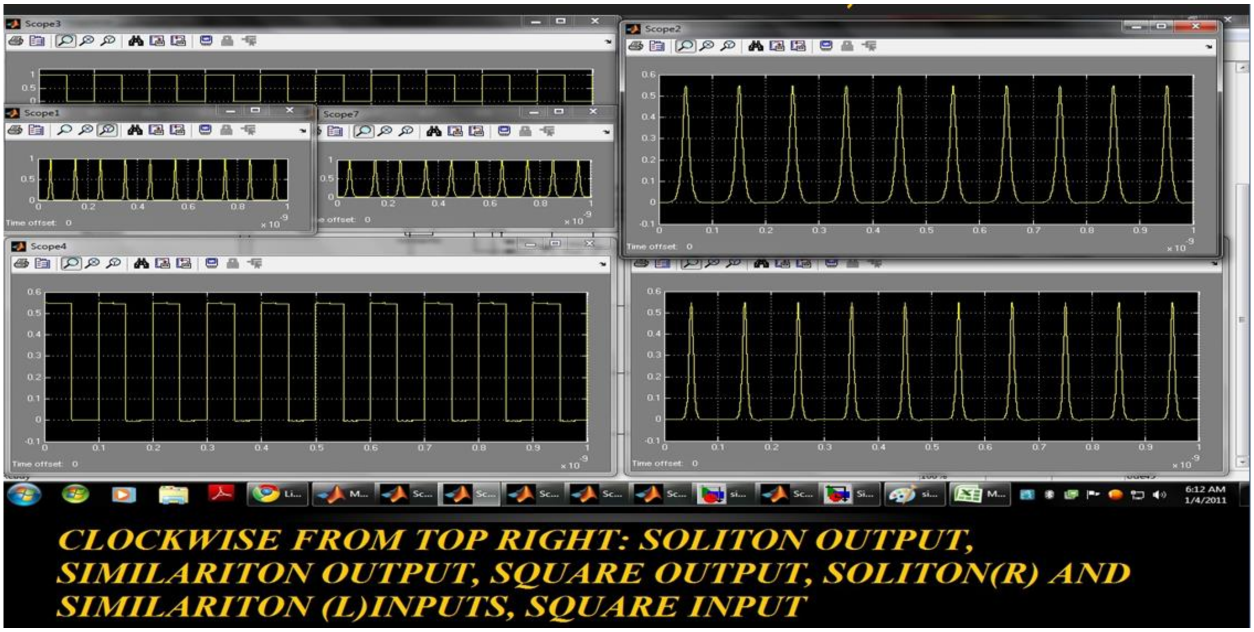


Figure 72 Eye Diagram of square soliton and similariton after propagating through microstrip, 1mm



CLOCKWISE FROM TOP RIGHT: SOLITON OUTPUT, SIMILARITON OUTPUT, SQUARE OUTPUT, SOLITON(R) AND SIMILARITON (L)INPUTS, SQUARE INPUT

Figure 73 Square, soliton and similariton propagation through Microstrip, 1um

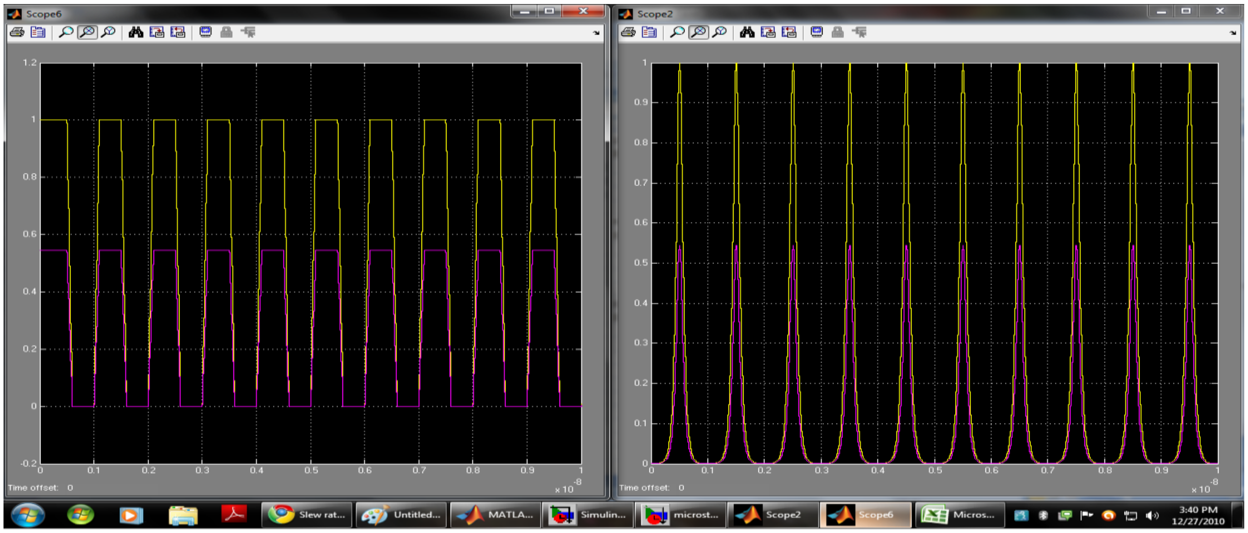


Figure 74 Soliton and square propagation through microstrip, 1um with slew

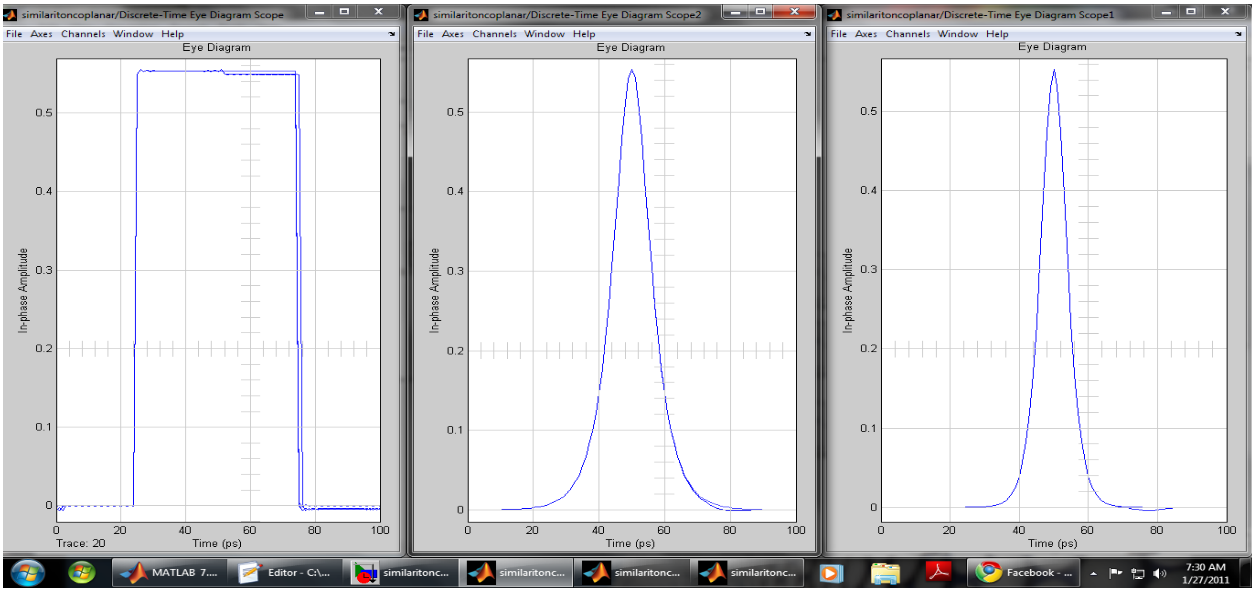
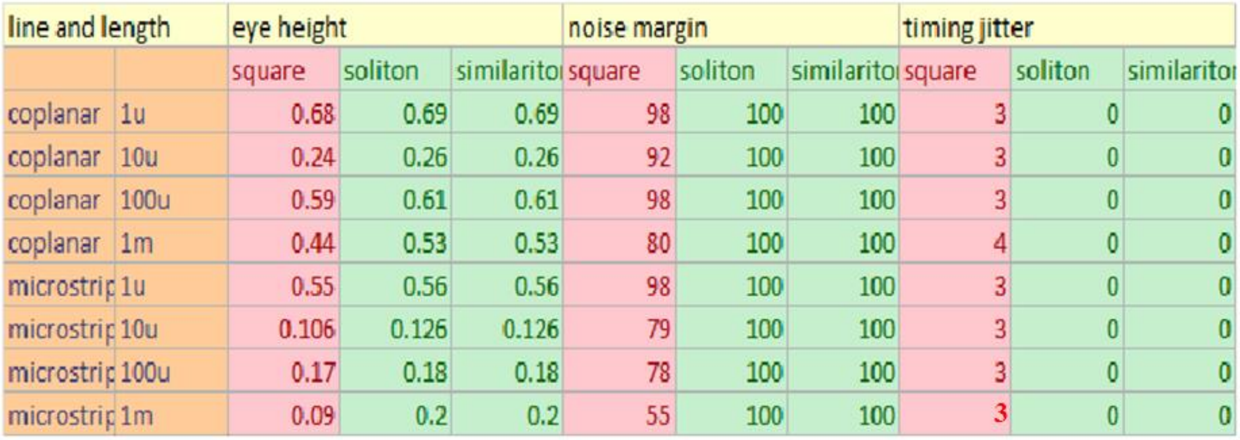


Figure 75 Eye Diagram of square soliton and similariton after propagating through microstrip, 1um

As can be seen from the preceding plots, solitons and similaritons show far less distortion when compared to square pulses, and in most cases, show no distortion at all. This can be seen further enhanced by tabulating the Eye diagram parameters as shown below:



line and length		eye height			noise margin			timing jitter		
		square	soliton	similarito	square	soliton	similarito	square	soliton	similarito
coplanar	1u	0.68	0.69	0.69	98	100	100	3	0	0
coplanar	10u	0.24	0.26	0.26	92	100	100	3	0	0
coplanar	100u	0.59	0.61	0.61	98	100	100	3	0	0
coplanar	1m	0.44	0.53	0.53	80	100	100	4	0	0
microstrip	1u	0.55	0.56	0.56	98	100	100	3	0	0
microstrip	10u	0.106	0.126	0.126	79	100	100	3	0	0
microstrip	100u	0.17	0.18	0.18	78	100	100	3	0	0
microstrip	1m	0.09	0.2	0.2	55	100	100	3	0	0

Figure 76 Eye diagram parameters for square, soliton and similariton

Here noise margin refers to the ratio of minimum eye height to maximum eye height. Timing jitter refers to difference in time (ps) between earliest and latest rising/falling edge.

As can be seen, the Square pulse shows a lot of amplitude fluctuations and timing jitter, whereas the Soliton and Similariton do not show any such thing, proving that less distortion occurs in Solitons and Similaritons.

The amplitudes and slew rates are also tabulates and the results are as follows:

	coplanar square			coplanar soliton			coplanar square			coplanar soliton		
freq	1um	10um	1mm	1um	10um	1mm	1um	10um	1mm	1um	10um	1mm
1g	63	36.5	67	69	42.5	72	0.2	0.4	0.9	0.1	0.4	0.8
10g	65	37	67	67	40	70	0.02	0.05	0.1	0.02	0.05	0.1
20g	67	38	63	70	40	70	0.001	0.02	0.05	0.001	0.017	0.05
	micro square			micro soliton			micro square			micro soliton		
freq	1um	10um	1mm	1um	10um	1mm	1um	10um	1mm	1um	10um	1mm
1g	50	11	10	55	13	15	0.3	0.3	0.6	0.2	0.25	0.6
10g	53	12	14	57	15	20	0.04	0.04	0.15	0.03	0.04	0.09
20g	55	17	15	55	18	20	0.01	0.04	0.08	0.01	0.02	0.06

Figure 77 Amplitude and slew rates for square and solitons

The results shown are for 1GHz, 10GHz and 20GHz. Columns with pink headers are amplitude ratios of receiving to transmitting end i.e. Ar/At in %. Columns with blue headers are slew rates of the format Trr - Trt where Trt and Trr are rising times at receiving end and transmitting end respectively. The slew rate of the transmitting end is fixed at 5% of the ON period of the pulse. For example at 1GHz Ton = 0.5ns and hence Trt = 25ps.

The figure below shows the magnitude spectrum of square (top), soliton(right bottom) and similariton (left bottom) pulses at the output end of the coplanar line at 1mm. As can be seen, the square pulse has considerable amplitudes at the high frequency region which are significantly attenuated by the low pass filtering action of the transmission line whereas the soliton has lesser amplitudes in high frequencies, thus being less affected, and the similariton is least affected as it has a monotonically decreasing spectrum.

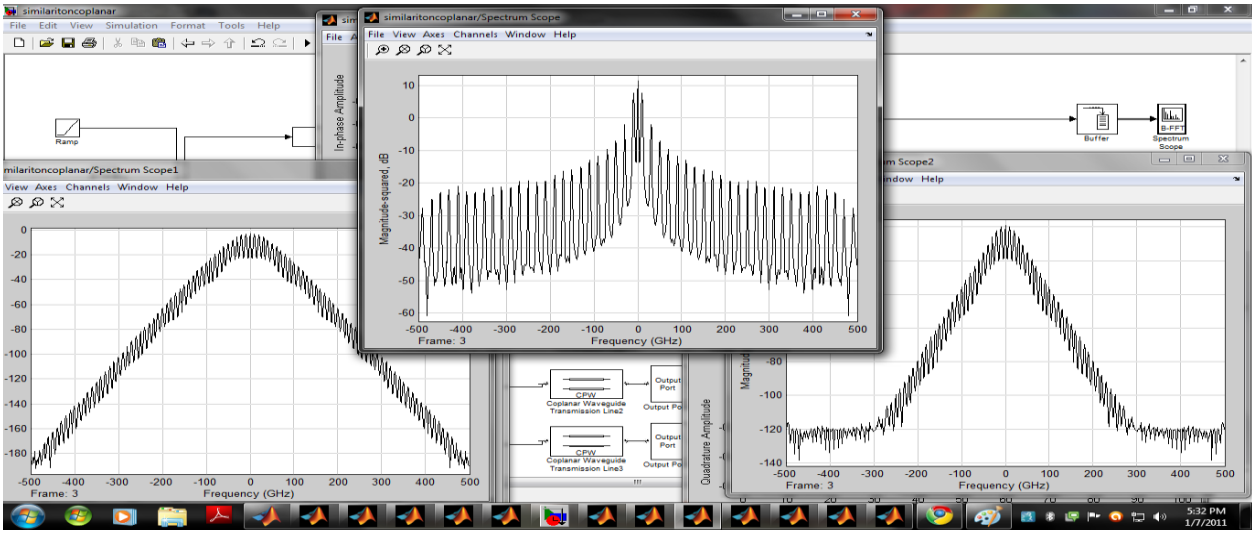


Figure 78 Spectrum of square, soliton and similariton

4.5 CONCEPT OF ELECTRICAL SOLITON OSCILLATOR

Solitons were brought into the electrical domain in 2000’s by Ricketts et al, who designed the first robust Electrical Soliton Oscillator. This was achieved by using Nonlinear Transmission lines (NLTL)

Nonlinear transmission lines (NLTL) can be constructed from linear transmission lines such as coplanar strips, by periodically loading them with varactors(nonlinear voltage dependant capacitors). In the NLTL, dispersion arises due to structural periodicity and nonlinearity arises due to varactors. Hence solitons are generated by balancing both effects.

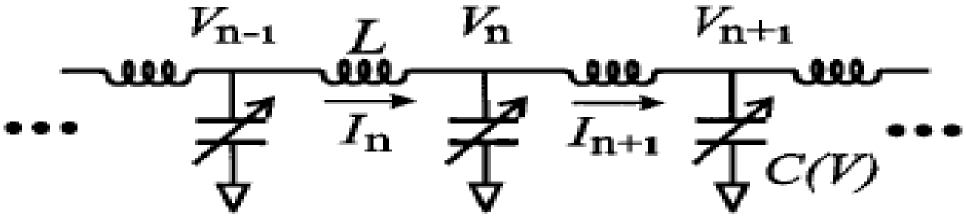


Figure 79 Nonlinear Transmission Line

When a square pulse or quasi square pulse or continuous wave is fed as input to the NLTL, it breaks up into solitons as shown below.

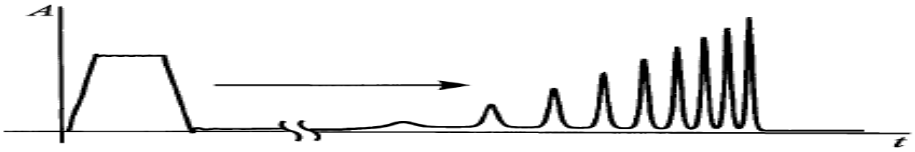


Figure 80 Square pulse propagation through NLTL

However, when a soliton is sent as input to NLTL, it passes undistorted due to balance of linearity and nonlinearity. Hence the above 2 concepts can be exploited for generating solitons using the NLTL. However to sustain the oscillations, we require a special type of amplifier as will be seen later. This oscillator is of ring type configuration as shown below:

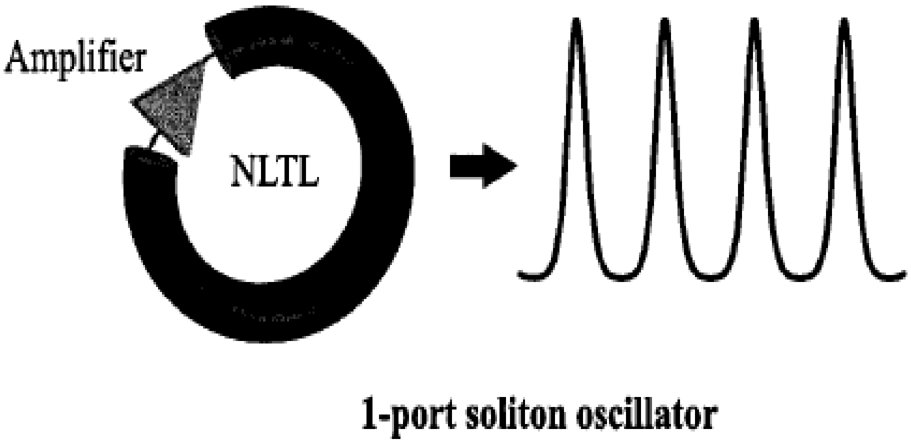


Figure 81 Topology of 1 port Soliton Oscillator

4.6 NONLINEAR TRANSMISSION LINE EQUATIONS

Toda lattice is a simple model of a completely integrable system with soliton solutions. NLTL is an exact toda lattice and produces solitons without any approximations.

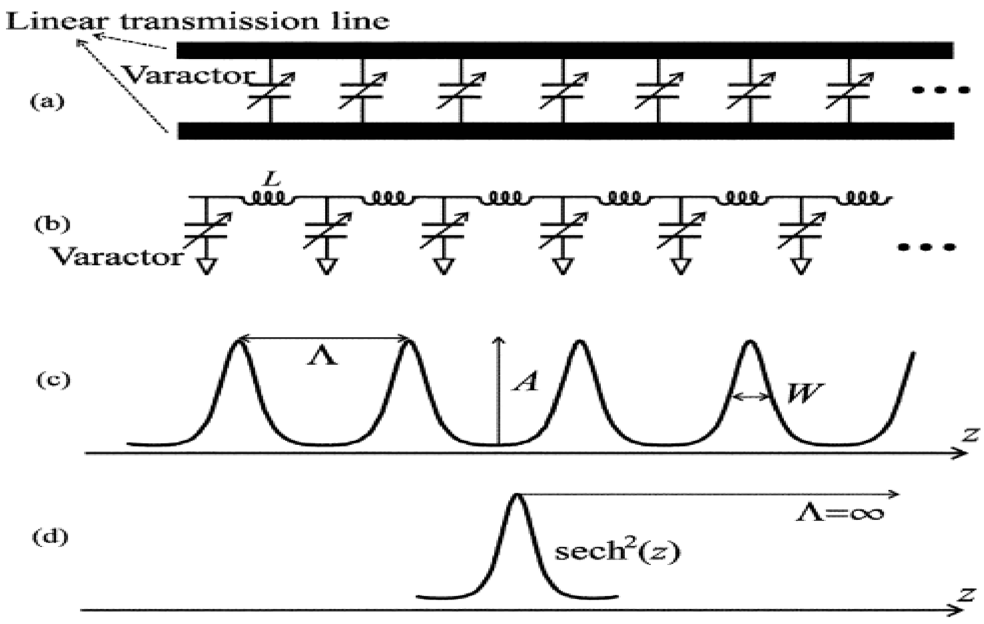


Figure 82 NLTL

Nodal Equations for the NLTL as discovered by Ricketts are as shown below:

$$V_{n-1} - V_n = L \frac{\partial I_n}{\partial t}$$

$$V_n - V_{n+1} = L \frac{\partial I_{n+1}}{\partial t}$$

$$I_n - I_{n+1} = \frac{\partial Q_n(V)}{\partial t}$$

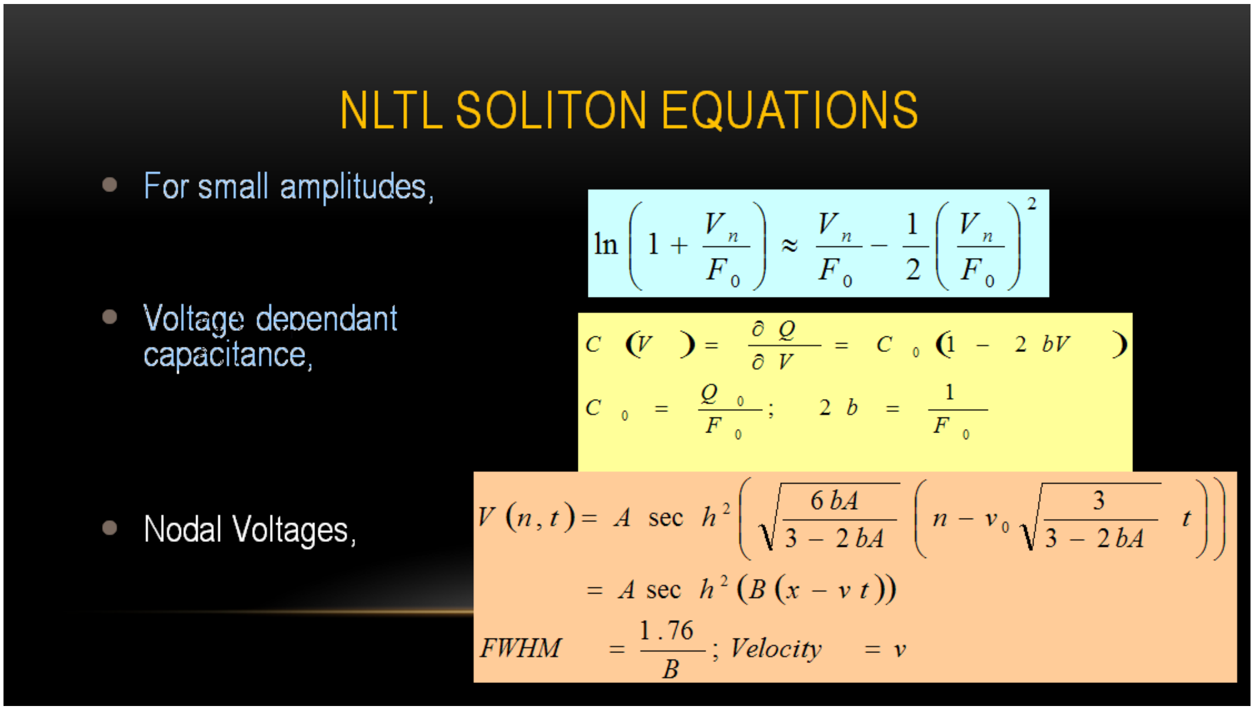
$$\frac{\partial^2 Q_n(V)}{\partial t^2} = \frac{1}{L}(V_{n+1} + V_{n-1} - 2V_n)$$

$$Q_n(V) = Q_0 \ln\left(1 + \frac{V_n}{F_0}\right)$$

$$Q_0 L \frac{\partial^2}{\partial t^2} \ln\left(1 + \frac{V_n}{F_0}\right) = (V_{n+1} + V_{n-1} - 2V_n)$$

