Free Space Optics using Soliton Carriers

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Abstract:

The concept of solitons has been successfully utilized in optical communications to handle signal distortion. In this light, the present work explores a signal-oriented perspective of solitons, where it is seen that the impulse responses of semiconductor devices such as PN-diodes and MOSFETs are obtained as solitons. Consequently, a simple circuit involving a single MOS inverter to generate a train of solitons from a sinusoidal input is proposed, designed and implemented in both TCAD Virtual Fabrication and Hardware levels. Following this, the free space optic transmissions of solitons are compared with square and sine wave signals, and it is seen that solitons are able to propagate longer distances with lesser attenuation values. Finally, a soliton free space optic AM communication system is designed and demonstrated in hardware level. The extreme simplicity of the soliton generator circuit owing to its ubiquity, coupled with the longer ranges and lower attenuation values obtained for soliton free space optic transmission forms the novelty of the present work, ultimately leading to next-gen applications such as LiFi.

Keywords: Solitons, Free Space Optics, Impulse Response, Amplitude Modulation

1. Introduction

It is a well-established fact that the most significant problem encountered in state-of-the-art communication systems is signal distortion, with contributions due to many factors such as intermodulation distortion, noise, nonlinearity, transmission losses and multipath fading effects [1-6]. In the domain of optical communications, similar problems have been handled efficiently, thanks to the concept of optical solitons, which are hyperbolic secant based solutions to the Nonlinear Schrodinger Equation describing pulse propagation in optical fibers [7]. Seen as a balance between linear dispersive and nonlinear effects, solitons are able to propagate for long distances undergoing minimal distortion [7]. Similar properties are observed for solitons in other aspects of nature, such as protein folding, tsunamis and neuron action potentials [8-10].

In this light, the present work explores the feasibility of solitons as carriers for telecommunication systems, albeit from a signal-oriented perspective. Firstly, it is observed that the impulse responses of typical semiconductor devices such as PN-junction diodes and MOSFETs are solitons, owing to the inherent roll-off rates in the corresponding AC responses. Based on this observation, extremely simple circuits involving single MOS inverter are designed effectively harnessing the MOS nonlinearity to convert a sinusoidal signal to a train of solitons. This design is verified using TCAD based Virtual Fabrication, as well in hardware level. Following this, a free-space optic transmission system, well known for its severe limitation in transmission range, is implemented in hardware level, where the maximum distance of propagation (range of transmission) is compared for soliton pulses vis-à-vis square and sinusoidal signals, which are conventional carrier choices in state-of-the-art systems. It is observed that solitons are able to propagate for much larger distances with lower attenuation values. Finally, a prototype Soliton Amplitude Modulation Free Space Optic Communication System is demonstrated. The ubiquitous nature of solitons in semiconductor device impulse responses leading to extremely simple soliton generator circuits, coupled with the longer transmission ranges of solitons compared with conventional carriers forms the novelty of the present work, which thus finds applications in next-gen communication systems such as Li-Fi [11-12].

2. Electrical Solitons

Most optical soliton solutions derived from the Nonlinear Schrodinger Equation consist of a temporal hyperbolic secant function based profile, defined as follows [7]:

$$A(t) = A_0 sech\left(\frac{t-S}{W}\right) \quad (1)$$

where A_0 denotes the peak amplitude and S and W denote the pulse shift (time offset) and width (measured at half-peak value) respectively. This signal represents a bell-shaped curve and is plotted in Fig. 1.

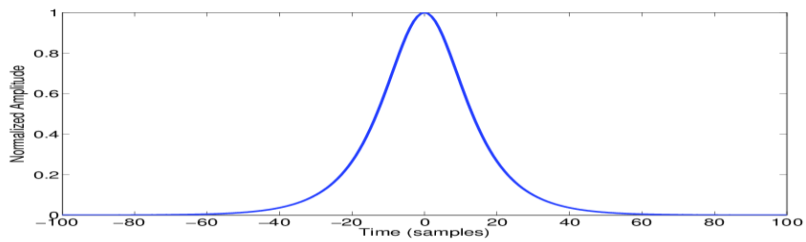
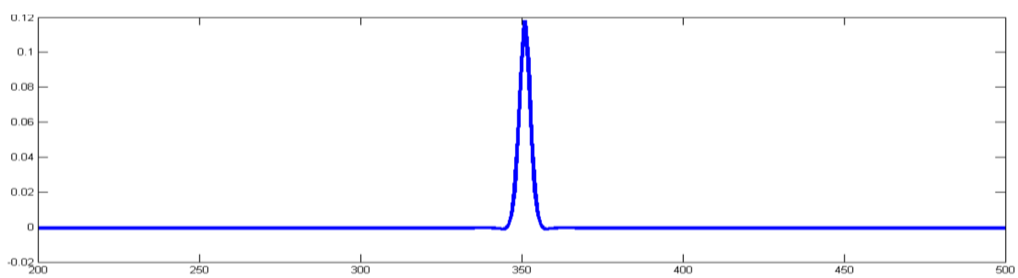


