Investigation of Semiconductor Optical Amplifier Direct Modulation Bandwidth

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***Abstract*—In-line and reflective semiconductor optical amplifiers can be advantageously utilized as external modulators because they can perform simultaneously two functions (amplification and modulation). When the SOA is used in next generation access networks the modulation bandwidth is a crucial property, because it will limit the application. In the paper theoretical and experimental investigations are presented with the result of improved modulation bandwidth. The experimental results confirm that by proper adjustment of the operation point and environmental conditions a significant improvement in the modulation bandwidth is achieved. Mainly the bias current and the level of the incident optical power determine the carrier lifetime. The modulation bandwidth can be doubled by this approach. The theoretical and simulation results represent the effect of the device parameters, like device length and electrode setup. However there is a trade-off between modulation efficiency and modulation bandwidth, which demands circumspect design of the device and system parameters.**

***Index Terms*—Semiconductor Optical Amplifier, intensity modulation, optical modulation, access network, optical communication**

I. Introduction

Reflective and in-line semiconductor optical amplifiers (RSOAs and SOAs) are looks like key components for next-generation access networks (NGANs), since they allow for directly-modulated colorless transceivers. Next generation access networks will probably gain great advantages in exploiting the potentialities of wavelength division multiplexing (WDM). It is true for both WDM based 60 GHz Radio over Fibre systems (60G-RoF) [1] and WDM Passive Optical Networks (WDM-PONs) [2]. The unit at the user side should be colorless in these systems. It can be obtained by the injection technique performed on Fabry-Perot lasers [1] and reflective semiconductor optical amplifiers (RSOA) [3] or even in Self-seeded RSOA [4]. Optical amplifiers are preferred devices for many solutions. RSOAs and SOAs have already demonstrated their multifunctional capability by combining optical amplification with either modulation, gating, photodetection, dispersion compensation, linearization, commutation, wavelength conversion, signal regeneration, etc. [5, 6]. The SOA offers a semiconductor based, small size, integrable, low cost optical intensity modulator. It requires relative low bias current and modulation signal. The detected electrical power is high because of the optical gain in contrary to the optical insertion loss of other modulators. Additionally it has better linearity than Mach-Zehnder modulator [7]. Contrary, the amplifier adds optical noise to the signal and the operation of SOA based modulator depends on system and device parameters [8].

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In the RSOA-based WDM PON, the upstream and downstream signals are propagating within the same fiber due to the single-fiber loopback configuration. On the other hand, the signal distribution of RoF systems can be realized by point-to-point, point-to-multipoint, bus, ring and open loop topologies, where in-line device structure is more powerful [5].

However modulation bandwidth of semiconductor optical amplifier is usually limited to around 1-3 GHz [14]. Increasing the modulation bandwidth is still a challenge. In this paper, the modulation response of a semiconductor laser amplifier will be analyzed, i.e., the frequency dependence of the amplitude modulation imposed on an injected CW optical beam when the bias current is modulated. The paper is organized as follows. Section II overviews the bandwidth enhancement methods. Section III discusses the optimal environmental parameters; the expected results are validated by experimental work. Section IV represents the modulation improvement applying optimal device structure and finally Section V concludes the paper.

II. Modulation Bandwidth Enhancement Methods

Various techniques have already been demonstrated to overcome band limitation of standard RSOA. The frequency response of the RSOA has a smooth roll-off with no relaxation oscillation peak, while its modulation has a good linearity similar to the laser diode [8]. It is perfect for the electronic equalization using the decision feedback equalizer, which can be combined with Forward Error Correction [10]. Set-off optical filtering aided by electronic equalization [11] or detuned ad-hoc delay interferometers [12] are also good perspectives.

On the other hand, introduction of advanced modulation formats with high spectral efficiency in optical communication systems led to significant improvements. Advanced modulation formats have been demonstrated both to effectively increase the transmission capacity of bandwidth-limited transmitters and to implement efficient multiplexing techniques, such Orthogonal Frequency Division Multiplexing (OFDM) [4]. However, the aforementioned approaches improve the complexity of the system.

