Multi-electrode quantum-dot semiconductor optical amplifier as an intensity modulator of signals in optical communication systems

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Abstract. In this paper, we are going to exhibit the system performance using the single, double and three-electrode quantum-dot semiconductor optical amplifier as an intensity modulator (3E-QD-SOA-IM) of the adaptively modulated optical orthogonal frequency division multiplexing (AMOOFDM) signals in the intensity-modulation direct-detection passive optical network (IMDD-PON) systems. Moreover, to compare the bit-rate versus transmission distance of the proposed fiber link model when using both configurations multi-electrode semiconductor optical amplifier intensity-modulator (ME-SOA-IM) and multi-electrode quantum-dot semiconductor optical amplifier intensity-modulator (ME-QD-SOA-IM), to study the improvement of the transmission capacity, distance reach and power efficiency when applying the proposed configurations for optical access networks for distances ranging from 20 km up to 120 km. The three-electrode configuration solved the nonlinearity of the two-electrode configuration and offered a considerably wider range of optimum operating conditions to achieve up to 35 Gbps. Furthermore, the 3E-QD-SOA-IM showed a better performance over the 3E-SOA-IM over all the 120 km, and a 5 Gbps enhancement in the bitrate with a 20 dB less optical input power at 20 km.

Keywords: multi-electrode semiconductor optical amplifier intensity modulator (ME-SOA-IM); multi-electrode quantum-dot semiconductor optical amplifier intensity modulator (ME-QD-SOA-IM); adaptively modulated optical orthogonal frequency multiplexing (AMOOFDM).

1. Introduction

Semiconductor optical amplifiers (SOAs) operate in a linear and nonlinear manner in the developed optical communications systems. Nonlinear applications of the SOA are wavelength conversion [1], logic gates [2], cross-gain modulators [3], cross-phase modulators [4], four-wave mixers [5], optical signal processing, signal regeneration and switching [6]. As a linear device, SOA used as an in-line optical amplifier [7]. However, as an intensity-modulator has evoked an increasing excitement in cost-sensitive applications such as WDM passive optical networks (WDM-PONs) [8].

Quantum-dot semiconductor optical amplifiers (QD-SOAs) have presented many notable unusualnesses for employment in different utilisation such as all-optical signal processing and fiber-optics communication systems. Some of the QD-SOAs advantages are ultrafast gain recovery [9, 10], high saturation power [11], patterning-free optical amplification [12], excellent performance speed [13]. Moreover, they can be integrated monolithically with additional optoelectronic devices (for example, laser sources), and they are cost-effective. All these significant hallmarks are approving that QD-SOA is a perfect candidate to be applied in cost-sensitive passive optical networks (PONs).

AMOOFDM signals showed an exceptional performance when it applied to intensity modulation, and direct detection (IMDD) based optical networks, where it allows exploiting the transmission bandwidth effectively by optimizing the transmission performance. AMOOFDM can drop the
subcarriers having a significant loss in transmission due to high error rate, assign a low modulation format to subcarriers suffering from error and higher modulation formats to the subcarriers with lower loss. The modulation format is determined relating to the frequency response of the transmission link [14].

In the above-mentioned system, several devices applied to carry out the electrical to optical conversion of the AMOOFDM signals, starting by semiconductor optical amplifier intensity modulator (SOA-IM) [15, 8], reflective semiconductor optical amplifier intensity modulator (RSOA-IM) [16], and quantum-dot semiconductor optical amplifier intensity modulator (QD-SoA-IM) [17]. To have the maximum bit rate it needs CW optical input power as high as 20 dBm when applying ME-SOA, which is expensive for cost-effective PONs, although it allows colourless AMOOFDM in WDM PONs, and substitute the drop of the system capacity after the distance of 60 km [18]. Applying ME-QD-SoA-IM allow a 20 dB reduction in CW optical input power injected into the modulator to achieve better performance, so it made the practical implementation of the system more applicable in cost-effective PONs.