Figure 83 NLTL nodal equations

The expressions for voltage, capacitance etc are given as follows:



NLTL SOLITON EQUATIONS

- For small amplitudes,

$$\ln\left(1+\frac{V_n}{F_0}\right) \approx \frac{V_n}{F_0} - \frac{1}{2}\left(\frac{V_n}{F_0}\right)^2$$

- Voltage dependant capacitance,

$$C(V) = \frac{\partial Q}{\partial V} = C_0(1-2bV)$$

$$C_0 = \frac{Q_0}{F_0}; \quad 2b = \frac{1}{F_0}$$

- Nodal Voltages,

$$V(n,t) = A\,\sec h^2\left(\sqrt{\frac{6bA}{3-2bA}}\left(n - v_0\sqrt{\frac{3}{3-2bA}}\,t\right)\right)$$

$$= A\,\sec h^2(B(x-vt))$$

$$FWHM = \frac{1.76}{B}; \quad Velocity = v$$

Figure 84 NLTL Expressions

4.7 ADAPTIVE BIAS CONTROLLED (ABC) AMPLIFIER

Normal linear amplifiers or voltage limiting amplifiers cannot be used for soliton oscillators as they cause the following instability mechanisms:

1. Distortion: DC component of voltage increases as the oscillation grows.

2. Perturbation: undesired soliton pulses of low amplitude appear at the output.

3. Multiple modes: multiple modes (different frequencies) of solitons are produced and the collisions between these modes can lead to instability.

Hence to produce stable solitons without the above effects, we us a special type of amplifier called an “adaptive bias controlled amplifier”. The adaptive bias controlled amplifier has a nonlinear transfer characteristics as follows:

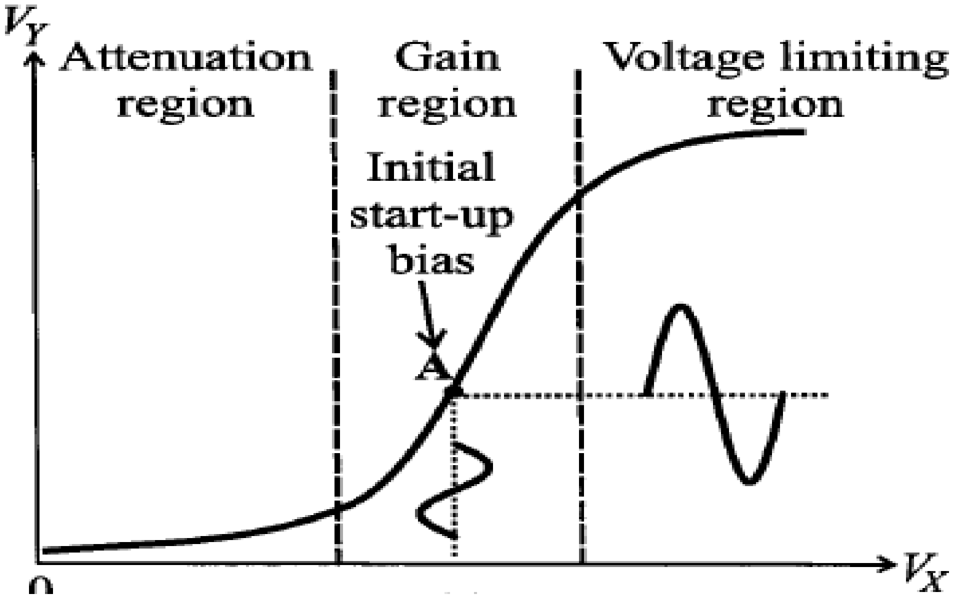


Figure 85 Transfer function of Adaptive Bias Controlled Amplifier

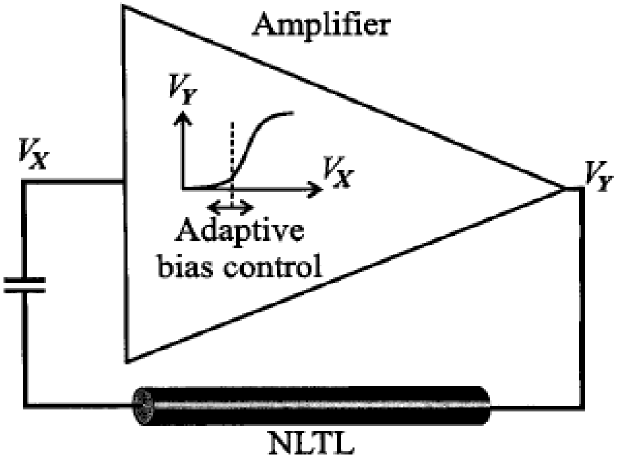


Figure 86 Soliton oscillator with ABC Amplifier

The adaptive bias control enables to move the amplifier bias point as the DC component of the output changes. Next we will see how the adaptive bias control helps to overcome the 3 instability mechanisms mentioned.

4.7.1 DISTORTION REDUCTION

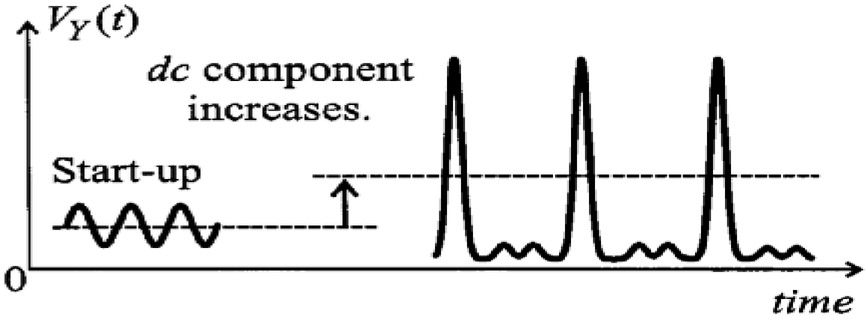


Figure 87 Distortion in oscillations

DC component of Vy (t) increases as oscillation grows. In steady state, input bias is sufficiently reduced due to adaptive bias control. Peak portions of input and output pulses do not go into voltage limiting region of amplifier transfer curve. Thus Signal distortion is prevented.

4.7.2 PERTURBATION REJECTION

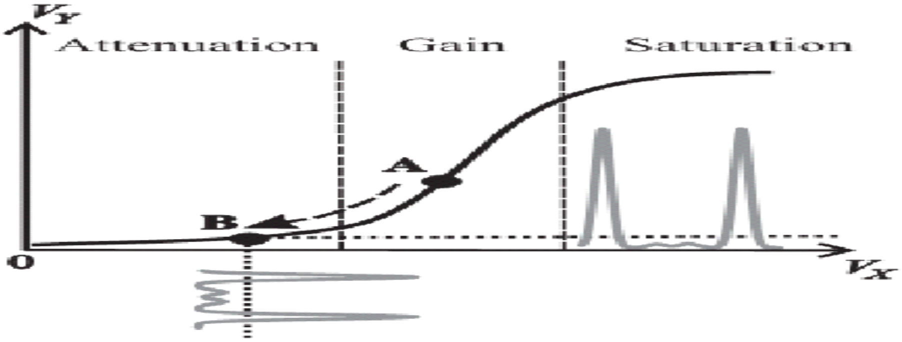


Figure 88 Perturbation rejection in ABC amplifier

The increased dc component lowers the bias point, leading to steady bias point moved into attenuation region. Small perturbations at the input of the amplifier are attenuated at the output; perturbation rejection is achieved. Higher portion of pulses receive enough gain to compensate loss.

4.7.3 SINGLE MODE SELECTION

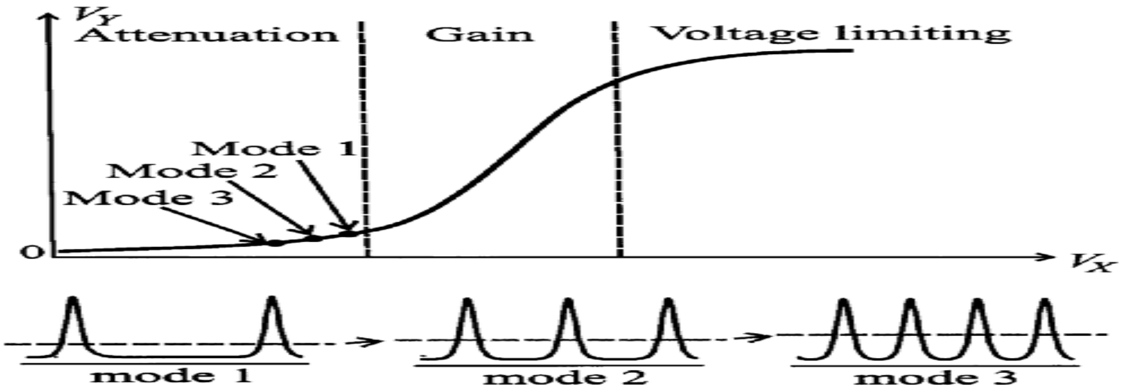


Figure 89 Modes in Oscillator

Higher mode has higher dc component but lower steady state bias due to adaptive bias control. Higher mode receives lower gain. Using the mode dependant gain, a particular mode is selected. Mode dependant gain allows only a single train of soliton pulses. Periodic boundary conditions demand l=nD; l-ring circumference; D-spacing between neighboring solitons.

4.8 ELECTRICAL SOLITON OSCILLATOR

Using the concepts mentioned in the previous sections, Ricketts et al. were able to design Soliton Oscillator. The schematics of the designs are as shown below:

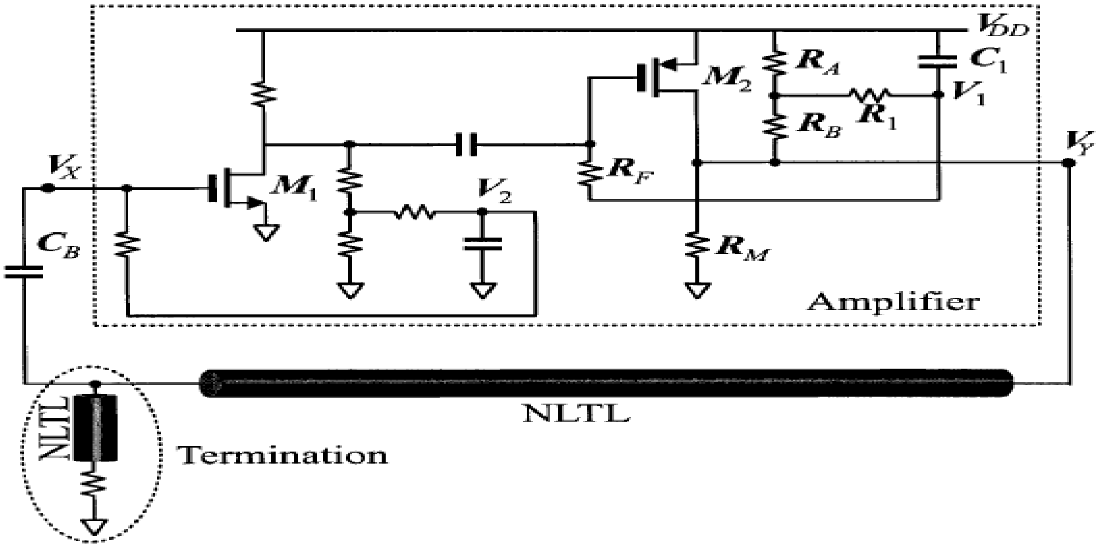


Figure 90 Low MHz prototype of Electrical Soliton Oscillator

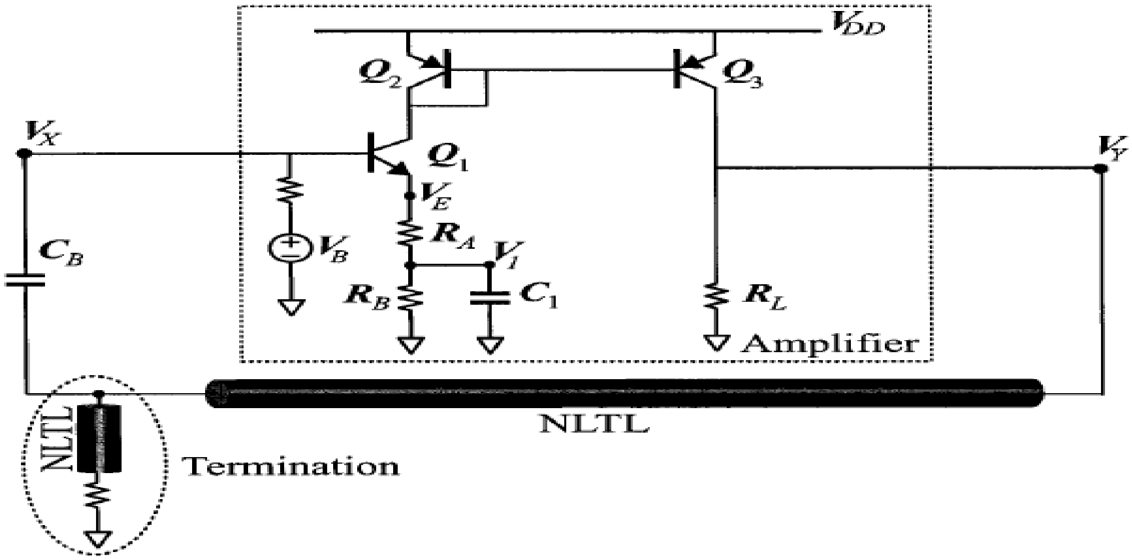


Figure 91 Microwave (High MHz) prototype of electrical soliton oscillator

4.8.1 REFLECTION SOLITON OSCILLATOR

Another version of the NLTL based soliton oscillator is the reflection soliton oscillator. Here one end of the NLTL alone is connected to the amplifier, while the other end is matched to free space. Due to reflections back and forth on the line, solitons are generated. The schematic is as shown below:

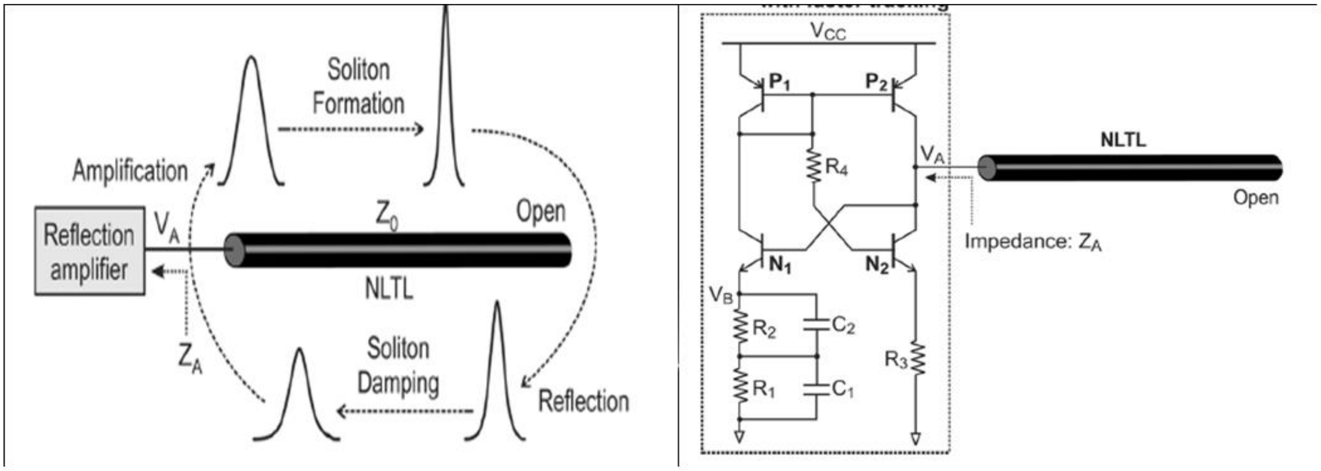


Figure 92 Reflection Soliton Oscillator

4.8.2 GHz SOLITON OSCILLATORS

All the soliton oscillators mentioned above self start from noise, which is invariably flicker noise. Flicker noise is inversely proportional to frequency. Hence at high frequencies, the noise is very small and even negligible and hence such circuits cannot be used to generate High frequency (GHz) solitons.

4.9 SOLITON GENERATOR

One solution to the GHz problem outlined in the previous sections is to use a Soliton generator, which generates solitons from Sinusoidal input. This has a lot of advantages such as:

1. It can be used for high frequencies as there is no dependence on flicker noise.
2. It is more stable as the sinusoid input sustains the oscillations.
3. The frequency of oscillations can be varied by using frequency multiplier circuits such as varactors etc hence making it a tunable soliton generator.
4. It is also a versatile convertor from sinusoids to solitons.