On the other hand, the problem of the limited modulation bandwidth can be overcome with system and device level. In principle, the modulation bandwidth is limited by the speed at which the carrier density can be changed. This is usually determined by the lifetime of the carriers in the RSOA active layer. Carrier lifetime is mainly governed by emission rate. Based on it, the operational and environmental parameters can be optimized from the viewpoint of the modulation speed. For example the length of the RSOA can be enlarged to increase photon density, hence reducing carrier lifetime. However the transmission will be degraded due to the chirp over long distances. So, the optimization of device and environmental parameters is effective method, but it demands circumspect design of the device and system parameters.

Naturally, SOA/RSOA's direct modulation capability is characterized by several parameters, like chirp, extinction ratio, ASE noise, Noise Figure, optical signal-to-noise ratio, Q-factor, linearity, etc. Each of these modulator characteristics are influenced by same device and system parameters. However the main problem is the bandwidth limitation. So the paper focuses the investigation of the modulation bandwidth.

III. EXPERIMENTAL WORK

The optimal environmental parameters and operating point of the device must be selected cautiously. It is difficult to give individual optimization and a trade-off is necessary, because different parameters are optimal for amplifier gain, modulation bandwidth, linearity, etc. The modulation depends on system and device parameters. So the presented investigation involves the theoretical and experimental study of transfer function and modulation bandwidth with different environmental constraints.

A. Measurement set-up

The frequency response of the RSOA can be measured by modulating the carrier density. Fig. 1 shows the simplified measurement setup. During the experimental work the RSOA-modulator under test was driven by the sum of bias (dc) current and sinusoidal modulation radio frequency (RF) signal via a bias tee. The RSOA under test was packaged in butterfly

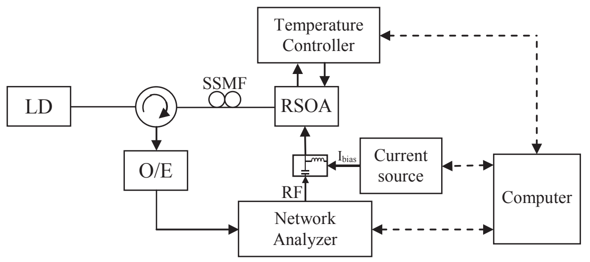

Fig. 1.Measurement setup

package and the impedance mismatching was moderate. Frequency of the RF signal is varied between 100 MHz and 10 GHz and it is generated by network analyzer. The required optical power and wavelength were produced by a tunable laser source. The incoming continuous wave and the reflected, modulated optical signals were separated by optical circulator.

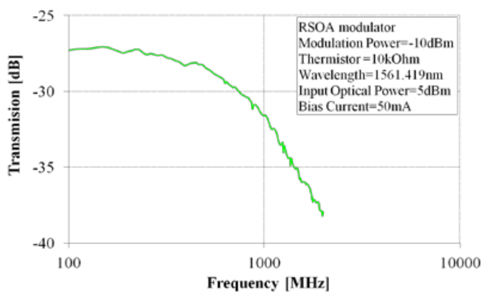

Fig. 2. Typical measured frequency response

The intensity modulated optical signal was detected by an amplified PIN photodetector. At the electrical output a network analyzer registered the detected electrical signal. The setup was controlled by a computer program, hence the measurement parameters were carefully set by the program and the measurement results were processed and stored.

Fig. 2 describes the typical frequency response of the RSOA. The bias current was 50 mA and the injection power was 5dBm, which is 7 dB higher than the 3 dB gain compression point. The 10 dB modulation bandwidth was measured to be 1.8 GHz. The slope of the curve is -20 dB/decade.

B. Modulation bandwidth versus bias current of the RSOA

The amplitude and shape of the transfer function depend on several parameters. The input optical power and the bias current of the RSOA-modulator are the two most important effects. Fig. 3 depicts the relative modulation bandwidth versus bias current as a function of the input optical power. The improvement of the bandwidth is about linear proportional to the bias current. The slope of the curve is higher in case of higher input power. So the bias current effect is more significant in the saturated regime.

