1.55-μm Dilute Nitride SOAs with Low Temperature Sensitivity for Coolerless On-Chip Operation

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Abstract—**The temperature dependence of GaAs and InP SOA materials is investigated experimentally in this work. The direct comparison study verified that Dilute Nitrides are less temperature sensitive showing enhanced thermal stability on ASE spectrum and gain measurements in CW mode. Wavelength Conversion experiment at 10 Gb/s verified that GaAs SOA keeps up with the fast gain dynamics and the proper data processing at elevated temperatures while the performance of InP material is drastically degraded by heating the SOA device.**

Keywords—Semiconductor Optical Amplifier (SOA), Photonic Integration, Wavelength Conversion, Passive Optical Network (PON)

I. INTRODUCTION

Passive Optical Networks (PONs) have been widely deployed in the optical access network segment offering cost efficient, high bandwidth services. The 'success story' of currently deployed access solutions based upon PONs (Wavelength Division Multiplexing-PON (WDM-PON), 10G-Ethernet PON (10GEPON), 10G-PON (XG-PON)) has stimulated the interest of network operators and system vendors towards Next-Generation PONs (NG-PON) that will offer stepwise capacity upgrade and will open the door to mobile backhaul applications promoting the cooperation between wireless and optical technologies [1],[2].

In this framework, Semiconductor Optical Amplifiers (SOAs) have already been identified as key amplification units into NG-PON topologies offering reach extension between the Optical Line Terminal (OLT) and Optical Network Units (ONUs) and thus an increase of the total number of end users [3]. Moreover, several SOA-based implementations have been conducted in the literature showing the realization of optical processing units [4] as well as ONU gating functions [5]. Entering the area of photonic integration, the above functionalities have been migrated on chip-scale using Photonic Integrated Circuits (PICs) that host a large number of active/passive circuitries [6]. However, the high-integration densities come at a cost of rising on-chip operational temperatures leading to SOA performance degradation [7]. As a result, power-hungry external cooling mechanisms are required to cope with the thermal loads. In this context, low temperature sensitivity of active SOA materials emerges as a key feature that could drastically reduce the total energy consumption, meeting thereby the manifested goals of green NG-PON devices [8]. The targeted coolerless operation could also reduce the packaging complexity and the capital/operational costs.

The fundamental advantage of large conduction band offsets between the GaInNAs(Sb) Quantum-Wells (QWs) grown on GaAs substrates, has made this material capable to support active implementations of low temperature sensitivity [9]. Considering also the maturity of large-scale GaAs wafer processing, the GaInNAs(Sb)/GaAs SOA material seems to be a quite competitive solution compared to conventional InP-based SOA material offering lower costs and reduced energy consumption. In this frame, the successful demonstration of 1.3 μm GaInNAs/GaAs SOA has been conducted showing fast gain dynamics and enhanced temperature stability [10]. Recently, a 1.55 μm GaInNAsSb/GaAs SOA device was reported showing competitive static and dynamic gain characteristics and even better thermal stability, suitable to support nonlinear optical data processing at elevated temperatures [11]. Even though the attractive thermal characteristics of dilute nitride SOA material have been experimentally verified, the thermal stability of the proposed technology in direct comparison with competitive InP-based SOA implementations is still missing.

This contribution fills the above gap by turning on a more detailed view on the SOA temperature sensitivity. A direct comparison between the recently reported GaAs-based novel SOA [11] and a state-of-the-art InP-based SOA device is presented in this work by carrying out experimental measurements in variable temperature conditions, up to 55°C. Static measurements focusing on the spectral profile of the SOA gain as well as the gain characteristics in Continuous Wave (CW) mode are reported through this work. The obtained results confirm that the GaAs SOA platform significantly outperforms the InP SOA in terms of thermal stability showing remarkable resilience on the above gain characteristics at elevated temperatures. The SOA gain dynamics and data processing at elevated temperatures were also investigated for both materials via a Wavelength Conversion (WC) experiment at 10 Gb/s. The results verified the preservation of the signal processing capabilities of GaAs

