Multifunctional Characteristics of 1.5-μm Two-Section Amplifier-Modulator-Detector SOA

G. Giuliani, P. Cinguino, and V. Seano

Abstract— **The multifunctional characterization of a two-section amplifier-modulator-detector semiconductor optical amplifier (AMD-SOA) is presented. Detectivity is analyzed in terms of bandwidth and responsivity while modulation properties are characterized by temporal response and extinction ratio. Receiver sensitivities of −26 dBm at 155 Mb/s and −19.5 dBm at 622 Mb/s and error-free signal modulation/transmission with simultaneous 10-dB amplification at 622 Mb/s with a $2^{23} - 1$ PRBS signal are reported. This device could find application as transparent add–drop node in photonic packet-switched optical ring networks.**

I. Introduction

Semiconductor optical amplifiers (SOA's) have demonstrated the capability of direct signal processing combining optical amplification with either gating, modulation [1], detection [2], [3] or wavelength conversion. In particular, two-electrode devices have been demonstrated as integrated SOA-photodetector for lossless signal tapping [4] and as channel dropping node [5] using the detector section in the absorbing region. A new application of the two-electrode structure consists of using the first electrode as modulator and the second as forward-biased transparent detector. Such an amplifier-modulator-detector device (AMD-SOA) can operate as a transparent unidirectional add-drop node with potential applications in photonic ring networks [6], whose main feature is the possibility of adding new nodes and/or increasing the bit-rate for the required nodes without reconfiguring the whole network. Furthermore, such read/write nodes need a minimum amount of external electronics, therefore reducing network cost and complexity.

In this work we report on detection and modulation characteristics of a packaged AMD-SOA multifunctional device and on the results of add and drop experiments carried out at 155 and 622 Mb/s bit-rates.

II. Device Description

The AMD-SOA device is based on a squared 0.4 × 0.4-μm^2 InGaAsP BRS active waveguide structure with a peak gain wavelength of 1500 nm designed to achieve moderate gain with low operating currents and low polarization sensitivity [7]. Antireflection coatings reduce facet reflectivity to about 10^{-3}. Split-contact devices are derived from 410-μm-long conventional SOA chips by means of a lift-off technique obtaining devices with 320-μm and 80-μm-long first and second sections with a 2 kΩ electrodes insulation resistance. Proper device packaging allows high-frequency operation, while series matching resistors of 47 Ω and 33 Ω are employed for first and second section, respectively. Fiber-to-fiber gains of 10 dB are obtained at 1530 nm signal wavelength for 30–50 mA first section and 4–10 mA second section currents with a saturation output power into the fiber of −2 dBm. In the modulation configuration the first electrode of the AMD-SOA acts as modulator and the second electrode as a power booster; in the detection configuration the first section acts as a pre-amplifier and the second section as a forward-biased transparent detector, thus achieving a higher responsivity with respect to monoelectrode devices [8].

III. Receiver Characteristics

Receiver functionality depends on device responsivity (defined as the ratio between electrode voltage change and input fiber optical power variation) and its frequency response. Static responsivity values as high as −100 V/W have been measured with 1-MΩ load; these values are halved with 50-Ω loads. Responsivity increases monotonically with first electrode current due to the pre-amplifying effect until gain saturates. The responsivity as a function of detector current is reported in Fig. 1. The decrease of the responsivity for high currents is mainly due to leakage effects since the voltage transfer function from the active region to the output electrode reduces for increasing total detector current because of the lowering of the dynamic impedance of the parallel leakage diode. Detection bandwidth is also reported in Fig. 1 as a function of detector current with 35 mA first section current (corresponding to the maximum pre-amplifying effect [9]). The measurement has been performed injecting a sinusoidally modulated signal into the AMD-SOA, yielding a small-signal voltage modulation, and measuring the response with a network analyzer. Detection bandwidth is limited by differential carrier lifetime and depends on spontaneous and stimulated recombination rates. As it will be noticed in the following, at high detector current the increased spontaneous photon density enhances the bandwidth beyond the spontaneous recombination limit. A maximum bandwidth of 1100 MHz has been measured and no bandwidth dependence on optical input power has been observed.

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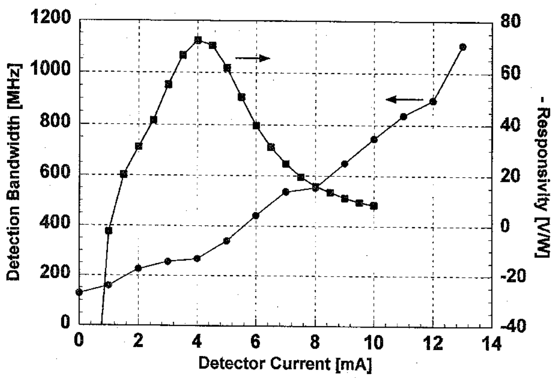

Fig. 1. Static responsivity (measured with 1-MΩ load) and detection bandwidth as a function of detector current. First electrode (pre-amplifier) current = 35 mA; received optical power = −19 dBm.