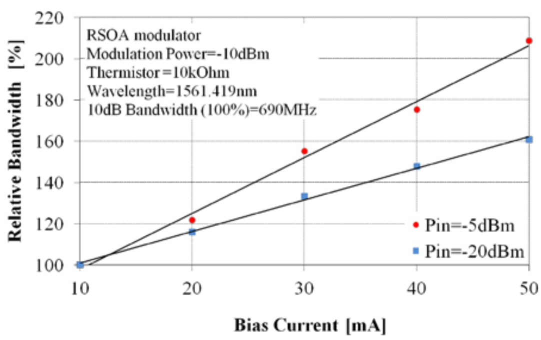

Fig. 3. Measured bandwidth improvement versus bias current in saturated and unsaturated regimes

C. Modulation bandwidth versus incident optical power

In general, the lifetime of the carriers in the presence of a strong, saturating input signal is reduced due to stimulated recombination. Hence the modulation bandwidth can be improved applying higher input optical power. Fig. 4 represents this effect, where the relative bandwidth versus input optical power curve is plotted. The modulation bandwidth is constant in the unsaturated regime. It can be extended by about 70 percents compared with the unsaturated value in the saturated regime. Same time, linearity will be improved [7], but the modulation depth will be decreased. Hence the detected electrical signal at the centre part of the system will be improved, because the higher output power of the RSOA modulator.

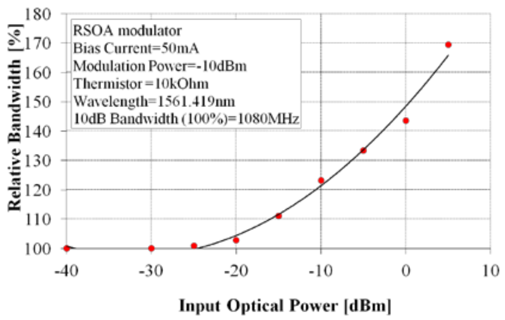

Fig. 4. Measured bandwidth improvement versus input optical power

D. Modulation bandwidth versus modulation index and temperature

The behavior of the RSOA is temperature sensitive. However it does not cause significant change in the modulation bandwidth. In a similar manner, the level of the electrical modulation power has no any remarkable effect for the modulation bandwidth. Naturally, the modulation depth, therefore the detected electrical power is proportional with the electrical modulation power. Hence the higher modulation signal is more effective, but the level of modulation electrical signal is limited by electrical nonlinearity.

To summarize the measured results, the optimization of operational and environmental parameters can double improve the modulation speed.

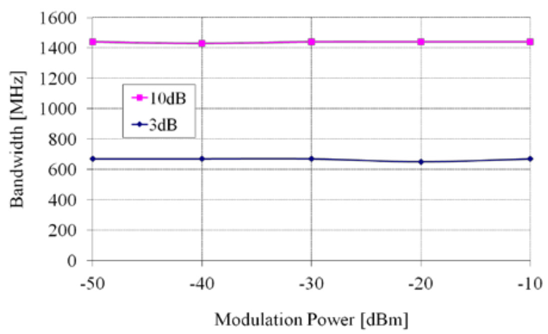

Fig. 5. Measured 3dB and 10dB bandwidths versus modulation power

IV. Simulation Work

The experimental work presented the effect of the environmental parameters (like temperature, input optical power, bias current, etc.). However the investigation of inside device parameters with simulation method is more efficient.

A. Description of the model

An optical field which propagates along a travelling wave semiconductor optical amplifier was considered in the model. The interaction of light with carriers in the SOA is governed by the carrier rate and field propagation wave equations. The amplifier's output power is calculated by solving numerically the coupled rate and wave equations [5]. First the operating point is calculated by a steady state consideration. Next a change in the carrier density around the mean value was considered due to a change in the injected signal and the differential equation was obtained. The associated change in the stimulated and spontaneous emissions can be calculated.

$$\frac{dN}{dt} = \frac{I}{e \cdot A} - R_{sp}(N) - v_g \cdot \Gamma \cdot g_m \cdot S$$
$$\frac{dS}{dz} = (\Gamma \cdot g_m - \alpha) \cdot S \qquad (1)$$

Where N is the carrier density, I is the injection current, e is the electron charge, A is the volume of active layer, $R_{sp}(N)$ is the spontaneous recombination rate, v_g is group velocity, Γ is the optical confinement factor, g_m is the material gain, α is the internal loss, S is the photon flux density, t is the local time, z is the spatial coordinate along the amplifier.

