

Theoretical Analysis of the Optical Filtering Effect on a Directly Modulated Reflective Semiconductor Optical Amplifier

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Abstract: The modulation bandwidth of a reflective semiconductor optical amplifier (RSOA) is limited by carrier lifetime. Therefore, it is hard to directly modulate an RSOA with high-speed electrical signals. We theorize that an optical filter can act as an optical equalizer, compensating for the narrow bandwidth limitation imposed by the RSOA. By modeling a time-varying RSOA with a modified transfer matrix method (TMM), we simulated 25 Gbps operation of an RSOA with optical filtering effects. We investigated the impact of detuning the center wavelength of the optical filter on the modulation of an RSOA. The numerical results show that it is possible to modulate an RSOA with an optical filtering effect at 25 Gbps without electronic equalization or digital signal processing.

Keywords: Semiconductor optical amplifier (SOA), Transfer matrix method (TMM), Passive optical network (PON), Optical filter, Optical equalization

1. Introduction

The wavelength-division-multiplexed passive optical network (WDM-PON) has been considered an attractive solution for next-generation broadband access networks capable of providing over 10 Gbps data throughput to each subscriber [1]. Since a WDM-PON can provide an independent wavelength channel to subscribers with a single fiber, it is possible to implement a cost-effective PON. As shown in Fig. 1, a WDM-PON network is composed of three parts: the central office (CO), the remote node (RN), and the optical network unit (ONU). The CO is an access service provider. The RN takes on two roles, as multiplexer and demultiplexer. The ONU is a subscriber and is connected to the CO on a specific wavelength. An independent wavelength is allocated to each subscriber. Therefore, the WDM-PON can mitigate complicated time-sharing issues that limit the performance of a time-division-multiplexed passive optical network (TDM-PON).

In addition, cost efficiency in a WDM-PON can be improved by adopting colorless light sources. A reflective

semiconductor optical amplifier (RSOA) is a good candidate, suitable to colorless light sources for adoption by the ONU. The RSOA can operate at any wavelength supplied by the CO across the C- and L-bands, and has low polarization dependency. The wavelength of the RSOA is determined by the seed light from the CO and RN. For the seed light, the broadband light source is located in the CO, and this broadband light will be sliced by the multiplexer and demultiplexer in the RN. The RSOA can amplify and modulate the seed light and act as the optical transmitter in the ONU. But the modulation bandwidth of the RSOA is limited by the carrier lifetime of the semiconductor [2]. Therefore, it is hard to directly modulate an RSOA with a high-speed data rate. Despite its limited modulation bandwidth, there have been various attempts to achieve 10 Gbps operation of an RSOA, such as electronic equalization and forward error correction (FEC) [2], detuned suitable delay interferometers [3], and multilevel signaling [4]. However, most of the previous attempts require a complex system, since these techniques need high-speed electronics, either at the transmitter or the receiver.

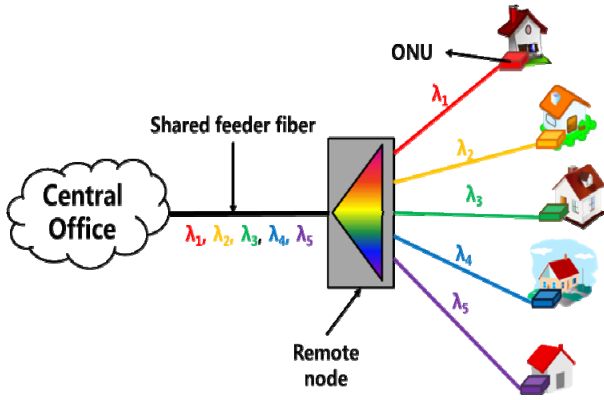


Fig. 1. Configuration of WDM-PON systems.

In this paper, we evaluated the quality of optical signals generated by an RSOA with optical filtering by adjusting the central wavelength of the optical filter. We achieved vestigial sideband (VSB) optical filtering and optical equalization with an offset filtering technique. We investigated theoretically the effect of the optical filter on a directly modulated 25 Gbps RSOA.