The concept is same as that of the ring type NLTL oscillator except that a sinusoid of the desired frequency is given as input to the ABC amplifier. The generator is designed and its MultiSim schematic is as shown below:

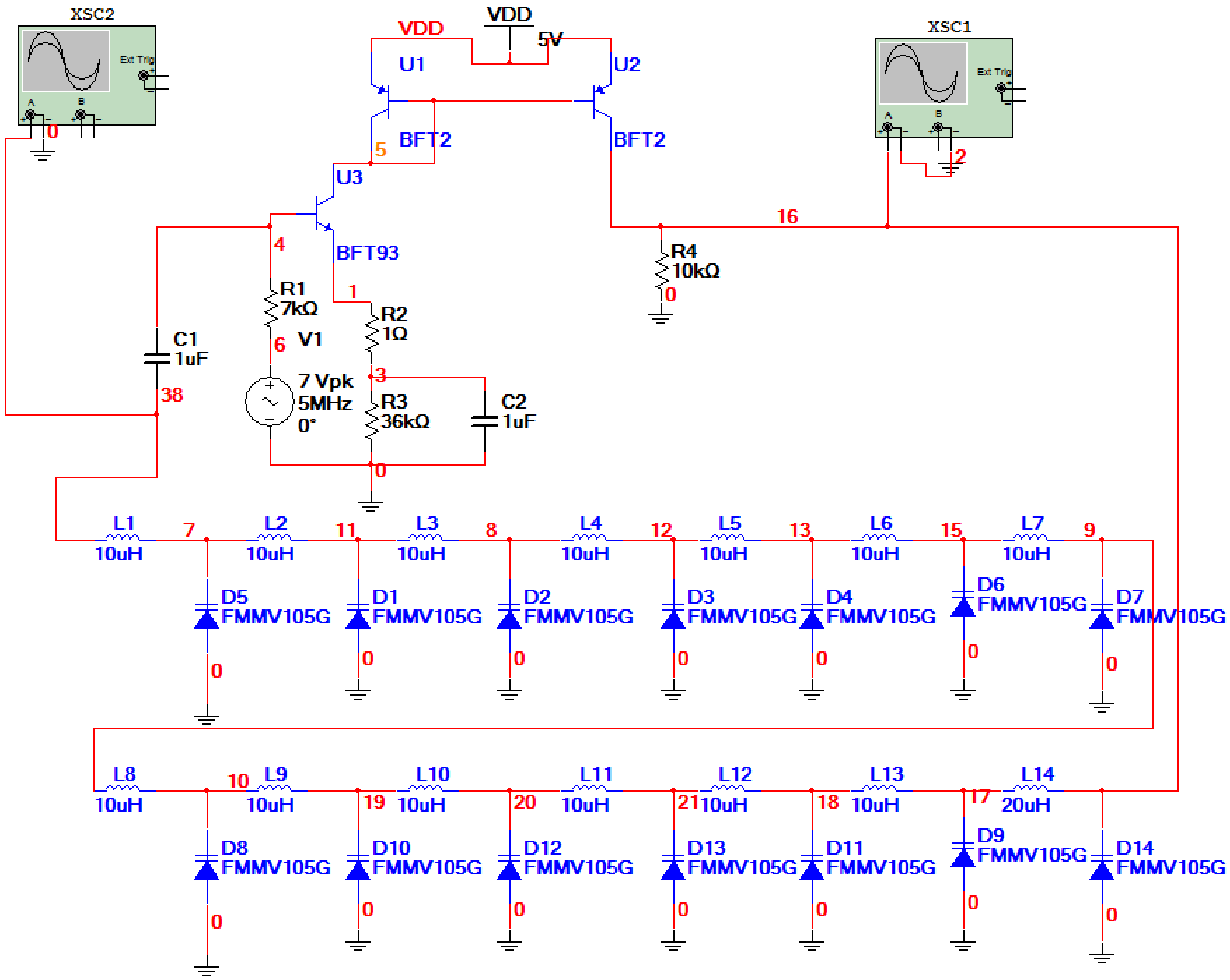


Figure 93 Soliton Generator

The transfer characteristic of the soliton generator is also plotted using MultiSim and is shown below:

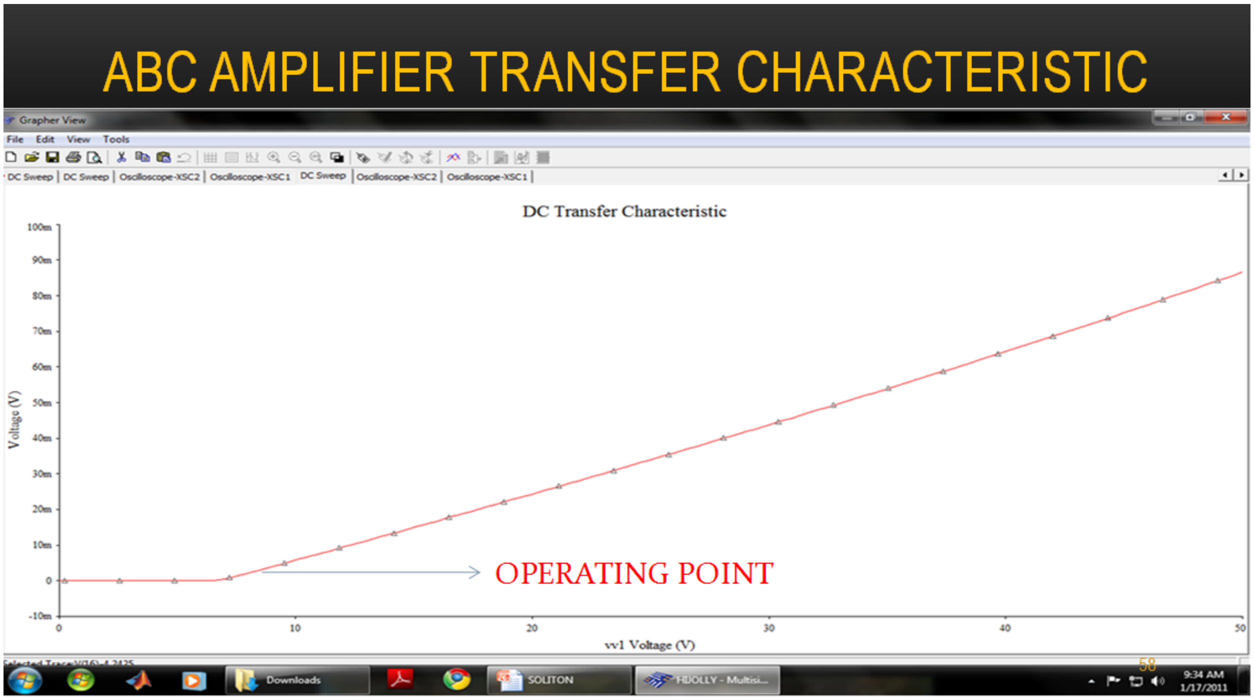
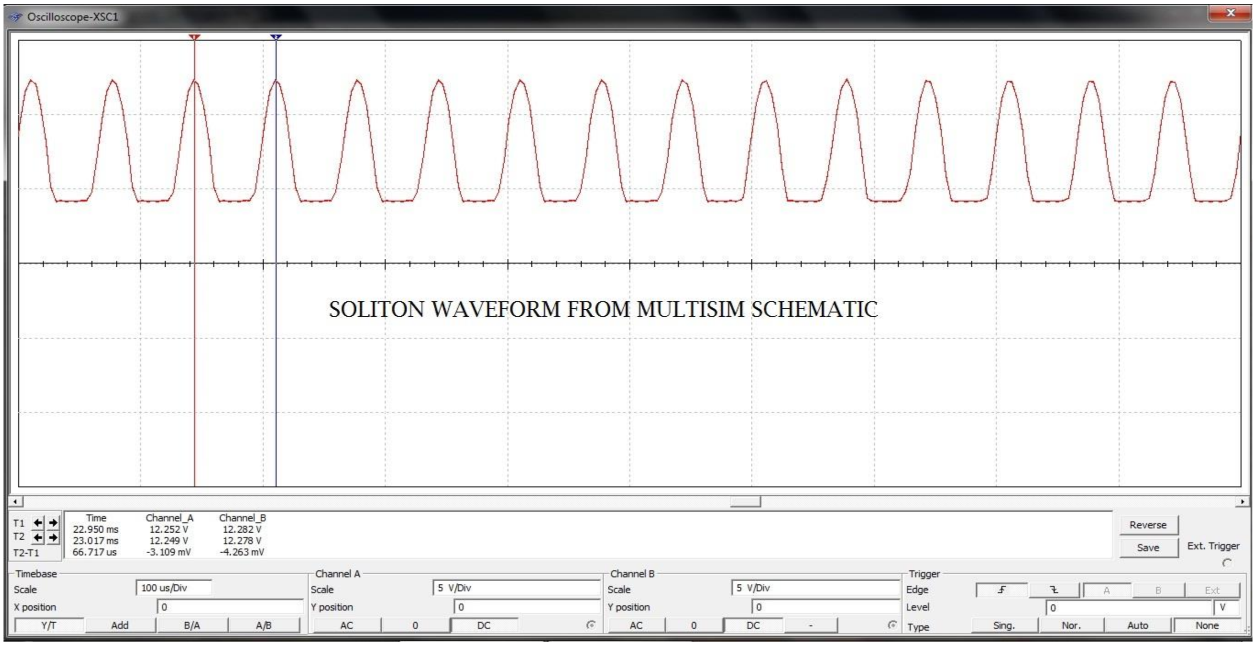


Figure 94 Operating point and transfer characteristic of soliton generator

The output waveforms of this generator for various frequencies are as shown below:



	Time	Channel_A	Channel_B
T1	22.950 ms	12.252 V	12.282 V
T2	23.017 ms	12.249 V	12.278 V
T2-T1	66.717 us	-3.109 mV	-4.263 mV

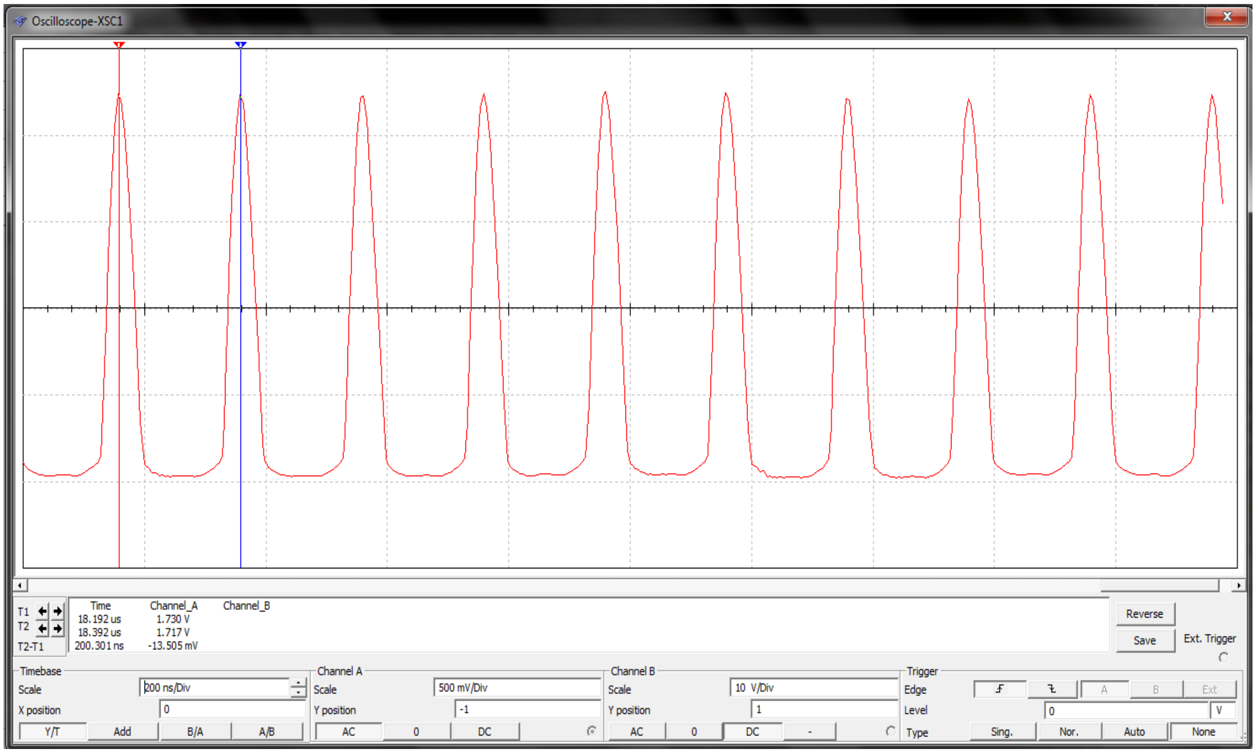
Timebase
Scale 100 us/Div
X position 0
Y/T Add B/A A/B

Channel A
Scale 5 V/Div
Y position 0
AC 0 DC

Channel B
Scale 5 V/Div
Y position 0
AC 0 DC -

Trigger
Edge A B Ext
Level 0 V
Type Sing. Nor. Auto None

Figure 95 15 kHz Soliton generator output



	Time	Channel_A	Channel_B
T1	18.192 us	1.730 V	
T2	18.392 us	1.717 V	
T2-T1	200.301 ns	-13.505 mV	

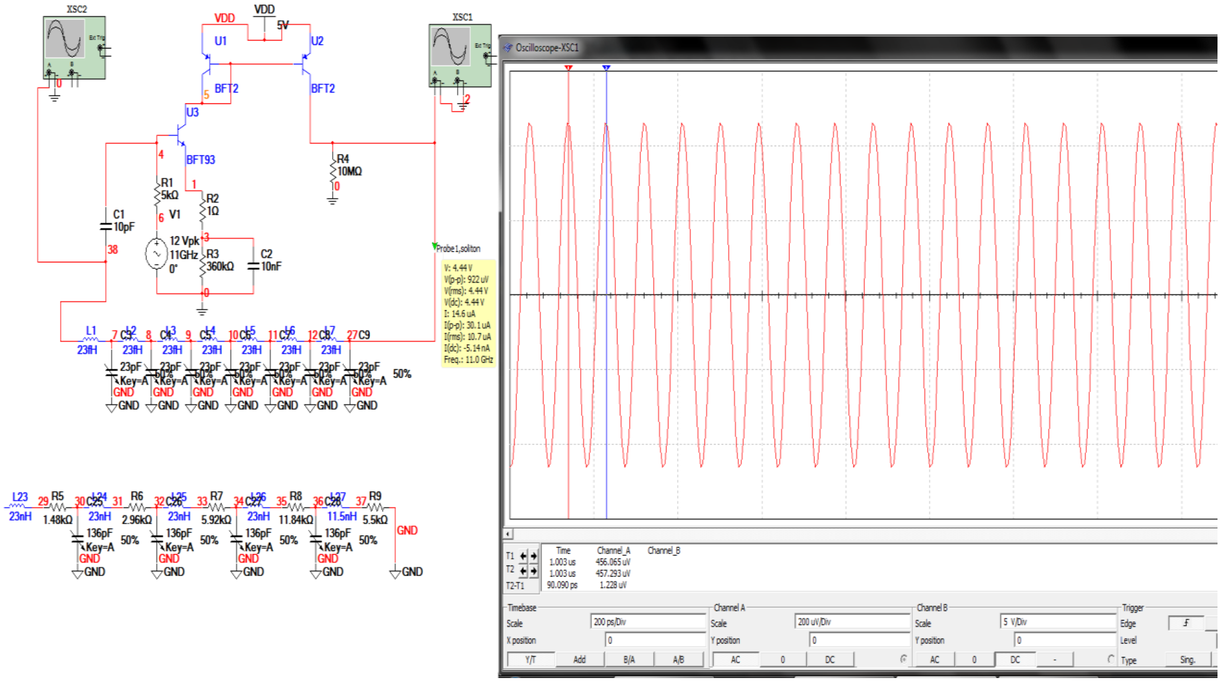
Timebase
Scale 200 ns/Div
X position 0

Channel A
Scale 500 mV/Div
Y position -1

Channel B
Scale 10 V/Div
Y position 1

Trigger
Edge
Level 0 V
Type

Figure 96 5MHz Soliton generator output



V: 4.44 V
V(p-p): 922 uV
V(rms): 4.44 V
V(dc): 4.44 V
I: 14.6 uA
I(p-p): 30.1 uA
I(rms): 10.7 uA
I(dc): -5.14 nA
Freq.: 11.0 GHz

	Time	Channel_A	Channel_B
T1	1.003 us	456.065 uV	
T2	1.003 us	457.293 uV	
T2-T1	90.090 ps	1.228 uV	

Timebase
Scale 200 ps/Div
X position 0

Channel A
Scale 200 uV/Div
Y position 0

Channel B
Scale 5 V/Div
Y position 0

Trigger
Edge
Level
Type

Figure 97 11GHz soliton generator output

4.10 DIGITAL ELECTRONICS USING SOLITONS

Owing to its high frequency switching capability, solitons can be used as switching signals and digital circuits, where a positive soliton (peaking upwards) is regarded as logic high and a negative (peaking downward) soliton represents logic low.

Complementary metal–oxide–semiconductor (**CMOS**) is a technology for constructing integrated circuits. CMOS technology is used in microprocessors, microcontrollers, static RAM, and other digital logic circuits. CMOS technology is also used for several analog circuits such as image sensors, data converters, and highly integrated transceivers for many types of communications. CMOS is also sometimes referred to as **complementary-symmetry metal–oxide–semiconductor** (or COS-MOS). The words "complementary-symmetry" refer to the fact that the typical digital design style with CMOS uses complementary and symmetrical pairs of p-typeand n-type metal oxide semiconductor field effect transistors (MOSFETs) for logic functions.

Two important characteristics of CMOS devices are high noise immunity and low static power consumption. Significant power is only drawn when the transistors in the CMOS device are switching between on and off states. Consequently, CMOS devices do not produce as muchwaste heat as other forms of logic, for example transistor-transistor logic (TTL) or NMOS logic. CMOS also allows a high density of logic functions on a chip. It was primarily for this reason that CMOS became the most used technology to be implemented in VLSI chips.

The phrase "metal–oxide–semiconductor" is a reference to the physical structure of certain field-effect transistors, having a metal gate electrode placed on top of an oxide insulator, which in turn is on top of a semiconductor material. Aluminum was once used but now the material is polysilicon. Other metal gates have made a comeback with the advent of high-k dielectric materials in the CMOS process, as announced by IBM and Intel for the 45 nanometer node and beyond.

We propose that Solitons are compatible with the normal CMOS logic used in most digital systems today. To verify this, the output of the electrical soliton oscillator was fed as the input to various CMOS circuits such as an inverter, a NAND gate, a NOR gate etc. And the output waveforms are observed.

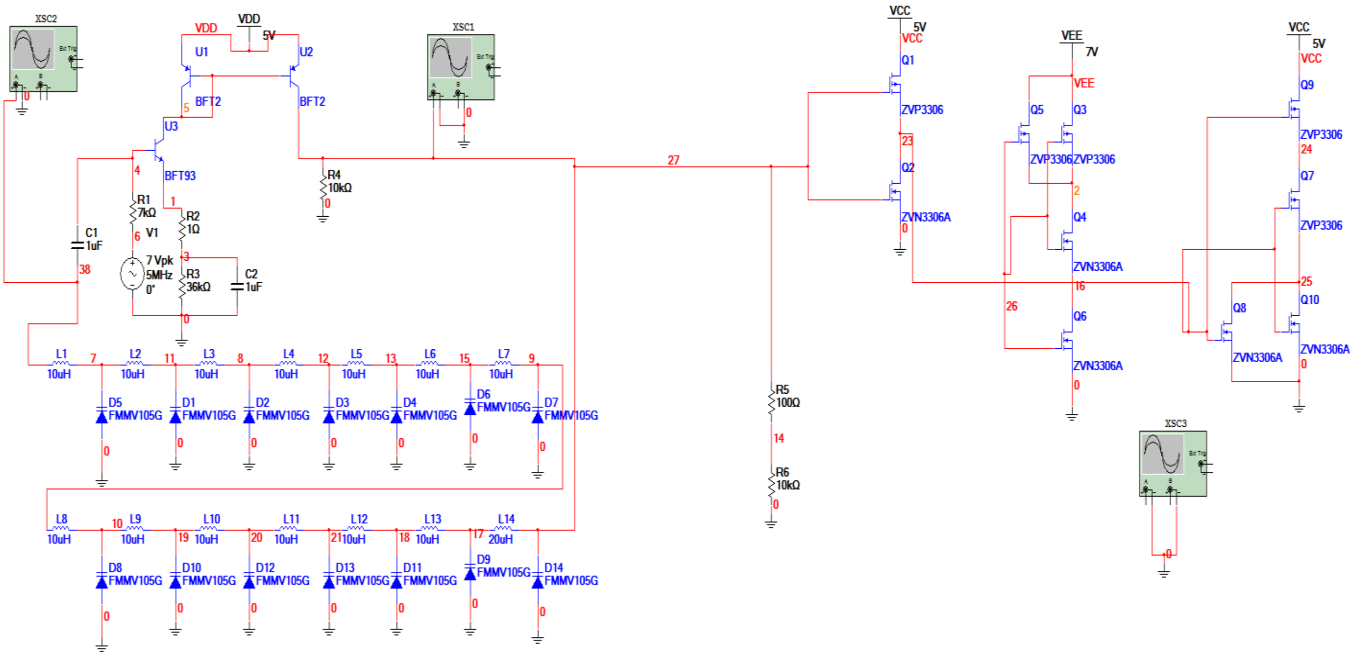


Figure 98 MultiSim schematic of Soliton CMOS NAND/NOR/Inverter

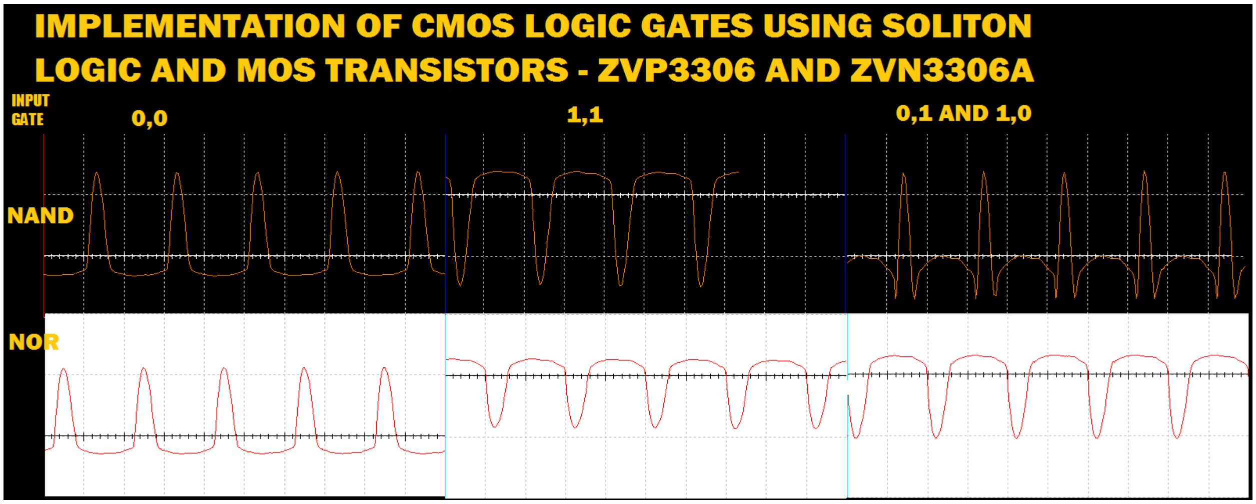


Figure 99 Outputs of Soliton CMOS NAND/NOR gates

4.11 SOLITONS IN COMMUNICATIONS

Since solitons exhibit lower distortions, we can use a train of solitons as a carrier instead of sinusoidal waves for passband analog and digital modulation. We now propose the use of such soliton carriers and on a simulation level, such modulation are compared with corresponding

Sinusoidal modulation and the results are tabulated. As will be seen later, soliton modulation yields better performance than sinusoidal modulation.

The proposed Soliton communication system was implemented in different platforms which are as follows:

1. Soliton based OFDM system implemented in LabVIEW
2. Soliton based CDMA system implemented in LabVIEW
3. Soliton Analog communication implemented in LabVIEW
4. Optical passband soliton modulation implemented in MATLAB
5. Chip to Chip soliton transmission implemented in FPGA using VHDL
6. Chaotic Soliton communication implemented in LabVIEW

4.12 SOLITON BASED OFDM AND CDMA

4.12.1 OVERVIEW OF MODULATION

1. **AM**: When amplitude modulated signal is created, the amplitude of the signal is varied in line with the variations in intensity of the sound wave. In this way the overall amplitude or envelope of the carrier is modulated to carry the audio signal. Here the envelope of the carrier can be seen to change in line with the modulating signal.

2. **FM**: The most obvious method of applying modulation to a signal is to superimpose the audio signal onto the amplitude of the carrier. However this is by no means the only method which can be employed. It is also possible to vary the frequency of the signal to give frequency modulation or FM. It can be seen that the frequency of the signal varies as the voltage of the modulating signal changes.

