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Performance Analysis Of Optical Communication Receivers Employing Second Harmonic Generation Effect Of Quantum Dots With Different Confinements

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Abstract

The achievement of reliable communication by having a low Bit Error Rate has been the constant aim of communication engineers and whilst optical communication has fulfilled many such aims but it has been observed to be severly affected when the photodetector response time increases with respect to the light pulse duration as then the photodetector will be unable to detect and discriminate the presence or the absence of a peak optical pulse. Therefore, the performance of the receiver degrades due to the limiting speed of the photodetector. Previous works have suggested and shown the use of nonlinear processing elements prior to the photodetector in an optical Receiver system to create a substantial discrimination between message signals and noise in optical domain. In this paper, we take up the case of quantum dots for non-linear processing and analyse their behaviour. The optical communication receiver model has been considered with reference to a noisy channel due to which the system performance worsens as the response time of photodetector increases. We explore the second harmonic generation effect (SHG)of quantum dots to achieve noteworthy improvement in bit error rate as the SHG effect generates new frequency components for the light pulse while the spectrum of low intensity noise is barely changed. The amplitude of the photodetector output in the modified model depends on second harmonic conversion coefficient which is directly proportional to the second order susceptibility of the quantum dot. The second order susceptibility is a function of the geometry of the confinement of particles inside the dot. Since it has been proved earlier that the spherical confinement brings a downfall in BER , we now compare the same with 2 more confinements-parabolic and rectangular.

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1.Introduction

Quantum dots are a unique class of semiconductors composed of periodic groups II-VI, III-V, IV-VI materials. Quantum dots can be of various shapes – cubical, spherical, ellipsoidal, pyramidal, dome, etc. The size and shape of these nanocrystals and therefore the number of electrons they contain can be precisely controlled which is known as confinement and can be of different types as are their geometrical shapes. Second Harmonic Generation (SHG) is a nonlinear optical process in which photons interacting with nonlinear material are effectively combined to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons.A detailed analysis of these may be found in [6] and [10]. This unique property of quantum dots are now finding application in many areas and we shall exploit this in the optical communication domain. The second order susceptibility , a non linear phenomenon observed in quantum dots has been made use of to provide an improvement in performance through a decrease in the Bit Error Rate in [21].To mathematically study quantum dots , Schrödinger equation is needed.The three dimensional Schrödinger Equation in spherical coordinates is given as

$$\nabla^2\Psi + \frac{2m}{\hbar^2}[E - V(r)]\Psi(r,\theta,\Phi) = 0$$

where,Ψ is the wavefunction ,$\hbar$ is the reduced Planck's Constant & m is the effective mass of an electron We can find the energy levels i.e. the energy eigen values and the wavefunctions by solving the 3 dimensional time independent Schrödinger Equation in spherical coordinates using boundary conditions as in [6] for any shape or confinement of particles of the dot..In solving these equations,a number of factors like binding energy or the spin orientation of particles are to be considered.These equations have been solved for the wavefunctions in [18] for all 3 confinements of our interest-parabolic,rectangular & spherical while a detailed analysis may be found in [10],[17] and [19].

As discussed in [8],[9] & [10],Nonlinear effects are due to the dependence of the properties of the material such as refractive index on the electric and magnetic fields associated with the light beam. In particular, Second harmonic generation is due to the non linear dependence of polarization on the electric field. In the case of two equal monochromatic light waves with the same polarization, frequency ω, and direction, cobining then the second order non linear polarization is determined by the product of the two electric fields. This second order non linear polarization $P^{(2\omega)}$shows terms with frequencies ω and 2ω.

$$P^{(2\omega)} = \epsilon_0 \chi^{(2)} E_1^{\omega} E_2^{\omega}$$

Where $\chi^{(2)}$ is the second order non linear susceptibility.

The behavior of the second order susceptibility with variation in shapes and sizes has been studied in [5].Again minor deviations occur with the composition of the dots but we can safely ignore them for our application purposes.