2. Time-Dependent Transfer Matrix Method

The time-dependent transfer matrix method (TMM) was proposed for the purpose of characterizing optical semiconductor devices. Generating waves by internal and facet reflections in optical semiconductor devices, it is possible for this model to involve not only waves traveling forward but also waves traveling backward. In this model, longitudinal variation of parameters, such as carrier-induced refractive index, gain, amplified spontaneous emission (ASE) noise, and alpha-parameters in each small section can be considered.

In conventional TMM form, a transfer matrix expresses the following relationship [5]:

$$\begin{bmatrix} u_i \\ v_i \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} u_{i+1} \\ v_{i+1} \end{bmatrix} \quad (1)$$

where u_i and v_i are normalized slowly varying envelopes of forward and backward fields in the i^{th} section, such that $|u_i|^2$ and $|v_i|^2$ represent the optical power in the i^{th} section. Conventional TMM was applied to model the steady-state operation of an RSOA.

The relationship between the transfer matrix and the corresponding scattering matrix is [5]:

$$\begin{aligned} a_{11} &= \frac{1}{s_{21}} & a_{12} &= -\frac{s_{22}}{s_{21}} \\ a_{12} &= \frac{s_{11}}{s_{21}} & a_{22} &= s_{12} - \frac{s_{11}s_{22}}{s_{21}} \end{aligned} \quad (2)$$

For a homogenous waveguide section of length L ,

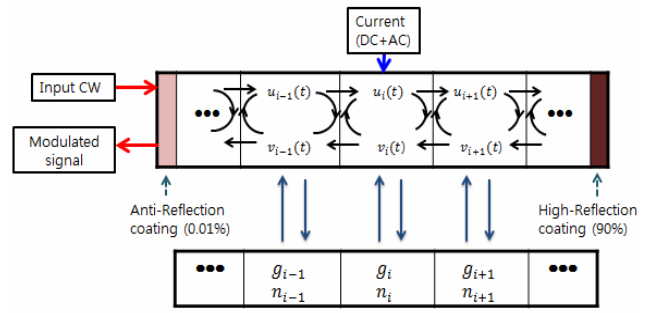


Fig. 2. TMM-based large signal dynamic RSOA model.

$a_{11} = \exp(jkL)$, $a_{12} = a_{21} = 0$, $a_{22} = \exp(-jkL)$, where k is the complex propagation constant. For RSOA modulation, the injected carrier and most of the other parameters are time-varying. Therefore, time dependency in the TMM should be considered.

In order to develop the time-dependent TMM, a schematic diagram called the modified transfer matrix, as shown in Fig. 2, is used. In Fig. 2, subscript i is a section number and n_i is the refractive index in the i^{th} section. Assuming that various parameters remain unchanged through each section for a small time period, Δt , output amplitudes u_i and v_i at time $t+\Delta t$ can be calculated from input amplitudes u_i and v_i at that time, as follows:

$$\begin{bmatrix} u_{i+1}(t+\Delta t) \\ v_i(t+\Delta t) \end{bmatrix} = \begin{bmatrix} a_{11}(t) & -\frac{a_{12}(t)}{a_{22}(t)} & \frac{a_{12}(t)}{a_{22}(t)} \\ -\frac{a_{21}(t)}{a_{22}(t)} & & 1 \end{bmatrix} \begin{bmatrix} u_i(t) \\ v_{i+1}(t) \end{bmatrix} \quad (3)$$

3. Pulse Propagation and Rate Equation

Evolution of the slowly varying amplitude $A(z, t)$ of optical signals inside the RSOA and gain section is derived as follows [6]:

$$\frac{\partial A(z, t)}{\partial t} + \frac{1}{v_g} \frac{\partial A(z, t)}{\partial z} = -\frac{i}{2} \alpha \Gamma g_m \partial A(z, t) + \frac{1}{2} g \partial A(z, t) \quad (4)$$

where α is the linewidth enhancement factor, and v_g , Γ , g_m , and g are group velocity, confinement factor, material gain, and net gain, respectively. The material gain is given by Eq. (5) [6]:

$$g_i = \frac{a_0 (N_i - N_0) - a_1 (\lambda - \lambda_0)^2 + a_3 (\lambda - \lambda_0)^3}{1 + \epsilon S_i} \quad (5)$$

where a_0 , a_1 , and a_3 are gain constants. λ_0 and ϵ are the gain peak wavelength and nonlinear gain saturation factor,

Table 1. Simulation parameters.