3. **BPSK**: The basic form of phase shift keying is known as Binary Phase Shift Keying (BPSK) or it is occasionally called Phase Reversal Keying (PRK). A digital signal alternating between +1 and -1 (or 1 and 0) will create phase reversals, i.e. 180 degree phase shifts as the data shifts state.

4. **QPSK**: QPSK, which stands for Quadrature Phase Shift Keying, refers to a type of phase modulation algorithm where there are four states involved. These four states also refer to four phases wherein a particular carrier is sent to QPSK. These states consist of 45, 135, 225, and 315 degrees.

5. **MSK**: When looking at a plot of a signal using MSK modulation, it can be seen that the modulating data signal changes the frequency of the signal and there are no phase discontinuities. This arises as a result of the unique factor of MSK that the frequency difference between the logical one and logical zero states is always equal to half the data rate. This can be expressed in terms of the modulation index, and it is always equal to 0.5.

6. **ASK**: The amplitude of an analog carrier signal varies in accordance with the bit stream (modulating signal) Keeping frequency and phase constant. The level of amplitude can be used to represent binary logic 0s and 1s. We can think of data signal as an ON or OFF switch. In the modulated signal, logic 0 is represented by the absence of a carrier, thus giving OFF/ON keying operation and hence the name given.

7. **FSK**: **Frequency-shift keying (FSK)** is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave. The simplest FSK is *binary FSK* (BFSK). BFSK literally implies using a pair of discrete frequencies to transmit binary (0s and 1s) information. With this scheme, the "1" is called the mark frequency and the "0" is called the space frequency.

8. **DPSK**: instead of using the bit patterns to *set* the phase of the wave, it can instead be used to *change* it by a specified amount. The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed **differential phase-shift keying (DPSK)**.

9. **QAM**:Quadrature Amplitude Modulation, QAM is a signal in which two carriers shifted in phase by 90 degrees are modulated and the resultant output consists of both amplitude

and phase variations. In view of the fact that both amplitude and phase variations are present it may also be considered as a mixture of amplitude and phase modulation.

4.12.2 OFDM CONCEPT

Orthogonal Frequency Division Multiplex or OFDM is a modulation format that is finding increasing levels of use in today's radio communications scene. OFDM has been adopted in the Wi-Fi arena where the 802.11a standard uses it to provide data rates up to 54 Mbps in the 5 GHz ISM (Industrial, Scientific and Medical) band. In addition to this the recently ratified 802.11g standard has it in the 2.4 GHz ISM band. In addition to this, it is being used for WiMAX and is also the format of choice for the next generation cellular radio communications systems including 4G, 3G LTE and UMB. OFDM, orthogonal frequency division multiplex is a rather different format for modulation to that used for more traditional forms of transmission. It utilizes many carriers together to provide many advantages over simpler modulation formats.

An OFDM signal consists of a number of closely spaced modulated carriers. When modulation of any form - voice, data, etc. is applied to a carrier, then sidebands spread out either side. It is necessary for a receiver to be able to receive the whole signal to be able to successfully demodulate the data. As a result when signals are transmitted close to one another they must be spaced so that the receiver can separate them using a filter and there must be a guard band between them. This is not the case with OFDM. Although the sidebands from each carrier overlap, they can still be received without the interference that might be expected because they are orthogonal to each another. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period.

To see how OFDM works, it is necessary to look at the receiver. This acts as a bank of demodulators, translating each carrier down to DC. The resulting signal is integrated over the symbol period to regenerate the data from that carrier. The same demodulator also demodulates the other carriers. As the carrier spacing equal to the reciprocal of the symbol period means that they will have a whole number of cycles in the symbol period and their contribution will sum to zero - in other words there is no interference contribution.

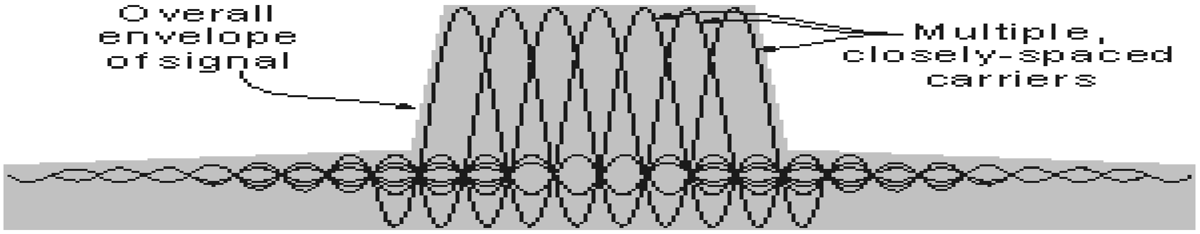


Figure 100 OFDM Concept

The data to be transmitted on an OFDM signal is spread across the carriers of the signal, each carrier taking part of the payload. This reduces the data rate taken by each carrier. The lower data rate has the advantage that interference from reflections is much less critical. This is achieved by adding a guard band time or guard interval into the system. This ensures that the data is only sampled when the signal is stable and no new delayed signals arrive that would alter the timing and phase of the signal. This Is Called CYCLIC PREFIX.

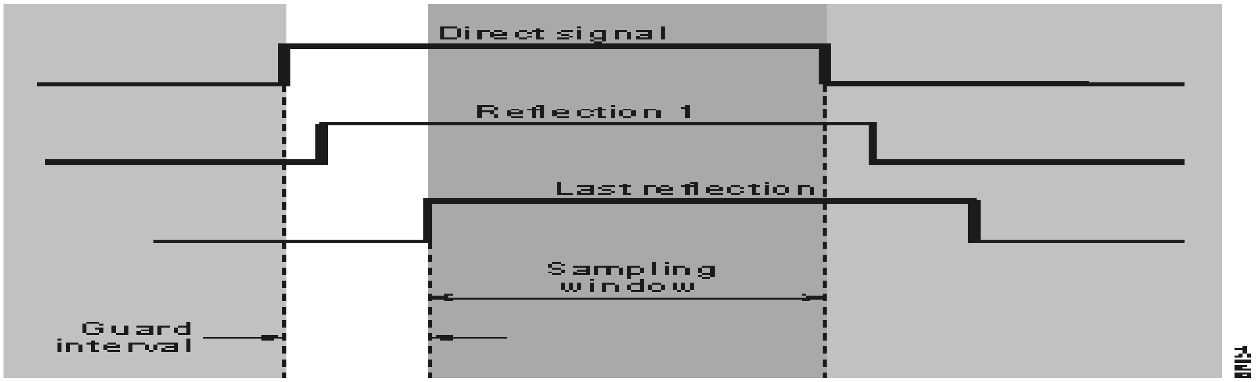


Figure 101 Concept of guard interval

The distribution of the data across a large number of carriers in the OFDM signal has some further advantages. Nulls caused by multi-path effects or interference on a given frequency only affect a small number of the carriers, the remaining ones being received correctly. By using error-coding techniques, which does mean adding further data to the transmitted signal, it enables many or all of the corrupted data to be reconstructed within the receiver. This can be done because the error correction code is transmitted in a different part of the signal.

4.12.2 SOLITON OFDM

The soliton based OFDM system is very similar to normal OFDM system, except that the carrier is replaced by a train of solitons. Shown below is the block diagram of the soliton OFDM system which is largely based on the IEEE 802.16 WiMAX system.

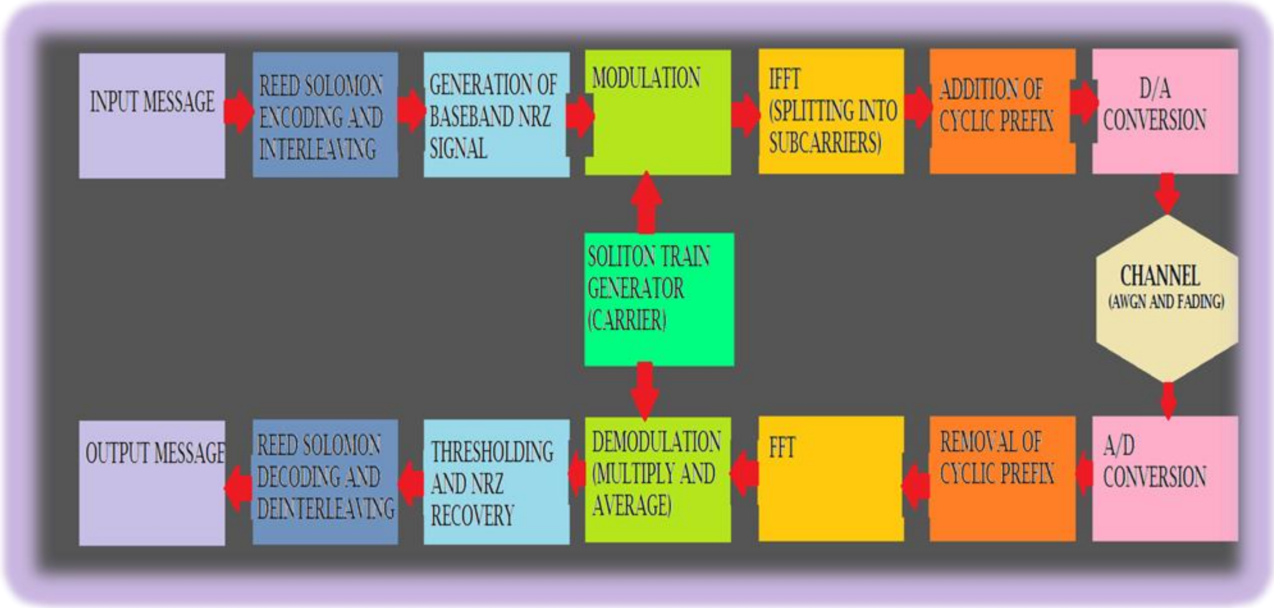


Figure 102 Soliton OFDM

The proposed communication system is implemented using NI's LabVIEW 8.5. The output of the MultiSim circuit (15 kHz generator) is taken as the carrier for modulation. Alternatively, a MATLAB code (Mathscript) incorporating the secht equation can also be used. Then different modulations such as ASK, FSK, BPSK, DPSK, QPSK, QAM and MSK are employed.

The modulation procedures are the same as for conventional digital modulation techniques. OFDM platform is used and for simplicity, encoding and interleaving is omitted. They will be added later. Just as how we specify no of cycles of sine for a bit, so also here we specify no of soliton pulses per bit. This determines the bit rate we can use.

To simulate the distortion due to channel, uniform white noise/awgn is added to the transmitted signal at the channel, before it enters the receiver. The performance of the system can be analyzed through two means:

1. Eye diagram: this is a very reliable means of analyzing the performance of any digital communication system and is used here too.
2. Bit error rate: this gives the fraction of erroneous bits. It is reliable only when the number of transmitted bits is relatively large.

4.12.3 CDMA CONCEPT

CDMA or Code Division Multiple Access is a form of access scheme that has been widely used within 3G cellular telecommunications systems as well as being used in a number of other technologies as well. CDMA technology gave some significant advantages when compared to the technologies used for previous in terms of overall performance and specifically in terms of spectrum efficiency.

CDMA uses spread spectrum technology with the use of different codes to separate between different stations or users rather than different frequencies or time slots as in the case of previous access technologies. In this way, CDMA is different to the previous schemes used to provide different cellular users with access to the radio network.

Direct sequence spread spectrum is a form of transmission that looks very similar to white noise over the bandwidth of the transmission. However once received and processed with the correct descrambling codes, it is possible to extract the required data. When transmitting a CDMA spread spectrum signal, the required data signal is multiplied with what is known as a spreading or chip code data stream. The resulting data stream has a higher data rate than the data itself. Often the data is multiplied using the XOR (exclusive OR) function.

Each bit in the spreading sequence is called a chip, and this is much shorter than each information bit. The spreading sequence or chip sequence has the same data rate as the final output from the spreading multiplier. The rate is called the chip rate, and this is often measured in terms of a number of M chips / sec.The baseband data stream is then modulated onto a carrier and in this way the overall the overall signal is spread over a much wider bandwidth than if the data had been simply modulated onto the carrier. This is because; signals with high data rates occupy wider signal bandwidths than those with low data rates.

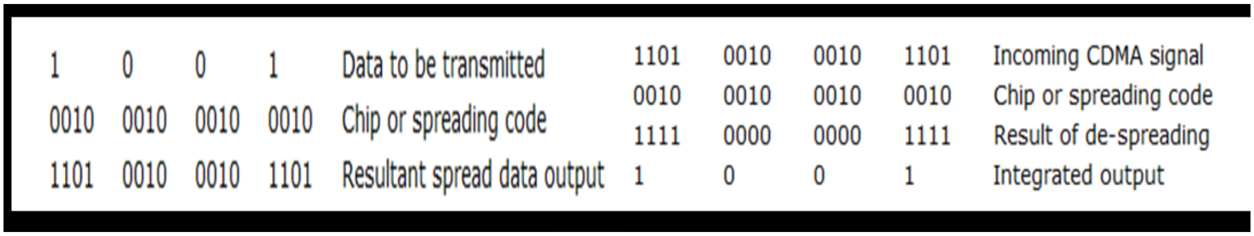
To decode the signal and receive the original data, the CDMA signal is first demodulated from the carrier to reconstitute the high speed data stream. This is multiplied with the spreading code to regenerate the original data. When this is done, then only the data with that was generated with the same spreading code is regenerated, all the other data that is generated from different spreading code streams is ignored.

The use of CDMA spread spectrum is a powerful principle and using this CDMA technique, it is possible to transmit several sets of data independently on the same carrier and then reconstitute them at the receiver without mutual interference. In this way a base station can communicate with several mobiles on a single channel. Similarly several mobiles can communicate with a single base station, provided that in each case an independent spreading code is used.

In order to visualize how the CDMA spread spectrum process operates, the easiest method is to show an example of how the system actually operates in terms of data bits, and how the data is recovered from the CDMA spread spectrum signal.

The first part of the process is to generate the CDMA spread spectrum signal. Take as an example that the data to be transmitted is 1001, and the chip or spreading code is 0010. For each data bit, the complete spreading code is used to multiple the data, and in this way, for each data bits, the spread or expanded signal consists of four bits.

With the signal obtained and transmitted, it needs to be decoded within the remote receiver:



1	0	0	1	Data to be transmitted
0010	0010	0010	0010	Chip or spreading code
1101	0010	0010	1101	Resultant spread data output

1101	0010	0010	1101	Incoming CDMA signal
0010	0010	0010	0010	Chip or spreading code
1111	0000	0000	1111	Result of de-spreading
1	0	0	1	Integrated output

Figure 103 Illustration of CDMA

In this way it can be seen that the original data is recovered exactly by using the same spreading or chip code. Had another code been used to regenerate the CDMA spread spectrum signal, then it would have resulted in a random sequence after de-spreading. This would have appeared as noise in the system. Commonly spreading codes may be 64 bits, or even 128 bits long to provide the required performance.

4.12.3 SOLITON CDMA

Similar to the OFDM model a CDMA model was also implemented using solitons as carrier using BPSK modulation and was compared with Sinusoidal. The block diagram is as follows:

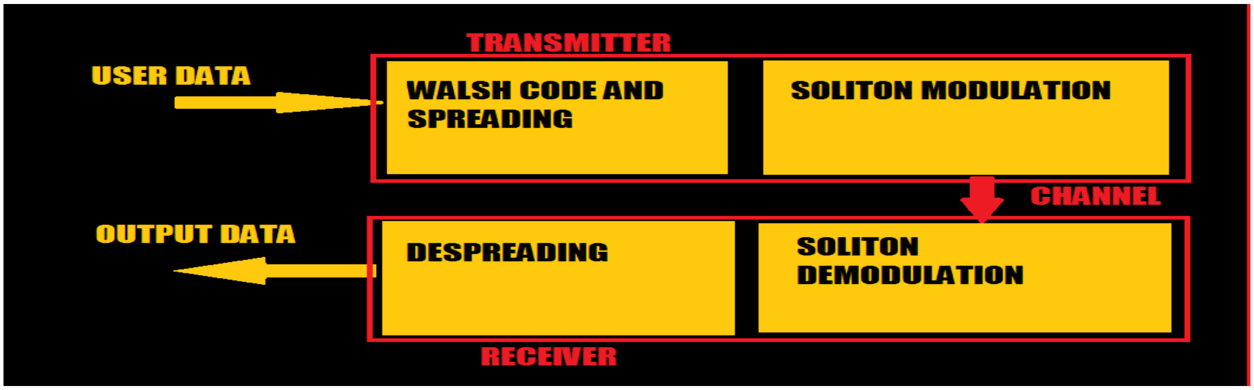
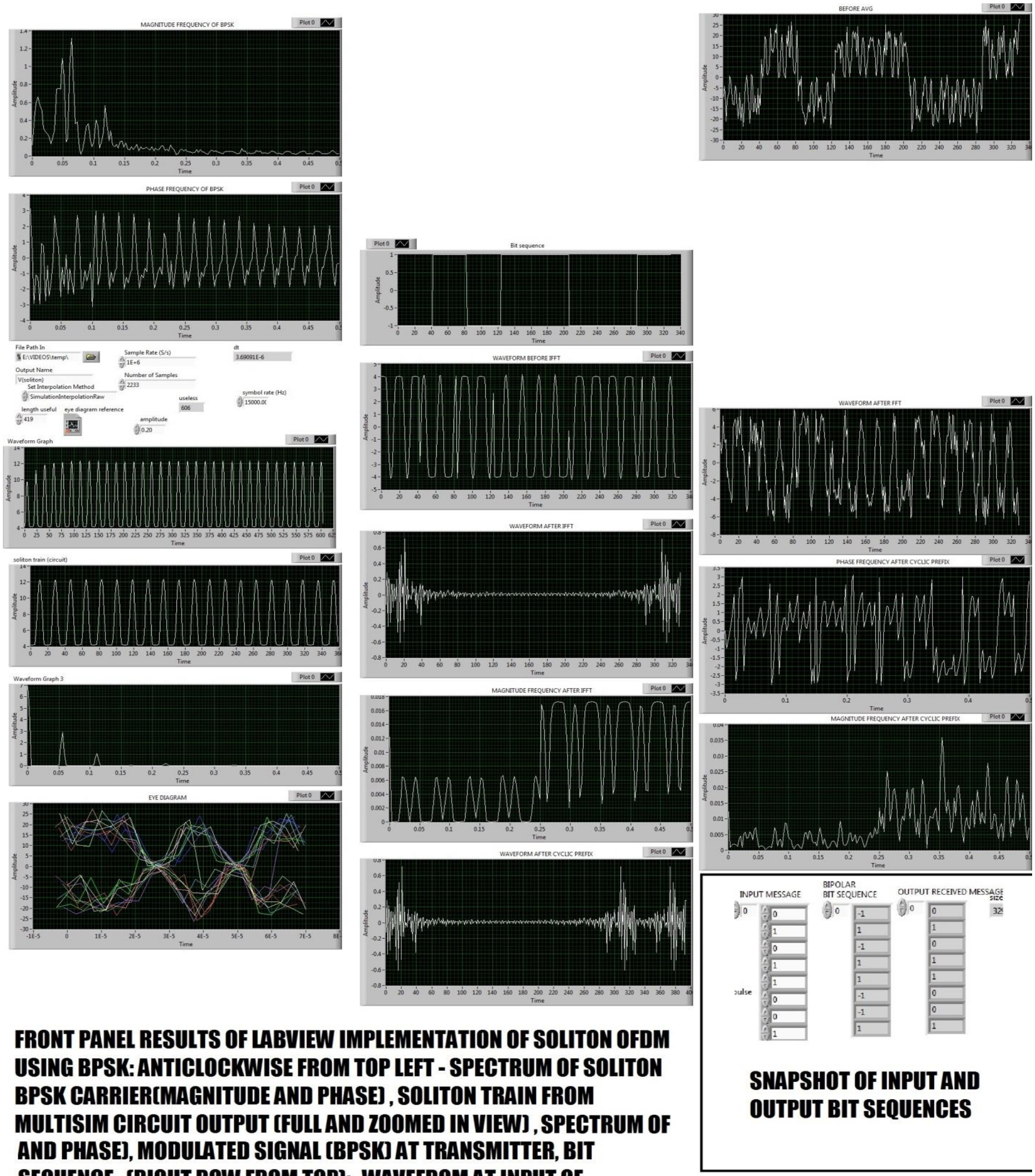


Figure 104 Soliton CDMA

4.12.4 RESULTS OF SOLITON OFDM AND CDMA

The front panel results of Soliton OFDM and CDMA as implemented in LabVIEW are as shown:



File Path In: E:\VIDEOS\temp\
Sample Rate (S/s): 1E+6
dt: 3.69091E-6
Output Name: V(soliton)
Number of Samples: 2233
Set Interpolation Method: SimulationInterpolationRaw
useless: 606
symbol rate (Hz): 15000.0
length useful: 419
eye diagram reference
amplitude: 0.20

INPUT MESSAGE	BIPOLAR BIT SEQUENCE	OUTPUT RECEIVED MESSAGE
0	0	0
0	-1	0
1	1	1
0	-1	0
1	1	1
1	1	1
0	-1	0
0	-1	0
1	1	1

size: 32

FRONT PANEL RESULTS OF LABVIEW IMPLEMENTATION OF SOLITON OFDM USING BPSK: ANTICLOCKWISE FROM TOP LEFT - SPECTRUM OF SOLITON BPSK CARRIER(MAGNITUDE AND PHASE) , SOLITON TRAIN FROM MULTISIM CIRCUIT OUTPUT (FULL AND ZOOMED IN VIEW) , SPECTRUM OF AND PHASE), MODULATED SIGNAL (BPSK) AT TRANSMITTER, BIT SEQUENCE , (RIGHT ROW FROM TOP):- WAVEFROM AT INPUT OF DEMODULATOR(RECEIVER) AND ITS SPECTRUM (MAGNITUDE & PHASE)