2.The Optical Receiver Model With SHG

The ordinary photodetector can be assumed to be an energy detector, which obtains the average power of input signal within its response time. Now due to various reasons,If the photodetector response time increases with respect to the light pulse duration the photodetector will be unable to detect and discriminate the presence or the absence of a peak optical pulse. Therefore, the performance of the receiver degrades due to the limiting speed of the photodetector. There are two vastly different approaches of establishing synchronization and detection of ultrashort light pulses, namely, using impractical extraordinary high-speed and complex electronic circuitry in order to obtain the optimum scheme or using a less complex and more robust suboptimum scheme using nonlinear optical elements such as two-photon absorption (TPA), highly nonlinear fiber (HNLF), or second harmonic generation (SHG) for uses in various optical communication systems as pointed out in [1].The second approach is very commonly used for improving system performance when various system noises such as background noise induced by the nonideal ON-OFF state of the laser sources, optical amplifier noise, electronically induced thermal noise, and the multiaccess noise(in the case of multiple access) are involved as mentioned in [2].

In [21] investigatins have been made for the case of an optical receiver which is receiving signals effected with a gaussian noise of purely random nature without accounting for the sources generating the noise. The non linear preprocessing was done by exploiting the second harmonic generation effect of quantum dots as suggested in [4]. In [7] the performance of a return- to-zero (RZ)-OOK lightwave communication system was evaluated using a TPA detector as the nonlinear receiver. These were studied based on Monte Carlo Simulation.In [3], an in depth study is carried out on the mathematical and statistical models of SHG effect thin and thick) observed in dielectric optical crystals. Hence to bring out a cost effective solution,SHG effect can be imposed in a dielectric crystal and it can be used to discriminate between ultrashort highly peaked light pulses and the low peak noise or interference signals prior to low-speed photodetectors. Since a spherical quantum dot closely approximates the behavior of thin crystals,the mathematical formulation developed in [1] was utilized in [21].Hence to show a comparison for different confinements we rely on results obtained in [21] and proceed further by utilizing results of [18].

The Mathematical model for conventional optical power linear receiver (incorporated with the SHG effect) can be obtained from [21] as shown in Figure.1.

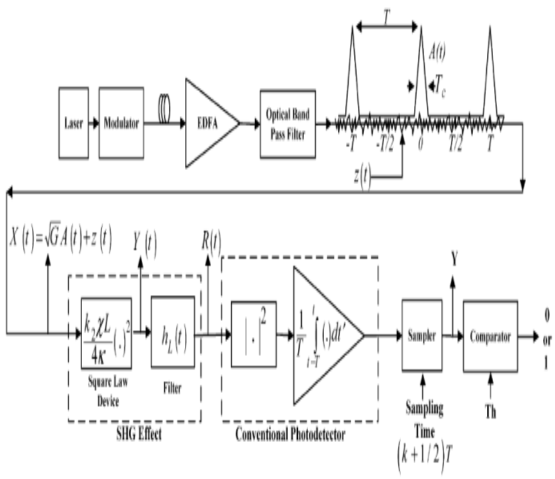

Figure.1 Modified Optical Communication Receiver Model Employing SHG Effect

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In [4], a simplified analysis has been done for the input-output behavior of light pulses of short duration. We employ the same alongwith that of [1].Taking the following as input field:

$$a(0,t) \triangleq X(t)\sin(\omega t)$$

The output equation can be written as:

$$b(0,t) = C \times X^2(t)\sin(2\omega t)$$

Clearly the argument of the sine part explains the generation of second harmonic.The dot basically acts as a square-law device on the envelope of the input optical field. The constant C is known as second harmonic conversion coefficient. It can be approximated by as in [1]:

$$C \triangleq K \times L$$

Where K = $k_2 \chi$ /(4k).The parameter k_2 stands for the second order wave number,k for the dielectric constant of the CdS QD and χ for the second order SHG susceptibility.The output equation written above would have the same form irrespective of the confinement of particles inside the dot.

Rest of the mathematical equations as in [21] show that the SHG effect first squares the signal which is again squared by the conventional photo detector giving a fourth order term in the output-input relationship:

$$Y = \int_{-\frac{T}{2}}^{\frac{T}{2}} |X(t)|^4 \, dt.$$

This is pretty simpler technique with the advantage that for obtaining the same result, if one uses any other squaring element that would further add to the random noise worsening the situation which is avoided here.The SHG effect generates new frequency components for the light pulse while the spectrum of low intensity noise is barely changed. As is visible from the curve given below in Figure.2, even at a very low SNR(0.3=5dB), a fall of 18 dB(approx.) in the Bit Error rate is achieved as in [21] using 2.3 nm spherical quantum dot composed mainly of CdS.