Figure 1 The Hyperbolic Secant Signal

It is seen that this signal consists essentially of an exponential rise and exponential fall in tandem. Thus, it is possible that the impulse responses of semiconductor devices that depict exponential roll-off rates, might be similar to this shape. To verify this, the impulse response *h(t)* is computed as an Inverse Fourier Transform of the AC Response *H(f)* [13], and is plotted for PN-Junction Diode and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) in Fig. 2.



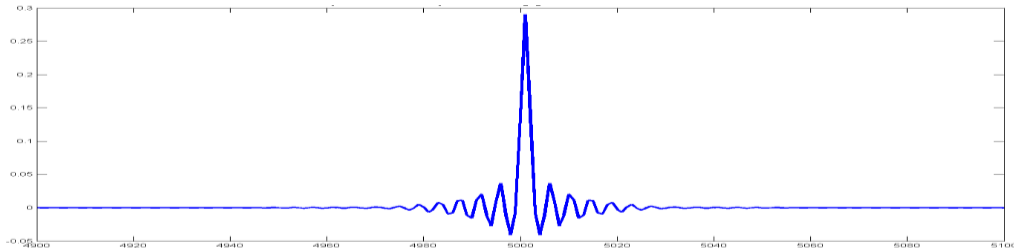


Figure 2 Impulse Response of PN Diode (Top) and MOSFET (Bottom)

Based on these observations, a simple circuit for generating electrical solitons is proposed, where the basis for the generation of solitons is the application of a sinusoidal signal to a MOS inverter, with the nonlinearity of the MOSFET providing appropriate wave shaping and harmonic generation to yield a train of solitons as the output. This is validated by constructing an NMOS Inverter in mixed-signal mode using the Silvaco TCAD Virtual Fabrication tool, and the fabricated MOSFET, its characteristics and the transient analysis for sinusoidal input are shown in Fig. 3-5 [14-16].

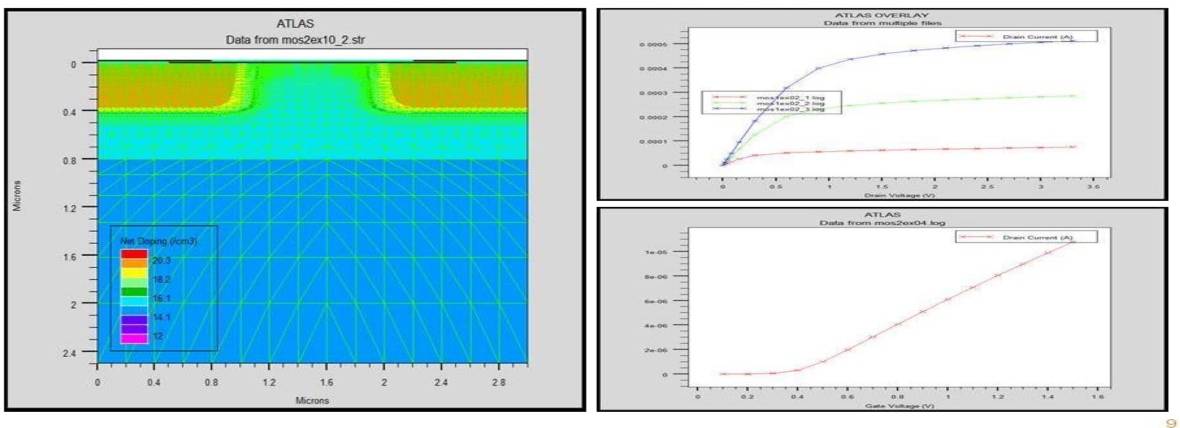


Figure 3 TCAD Virtual Fabrication Results – NMOSFET Structure and Characteristics