SNAPSHOT OF INPUT AND OUTPUT BIT SEQUENCES

Figure 105 Waveforms of Soliton BPSK OFDM

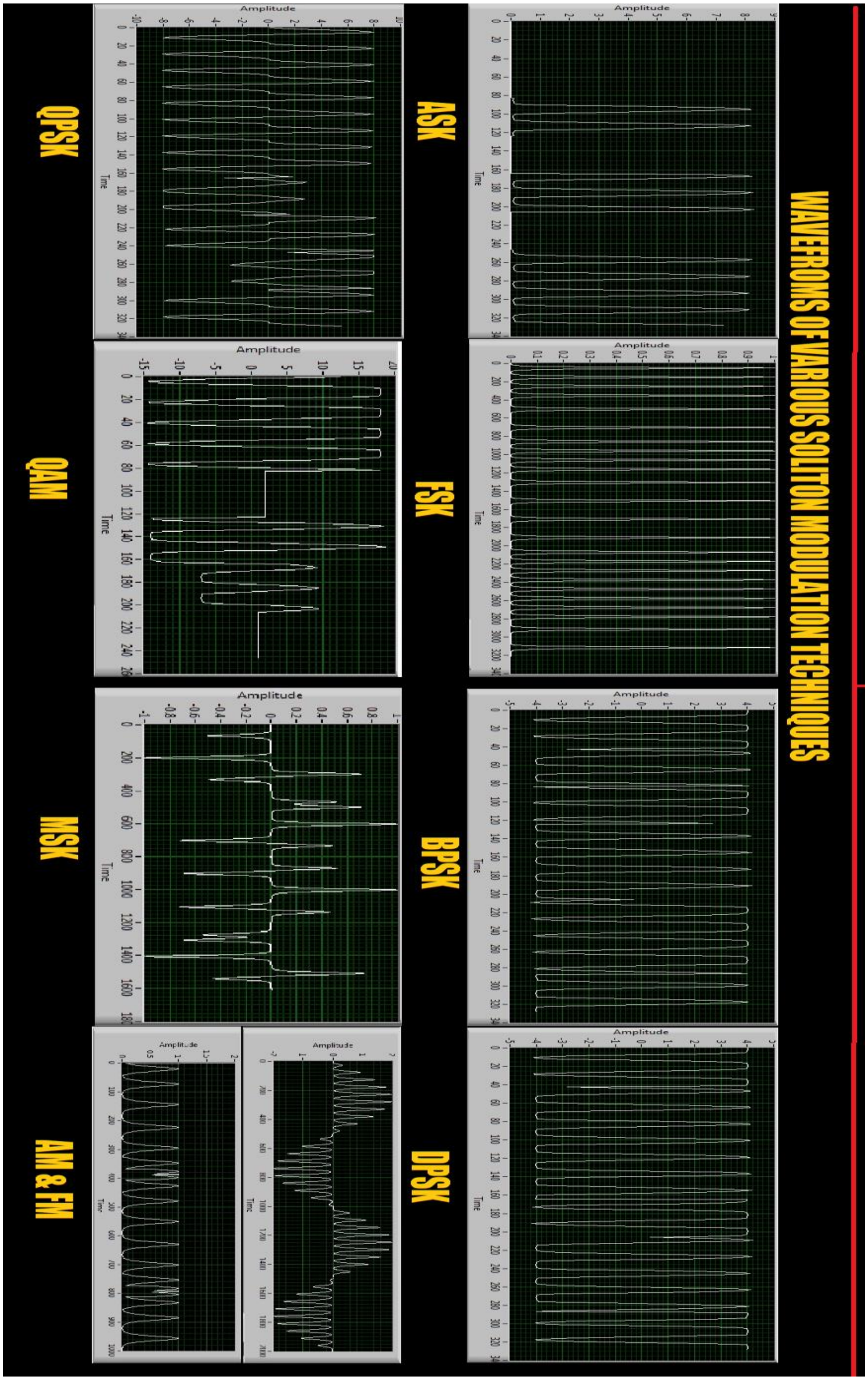


Figure 106 Soliton modulation Waveforms

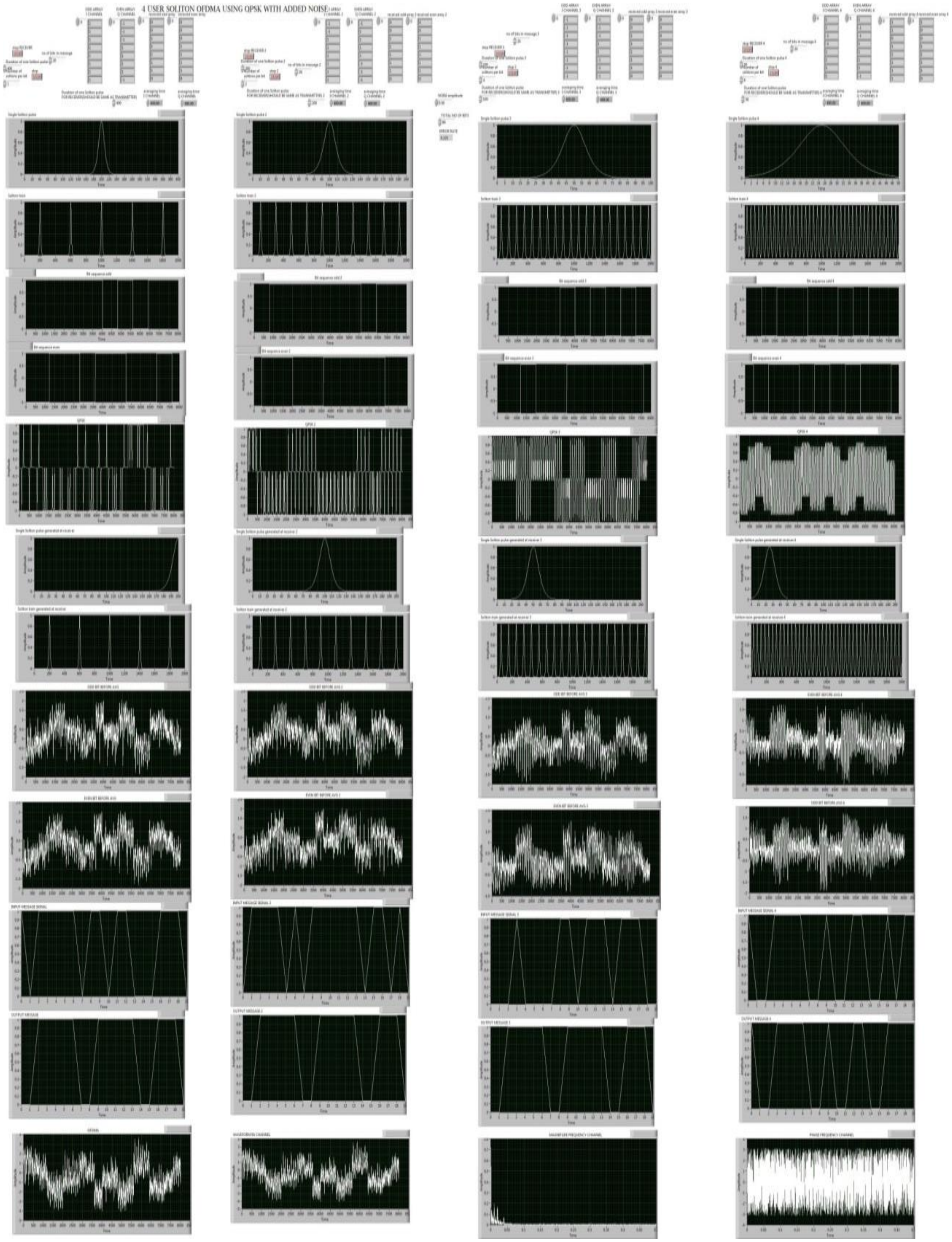

4 USER SOLITON OFDMA USING QPSK WITH ADDED NOISE

Figure 107 Soliton QPSK OFDMA for 4 users

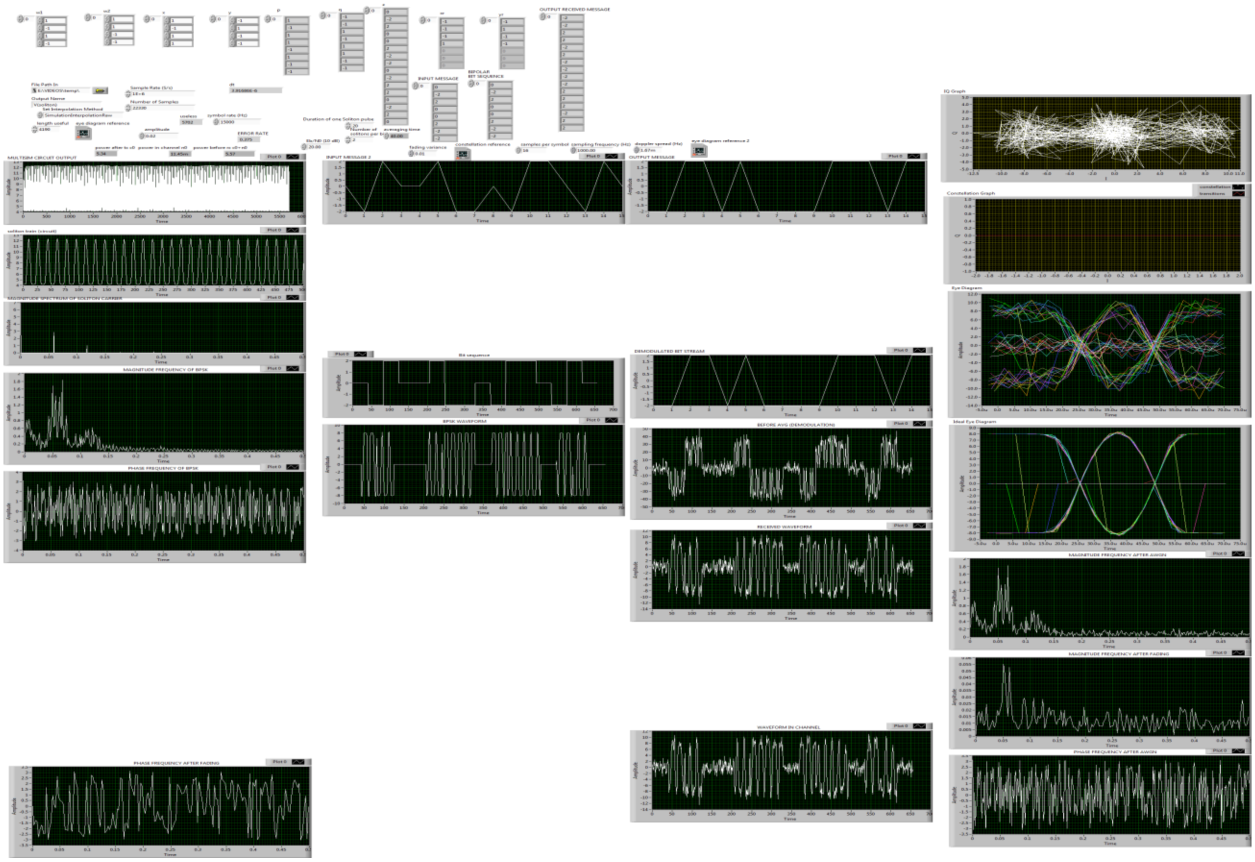


Figure 108 2 user Soliton BPSK CDMA

A detailed OFDM BPSK modulation using soliton is also implemented, including the encoding and interleaving blocks. Reed-Solomon encoding (RS (7, 3)) and block interleaving is used. To simulate a practical wireless channel, fading effect is added in addition to the noise. This fading is based on Rayleigh – Jakes model with a variance of 0.01, Doppler spread of 1.67MHz and a sampling frequency of 1000Hz.

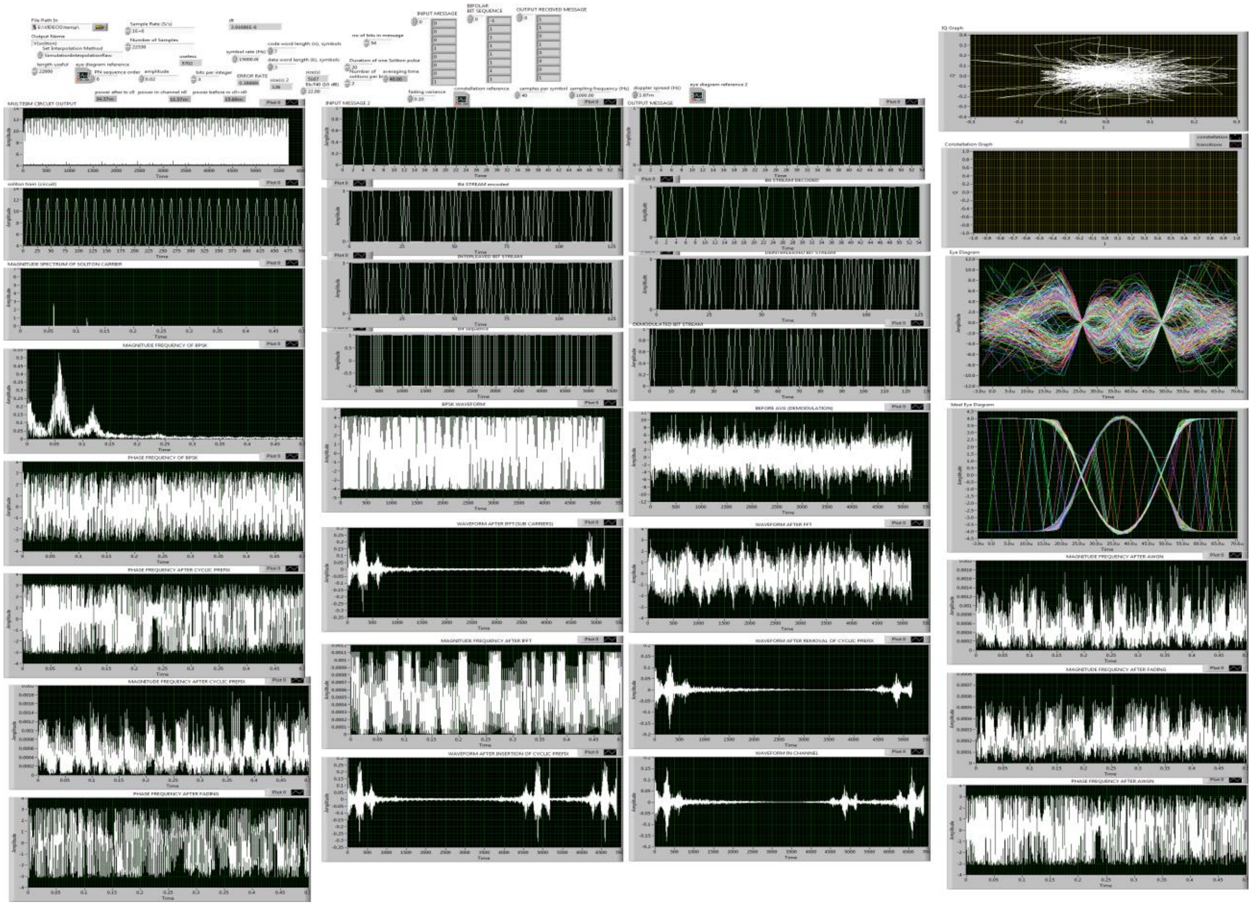

File Path In: E:\VIDEOS\temp\
Output Name: V(soliton)
Set Interpolation Method: SimulationInterpolationRaw
length useful: 22000
PN sequence order: 6
amplitude: 0.02
Sample Rate (S/s): 1E+6
Number of Samples: 22330
useless: 5702
bits per integer: 1
dt: 2.01606E-6
symbol rate (Hz): 15000.00
ERROR RATE: 0.38888
code word length (n), symbols: 7
data word length (k), symbols: 3
size(x) 2: 126
size(x): 5667
Eb/N0 (10 dB): 22.00
no of bits in message: 54
Duration of one Soliton pulse: 20
Number of solitons per bit: 2
averaging time: 40.00
fading variance: 0.10
samples per symbol: 40
sampling frequency (Hz): 1000.00
doppler spread (Hz): 1.67m
power after rx c0: 34.37m
power in channel n0: 11.57m
power before rx c0+n0: 15.68m
INPUT MESSAGE: 0, 0, 0, 1, 0, 0, 0, 1
BIPOLAR BIT SEQUENCE: -1, 1, 1, 1, 1, 1, 1, 1
OUTPUT RECEIVED MESSAGE: 1, 1, 0, 1, 0, 0, 0, 1

Figure 109 Detailed BPSK result for solitons

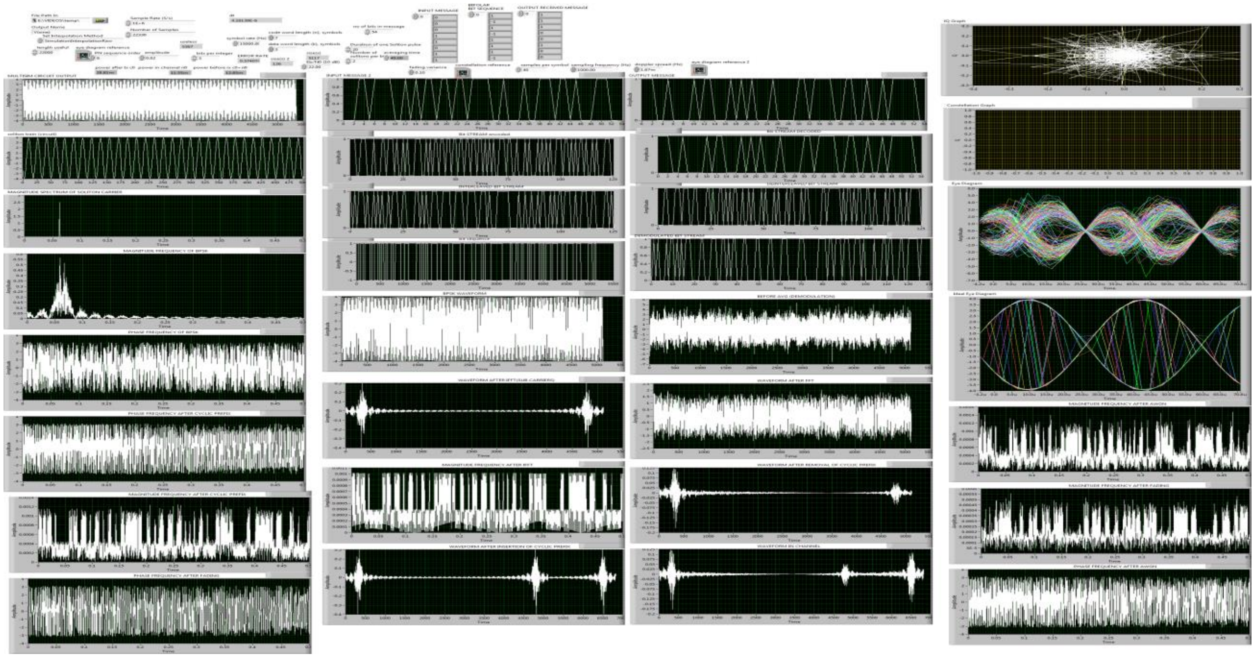
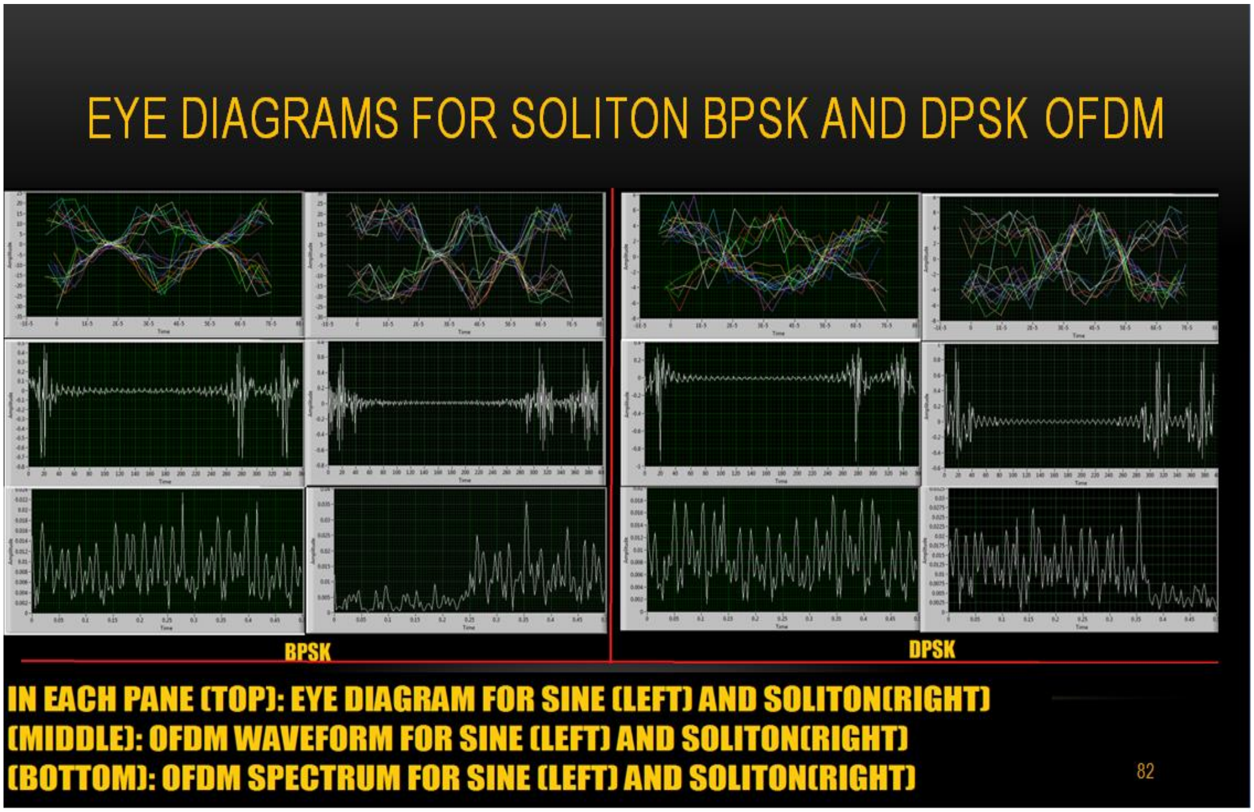