In case of modulation, the current is divided into dc and modulation part. So the carrier density and consequently the photon density include modulation part, too.

$$I = I_{DC} + \Delta I \cdot \exp(i \cdot \omega \cdot t)$$
$$S(t,z) = S_{DC}(z) + \Delta S(z) \cdot \exp(i \cdot \omega \cdot t) \qquad (2)$$
$$N(t,z) = N_{DC} + \Delta N(z) \cdot \exp(i \cdot \omega \cdot t)$$

Based on this model the modulation amplitude of the photon density can be calculated at the output of the device.

$$\frac{d\Delta S}{dz} = (g_{sat}(z) - \alpha) \cdot \Delta S(z) + \Gamma \cdot a \cdot \Delta N(z) \cdot S_{DC}(z) =$$
$$= (g_{sat}(z) - \alpha) \cdot \Delta S(z) + \qquad (3)$$
$$+ \Gamma \cdot a \cdot \frac{\frac{\tau_s}{e \cdot V} \cdot \Delta I(z) - \frac{v_g \cdot \tau_s \cdot g_{sat}(z)}{\Gamma} \cdot \Delta S(z)}{1 + i \cdot \omega \cdot \tau_s + \frac{S_{DC}(z)}{S_{sat}}} \cdot S_{DC}(z)$$

where g_{sat} is the saturated gain, S_{sat} is the saturated photon flux density, τ_s is the carrier lifetime, a is the differential gain.

The equation suggests that an increased bandwidth will be obtained with increased current, input optical power, differrential gain and confinement factor.

The carrier density is non-uniform along the SOA active region. To solve the problem the SOA is divided into many longitudinal sections and in each section my model assumes both uniform carrier and photon densities. The sectioned amplifier cavity is used to account for longitudinal effects; and the spatial variation of the material gain and other parameters of the SOA can be captured. The suitable adjustment of the model parameters enables the simulation of both in-line and reflective devices. The effect of spatial dependence in in-line device is more significant than in reflective device.

B. Simulation results

The slope of the transfer function is determined by different effects. The local modulation is low pass type, but the saturation and propagation effects [13] causes high pass filtering and it can improve the modulation bandwidth. Fig. 8 represents the typical transfer functions in case of different device length and bias current. During the simulation the modulation response was investigated, next 3 dB and 10 dB modulation bandwidths were calculated from the simulated transfer function.

1) Local modulation, operation point

The general transfer function is low-pass type and the bandwidth is usually limited by the carrier lifetime. The carrier lifetime is inversely proportional to the recombination rate. The carrier recombination rate can be described by different parts; there are the nonradiative recombination rate, the radiative recombination coefficient (spontaneous and stimulated) and the defect or Auger recombination coefficient. The effective carrier lifetime depends on the operating conditions. At low input optical power (unsaturated regime), the spontaneous and non-radiative recombination rates are dominant, and the carrier lifetime depends on these recombination terms. So the bandwidth increases by increasing the electrical bias current, because it increases all recombination terms and the carrier lifetime is decreased. The experimental work validated this effect (Fig. 3). On the other hand, it is advantageous to employ long SOA, since it tolerates larger bias currents, and have a larger differential gain for a given chip gain compared to short SOA.

The carrier lifetime in amplifier is larger than in laser because of the smaller photon density. The unsaturated carrier lifetime of a typical device is about 200-300 ps. It determines less than 1 GHz bandwidth.

2) Saturation effect

High input optical power and electrical current induce high photon density inside the active zone increasing the stimulated recombination rate. So, the stimulated recombination rate tends to overcome the spontaneous and non-radiative recombination terms. The stimulated lifetime is reduced and the average carrier lifetime is also smaller. The saturation level depends on the electrical bias current. At large optical input power, the saturation effect is much stronger than with low input injection at low bias current. Similarly, the saturation effect is significant at high bias current, when signal and ASE

