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Richard P. Mirin
Carmen S. Menoni
Chairs/Editors

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TUNABLE LASER TECHNOLOGIES

Invited Paper

A Variable Gain Semiconductor Optical Linear Amplifier (OLA)

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ABSTRACT

The semiconductor optical amplifier (SOA) is a versatile component that can be deployed to meet the expanding applications associated with the introduction of additional functionalities at the optical level in wavelength division multiplexed systems. The future network requires low cost, small footprint, directly controllable amplification throughout the different application layers from long haul through to metro; the intrinsic size and integration capability advantages will ensure that the SOA plays a key role in this evolution. In multi-wavelength gating/amplification applications the gain dynamics, oscillating at timescales comparable to that of the data which is being amplified, introduce issues of pattern dependent waveform distortion (patterning) in single channel, and inter-channel cross-talk in multi-wavelength cases which require management through careful SOA design and understanding of the network application scenarios. In this paper, an optical linear amplifier (OLA) architecture with the unique capability to provide variable gain whilst maintaining linear operation at high output saturation powers will be described. Initial characterisation results for the OLA will be presented.

Keywords: semiconductor optical amplifiers, multi-wavelength amplification, linear optical amplifiers

1. Introduction

The Long Haul segment of the Telecomms infrastructure has for some years now been capable of transporting large amounts of data between cities, and today these networks can provide up to 160 channels each operating at 10Gbps over a single fibre. Recent advances in the bandwidth available in enterprise networks (e.g. 1G Ethernet and 10G Ethernet) has focussed attention on the data 'bottleneck', the Metropolitan Area (or Metro) Network which links the long haul segment with the end users (or enterprises).

Metro networks have to deliver multiple services at high capacity, over reasonable distances, with maximum flexibility, and at low cost. This has forced equipment vendors to manipulate wavelengths in bands of say 4 or 8 rather than individually, and to design static rather than dynamic systems. To enable the next generation of Metro Networks, a low cost, compact amplifier able to amplify several channels simultaneously without interference is required to implement more flexible and dynamic systems. The semiconductor optical amplifier (SOA) is a highly versatile component that can be deployed to meet these expanding applications. The intrinsic cost, size and integration capability advantages will ensure that the SOA plays a key role in future Metro networks both as a discrete component and in tandem with other passive/active optical components.

Central to wavelength banded transmissions is the need for an amplifier that provides a fixed gain independent of the number of wavelengths being amplified and also that the gain value can be changed to provide flexibility to the system architect. This can be achieved with proper management of signal power levels using linear modes of operation for SOAs. However this does restrict the dynamic range of operation and in certain circumstances it is desirable to have a linear operational range that extends into high output powers. This paper reports an optical linear amplifier (OLA) that has the unique capability to provide variable gain whilst maintaining linear operation over a wide dynamic range. The operation of the OLA and initial characterisation results will be presented.

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2. Semiconductor Optical Amplifiers (SOAs)

The SOA can be deployed in classical amplifier roles within in DWDM or CWDM scenarios as long as the signal levels fall within the linear regime. In this mode, it exhibits the characteristics of any linear amplifier permitting its use in a wide variety of network applications, for example as a receiver pre-amplifier, transmitter power booster and in multi-channel gating/amplification. It is well known that operating an SOA outside the linear region causes interference noise since at high output powers the gain saturates and compresses (Figure 1). The resulting gain modulation can cause interference noise in the time domain viz. inter-symbol interference or patterning, because the gain recovery time of an SOA is typically of the same order as the data modulation speeds. Similarly, gain modulation can cause interference noise in the frequency domain, specifically inter-channel cross-talk between different wavelength channels.

In order to ensure linear functionality, one of the key operating issues with conventional SOAs is the management of the input power levels so that the SOA is not driven into saturation. This is especially true in multi-wavelength applications where a band of channels are to be amplified, sharing the available output power. The gain of the SOA is controlled via the bias current. However reducing the bias current to lower the gain causes the saturation output power, and hence the linear region, to fall by a similar amount which in turn limits the dynamic range of the variation in gain. Figure 1 shows an SOA with a dynamic range of 10dB at –5dBm output power.