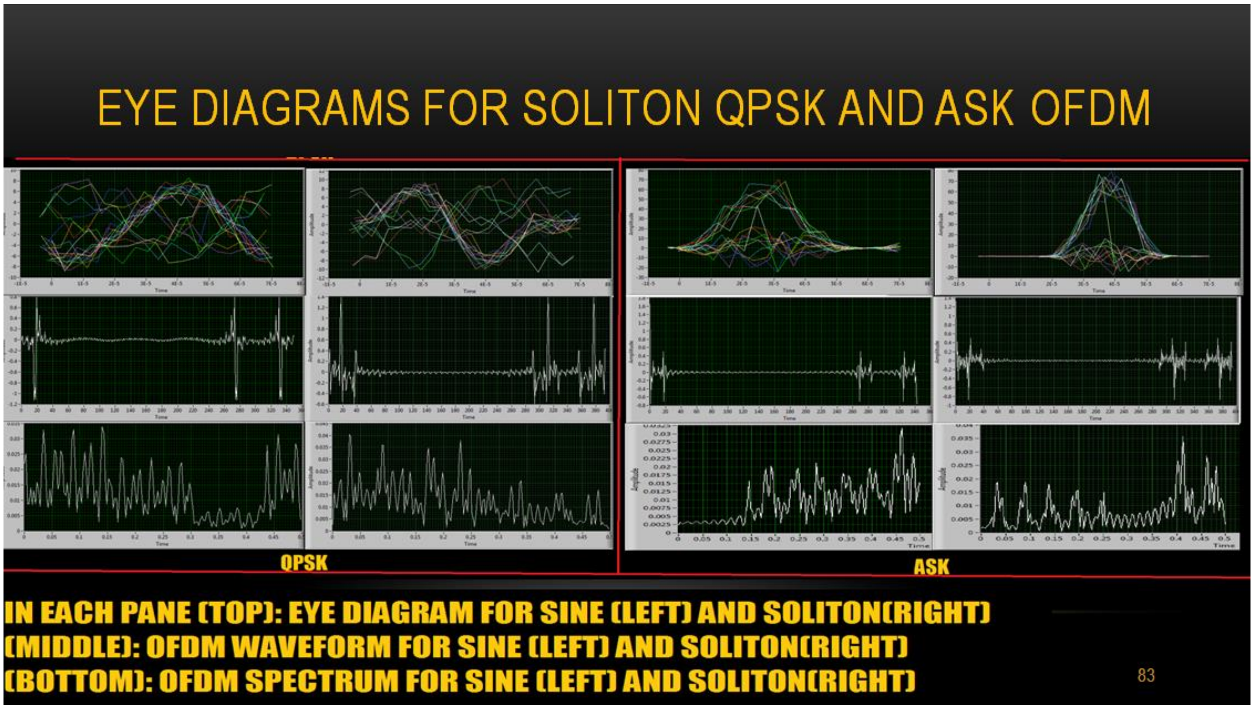
Figure 110 Detailed BPSK result for Sine



EYE DIAGRAMS FOR SOLITON BPSK AND DPSK OFDM

IN EACH PANE (TOP): EYE DIAGRAM FOR SINE (LEFT) AND SOLITON(RIGHT)
(MIDDLE): OFDM WAVEFORM FOR SINE (LEFT) AND SOLITON(RIGHT)
(BOTTOM): OFDM SPECTRUM FOR SINE (LEFT) AND SOLITON(RIGHT)

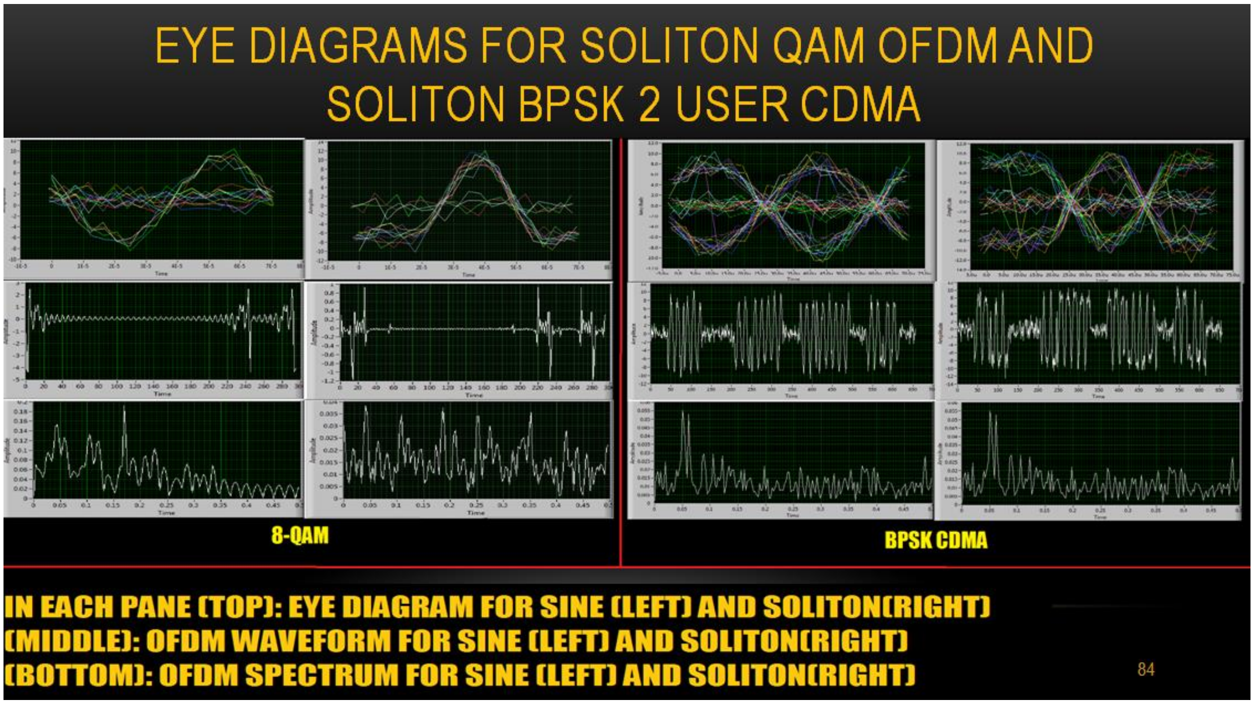
Figure 111 Eye diagrams 1



EYE DIAGRAMS FOR SOLITON QPSK AND ASK OFDM

IN EACH PANE (TOP): EYE DIAGRAM FOR SINE (LEFT) AND SOLITON(RIGHT)
(MIDDLE): OFDM WAVEFORM FOR SINE (LEFT) AND SOLITON(RIGHT)
(BOTTOM): OFDM SPECTRUM FOR SINE (LEFT) AND SOLITON(RIGHT)

Figure 112 Eye diagrams 2



EYE DIAGRAMS FOR SOLITON QAM OFDM AND SOLITON BPSK 2 USER CDMA

IN EACH PANE (TOP): EYE DIAGRAM FOR SINE (LEFT) AND SOLITON(RIGHT)
(MIDDLE): OFDM WAVEFORM FOR SINE (LEFT) AND SOLITON(RIGHT)
(BOTTOM): OFDM SPECTRUM FOR SINE (LEFT) AND SOLITON(RIGHT)

Figure 113 Eye diagrams 3

The eye heights and other related parameters for soliton and sinusoidal modulations are tabulated as follows:

TITLE	EYE HEIGHT		IMPROVEMENT IN EYE HEIGHT(%)	NOISE MARGIN (%)		TIMING JITTER (%)		SNR/ Eb/N0 MAINTAI-NED	BIT ERROR RATE (%)
TYPE	SOLITON	SINE	SOLITON/SINE	SOLITON	SINE	SOLITON	SINE	BOTH	SOLITON
ASK	40	30	33.33	40	31.5	9	15	-5	44.66
BPSK	22	15	46.67	44	33	6	13	-5	15
DPSK	5	3	66.67	38.5	26	7.5	15	-5	38
QPSK	13	9	44.44	72	56.2	4.5	9	-5	29
8-QAM	11	9	22.22	55	50	9	15	-5	24
DETAILED BPSK	3	2	50	18	15	6	18	22	38
DIRECT MICROWAVE BPSK	500	350	42.85	50	25	11	22	15	38
CDMA	13	12	8.33	62	60	10	15	20	37.5

Figure 114 Eye diagram parameters

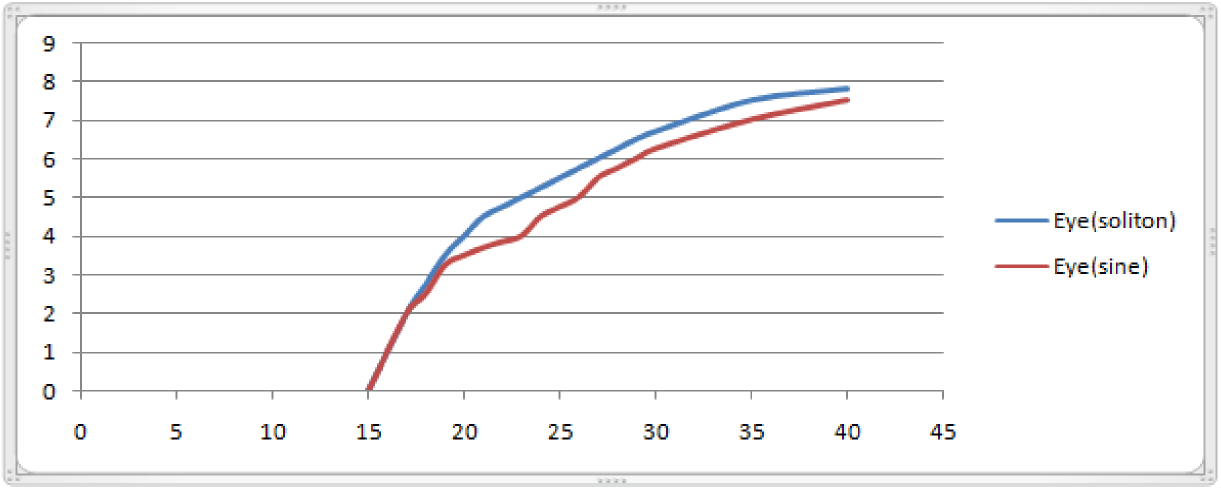
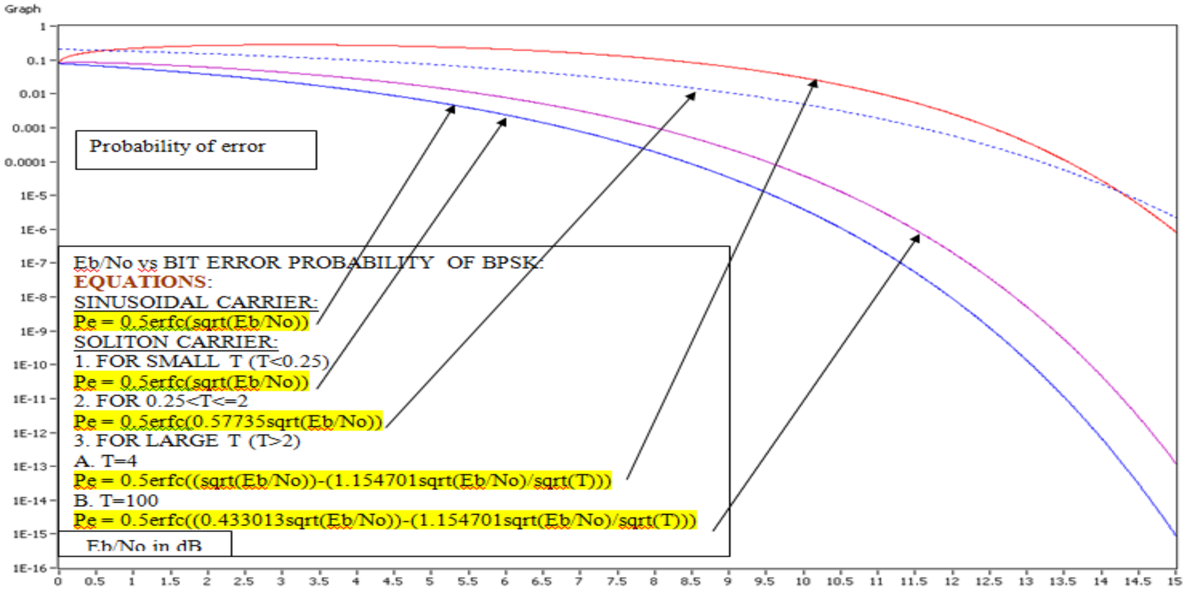


Figure 115 Eye height vs Eb/N0 for BPSK OFDM



Probability of error

Eb/No vs BIT ERROR PROBABILITY OF BPSK:

EQUATIONS:

SINUSOIDAL CARRIER:

Pe = 0.5erfc(sqrt(Eb/No))

SOLITON CARRIER:

1. FOR SMALL T (T<0.25)

Pe = 0.5erfc(sqrt(Eb/No))

2. FOR 0.25<T<=2

Pe = 0.5erfc(0.57735sqrt(Eb/No))

3. FOR LARGE T (T>2)

A. T=4

Pe = 0.5erfc((sqrt(Eb/No))-(1.154701sqrt(Eb/No)/sqrt(T)))

B. T=100

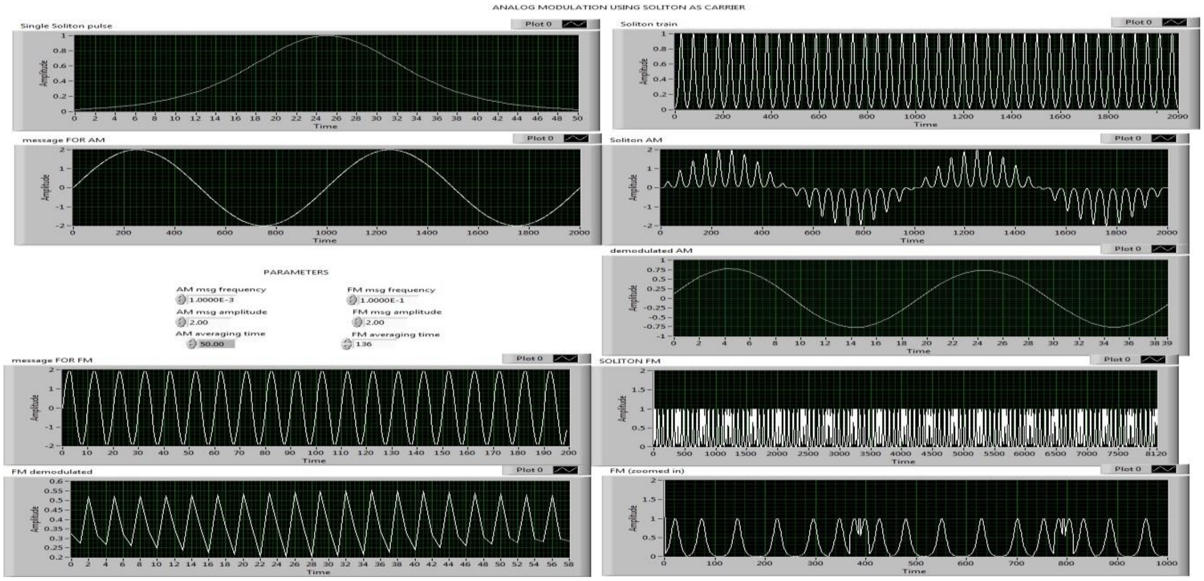
Pe = 0.5erfc((0.433013sqrt(Eb/No))-(1.154701sqrt(Eb/No)/sqrt(T)))

Eb/No in dB

Figure 116 Probability of Error vs Eb/N0 of BPSK

4.13 SOLITON ANALOG COMMUNICATIONS

Just as digital modulation, analog modulation can also be performed using soliton carriers. The LabVIEW results for soliton AM and FM are as shown below.



PARAMETERS

AM msg frequency 1.0000E-3

AM msg amplitude 2.00

AM averaging time 50.00

FM msg frequency 1.0000E-1

FM msg amplitude 2.00

FM averaging time 136

Figure 117 Soliton AM and FM

4.13 SOLITON CHAOTIC COMMUNICATION

4.13.1 IMPULSE AND CHAOTIC COMMUNICATIONS

Certain nonsinusoidal waves may enrich the scope and capacity of Modern wireless engineering. Two notable nonsinusoidal examples are *impulses and chaotic signals.* Advantages: large bandwidth, immunity to multipath fading, good penetrating capability, and low probability of detection *Electrical soliton oscillator* self-generates a periodic train of short impulses or, alternatively, a chaotic signal, the essential Commodities of impulse and chaotic communications, and thus crosses the two poles of spectrum, order and chaos. The distinctive engineering advantage of electrical soliton pulses lies in their extremely short pulse duration, which can be made as small as one picosecond. An example of a wireless system that uses impulses is the impulse ranging radar

4.13.2 CHAOTIC SOLITON COMMUNICATION

Just as two coupled sinusoidal oscillators can be frequency-synched via injection locking, two coupled chaotic oscillators can synchronize their chaotic outputs, converging from distant initial condition.

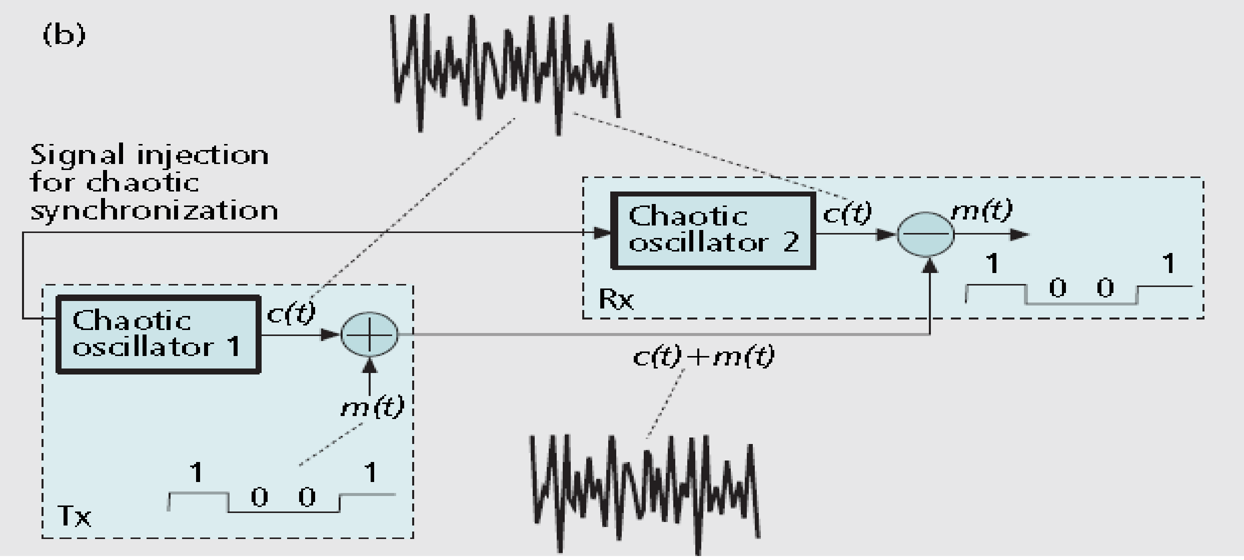


Figure 118 Chaotic soliton Communication system

Chaotic transmitter generates a chaotic carrier signal $c\ (t)$ *and the transmitter* sends out a modulated version $c\ (t) + m\ (t)$, *where* $m\ (t)$ *is the information signal. An identical* chaotic oscillator acts as a receiver, and coupled with the transmitter's oscillator by a common signal, produces a synchronized replica of $c\ (t)$. The information $m\ (t)$ *is recovered as the difference* between the receiver's input $c\ (t) + m\ (t)$ and the synchronized replica of $c\ (t)$.

The chaotic signal produced by the chaotic soliton oscillator can potentially have a bandwidth as large as one terahertz due to the extremely short soliton pulse. This directly corresponds to an increased data rate in chaotic communication.