Symbol	Description	Values
V	Active layer volume	$1.5 \times 10^{-16} \text{m}^3$
A_{cross}	Cross-section area	$3 \times 10^{-13} \text{m}^2$
ε	Nonlinear gain saturation factor	1.3×10^{-23}
v_g	Group velocity	$7.5 \times 10^7 \text{m/s}$
Γ	Confinement factor	0.3
λ_0	Wavelength at transparency	$1.605 \times 10^{-6} \text{m}$
N_0	Carrier density at transparency	$1.1 \times 10^{24} \text{m}^{-3}$
c_1	Recombination rate	$1 \times 10^8 \text{s}^{-1}$
c_2		$2.5 \times 10^{17} \text{m}^3/\text{s}$
c_3		$9.4 \times 10^{41} \text{m}^6/\text{s}$
a_1	Gain constant	$2.5 \times 10^{-20} \text{m}^2$
a_2		$7.4 \times 10^{18} \text{m}^{-3}$
a_3		$3 \times 10^{-32} \text{m}^4$

respectively. The propagation equations are coupled with the rate equation for carrier density. The rate equation in each section is solved as follows [7]:

$$\frac{\partial N_i}{\partial t} = \frac{I}{qV} - N_i (c_1 + c_2 N_i + c_3 N_i^2) - \sum v_g \Gamma g_i S_i \quad (6)$$

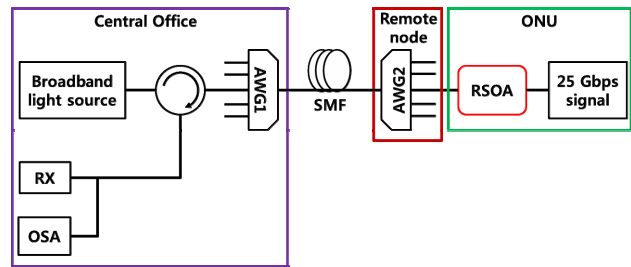
where I is the injection current, V is the active volume, and q is the electronic charge. c_1 , c_2 , and c_3 are related to recombination constants. The average photon density, S_i , is given by Eq. (7) [7]:

$$S_i = \frac{|A_i|^2 + |A_{i+1}|^2 + |B_i|^2 + |B_{i+1}|^2}{2v_g E A_{cross}} \quad (7)$$

where A_i is a forward-traveling wave amplitude, and B_i is a backward-traveling wave amplitude. E is photon energy, and A_{cross} is a cross-sectional area of the active region. The simulation parameters used in this work are summarized in Table 1.

4. Simulation Setup

In order to investigate the impact of a detuning optical filter on RSOA modulation, we simulated an uplink in a WDM-PON system using RSOAs as colorless transmitters in the ONU, as shown in Fig. 3. The CO is composed of a broadband seed light, array waveguide grating 1 (AWG1), an optical circulator, an optical filter, and a receiver for the uplink. AWG2 played the role of the RN, and the ONU of a subscriber for the uplink includes an RSOA. The continuous-wave (CW) seed light in the CO went through the downlink of the WDM-PON, and the seed light was sliced by the multiplexer (AWG1) and the demultiplexer


Fig. 3. Simulation setup.

(AWG2) in the CO and RN, respectively. The sliced seed light at 1550 nm was coupled into the RSOA. The optical power of the sliced seed light was adjusted to provide an injection power of -10 dBm. For the uplink, the RSOA was modulated by 25 Gbps electrical signals. The optical filtering effect can be implemented by detuning the center wavelengths of AWG1 and AWG2.

In the modified TMM, the RSOA was divided into 25 sections, with each section at a length of 20 μm . The front facet of the RSOA had an anti-reflection coating (0.01%), allowing more seed light to enter the RSOA, and the rear facet of the RSOA had a high-reflection coating (90%). The RSOA was directly modulated with 25 Gbps non-return-to-zero (NRZ) electrical signals with a bias current of 70 mA. At the CO, the received RSOA-based optical signals were first filtered by the Gaussian optical filter. These signals were sent to an optical spectrum analyzer (OSA) and were detected by using a PIN photodetector-based receiver (Rx) with an electrical 3 dB bandwidth of 16.3 GHz. The receiver bandwidth was numerically optimized to minimize the noise signals from the RSOA.