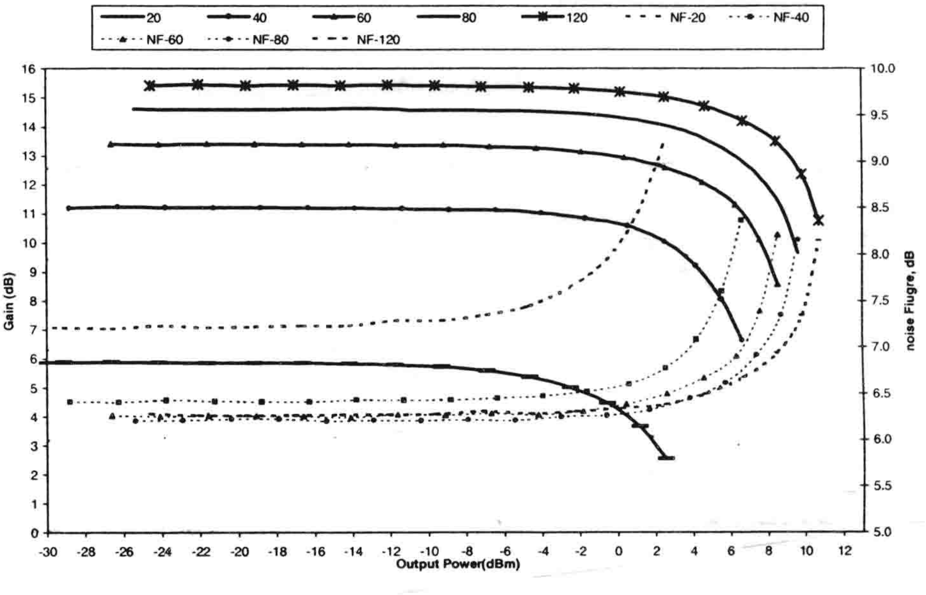
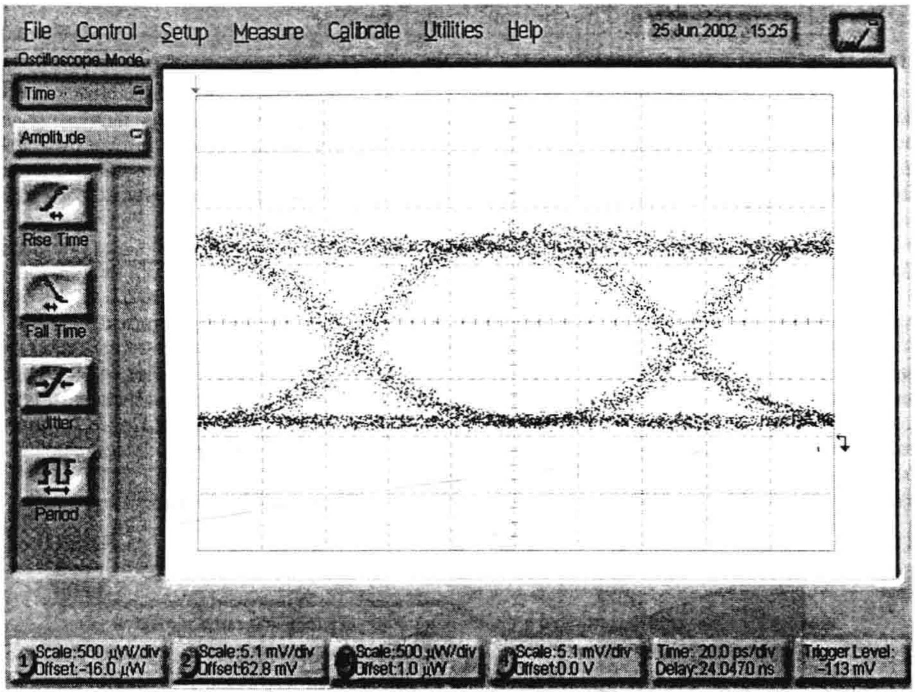


Fig. 1: Gain as a function of output power for an SOA

In certain network applications the power levels of each individual wavelength channel in a multiplexed signal are monitored throughout the optical path connection. Under theses circumstances, and as long as the input power levels of all channels is sufficiently low so that when amplified the total output power requirement falls within the linear region of the SOA characteristic, each channel will suffer virtually no cross-talk. As an example of this mode of operation, Figure 2 shows the output eye diagram for one channel (of four) of input power –20dBm after amplification in a conventional SOA with a gain of 13dB and output saturation power of +5dBm. This is a powerful route to bringing down the cost of amplification per wavelength channel, as the cost of a conventional SOA is shared over, in this case, four channels.



Scale:500 µW/div Offset:-16.0 µW

Scale:5.1 mV/div Offset:62.8 mV

Scale:500 µW/div Offset:1.0 µW

Scale:5.1 mV/div Offset:0.0 V

Time: 20.0 ps/div Delay:24.0470 ns

Trigger Level: -113 mV

Fig. 2: Output eye diagram for one wavelength channel from a band of four being amplified by an SOA.
Input power per channel –20 dBm, Gain 18dB.