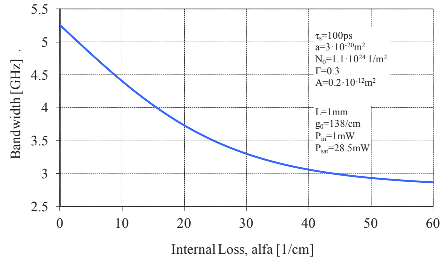

Fig. 6. Simulated bandwidth versus internal loss

are strongly amplified along the device. Consequently, the carrier lifetime decreases (the bandwidth increases) as the optical power is increased. Contrary, the bandwidth decreases as the internal loss increases, because the attenuation of the optical signal higher, namely the optical power is lower (Fig. 6). The experimental work validated this effect (Fig. 3). So, the 10-20 ps carrier lifetime can improve the bandwidth to the 100 GHz regime.

3) Propagation effect

The non-uniformity of the carrier lifetime along the device affects the transfer function. To illustrate the intrinsic propagation effect multisection model was applied. The current amplitude was independent of localization, but the spatial variation of average carrier and photon densities were taken into account.

The simulation results demonstrated the photon density modulation amplitude is high pass filtered as it travels along the SOA, since higher frequencies saturate the amplifier less. This tends to compensate the low pass filter type transfer function and increase the bandwidth of the device. Consequently, the whole transfer function has resonance, but it is also low past type.

So, the modulation bandwidth increases versus device length (Fig. 7). The slope of the curve depends on the optical power propagating over the device. As the optical power increases (the internal loss decreases) the situation goes to saturation and the propagation has more significant effect.

Summarizing, the modulation bandwidth cannot be accounted by the simple low pass transfer function determined by the effective carrier lifetime. It is affected by the evaluation of the signal as it propagates through the amplifier and the saturation. Figure 8 shows modulation responses for different

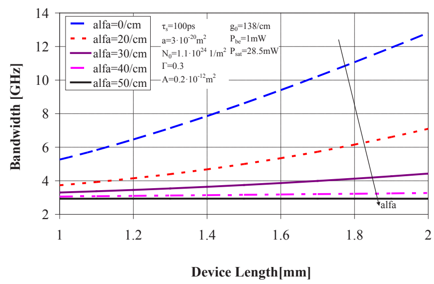

Fig. 7. Simulated bandwidth versus device length

amplifier lengths and different values of the internal loss. It represents the effect of the propagation. As the device length increases the bandwidth is improved and a resonance can be observed. On the other hand lower attenuation, namely higher intensity also improves the bandwidth.

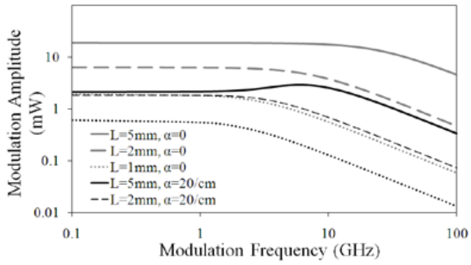

Fig. 8. Simulated modulation response for different amplifier lengths (L) and internal losses (α)

4) *Effect of microwave and optical signal mismatch*

The modulation signal propagates with a speed different from the optical mode the same or opposite directions and it is attenuated over the device. The model can take into account these effects, if appropriate phase and amplitude of the current density change are applied in the sections. The phase velocity of the microwave is in the range of 8-12% of the velocity of the light in vacuum for the frequencies in the range of 5-40 GHz [12]. So the refractive index of the microwave signal (n_μ=light speed/microwave signal speed) is in the range 14.3-8.3. The mismatch between the microwave and the light leads to a dip in the modulation response (Fig. 9).

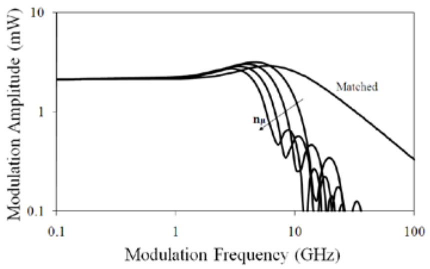

Fig. 9. Simulated modulation response for different mismatches

Fig.10 demonstrates that the modulation bandwidth decreases versus the level of the mismatch. The shape of the curve depends on the length of the device.