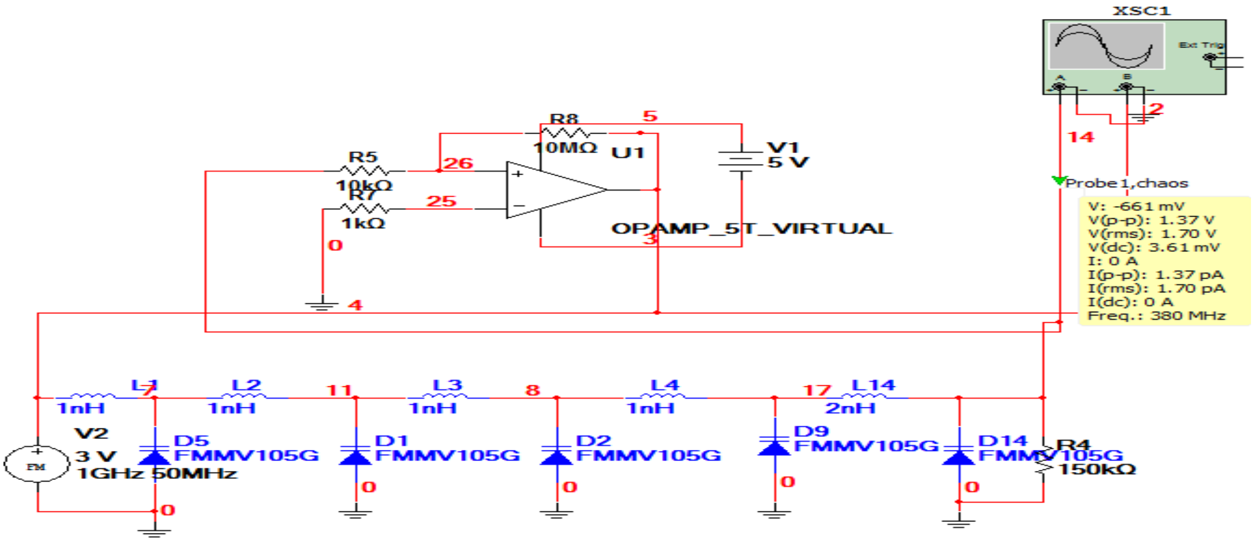
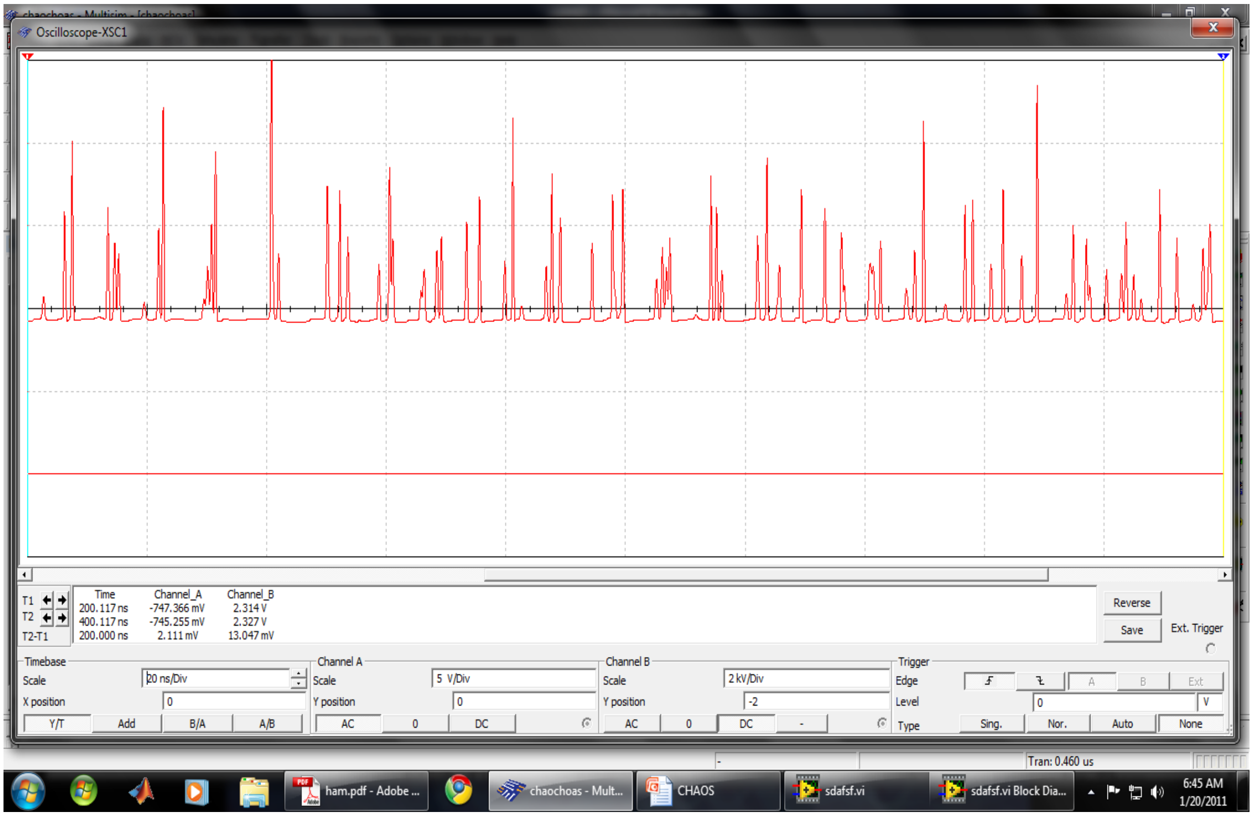


Figure 119 Chaotic oscillator schematic



	Time	Channel_A	Channel_B
T1	200.117 ns	-747.366 mV	2.314 V
T2	400.117 ns	-745.255 mV	2.327 V
T2-T1	200.000 ns	2.111 mV	13.047 mV

Timebase
Scale 20 ns/Div
X position 0

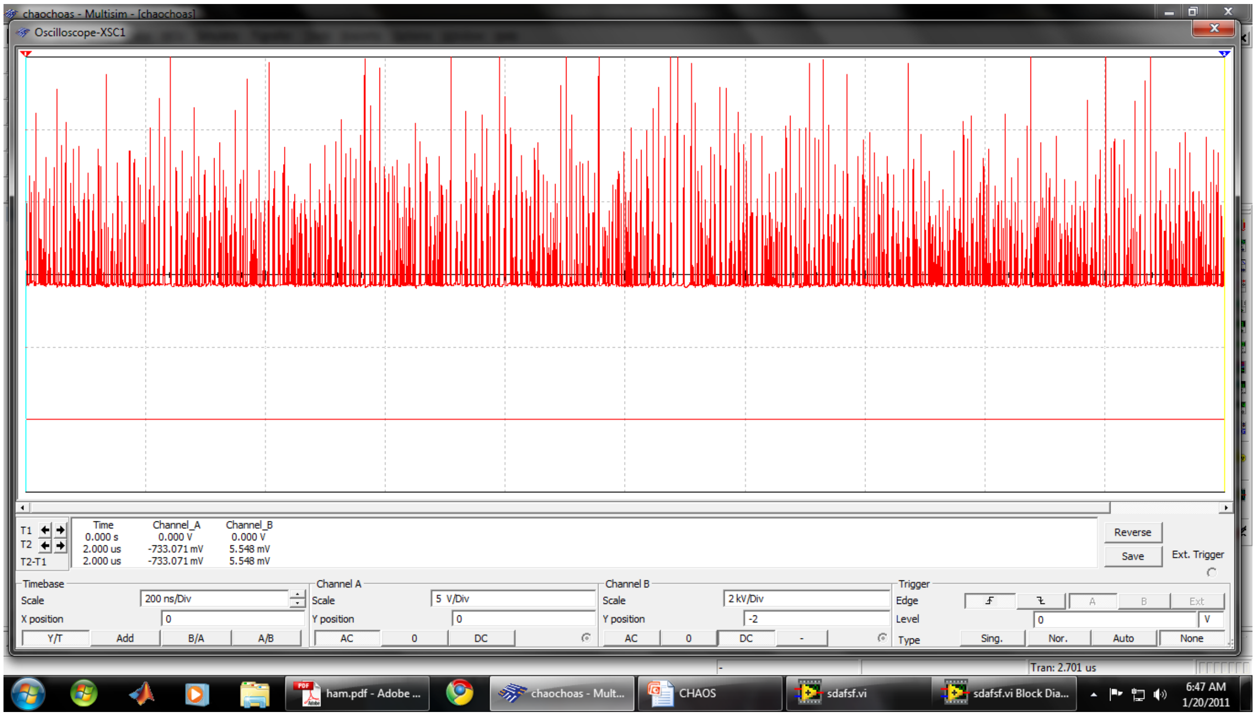
Channel A
Scale 5 V/Div
Y position 0

Channel B
Scale 2 kV/Div
Y position -2

Trigger
Edge
Level 0 V
Type

Tran: 0.460 us

Figure 120 Chaotic waveforms



	Time	Channel_A	Channel_B
T1	0.000 s	0.000 V	0.000 V
T2	2.000 us	-733.071 mV	5.548 mV
T2-T1	2.000 us	-733.071 mV	5.548 mV

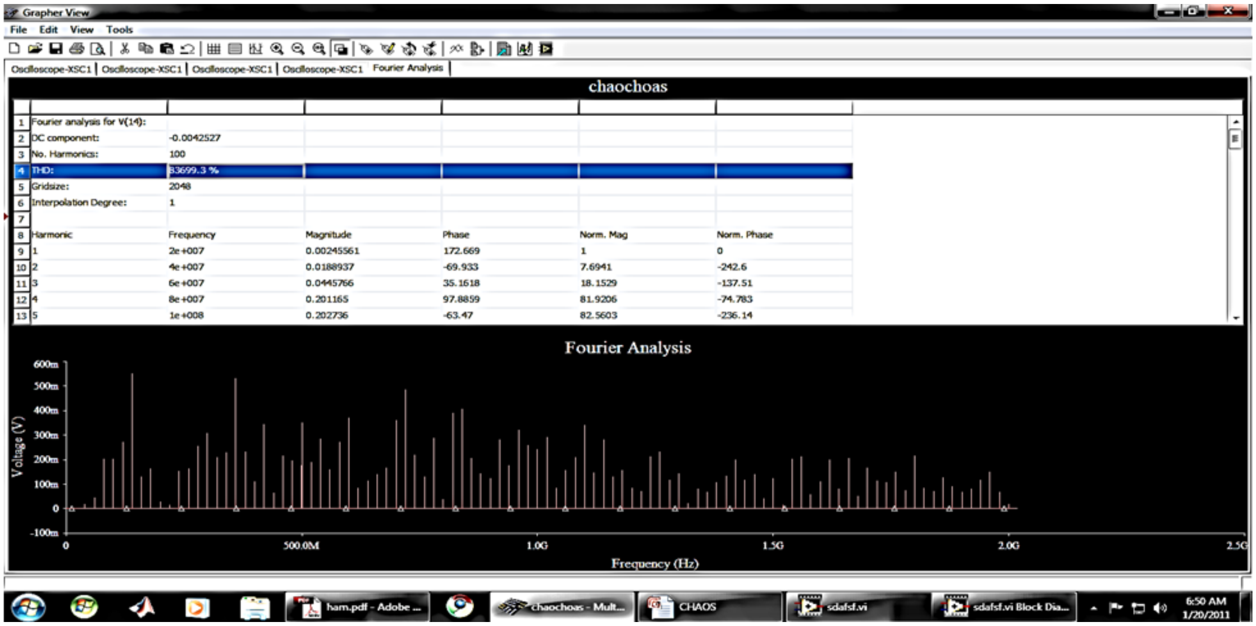
Timebase
Scale: 200 ns/Div
X position: 0

Channel A
Scale: 5 V/Div
Y position: 0

Channel B
Scale: 2 kV/Div
Y position: -2

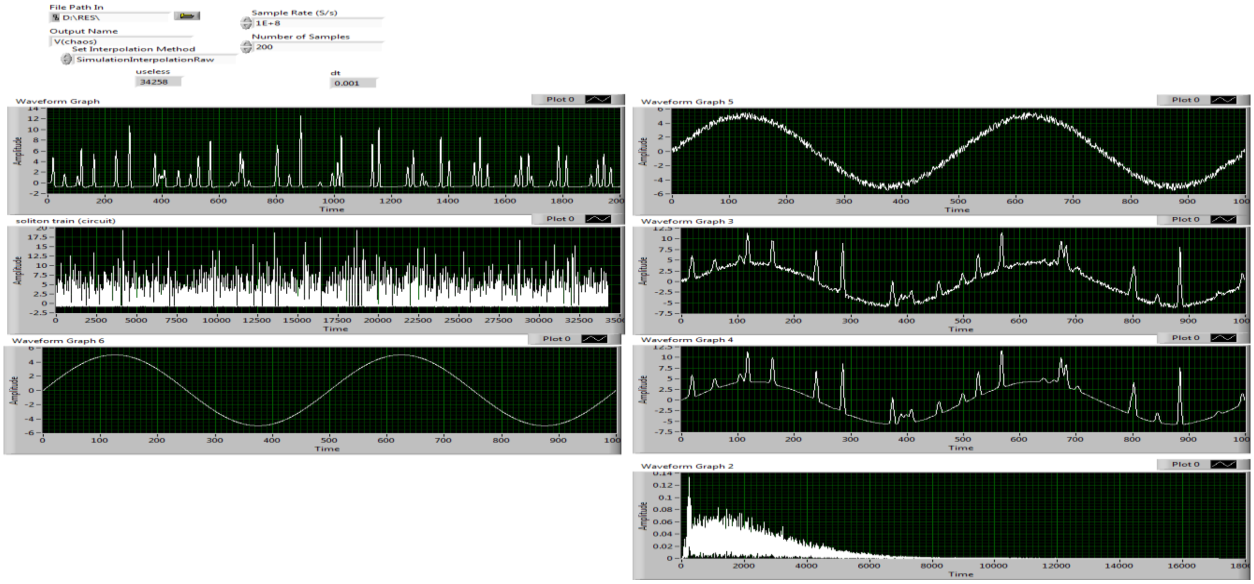
Trigger
Level: 0 V

Figure 121 Chaotic Waveforms



1	Fourier analysis for V(14):					
2	DC component:	-0.0042527				
3	No. Harmonics:	100				
4	THD:	83699.3 %				
5	Gridsize:	2048				
6	Interpolation Degree:	1				
7						
8	Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
9	1	2e+007	0.00245561	172.669	1	0
10	2	4e+007	0.0188937	-69.933	7.6941	-242.6
11	3	6e+007	0.0445766	35.1618	18.1529	-137.51
12	4	8e+007	0.201165	97.8859	81.9206	-74.783
13	5	1e+008	0.202736	-63.47	82.5603	-236.14

Figure 122 Fourier analysis of chaotic waveform



File Path In
D:\RES\

Output Name
V(chaos)

Set Interpolation Method
SimulationInterpolationRaw

Sample Rate (S/s)
1E+8

Number of Samples
200

useless
34258

dt
0.001

Figure 123 Chaotic soliton communication system implemented in LabVIEW

4.14 SOLITON BASED CHIP-TO-CHIP COMMUNICATION

Data transfer between two chips can also be done using solitons. Here the data to be transferred is first superimposed on a soliton, whose samples are stored in a lookup table, using some modulation technique like ASK or BPSK. Then it is transmitted. The block diagram is as follows

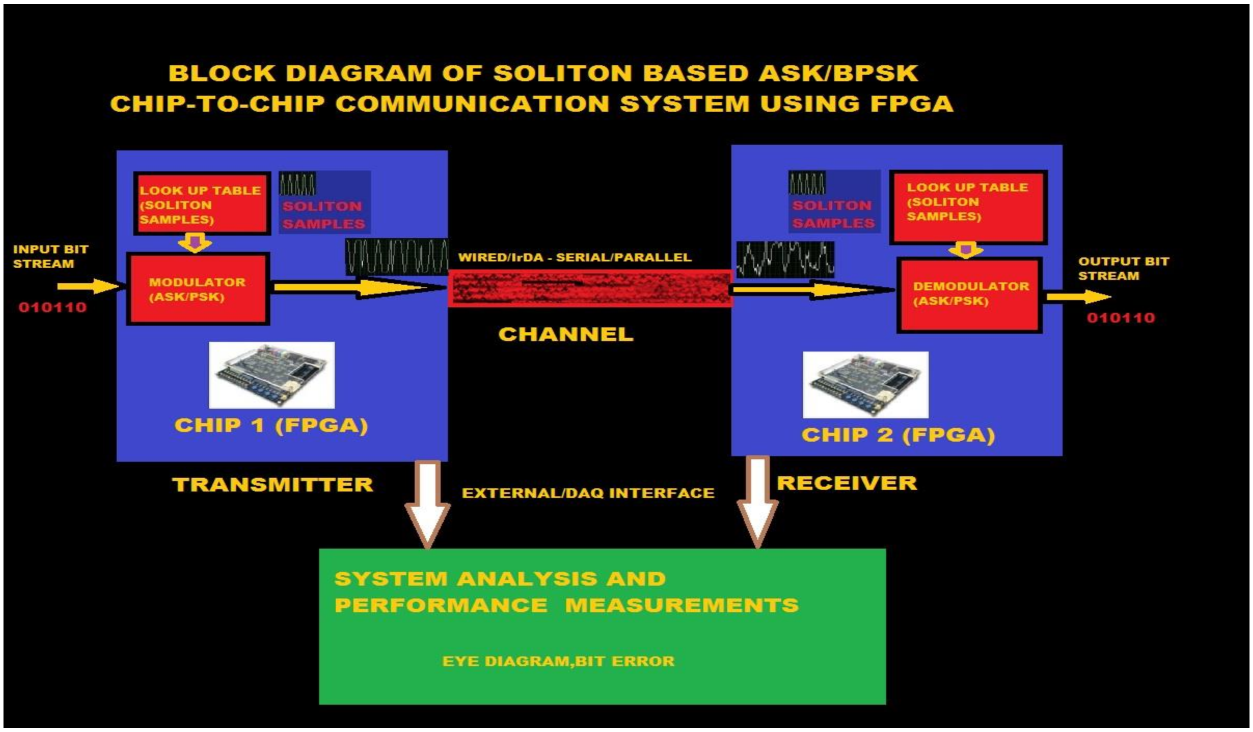


Figure 124 Block diagram of Chip to Chip Soliton Communication

This was first implemented in ModelSim using VHDL and the waveforms were plotted for ASK and BPSK. The results are as follows:

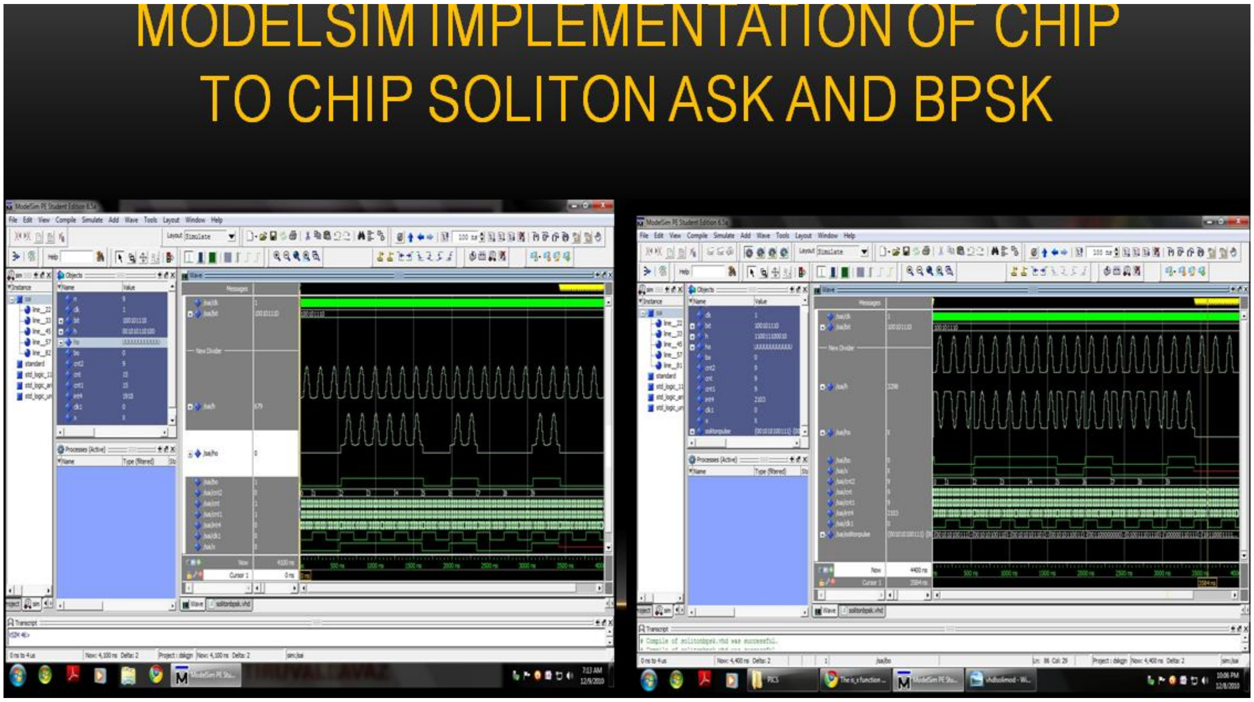
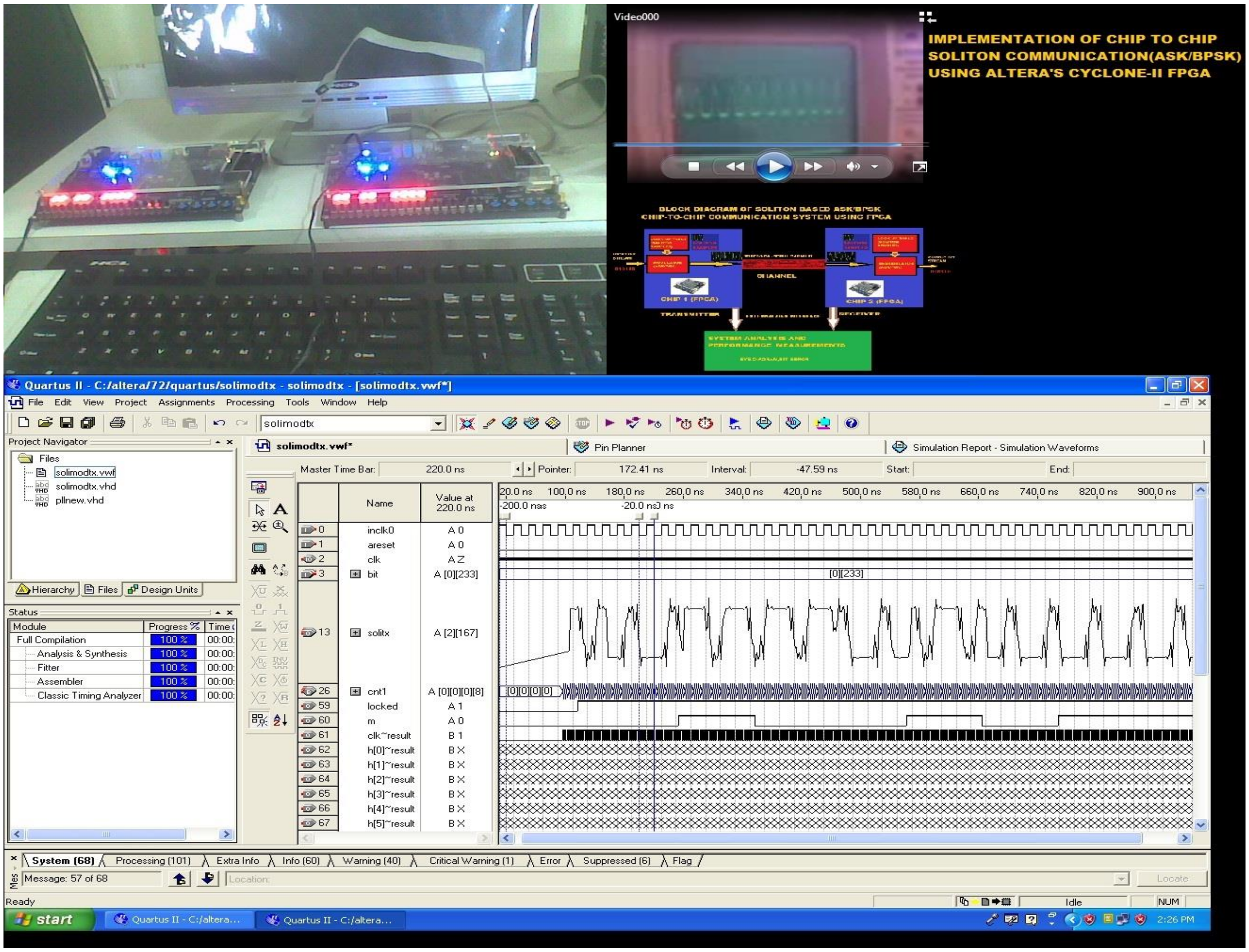