SOA has an electrical bandwidth limited to 1 GHz, and it can reach 2 GHz when applying high optical confinement. Previously published studies show that the use of two-electrodes based SOA (2E-SOA-IM) improves the modulation bandwidth of an SOA from 2 GHz up to 6 GHz [19], and up to 7.8 GHz as a colourless source for WDM-PONs [20]. In this work, we reveal for the first time in our knowledge, that the use of multi-electrode quantum-dot semiconductor optical amplifier as an intensity modulator (ME-QD-SoA-IM) by using adaptively modulated optical orthogonal frequency division multiplexing (AMOOFDM) signals in intensity-modulation direct-detection (IMDD) based optical networks can considerably enhance the signal line rate in comparison to those utilizing a single electrode QD-SoA-IM. Because the constant current distribution coupled to the metal contact of a single electrode will lead to non-uniform electronic occupation probability in the QD-SOA material, leading to a drop in AMOOFDM signal high-frequency subcarriers power level, accordingly a drop in the bit rate due to low modulation format allocated to those subcarriers. While, when a non-uniform current injected to the QD-SoA, there will be a uniform electronic occupation probability in it causing an enhancement in the power level of the high-frequency subcarriers, and the electrical bandwidth of the QD-SoA-IM allowing higher modulation format allocated to the higher frequency subcarriers, consequently it enhances the transmission performance.

1.1. AMOOFDM system

Figure 1 illustrates the utilized IMDD transmission system in this paper, made up of three main sections: the AMOOFDM transmitter, a chromatic dispersion compensation-free and in-line optical-amplification-free SMF link and the AMOOFDM receiver. The AMOOFDM transmitter contains a CW laser diode, an electrical OFDM modem transmitter to generate the electrical modulating signal, an...
electrical to optical converter ME-QD-SOA-IM to modulate the laser by the electrical OFDM signal and a variable optical attenuator (VOA) to keep the power of the optical signal to 13 dB. The AMOOFDM receiver contains an electrical OFDM modem as a receiver and a simple square-law photodetector playing the role of the optical to electrical converter. There is a detailed explanation of this system in [21, 22].

2. Materials and methods

2.1. QD-SOA-Based Intensity Modulator Model

In this work, we are using a functional QD-SOA model but notably uncomplicated two-level rate equation model 2LREM [23, 24, 25], a theoretical QD-SOA-IM model was built in a way that all the quantum-dots inside the SOA are supposed to be uniform and identical, and there is only one confined energy level in both the conduction and valence band of each quantum-dot. By calculating the carrier occupation probability close to the band edge of the wetting layer, the excited state is replaced. The injected current populates the wetting layer. The 2LREM model is reliable if there are in the wetting layer a significant population of carriers, which applied in picoseconds to the discrete quantum-dots, at the moment when the two carrier population levels go through recombination processes, stimulated emission and pumping. In developing the QD-SOA-IM model like the work introduced in [15-18] [26, 27], many ultrafast intraband dynamic processes like spectral hole burning, carrier heating, two-photon absorption and ultrafast nonlinear refraction are neglected because of two explanations. The first is that in the AMOOFDM transceivers the sampling rates of the DACs/ADCs under 20 GS/s, which is less than 50 ps sampling time. This period is way more than the intraband dynamic process response times, which is around one picosecond. The effective-intraband carrier lifetime for a QD-SOA-IM under an optimum optical input power is about 30 ps, which is indeed more significant for practical optical input power conditions of < 10 dBm for QD-SOA-IMs. Hence, the effective-intraband carrier lifetime is way ahead of the response times of the intraband dynamic process. The second reason for ignoring the ultrafast intraband dynamic processes is that the active DC component of an optical signal passing through the QD-SOA-IMs determines its optical gain saturation properties. For instance, at the front face of the QD-SOA-IMs, the noise-like waveforms modulated optical signals have reasonably slight signal extinction ratios about 1 dB [15-18] [26, 27].

According to the above two reasons, ignoring the effect of the intraband dynamic process in the optical gain saturation characteristics of QD-SOA-IMs for the transmission system is precisely enough of interest in this work.

Following the method in [15-18] [26, 27] building the transformation $T = t - z / v_g$ where $v_g$ and $T$ denoting the group velocity and the measured reduced time in a reference frame in motion with the optical signal, respectively. $z$ stands for the distance in a longitudinal direction, i.e. $z = 0$ and $L$ (length of the active region) is the input and output of the QD-SOA-IM, respectively. The optical field $A(z, T)$, is formulated as:

$$A(z, T) = \sqrt{P(z, T)} \exp[j\Phi(z, T)]$$  \hspace{1cm} (1)

Considering that $P(z, T)$ and $\Phi(z, T)$ being the optical power and the phase, respectively. The optical signal travelling through the QD-SOA-IM is given by:

$$\frac{\partial P(z, T)}{\partial z} = g(z, T)P(z, T)$$  \hspace{1cm} (2)
\[
\frac{\partial\phi(z,T)}{\partial z} = -\frac{1}{2} \alpha g(z,T)
\]