3. Gain Clamped SOAs (GC-SOA)

If the network management overhead resulting from the above operating scenario proves significant, then other SOA designs based on gain clamping can be used to relax some of the operating constraints with respect to power management. In particular gain clamping allows the linear operating region of the SOA to be extended to higher output powers. Gain clamping is accomplished by causing the SOA to lase at a wavelength outside the desired signal band. This can be done using wavelength dependant reflectors before and after the SOA to form a laser cavity longitudinally along the signal path. This approach is an extension of existing SOA technology, allowing a range of gains to be implemented by design of the grating wavelength and strength. Alternatively, distributed Bragg reflectors can be made to form a laser cavity extending vertically, perpendicular to the signal propagation axis and the layered SOA structure.

In a gain clamped SOA, the lasing action in the cavity clamps the gain of the active material at the laser threshold, the clamped gain being imposed on the amplification of signals in the signal band. By clamping the gain at a level below the normal unclamped gain, the linear region is extended to the saturation output power which, for a given bias current, has a higher level at the lower, clamped gain than at the higher, unclamped gain, thereby reducing the gain modulation and interference noise. Gain clamping is therefore an approach which enhances SOA performance with respect to multi-wavelength amplification when contrasted to the use of a standard SOA but at the expense of flexibility (since the gain is fixed at a particular value), and cost (since these device structures are inherently more complex to manufacture in volume).

4. Variable-Gain GC-SOAs; The Optical Linear Amplifier

GC-SOAs provide a convenient means for amplifying low channel count bands of wavelengths, typically around 4 but may be extended to 8 and 16 depending on the output power per channel requirement. Gain clamping occurs at the expense of gain variability in that the gain is fixed at the point of manufacture. However there are many network application scenarios where it is desirable to provide a GC-SOA characteristic for which the level of the clamped gain is controllable. The Optical Linear Amplifier, OLA, has such features and thus maximises the saturated output power of the SOA while providing linear operational characteristics with amplification that can be tuned to the desired level (Figure 4).

The OLA architecture comprises two active (amplifier) regions defining a signal path passing through the signal SOA (SOA1) and a laser cavity containing SOA1 and a control SOA (SOA2), see Figure 3. SOA1 amplifies light in the signal path. The lasing mode derives gain from both SOA1 and SOA2. The composite gain provided by both SOAs and the cavity losses determines the condition for onset of lasing and hence the carrier concentration (gain) of the signal SOA. Hence by regulating the drive to SOA2, the gain imparted by SOA1 can be adjusted. SOA1 is therefore continually operated at full current and the OLA allows signals to be amplified by SOA1 at a clamped gain varied by SOA2, so maximising the saturation output power whilst maintaining an extended linear range. A number of laser cavity configurations may be harnessed in the implementation of the OLA, both in discrete or single chip formats.

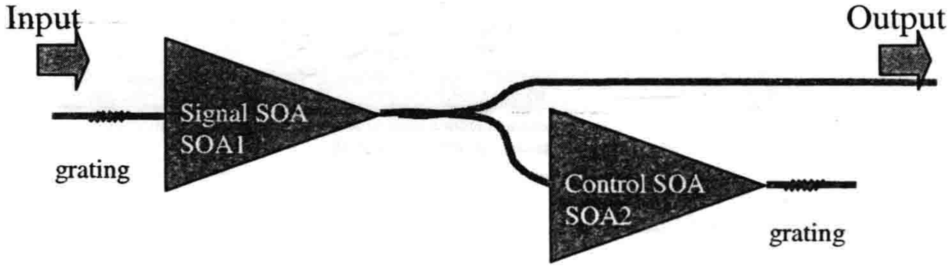


Fig. 3: Optical linear amplifier (OLA).

Figure 4 shows an experimental plot of the gain as a function of output power for an OLA at 1550nm. In comparison to Figure 1, it is clear that as the gain varies, the wide linear region of operation is maintained as well as a high output saturation power. It is also important to note that the OLA can attenuate as well as amplify whilst preserving the advantageous gain clamping characteristic. This is important for example, under network fault conditions where perhaps one channel is subjected to high gain (when all others in the multiplexed signal disappear) and consequently may damage receiver operation. A gain dynamic range of around 30dB with linear operation is routinely achievable.