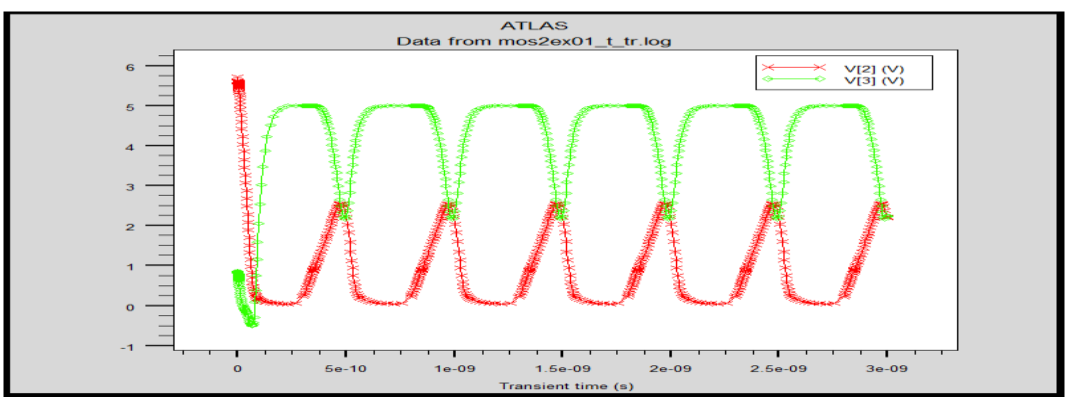


Figure 4 TCAD Virtual Fabrication Results – Transient Analysis using sinusoidal input

It is seen that the transient analysis using sinusoidal input yields a train of solitons as the output. The same is also verified experimentally at hardware level with the observed output waveform illustrated in Fig. 4.

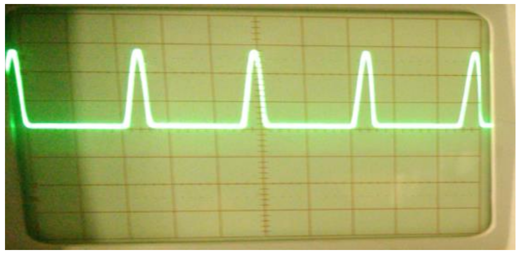


Figure 4 Generation of Solitons in Hardware

Finally, in order to examine the choice of substrate material and technology, the soliton generator is implemented in deep submicron VLSI layout level using 2λx4λ transistor CMOS inverters in 120nm CMOS and 20nm Silicon on Insulator (SOI) Technologies using Microwind. The schematic is shown in Fig. 5, along with comparison of transfer curves and the generated solitons for a 15GHz input are compared in Fig. 6.

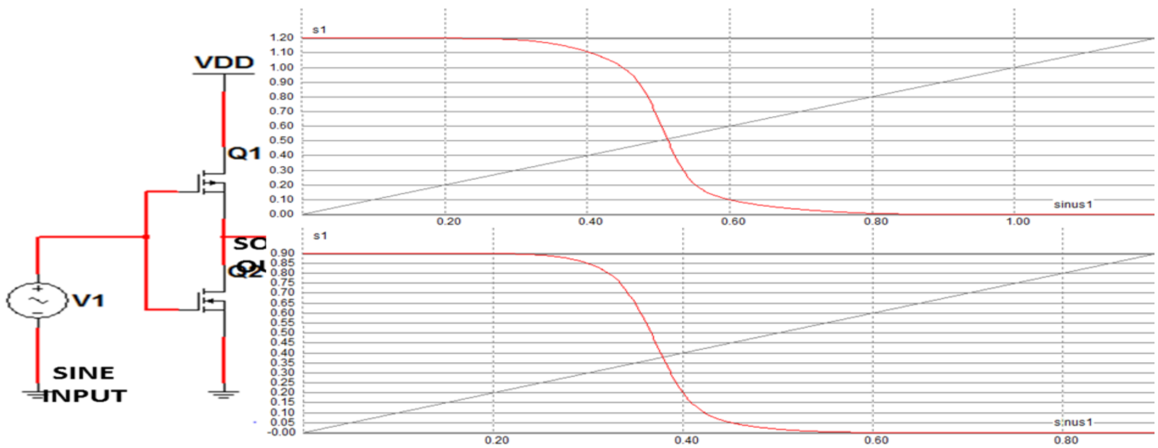


Figure 5 CMOS Inverter Schematic and Transfer Curves for 120nm CMOS (above) and SOI (below)