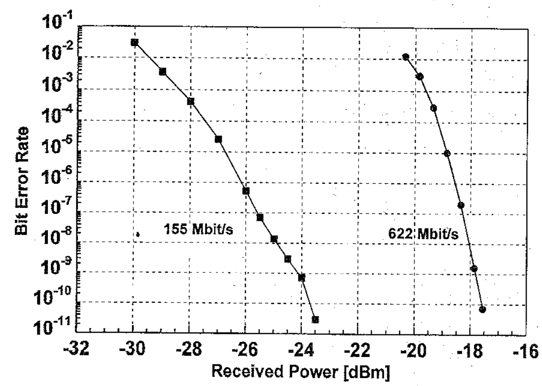

Fig. 2. AMD-SOA detection function: Bit-error-rate curves at 155 Mb/s and 622 Mb/s with a PRBS of $2^{23}-1$. First electrode (pre-amplifier) current = 35 mA; detector current = 4 mA (155 Mb/s) and 6 mA (622 Mb/s).

For the purpose of digital signal detection for channel drop applications the optimum bias of the detector has to be determined accordingly to the bit-rate, as a consequence of the results reported in Fig. 1. In fact, for low bit-rates the best sensitivity is obtained in correspondence with maximum responsivity (i.e., 4-mA detector current at 155 Mb/s), while at higher bit-rates a compromise exists between responsivity and bandwidth and the optimum detector bias current is higher (6 mA at 622 Mb/s) [9]. Detection experiments at 155 and 622 Mb/s have been carried out employing a tunable laser source externally modulated by a NRZ format signal with a PRBS of $2^{23}-1$; the detected voltage signal is amplified 40 dB by a 50-Ω amplifier and properly filtered before decision circuit. An example of measured bit-error-rate curves is reported in Fig. 2, yielding a sensitivity of −24 dBm at 155 Mb/s and of −17.8 dBm at 622 Mb/s for 10^{-9} BER. The best sensitivities obtained have been −26 dBm at 155 Mb/s and −19.5 dBm at 622 Mb/s. The smaller responsivity and the larger electrical filter bandwidth in the 622-Mb/s operating conditions account for the 6 dB difference in sensitivities. The power penalty due to dichroism is measured to be 1.5 dB at 622 Mb/s and 1.3 dB at 155 Mb/s while the penalty due to gain ripple is 4 dB at 622 Mb/s and 3 dB at 155 Mb/s. In the 622-Mb/s configuration, the noise of the electrical amplifier is 5 dB larger than device intrinsic electrical detection noise, thus introducing a 3 dB penalty on the measured sensitivity with respect to the ideal device-noise-limited performance; this penalty reduces to 2.5 dB at 155 Mb/s. Device detection noise does not depend on input optical power at the considered levels, being primarily due to intrinsic junction voltage fluctuations [10].

IV. Modulation Characteristics

Small-signal modulation bandwidth is reported in Fig. 3 as a function of modulator bias current for different values of second electrode current. The beneficial effect of high booster current is due to differential carrier lifetime reduction caused by increased ASE photon density. At 40-mA bias modulator current a bandwidth in excess of 1600 MHz is reported for 14-mA booster current, which is four times larger than for 1 mA booster current.

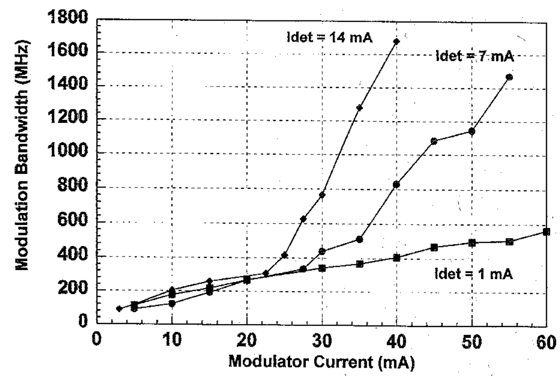

Fig. 3. Small-signal modulation bandwidth as a function of bias modulator current for different second electrode (booster) current. CW input power = −12.6 dBm.