MODELSIM IMPLEMENTATION OF CHIP TO CHIP SOLITON ASK AND BPSK

Figure 125 ModelSim results

Then this was also implemented in FPGA using Altera's Cyclone DE-II and Quartus software. The compilation of snapshots and waveforms are as follows:



Status

Module	Progress %
Full Compilation	100 %
Analysis & Synthesis	100 %
Fitter	100 %
Assembler	100 %
Classic Timing Analyzer	100 %

Figure 126 FPGA implementation

4.15 OPTICAL SOLITON MODULATION

It is also possible to optically modulate solitons by first converting the output of an electrical soliton generator using an electro-optic modulator. This was simulated in MATLAB, where the Photonic crystal fiber acted as channel. This was modeled using Predictor Corrector Symmetrized Split Step Fourier Method which is one of the methods used to model a nonlinear fiber using piecewise methods. The block diagram is as shown below:

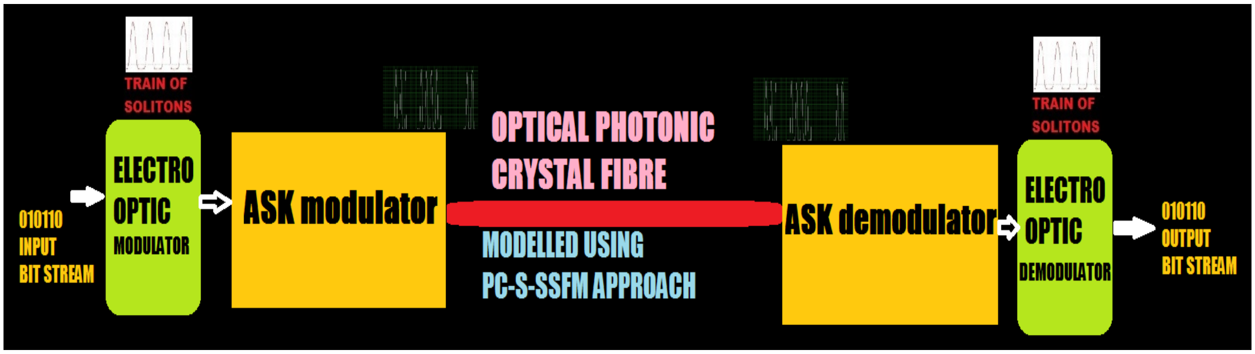
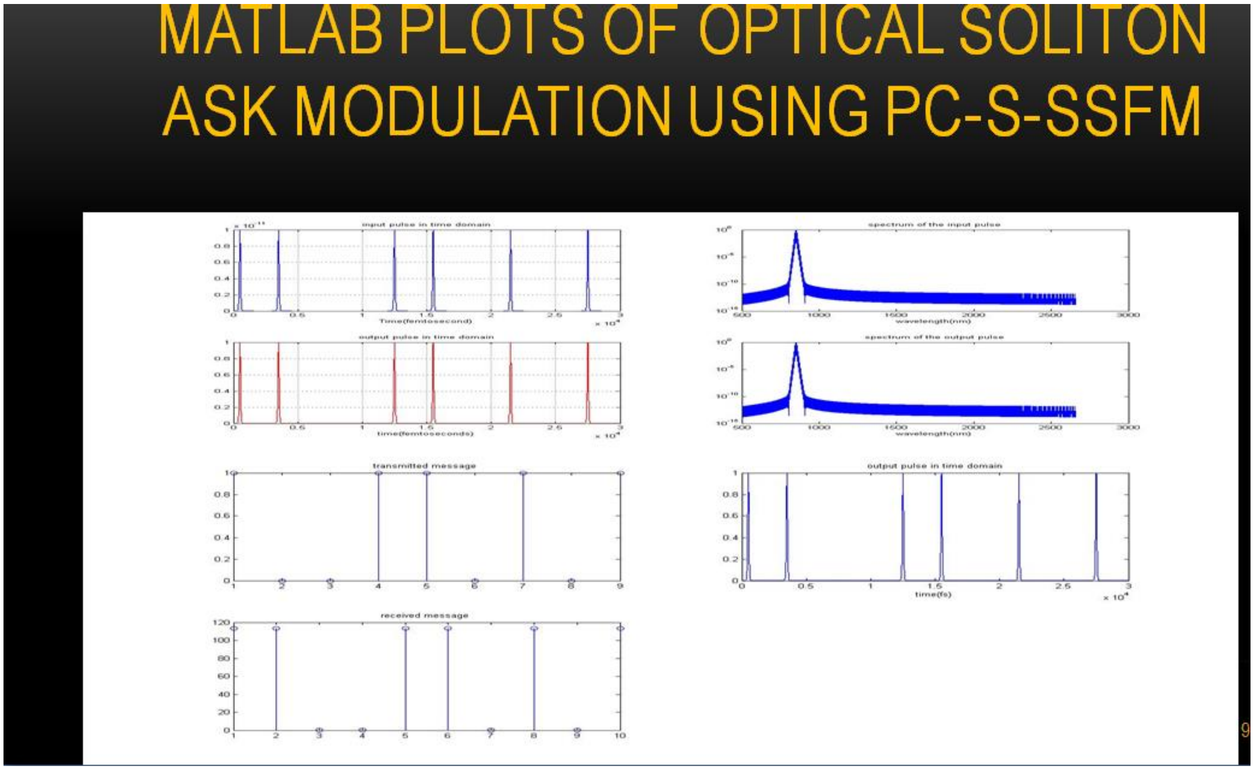


Figure 127 Optical soliton modulation

4.15.1 IMPLEMENTATION IN MATLAB

Optical Soliton ASK modulation and propagation through photonic crystal fiber was implemented in MATLAB and the input and output waveforms were plotted as follows:



MATLAB PLOTS OF OPTICAL SOLITON ASK MODULATION USING PC-S-SSFM

Figure 128 Optical Soliton ASK using PC-S-SSFM

Next, the same modulation is done for Sinusoidal square and sine with time periods of 10ps and soliton pulse width of 14 fs are done and results are plotted:

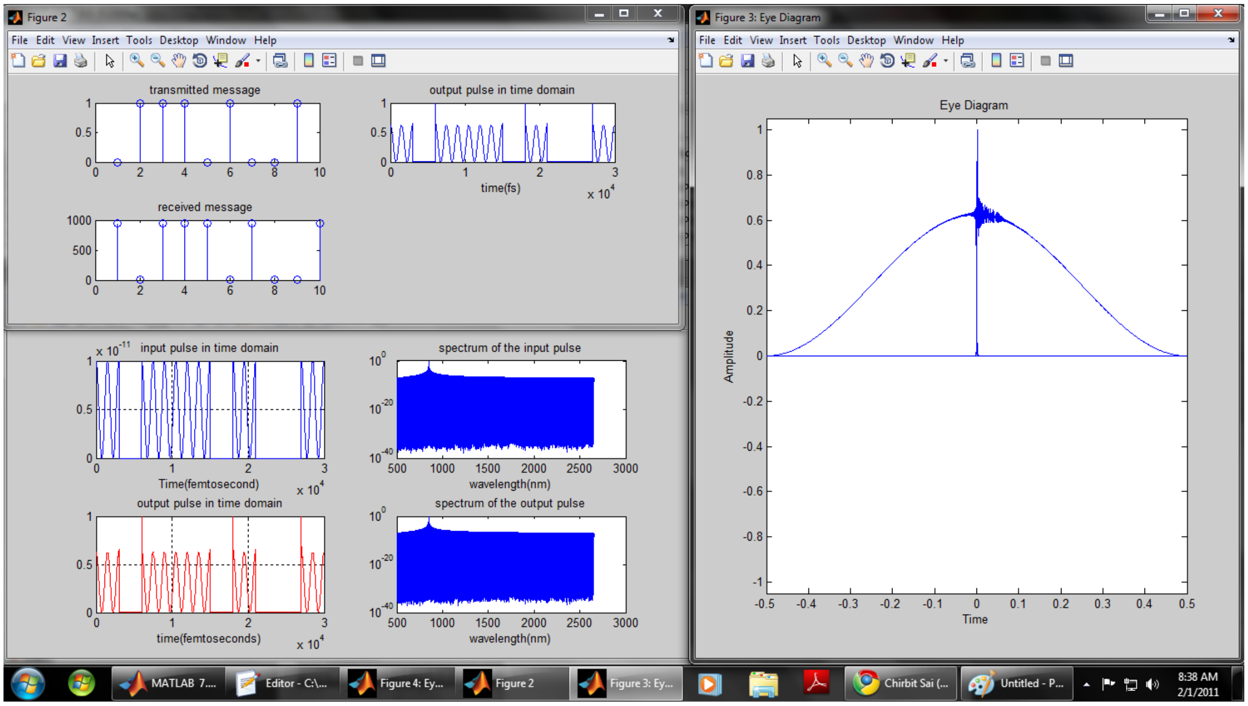


Figure 129 Sine THz optical modulation

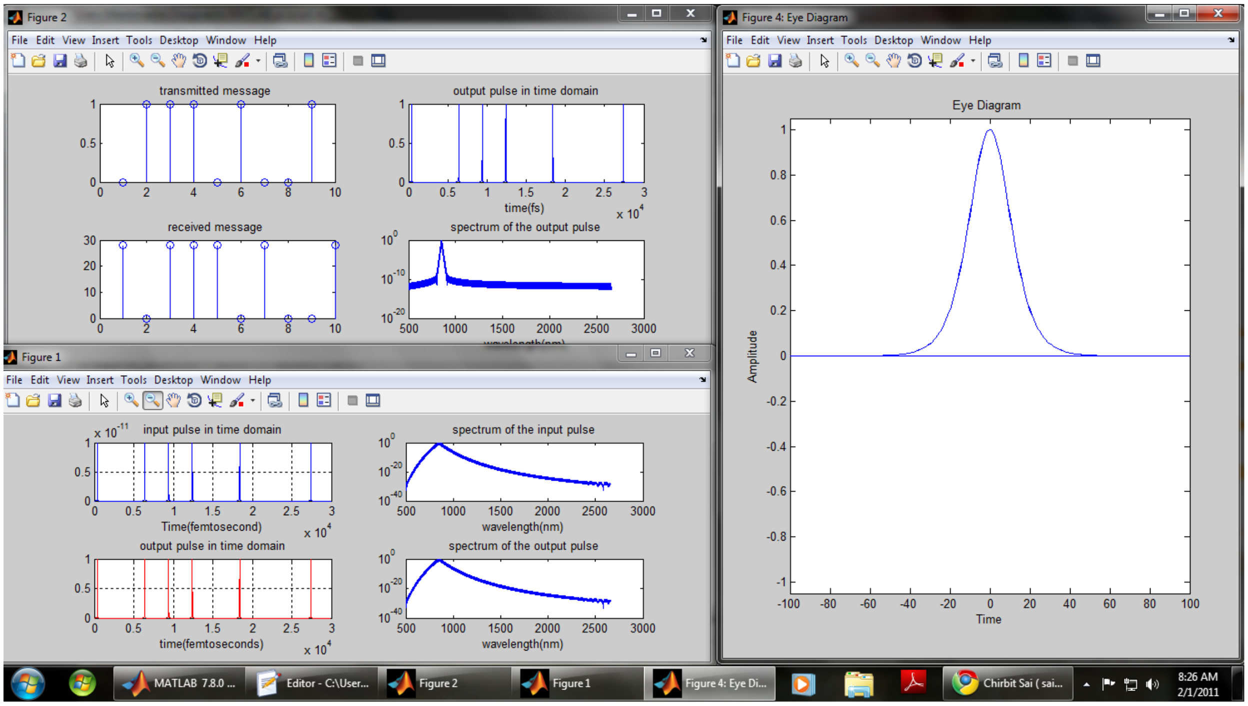


Figure 130 Soliton THz optical modulation

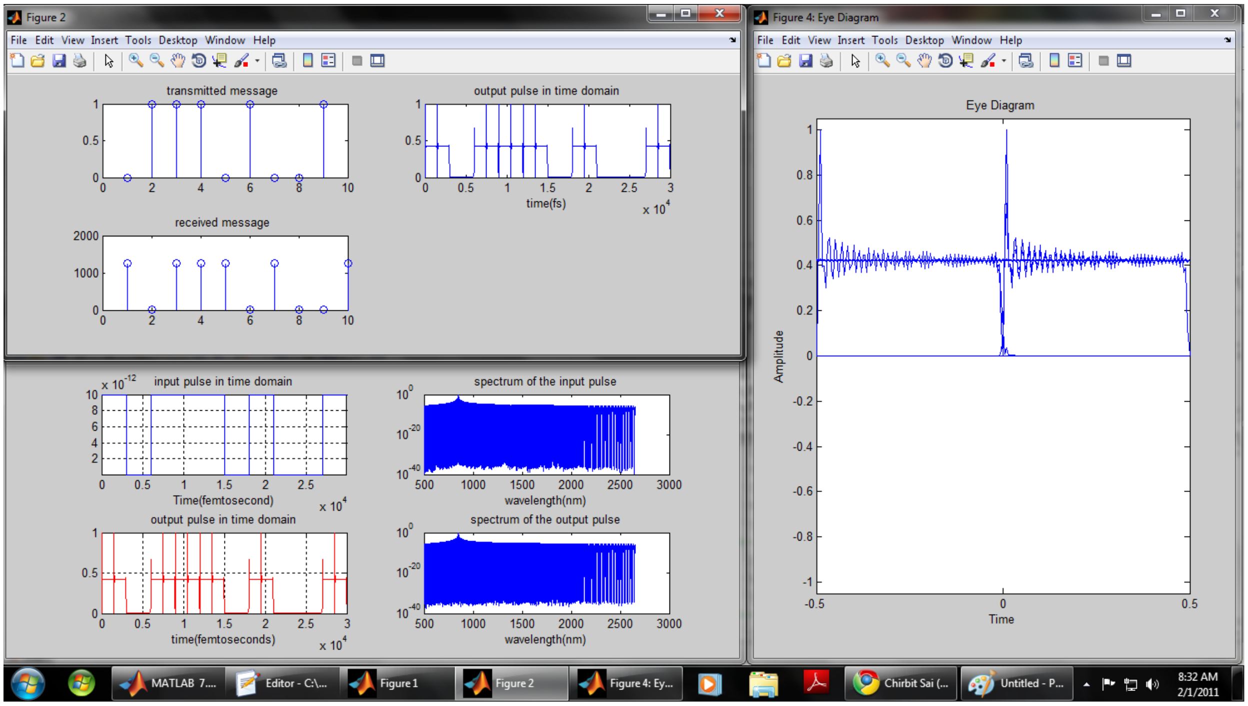


Figure 131 Square THz optical modulation

Here also the eye diagram shows minimal distortion for solitons thus suggesting the possibility of increased data rates in optical communication.

4.16 FUTURE DIRECTIONS - SOLITON LASER

The electrical soliton generator described earlier can be used in conjunction with an electro-optical modulator to provide a “soliton laser”, which can become a promising option because of the following factors:

1. Very high switching speeds and hence very high frequencies can be obtained
2. It is very cost effective compared to other lasers currently in use.
3. It provides more accuracy and less distortion
4. We can go even for femtosecond lasers.

In order to construct such a laser we need an electro-optic modulator which can be integrated along with the electrical circuitry, for which, silicon photonics employing silicon-on-insulator technology can be a promising option. These can be effectively used in radio over fiber communication.

4.16.1 SILICON PHOTONICS

Silicon photonics use silicon as an optical medium. The silicon typically lies on top of a layer of silica in what is known as **silicon on insulator** (SOI).Using SOI, it is possible to create hybrid devices in which optical and electronic components are integrated onto a single microchip. Silicon waveguides also support exotic nonlinear optical phenomena such as soliton propagation. They can be made using existing semiconductor fabrication techniques and, it is possible to create hybrid devices in which the optical and electronic components are integrated onto a single microchip. Typical SOI Rib Waveguide and mode profile:

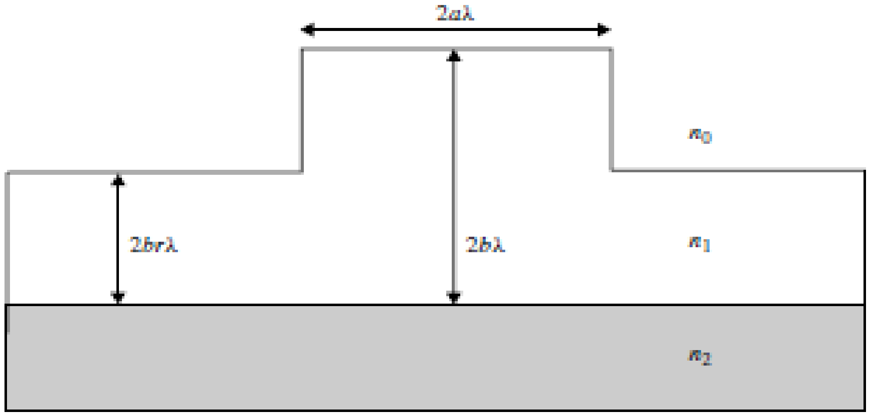


Figure 132 SOI Rib Waveguide

Silicon is transparent to infrared light with wavelengths above about 1.1 microns and has a very high refractive index, of about 3.5. The tight optical confinement provided by this high index allows for microscopic optical waveguides and Single mode propagation can be achieved. In order for the silicon photonic components to remain optically independent from the bulk silicon of the wafer on which they are fabricated, it is necessary to have a layer of intervening material. This is usually silica, which has a much lower refractive index and thus light at the silicon-silica interface will undergo total internal reflection, and remain in the silicon. Silicon photonics is useful for interconnects, due to the ability to integrate electronic and optical components on the same silicon chip.

4.16.2 ELECTRO OPTIC MODULATOR

The fastest modulation in silicon-on-insulator (SOI) waveguides was achieved by free-carrier injection at 20GHz and data rates of 30GBits. There are 3 popular constructions for Electro optic modulators as shown below:

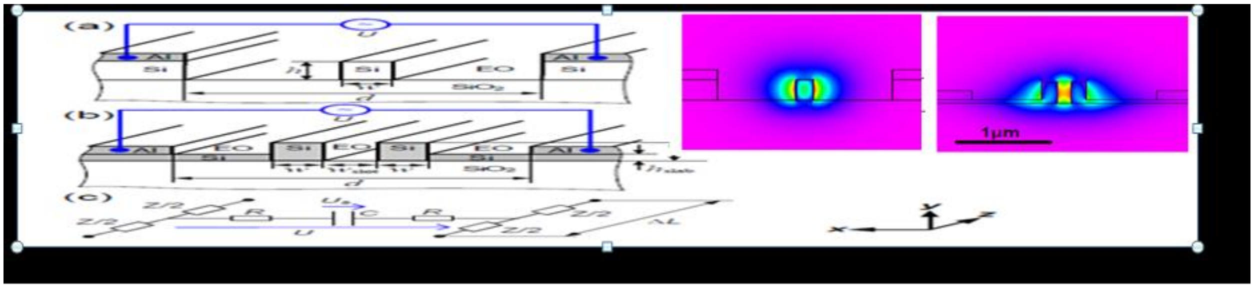


Figure 133 EO Modulator 1

In the **strip** structure (a), the light is guided by silicon strips which are embedded in the electro-optic material (EO) such as Lithium niobate - $LiNbO_3$. For the **slab** structure (b), both silicon strips are doped and connected to the aluminum conductors by thin silicon slabs. The modulation frequency is limited by the RC time constant. Equivalent circuit of (b) is shown in (c).

The size and power consumption of Electro optic devices can be considerably reduced by exploiting slow light in photonic crystal (PhC) waveguides

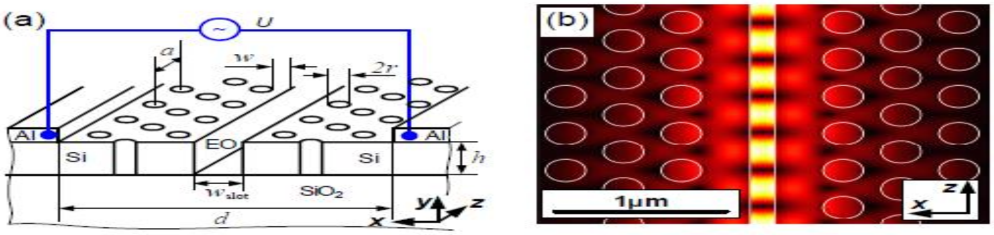


Figure 134 EO Modulator 2

The group velocity of the optical signal can be significantly reduced by an appropriate design of the PhC. The interaction time with the electro-optic material can thus be increased; this decreases the operating voltage and/or the device length.

4.17 SUMMARY

The following were learnt and achieved:

1. A robust electrical soliton oscillator/ generator was designed.
2. Soliton and similariton pulses propagated with far less distortion than their square counterparts.
3. Soliton trains could be implemented effectively in digital communication techniques with better results than sinusoidal waves.
4. Soliton modulation could be used in optical communication, leading to a cost effective yet powerful laser.
5. Chip to chip communication is successfully implemented using solitons.

4.18 REFERENCES

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