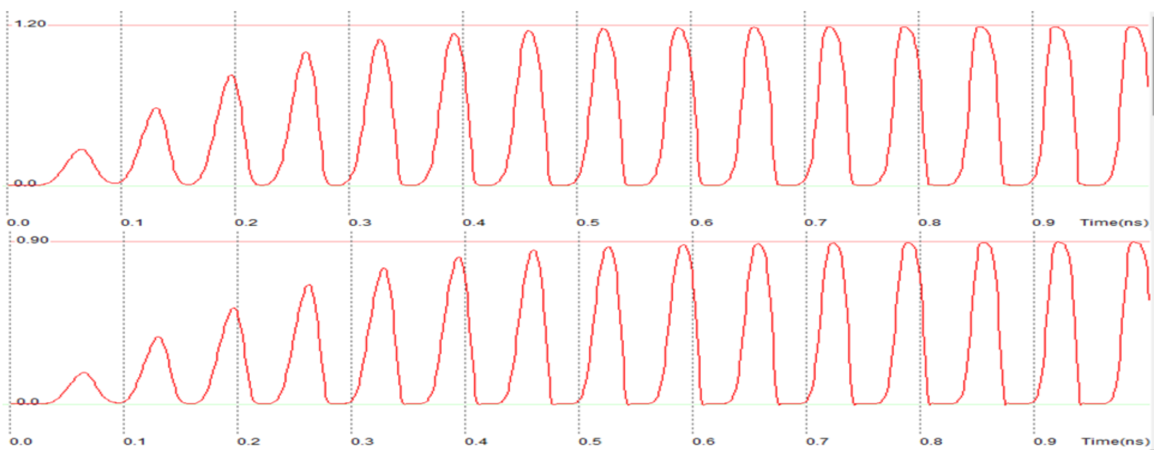


Figure 6 Generated Solitons using 120nm CMOS (above) and SOI (below)

3. Free Space Optics using Solitons

The next step involves the comparison of propagation distance between solitons and conventional carrier signals (square and sine waves). This is performed using a simple setup with a crude decoration purpose Light Emitting Diode (LED) acting as the transmitter and a PIN Photodiode acting as the receiver, as shown in Fig. 7 [17]. An operating wavelength of green is chosen, with solitons generated using MOS inverters as described earlier, and square and sine waves generated using function generators. A sample snapshot of the transmitted and received signals for soliton and square wave cases is shown in Fig. 8.

Figure 7 Setup for Free Space Optic Transmission

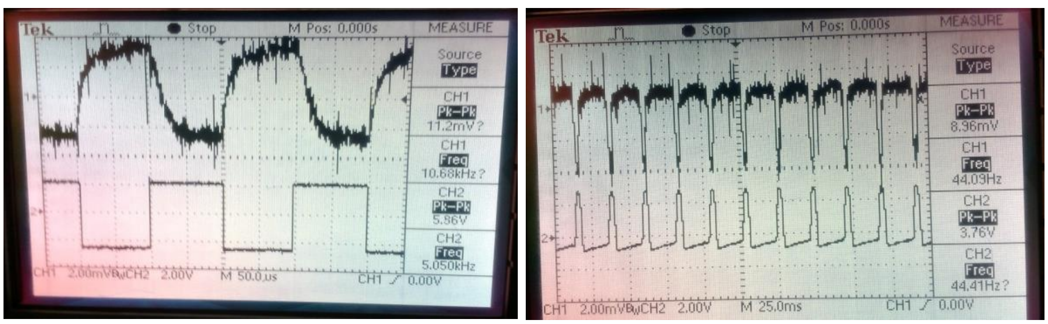


Figure 8 Transmitted and received signals for Square (left) and Soliton (right) cases

The propagation distance is tabulated along with corresponding attenuation values for soliton, square and sine wave transmissions in Table 1.