5. Result and discussion

Fig. 4 shows the simulated eye diagrams for 25 Gbps NRZ signals obtained from direct modulation of the RSOA. The Gaussian optical filter at a 3 dB bandwidth was 0.2 nm (25 GHz). The center wavelength of this filter was detuned from 1550 nm. Optical power was continuously reduced in accordance with the increase in detuning wavelength, because a high detuning wavelength creates excessive insertion loss in the optical filter. In Fig. 4(a), the eye diagram without detuning was completely closed due to the severely limited modulation bandwidth of the RSOA. As detuning wavelength increases to 0.15 nm, the eye clearly opens. But at a detuning wavelength greater than 0.20 nm, the eye closes again. Since detuning of optical filtering can provide the loss for the low-frequency components and the gain for the high-frequency components, it can compensate for the limited bandwidth of the RSOA. For optical filtering, the bandwidth and the detuning of the optical filter are the most important factors for improving optical signal quality.

We investigated the system performance by bit error rate (BER) curve. Fig. 5 shows the calculated BER curve for different detuning wavelengths with an optical 3 dB bandwidth of 0.2 nm. As shown in Fig. 4, the eye diagrams are highly dependent on detuning of the optical filter. By

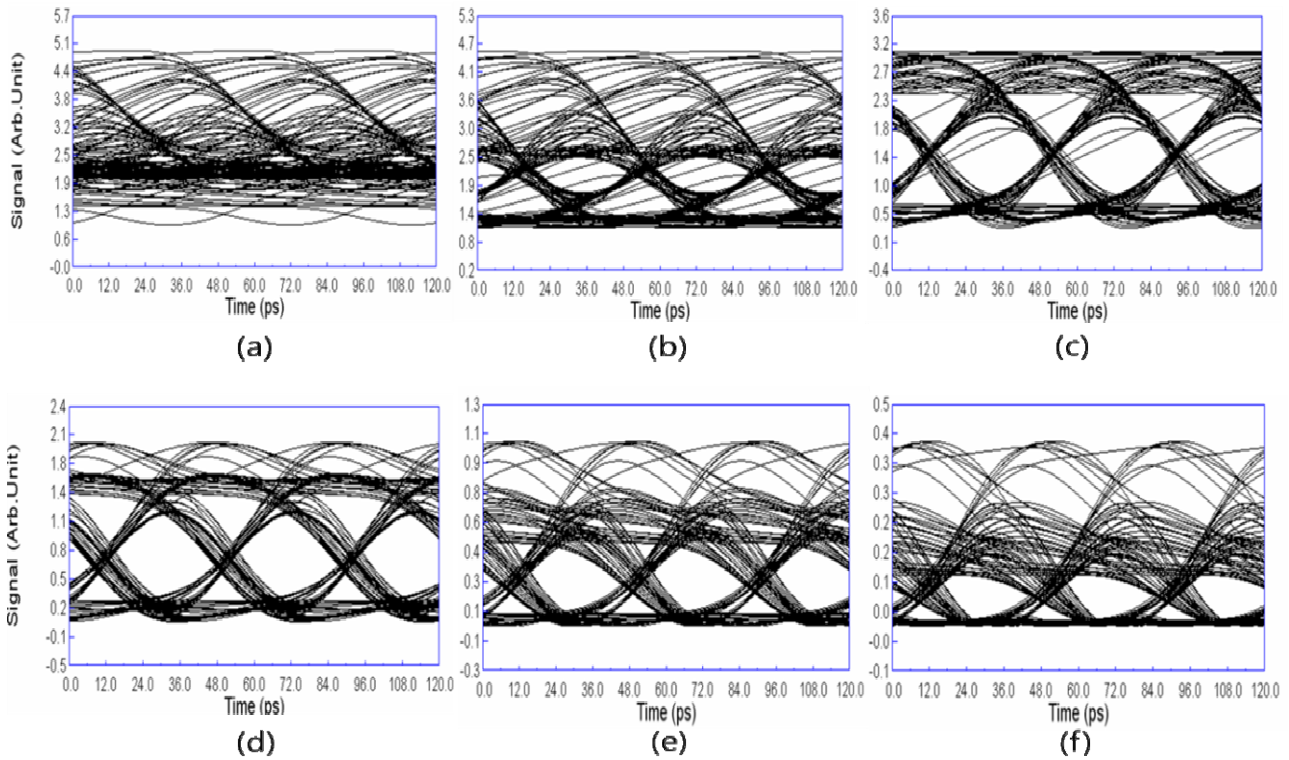


Fig. 4. Eye diagrams with various detuning wavelengths (a) no detuning, (b) 0.05 nm, (c) 0.10 nm, (d) 0.15 nm, (e) 0.20 nm, (f) 0.25 nm.

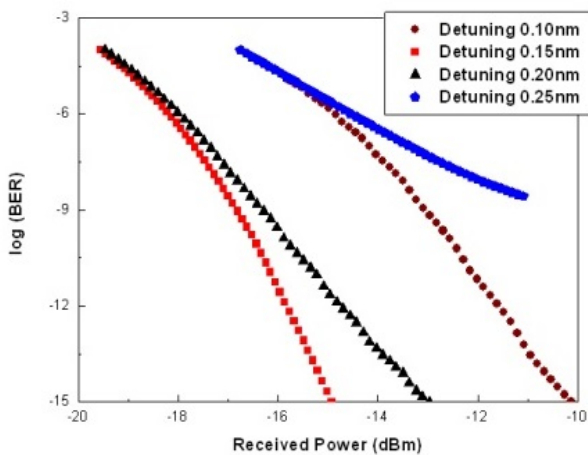


Fig. 5. Calculated BER curves at various detuning values.