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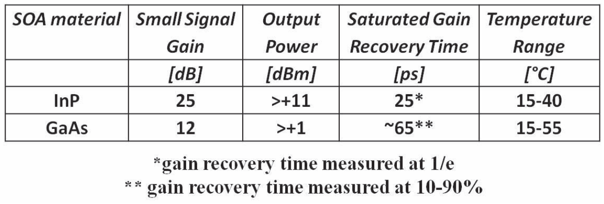
material at temperatures up to 45°C while a performance degradation occured for InP implementations for temperatures higher than 30°C.

II. THERMAL STUDY OF OPTICAL GAIN CHARACTERISTICS

A. *GaAs- and InP-based SOA device characteristics*

The comparative study involves the performance evaluation on optical gain characteristics of GaAs- and InP-based SOA materials at different operating temperatures. The InP-based SOA –a commercially available unit from CIP- is based on the buried heterostructure design. The ultra-fast gain dynamics make this device suitable for nonlinear data processing and switching applications [12]. The novel GaAs-based SOA material has also been optimized to ensure fast gain dynamics allowing for high speed data processing. Detailed information about the design parameters and fabrication process for this 2-mm long device can be found in [11].

The SOA key characteristics measured at 15°C are summarized in Table I. The small signal gain of the GaAs SOA was found to be 12 dB and the output power higher than 1 dBm. Since these values were measured on the unpackaged GaAs SOA chip, approximately 5 dB fiber-to-chip coupling losses per facet are also included. The packaged InP device from CIP exhibited a small signal gain of 25 dB and emitted an output power of more than 11 dBm at the deep saturation regime. Regarding the gain dynamics of the GaAs SOA, the 10-90% gain recovery time was found to be ~65 ps for a maximum gain compression of 14.35 dB obtained on the probe signal. The InP SOA exhibited a saturated gain recovery time of ~25 ps measured at 1/e. For the above measurements, a Mode Locked Laser (MLL) operated at 10 GHz was used. The gain recovery time was measured by means of pump-probe technique using the experimental setup discussed in section III.



SOA material	*Small Signal Gain*	*Output Power*	*Saturated Gain Recovery Time*	*Temperature Range*
	[dB]	*[dBm]*	*[ps]*	*[°C]*
InP	25	>+11	25*	15-40
GaAs	12	>+1	~65**	15-55

***gain recovery time measured at 1/e**
**** gain recovery time measured at 10-90%**

Table I: Key characteristics of the tested SOA devices measured at 15°C.

B. *Spectral gain characteristics vs Temperature*

A thermal study of the spectral gain profile was carried out for both devices. Amplified Spontaneous Emission (ASE) spectra at different operating temperatures for SOA driving current of 275 mA are depicted in Fig.1a. Lasing resonances were perfectly suppressed for GaAs material within the temperature range limited by the measurement setup (15-55°C) while the InP material exhibited a gain ripple (<3 dB) at 15°C that was removed by heating up the device. Moreover, a typical spectral redshift of the emission peak was observed for both materials at rising temperatures. It is worth mentioning that the InP SOA manufacturer defines the maximum operating temperature of the device at 40°C.

Fig.1b. illustrates the dependence of the ASE peak power and the 3-dB gain bandwidth on the SOA temperature. It is evident that the ASE peak gain power level is less sensitive for the GaAs material (-0.11 dB/°K) compared to InP material (-0.17 dB/°K). The reported results reveal the enhanced thermal stability of the dilute nitride material at 1.55 µm, being in line with previously reported results from 1.3µm SOA devices [13]. The 3-dB bandwidth of the spectral gain profile was broadened from ~65 nm at 15°C to ~76 nm at 55°C for the GaAs SOA. The InP SOA exhibited similar behavior by broadening its 3-dB gain bandwidth from ~43 nm at 15°C to ~51 nm at 40°C.