Whereas \(\alpha\) stands for the linewidth enhancement factor (LEF) attending with the interband transitions. \(g(z,T)\) being the optical gain which is linearly denoting the carrier density inside the active region by \(g(z,T) = \Gamma \alpha (N_d - N_0)\) where \(\alpha\) is the differential gain, \(\Gamma\) is the optical confinement factor, \(N_d\) is the overall carrier density of all quantum-dots, and \(N_0\) represents the transparency carrier density. Stating

\[
h_d(T) = \int_0^L g(z',T) \, dz'
\]

Furthermore, taking into consideration the 2LREM model created in [24, 25] and the assumptions mentioned previously, the temporal gain representing the QD-SOA-IM dynamic characteristics is given by:

\[
\frac{dh_d(T)}{dT} = \frac{h_w(T)}{\tau_{w\rightarrow d}} \left( 1 - \frac{h_d(T)}{h_{\text{max}}} \right) - \frac{h_d(T)}{\tau_{dw}} \left[ \exp(h_d(T) - 1) \frac{P_{in}(T)}{\hbar \omega_0} \right]
\]

Where

\[
h_{\text{max}} = \int_0^L G_{\text{max}} \, dz = \int_0^L \Gamma \alpha (N_{\text{max}} - N_0) \, dz
\]

And

\[
h_{in} = \int_0^L \frac{\Gamma \alpha f(T) \tau_{wR}}{ed} \, dz
\]

\(h_w(T)\) being the overall integrated gain factor of the wetting layer. \(\tau_{w\rightarrow d}\) stands for the electron relaxation time heading from the to the ground state inside the quantum-dots. \(\tau_{wR}\) is the spontaneous radiative lifetime in the wetting layer and \(\tau_{dr}\) being the spontaneous radiative lifetime in the quantum-dots. \(h_{\text{max}}\) denoting the integrated gain maximum merit and \(G_{\text{max}}\) stands for the unsaturated gain. The power of the optical input wave represented by \(P_{in}(T)\). The electron charge denoted by \(e\), the current injection density is \(J(T)\), \(d\) is the wetting layer thickness, \(\omega_0\) is the optical signal frequency, and \(w\) is the wetting layer region width. Then, at the QD-SOA-IM output facet, the power and the phase of the modulated optical signal are designated by:

\[
P_{out}(T) = P_{in}(T) \exp[h_d(T)]
\]

\[
\Phi_{out}(T) = \Phi_{in}(T) - \frac{1}{2} \alpha h_d(T)
\]

Where \(\Phi_{in}(T)\) being the optical input wave phase. Noting that the QD-SOA-IM adds amplified spontaneous emission (ASE) noise to the modulated optical signal. The ASE total power \(P_{\text{ASE}}\), designated by [28]:

\[
P_{\text{ASE}} = [N_f \exp(h_d(T)) - 1] B_0 \hbar \omega_0
\]
Where $N_f$ represents the noise figure of the QD-SOA, $B_0$ being the optical bandwidth and $\hbar \omega_0$ being the photon energy. The impact of ASE on gain saturation is neglected for the simplicity of the model. The final set of equations are (6)-(11) can be solved numerically when $G_{\text{max}}$, $P_{\text{in}}(T)$ and $\Phi_{\text{in}}(T)$ come to be known. The final optical signal “intensity-modulated” is obtained after adding the ASE noise into $P_{\text{out}}(T)$ and $\Phi_{\text{out}}(T)$.

2.2. (ME-QD-SOA)-Based Intensity Modulator Model

The model we used here for simulating the multi-electrodes quantum-dot semiconductor optical amplifier (ME-QD-SOA) is similar to that we have used for simulating the one electrode semiconductor optical amplifier (1E-QD-SOA). However, the difference is that in the multi-electrodes QD-SOA (e.g. 2E-QD-SOA) we have two sections the first section is used as a preamplifier section, while the other section used as an intensity modulator (see Figure 2a). We inject a DC bias current to both electrodes. The bias current is divided between the two sections according to the lengths L1 and L2. The total input biasing current equal the sum of all input bias currents (I-bias=I1+I2), while the RF signal (electrical AC driving current) is only injected into the second section which is used as an intensity modulator.

The same concept for (3E-QD-SOA) we have three sections the first sections are used as a preamplifier section, while the third section uses the model as an intensity modulator. (see Figure 2b). We inject a DC bias current to the three electrodes. The bias current is divided between the three sections according to lengths L1, L2 and L3. The total input biasing current equal the sum of all input bias currents (I-bias=I1+I2+I3), while the RF signal (electrical AC driving current) is only injected into the third section which is used as an intensity modulator.