A very simple set-up is used to achieve large-signal digital modulation since the low operating current and 47-Ω matching resistor allows the modulator to be directly driven by the PRBS generator, yielding a maximum current swing of approximately 40 mA peak-to-peak. For a fixed current swing, total output power (ASE + signal) and signal output power response may be quite different; hence, output signal extinction ratio depends on the bandwidth of the optical filter inserted at amplifier output. All modulation experiments reported here have been carried out with a 1.3 nm output optical filter and with 14 mA booster current to minimize rise and fall times. Characteristics of the 622 Mb/s modulated signal are reported in Fig. 4; signal extinction ratio is measured with a dc-coupled high speed photoreceiver connected to a sampling oscilloscope. The CW input light experiences an unsaturated gain of 10 dB for logic state "1", while the extinction ratio is around 6 dB and decreases when gain saturation occurs. Since for low-modulator current a slower response and a steeper gain variation are observed, at 155 Mb/s an unsaturated extinction ratio larger than 10 dB can be obtained, confirming that the attainable extinction ratio increases for lower bit-rate [11]. The extinction ratio values obtained with these prototypal devices can be improved by reducing electrical leakage effects of the BRS structure and operating with a CW signal lying on the

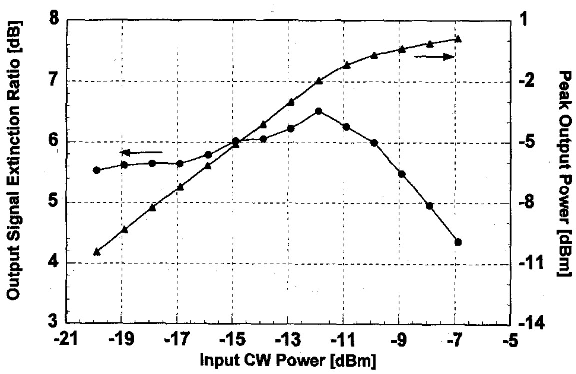

Fig. 4. AMD-SOA modulation function: Output signal characteristics at 622 Mb/s (direct modulation from PRBS generator). Bias modulator current = 35 mA; PRBS generator voltage swing = 1.56 $V_{p\text{-}p}$; second electrode (booster) current = 14 mA; output optical filter bandwidth = 1.3 nm.

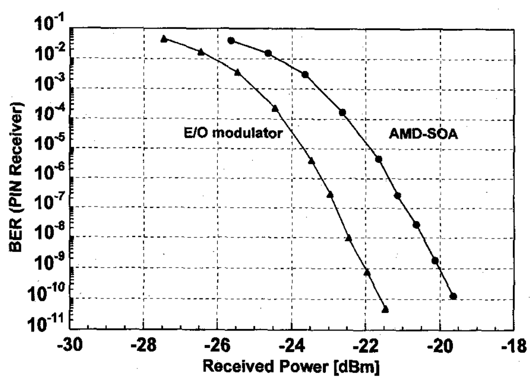

Fig. 5. AMD-SOA modulation function: PIN receiver BER curves at 622 Mb/s with a PRBS of $2^{23}-1$. Circles: Modulated signal from AMD-SOA; CW input power = −12 dBm; other parameters as in Fig. 4. Triangles: Modulated signal from M–Z $LiNbO_3$ modulator.

shorter wavelength-side of the peak gain, which gives a high differential gain even at high currents where the response is faster.

Fig. 5 reports the bit-error-rate curve obtained at 622 Mb/s with a PIN photoreceiver when a −12-dBm CW input signal is modulated by the AMD-SOA with 6.5 dB extinction ratio. The bit-error-rate curve measured using a 5-GHz $LiNbO_3$ Mach–Zehnder modulator capable of a signal extinction ratio of 13 dB is also reported for comparison. The 2 dB penalty on PIN receiver sensitivity obtained with AMD-SOA modulation is entirely due to the smaller extinction ratio. Finally, to test high-speed modulation characteristics, digital modulation at 2 Gb/s has also been performed with a 6 dB extinction ratio and a good eye-opening. Though at such high bit-rates direct SOA modulation is affected by signal chirping, two-section structures offer the possibility of reducing this detrimental effect [12].

V. Conclusion

The use of a single device for both detection and modulation of NRZ optical signal has been investigated. Channel add and drop experiments yielded −26-dBm detection sensitivities at 155 Mb/s and −19.5 dBm at 622 Mb/s as best results and error-free signal modulation/transmission with simultaneous 10-dB amplification at 622 Mb/s. The AMD-SOA device is a promising alternative for use as a monolithic add-drop node in photonic ring networks, as confirmed by test transmission experiments performed with cascaded devices working in add-drop mode [13].

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