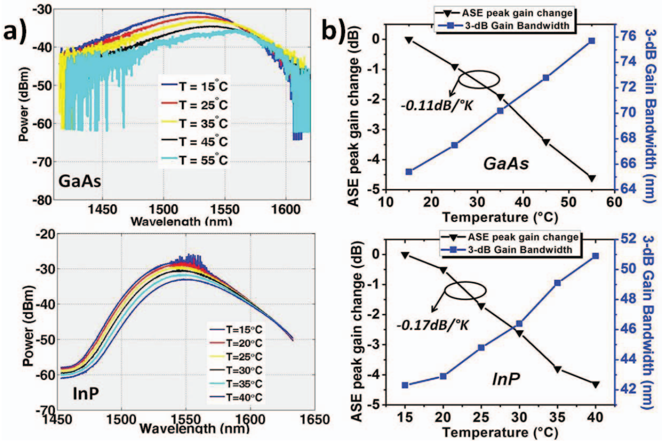


Fig. 1: (a) ASE spectra at different operating temperatures for GaAs- and InP-based devices, (b) ASE peak gain change and 3-dB gain bandwidth with respect to operating temperature of the SOAs.

C. *Static gain performance vs Temperature*

A study on the temperature dependence of the small signal gain and output power was performed by using an input signal from a CW laser emitting at 1545 nm. The SOA driving current was set at 275 mA for both devices. Polarization controllers were also used to tackle the polarization sensitivity of the tested devices. Fig. 2 illustrates the obtained measurements for both SOA materials. The small signal gain difference was found to be 1.7 dB for GaAs material within the temperature range of 15-55°C. This measurement implies that the reported GaAs SOA exhibits even better results compared to state-of-the-art QWs with low temperature sensitivity [14].

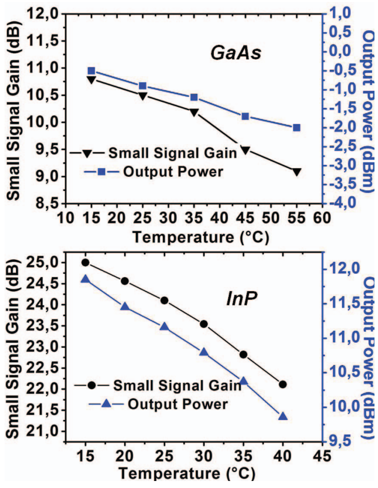


Fig. 2: Temperature dependence of SOA small signal gain and output power measured at 1545 nm for GaAs and InP materials.

On the contrary, the difference for InP material was measured to be 2.7 dB within the range of 15-40°C. It is evident that the temperature sensitivity in CW mode is quite lower for GaAs material compared to the InP material. Taking also into account the temperature range for each measurement, a gain reduction of -0.04 dB/°K was measured for GaAs while the respective value for InP SOA was found to be -0.11 dB/°K.

Using a 0 dBm input power level of the CW signal at 1545 nm, the variance of the SOA output power at different temperatures was measured. The SOA output power reduction was found to be 1.5 dB for GaAs material within the 15-55 °C range and 2.1 dB for InP material within the 15-40°C range. It should be noted that the difference between the small signal gain reduction and reduction of emitted power within the same temperature range occurs as a result of saturation behavior of each tested SOA.

III. THERMAL STUDY ON WAVELENGTH CONVERSION

A. *Experimental setup*

Additional measurements in variable temperature conditions were performed in order to investigate the effect of heating on SOA gain dynamics and data processing capabilities for both materials. For this purpose, Wavelength Conversion (WC) based on Cross Gain Mechanism (XGM) was selected because in this function, the SOA gain dynamics play a crucial role on performance. Following this rationale, the performance evaluation of WC scheme at 10 Gb/s for different temperatures was experimentally performed.