detuning the optical filter, receiver sensitivity can be improved by more than 2 dB because of the improved eye diagrams. For 0.15 nm detuning, the best BER performance is obtained, and receiver sensitivity is -16.8 dBm.

Fig. 6 shows a comparison of two optical spectra detuning cases: 0 nm and 0.15 nm. Due to the detuning of the optical filter, the optical spectrum becomes asymmetric. For 0.15 nm detuning, the optical spectrum still shows low power at +25 GHz, but a relative increase in power at -25 GHz. Since the center wavelength of the optical filter is detuned, the signal filters out the right sideband and leaves the left sideband, similar to vestigial sideband modulation. Thus, the spectrum shows asymmetry, and looks like VSB

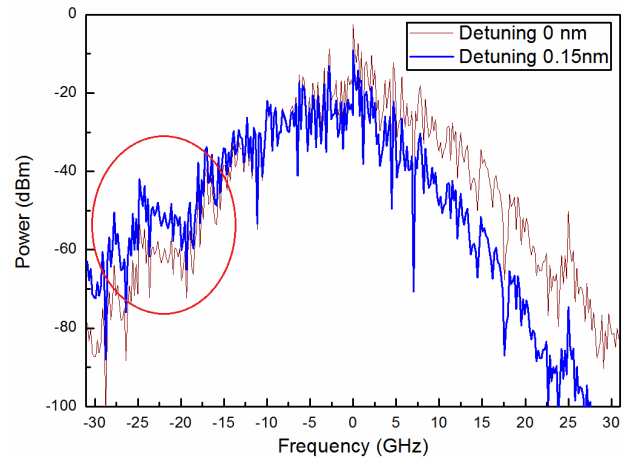


Fig. 6. Comparison of optical spectra two detuning cases: 0 nm and 0.15 nm.

signals. In addition, the higher frequency components in the left sideband increased relatively, but the lower frequency components decreased. This can compensate for the limited bandwidth of the RSOA.

6. Conclusion

By using a modified TMM, we simulated the effect of optical filtering on 25 Gbps direct modulation of an RSOA. Adjusting the center wavelength of the optical filter, we achieved VSB-like signals and optical equalization, which

can improve the quality of optical signals. It was shown that 25 Gbps direct modulation of an RSOA is feasible without complex electronic equalization, despite the inherent narrow modulation bandwidth of the RSOA.

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