![Figure 2.](a) Two-electrode QD-SOA (2E-QD-SOA), (b) Three-electrode QD-SOA (3E-QD-SOA)

2.3. Simulation Parameters

To simulate the AMOOFDM signal, we used 64 subcarriers. Thirty-two subcarriers in the negative frequency bins act the Hermitian symmetry. While, in the positive frequency bins Thirty-two subcarriers, 31 subcarriers carry data, and the remaining subcarrier adjacent to the carrier frequency is discarded.

The signal modulation format in each subcarrier is different using DBPSK, DQPSK, 8-QAM up to 256-QAM. The sampling rate of the DAC/ADC set to 12.5 GS/s; accordingly, 6.25 GHz the signal bandwidth for the positive frequency bins, means that the bandwidth of each subcarrier is 195.3 MHz. The quantization bits of ADC/DAC are set to 7 bits, and the signal clipping ratio is fixed to 13 dB, which are the optimum rates named in [15]. The cyclic prefix is regarded as 25 % to avoid link dispersion; therefore, in every OFDM symbol with a total time of 6.4 ns, the cyclic prefix period is 1.28 ns. The receiver sensitivity of the PIN photodetector is set to be −19 dBm agreeing with a 10 Gb/s NRZ with a BER of 10-9. The standard value of the linewidth enhancement factor can be regarded as $\alpha \approx 2.7$ [24],
in our work, it is set to be $\alpha = 5$. Table 1 and 2, [15-18] [23, 24, 26, 27] present the parameters adopted in simulating the ME-QD-SOA-IM, SMF, and the photodetector.

**Table 1. ME-QD-SOA, SMF and PIN Parameters.**

| Parameter       | Value    |
|-----------------|----------|
| $\tau_{w\rightarrow d}$ | 6ps      |
| $\tau_{w}$      | 0.2ns    |
| $\tau_{d}$      | 0.4ns    |

| Parameter                     | Value           |
|-------------------------------|-----------------|
| Width of active region cavity | 1.5$\mu$m       |
| Depth of active region        | 0.27$\mu$m      |
| Carrier lifetime SOA          | 0.3ns           |
| Confinement factor            | 0.35            |
| Linewidth enhancement factor  | 5               |
| Group velocity                | 8.43$\times$10$^7$m/s |
| Optical frequency             | 1550nm          |
| Differential gain             | 3$\times$10$^{-20}$m$^2$ |
| Carrier density at transparency | 1.05$\times$10$^4$m$^{-3}$ |
| Noise figure                  | 8dB             |
| Unsaturated gain              | 20dB            |

| Parameter   | Value  |
|-------------|--------|
| Effective area | 80$\mu$m$^2$ |
| Dispersion  | 17.0ps/nm/km |
| Dispersion slope | 0.07ps/nm/nm/km |
| Dispersion wavelength | 1550nm |
| Loss        | 0.2dB/km |
| Kerr coefficient | 2.35$\times$10$^{-20}$m$^2$/W |

| Parameter | Value |
|-----------|-------|
| Quantum efficiency | 0.8    |
| Noise current density | 8pA/$\sqrt{Hz}$ |

**Table 2. ME-QD-SOA sections parameters.**

| Parameter                      | Value    |
|-------------------------------|----------|
| Length of the first section (L1) | 250 $\mu$m |
| Length of the second section (L2) | 50 $\mu$m  |
| Biasing Current of the first section (I1) | 250 mA   |
| Biasing Current of the second section (I2) | 50 mA    |

| Parameter                      | Value    |
|-------------------------------|----------|
| Length of the first section (L1) | 125 $\mu$m |
| Length of the second section (L2) | 50 $\mu$m  |
| Length of the third section (L3) | 125 $\mu$m |
| Biasing Current of the first section (I1) | 125 mA   |
| Biasing Current of the second section (I2) | 50 mA    |
| Biasing Current of third section (I3) | 125mA   |