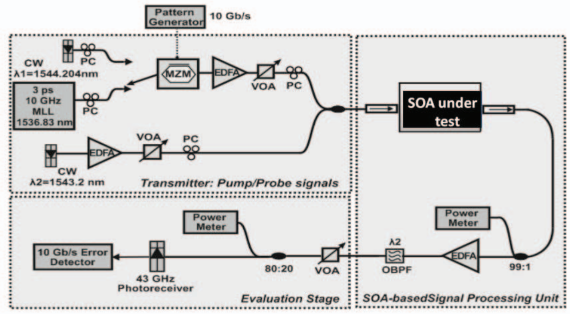


Fig. 3: Experimental setup of the 10Gb/s XGM-based Wavelength Conversion scheme.

Fig. 3 illustrates the experimental setup for the Wavelength Conversion (WC) experiment at 10 Gb/s. A CW laser emitting at 1544.204 nm was fed into a Mach-Zehnder Modulator (MZM) driven by a Pseudo-Random-Bit-Sequence (PRBS) pattern generator yielding a 2^7-1 Non-Return-to-Zero (NRZ) encoded data sequence at 10 Gb/s. The modulated data sequence serving as pump signal was then launched into the SOA under test alongside with the probe signal that was provided from a CW laser source emitting at 1543.2 nm. The signal at the output of the SOA which was driven at 275 mA was filtered using a tunable optical bandpass filter (OBPF) of 0.9 nm bandwidth to extract the complementary data sequence copied on the probe signal. Chirp-filtering technique by controlling the spectral allocation of the OBPF was employed to attain the acceleration of SOA gain recovery time, leading thereby to better signal quality on the probe signal [15]. At the receiver side, a 50 GHz oscilloscope allowed us to capture the full characteristics of the WC signal. Bit-Error-Rate (BER) measurements were taken using a 10 Gb/s Error Detector.

B. *Results and Discussion*

Fig. 4 shows the obtained BER measurements during the WC experiment using the GaAs device. The back-to-back (b2b) measurement was taken by removing any data processing on the SOA. Error-free operation (i.e. BER <10^{-9}) was obtained for the WC signal at 15°C with a power penalty of 1.7 dB compared to the b2b measurement. By heating up the SOA device, the BER performance was degraded leading to an additional power penalty of 3.1 dB compared to the operational temperature of 15°C. The power penalty degradation appeared as a result of eye opening reduction as it is depicted in the oscilloscope measurements and stems from the reduction of the delivered differential gain.

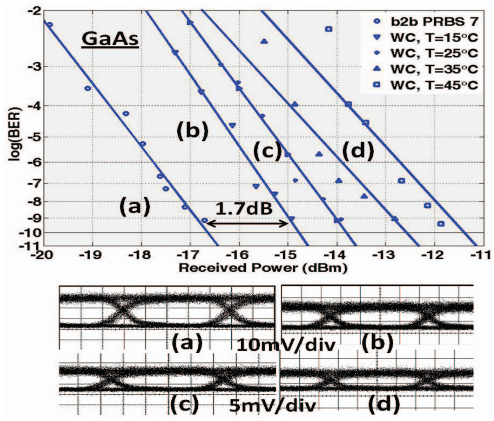


Fig. 4: BER measurements for various GaAs SOA operating temperatures in case of NRZ signal format. Insets show the obtained eye diagrams for (a) b2b case and WC signal for (b) T=15°C, (c) T=25°C and (d) T=35°C.

Fig. 5 shows the respective BER measurements taken from the InP device. Error-free operation (i.e. BER <10^{-9}) for the WC signal was achieved at temperatures up to 25°C. The power penalty between the b2b measurement and WC signal at 15°C was measured to be 1.2 dB. At elevated temperatures (T>25°C), the WC signal exhibited an error-floor behavior with BER performance of $2 \cdot 10^{-4}$ at 40°C. The oscilloscope measurements included in the insets of Figure 5, confirm that the SOA gain recovery time becomes longer at elevated temperatures, leading thereby to inferior signal quality.