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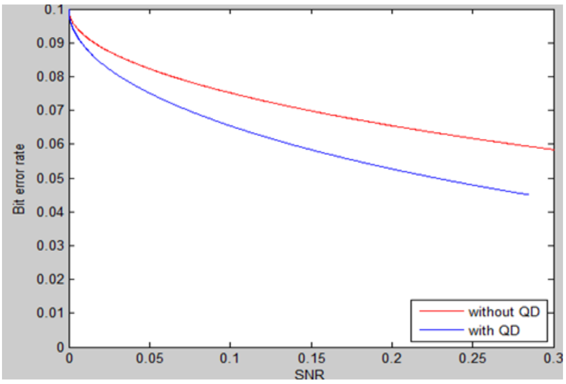

Figure.2 Plot Of BER v/s SNR For Spherical Confinement

Similar to that of above different shapes of quantum dots can be investigated so as to select a shape which can provide the best optimum BER.Also given a geometrical confinement ,they can be investigated fot the best possible composition. We have tried to simulate the variation in the downfall of BER corresponding to different confinements since for different confinements,the second order susceptiblty would be different causing a change in the results of the aforesaid optical receiver model. From [18] we can relate diamagnetic susceptibility with the mean square distance of the electrons from the nucleus in the following manner:

$$\chi_{dia} = -\frac{e^2}{6m{*}\varepsilon_0 c^2}[r^2]$$

The above relation very well applies to the second order susceptibility in our case.

3.Results

Taking a return- to-zero (RZ)-OOK light wave communication system, the modulation scheme as BPSK & Using a simple,non-probabilistic threshold ,the mathematical model developed in [21] can be utilized to obtain a comparison for 2 more confinements-rectangular and parabolic.For the purpose of numerical simulation,we have employed the same procedure as in [5] to obtain values for second order susceptibility.As outlined in previous section,,in [18] it has been shown that out of 3 confinements –parabolic confinement has the highest

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second order susceptibility due to smallest mean square distance of the electrons from the nucleus.Subsequently the amplitude of the photodetector output is highest among the three thereby creating highest difference in the intensity of message signal and the noise.This leads to the lowest BER out of the 3 confinements. Similarly the case for remaining 2 follows.The simulation result for all three confinement is shown in Figure.3.

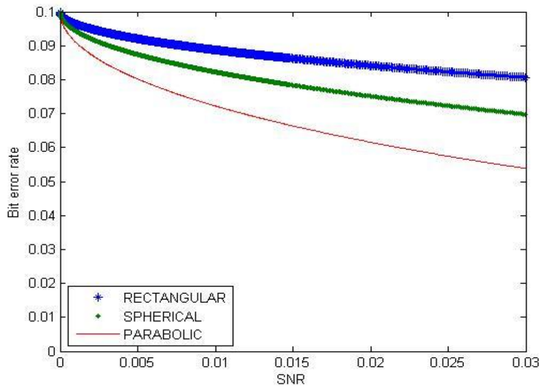

Figure.3 Plot Of BER v/s SNR For 3 Different Confinement (With Modified Model)

Here, we have the derived BER considering the conditional probability distributions and taking variance of noise into account which is very simple and yields into an expression of some form of complementary error function.. A more optimum threshold at the receiver would further enhance the analysis of the improvement in BER. The probability distribution function might be evaluated from the fourth order integration equation [21] and then simulated using Monte Carlo method. A related study has been carried out on the usefulness of the method in [14]and [16]. There are various tools available for BER simulation, but stochastic BER simulation has been found to be most relevant by us in our on-going works. A good glance of this method is made in [12]and [13].The two widely used approaches-histogram estimation and importance sampling may also be tried out as is done in [11],[15] and [20].

4.Conclusion

A safe conclusion that can be drawn from our works is that SHG in quantum dots can act as an amplifier (subject to certain restrictions) which is helping here to supress the noise thereby improving the performance of photodetector in optical communicatio.This property of quantum dots is a function of their composition,shape ,size and spatial distribution of particles inside the dot proof of which lies in our present work showing that the parabolic confinement is providing the best optimum results.

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