### 3. Results

#### 3.1. System performance
Figure 3. System performance of the (a) 1E-QD-SOA, (b) 2E-QD-SOA

Figure 3 depicts the system capacity of the optical transmission system for both the 1E-QD-SOA and the 2E-QD-SOA for an optical input power range from -10 dBm up to 30 dBm. So for a bias current range from 50 mA up to 300 mA. The transmission distance is 60 km, and the fiber channel wavelength is 1550 nm. The results for the 1E-QD-SOA show that to achieve the maximized transmission capacities of 30 Gb/s we have a wide range of optical input powers and bias current values, we can have a 17 dBm optical input power with 50 mA, or we can go down to an optical input power of 8 dBm but for a high bias current value of 300 mA. The problem of the QD-SOA is that it is very nonlinear, and this leads to a complete failure of the system at low optical input powers, as illustrated in Figure 3 (a). Figure 3 (b) shows that using a 2E-QD-SOA we can solve the previously mentioned problem. Using this configuration, we can achieve 30 Gb/s for optical input powers from 10 dBm down to optical input powers as low as – 10 dBm and for a bias current range from 50 mA up to 275 mA. The reduction in system capacity at higher optical input powers from 10 dBm and higher is since, although increasing the optical input power increases the component bandwidth; the component nonlinearity increases causing an increased clipping effect leading to a high reduction in signal to noise ratio at the receiver side.

Figure 4. System performance of the 3E-QD-SOA

Figure 4 represents the system capacity of the optical transmission system for the 3E-QD-SOA for an optical input power range from -10 dBm up to 30 dBm. So for a bias current range from 50 mA up to
300 mA. The transmission distance is 60 km, and the fiber channel wavelength is 1550 nm. The results show that we can achieve 35 Gb/s for a wide range of optical input powers or bias current values giving us much higher flexibility in designing the optical access network for achieving maximized system capacities. This result is significant because it allows achieving the same maximized bit rates using 20 dB less optical input power and for bias current values less than 300 mA. This achievement can allow extending the range of the optical access network for longer distances than 20 km while keeping the same performance. Alternatively, it can allow us to use lower-cost laser sources.

3.2. **ME-QD-SOA compared to ME-SOA**

![Figure 5](image)

**Figure 5.** Bit-rate versus transmission distance for 3E-QD-SOA at -10 dBm input power, 3E-SOA at -10 dBm input power, and 3E-SOA at 10 dBm input power and a 300 mA bias current

Figure 5 represents a comparison of the system capacity versus transmission distance for 3E-QD-SOA at -10 dBm input power, 3E-SOA at -10 dBm input power, and 3E-SOA at 10 dBm input power and a 300 mA bias current with 80 % modulation index and 1550 nm wavelength. The results show that the 3E-SOA at 10 dBm has a better performance than the 3E-SOA at -10 dBm. However, when we see the 3E-QD-SOA, we notice that we have a better result than the 3E-SOA for distances up to 120 km applying 20 dB less optical input power. This result is significant since, for practical applications of the SOA configurations in next-generation passive optical networks (see Figure 6), we require the SOA to be able to send high data rates using as low optical input powers as possible. Since the laser source is at the transmitter side, and the SOA will be at the optical network unit (ONU) side. The SOA needs to send the data from the ONU side to the optical line terminal (OLT) side using the extremely reduced power from the OLT side. Due to the attenuation of the laser power in the fiber link between the OLT and the ONU. The reason for utilising the laser signal of the OLT is to remove the need for a laser source at the ONU, thus reducing system cost and complexity.
Figure 6. WDM-PON diagram emphasizes the significance of applying the SOA/QD-SOA configuration operating a high speed for the uplink transmission while working at low optical input power from the laser source at the transmitter side.

4. Conclusion
A detailed numerical simulation proved that the multi-electrode configuration for the intensity modulator, considerably enhance the transmission performance of the passive optical networks for a distance reach between 20 km up to 120 km. Besides, simulations also showed that three-electrode configuration solved the problem of the nonlinearity of the two-electrode configuration; thus, it improves the transmission performance for distances up to 120 km. Moreover, we have verified that the 3E-QD-SOA configuration can achieve a 10 Gb/s increase in system capacity as opposed to the 3E-SOA at 20 km. Alternatively, achieving a 5 Gb/s more using 20 dB less input optical power. Furthermore, the system performance of the 3E-QD-SOA shows that we have a vast range of optical input powers and bias current values. Giving us much higher flexibility in designing the optical access network to reduce the cost, complexity, and power consumption; while achieving maximized bit rates of more than 35 Gb/s, by merely keeping the same network infrastructure and only changing the electrical to optical converter component at the ONU side.

For future works, research can be done to investigate the proposed configurations for various structures of PON systems in which we assess the benefits and shortcomings of these configurations in terms of transmission capacity and distance extension, optical power budget, cost-effectiveness and complexity.

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