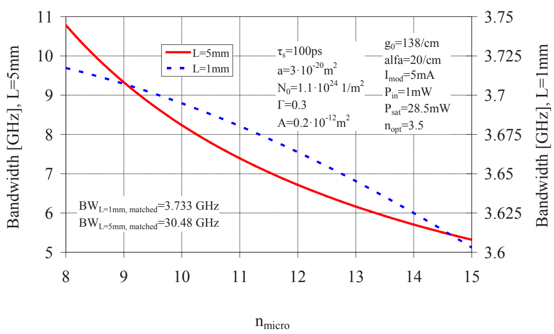

Fig. 10. Simulated bandwidth versus mismatch with different device length

5) *Effect of bonding position*

The simulation results show that the waveguide (scattering loss) plays a very important role. The transfer function depends on the location of the bonding point. In the previous simulations the modulation signal was coupled at the starting point of the device. So I calculated with copropagation between the microwave electrical and the optical signals. Fig. 11 presents the transfer functions when the bonding position is the end of the device. It causes counter propagation. The transfer function shows the effect when the microwave signal is faster than the optical signal. Fig. 12 shows the situation when the bonding position is the center of the device. It means both co- and counter propagations.

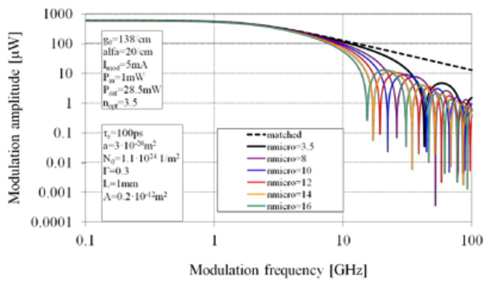

Fig. 11. Effect of bonding position, bonding point: end of the device

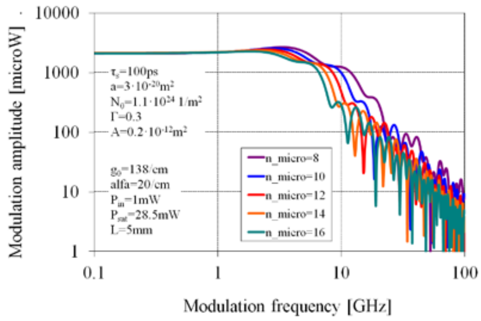

Fig. 12. Effect of bonding position, bonding point: middle of the device

6) *Effect of microwave attenuation*

In case of a real device the microwave modulation signal is attenuated, too. The level of the attenuation depends on the microwave frequency, it is about 500 dB/cm at 40 GHz and „just" 10 dB/cm at 10 GHz. The attenuation of the modulation signal decreases the intensity modulation amplitude, but same

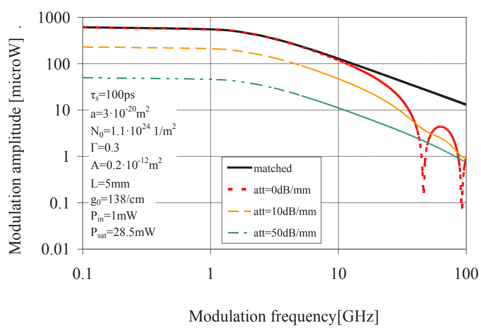

Fig. 13. Effect of electrical attenuation

time it decreases the mismatch effect. Hence reduced dips can be observed (Fig. 13).

V. Conclusion

This paper has provided a summary of the work, which proves the importance of electrical modulation bandwidth investigation of in-line and reflective semiconductor optical amplifier based external intensity modulators in next generation optical access networks. It means both baseband modulated WDM-PON and high speed WDM-RoF applying Subcarrier Multiplexing. The paper proposes device and system level solutions for enhancing the data speed at which the device is directly modulated.

The experimental results confirm that a significant improvement in the modulation bandwidth can be achieved by proper adjustment of the operation point and environmental conditions. Mainly the bias current and the level of the incident optical power determine the carrier lifetime. The modulation bandwidth can be doubled by this approach.

Bandwidth enhancement can be also achieved by applying optimal device structure. The comparison of in-line and reflective structure and the effect of device length and electrode structure were investigated by simulations.

The obtained results suggest that the methods enable the use of the RSOA as intensity modulator with improved performance at an extended data rate or subcarrier frequency.

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