Table 1 Propagation Distances of Carrier Signals in Free Space Optical System

Signal	Distance	Attenuation (dB)
Sine	1 cm	-4.33
	10 cm	-15.67
	15 cm	-14.69
Square	1 cm	-3.95
	10 cm	-13.91
	15 cm	-14.69
Solitons	1 cm	-0.11
	10 cm	-9.19
	15 cm	-10.58

It is clearly seen from the table that solitons are easily able to outperform the sine and square signals with respect to the observed attenuation levels. It is also found that using Infra-red wavelengths (1310nm), a range of 35cm is observed for solitons with an attenuation of merely -4.9dB.

Finally, taking cue from the above mentioned results, a Free Space Optic Amplitude Modulation (AM) Communication System, with schematic as shown in Fig. 9 is implemented for soliton carriers, and the modulated and demodulated signals are shown in Fig. 10 for a sinusoidal based message input signal.

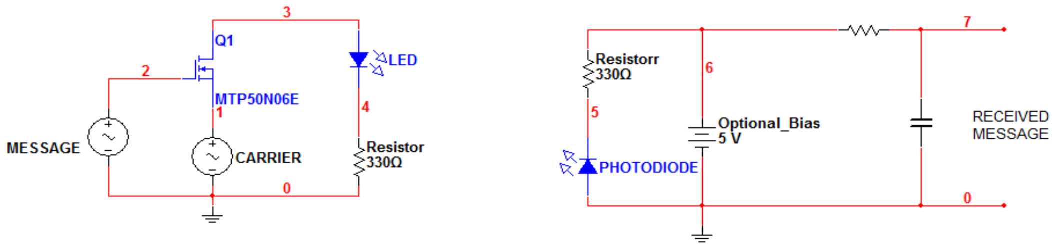


Figure 9 Schematic for Free Space Optic AM Communication System

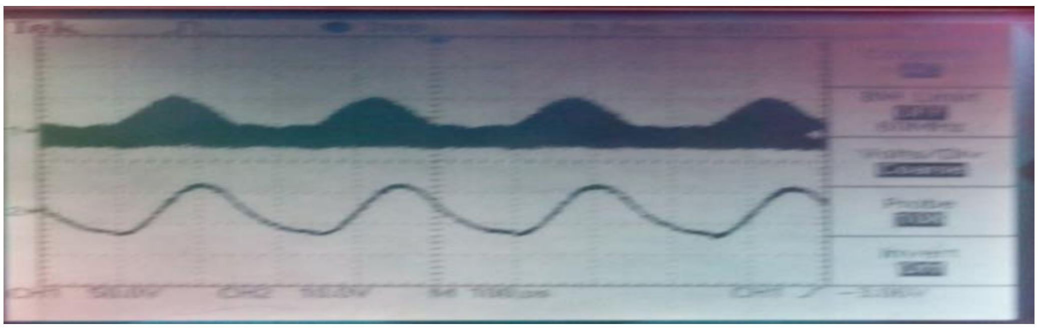


Figure 10 Modulated (Top) and Demodulated (Bottom) signals of Free Space Optic AM Communication System

From the results, it is clearly seen that the low attenuation and long range properties of soliton make it an ideal carrier for free space based communication systems with minimal distortion values.

4. Conclusion

Based on the successes enjoyed by the soliton concept in optical communications, the present work proposed a signal-oriented perspective of the soliton, with the observation of solitons as impulse responses of various semiconductor devices such as PN-diodes and MOSFETs. A simple circuit harnessing the nonlinearity of a single MOS inverter is proposed to generate a train of solitons from a sinusoidal input, and this design is validated using TCAD as well as hardware results. Following this, free space optic propagation of solitons is compared vis-à-vis conventional sine and square waves, and it is seen that solitons are able to cover longer ranges of transmission with lower attenuation values. Finally, a Soliton AM Free Space Optic Communication System using very simple circuitry is proposed. The extreme simplicity in design of the soliton generator, coupled with the ability of electrical solitons to cover long transmission ranges with low attenuation forms the novelty of the present work, and such results are very relevant in the current era of big data and internet of things, where the possibility of next-gen new free space optic systems such as Li-Fi are being considered [11-12].

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