Fig. 6 shows the obtained power penalties as a function of operating temperature for BER level of $2 \cdot 10^{-4}$ of the WC signal. It is evident that the data processing capability of InP material significantly outperforms GaAs at low operating temperatures. In particular, the measured power penalty was found to be only 0.6 dB for InP and 1.9 dB for GaAs respectively as a result of the higher optical gain characteristics and faster gain recovery of the InP at 15°C. By heating up the devices, the WC performance becomes worse as a result of reduced gain compression obtained on XGM mechanism. The resilience of GaAs material at elevated temperatures is better, offering lower penalties compared to InP material for temperatures higher than 35°C. The increase on power penalty was found to be 2.7 dB for GaAs between the 15-45°C range, while the corresponding increase for InP material was found to be 4.6 dB within the 15-40°C range. The longer gain recovery time at elevated temperatures for InP material seems to be the reason behind this performance degradation as it has been previously discussed.

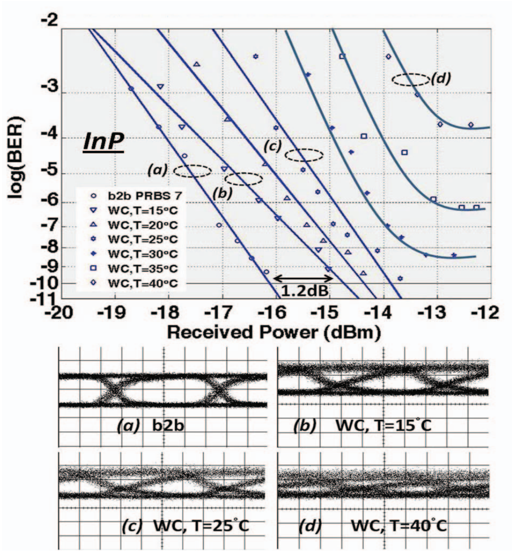


Fig. 5: BER measurements for various InP SOA operating temperatures in case of NRZ signal formatting. Insets show the obtained eye diagrams for (a) b2b case, (b) WC signal for T=15°C, (c) T=25°C and (d) T=40°C.

IV. CONCLUSION

We have presented a thorough experimental study comparing the temperature sensitivity of two state-of-the-art SOA materials. The results showed that the GaAs SOA material is thermally more stable, showing lower ASE peak power level change (-0.11 dB/°K) compared to InP (-0.17 dB/°K) and weaker temperature dependance of static optical gain in CW mode. Wavelength Conversion experiment at 10 Gb/s verified that the GaAs SOA material can properly cope with data processing at elevated temperatures showing error-free operation (i.e. BER < 10^{-9}) up to 45°C. On the contrary, the InP SOA suffers from longer gain recovery times at increased temperatures, leading thereby to substantial degradation on the BER performance (error-floor with BER value of $2{\cdot}10^{-4}$ at 40°C). The reported results denote the strong potential of dilute nitride SOAs to enable on-chip active circuitries of low temperature sensitivity, opening the door to coolerless integrated photonic components for low-power NG-PON implementations.

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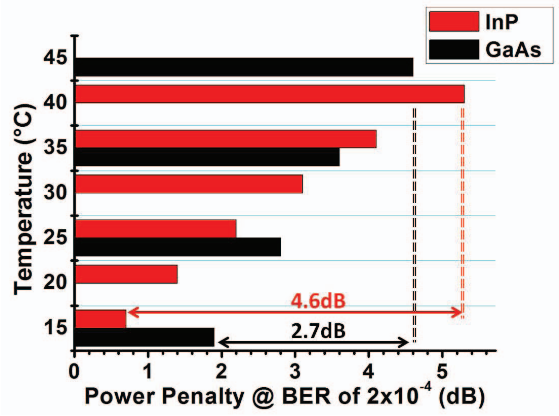

Fig. 6: Power penalty between the WC and b2b signals measured for various temperatures of both SOA devices. Measured at BER value of $2{\cdot}10^{-4}$

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