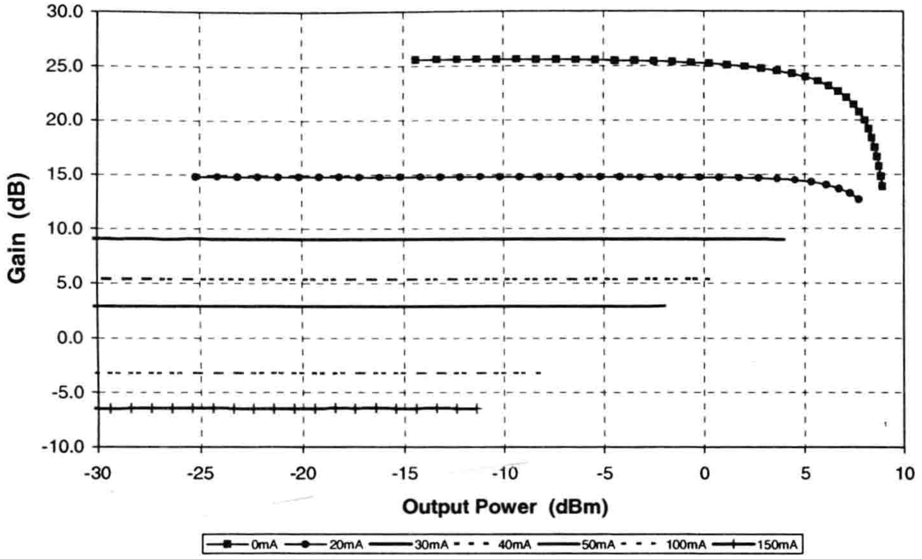


Fig. 4: Gain as a function of output power for an OLA for a range of different clamping currents.

One clear application for linear SOAs is in the gating and/or amplification of low channel count bands of wavelengths in dynamic optical add/drop or cross-connect nodes. In these wavelength routed, flexible networks dynamic power changes and the dropping and adding of wavelengths becomes routine. Competing amplifier technologies, most notably the erbium doped fibre amplifier (EDFA), exhibit gain transients since it normally operates in saturation. The timescales associated with the EDFA in gain saturation are very much longer and hence there are no significant issues of crosstalk with multi-wavelength operation in Gbit/s regimes. However relatively slow power changes, such as those encountered in the dropping of one or many channels in a multiplexed signal amplified by the EDFA, results in gain transients which requires extra components and hence cost to counter.

Figure 5 shows the performance of the OLA measured experimentally in order to determine the influence of marked power transients on its operation. One wavelength (data) channel is monitored whilst adjacent channels are switched on and off using an acousto-optic switch. The change in steady state gain with respect to input power level is plotted for the OLA and contrasted with an EDFA. The performance of the OLA is flat and indirectly, indicates the level of linearity afforded by the device.

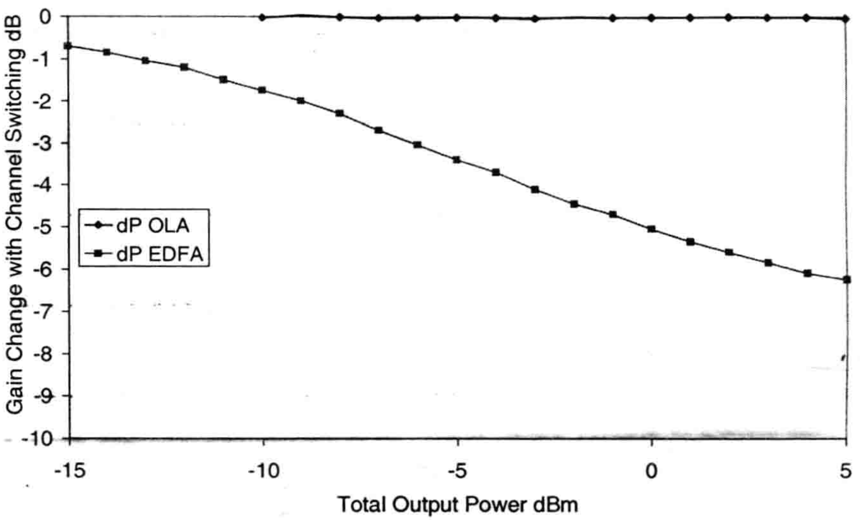


Fig. 5: The transient performance of an OLA and uncompensated EDFA

In multi-channel transmissions cross channel interference associated with non linear interactions must be minimised in order to maintain signal integrity. The extended linear operating range afforded by the OLA is key in this respect. Preliminary characterisation of the performance of the OLA with respect to Four Wave Mixing, FWM is shown in Figure 6 which shows FWM rejection ratio for the case where four signals are simultaneously amplified to provide a constant output power of either 0dBm per channel or –5 dBm per channel. Two traces representing the input power (per channel) against the FWM rejection ratio are shown. The FWM rejection ratio was estimated from the ratio of the amplitude of the largest mixing product to that of the lowest signal channel (there was a slight variation of around 1 dB across the band, principally due to unequal signal launch strengths). In all cases a high FWM rejection ratio was observed, in the case of the –5 dBm per channel output, the measurement was limited by OSNR..

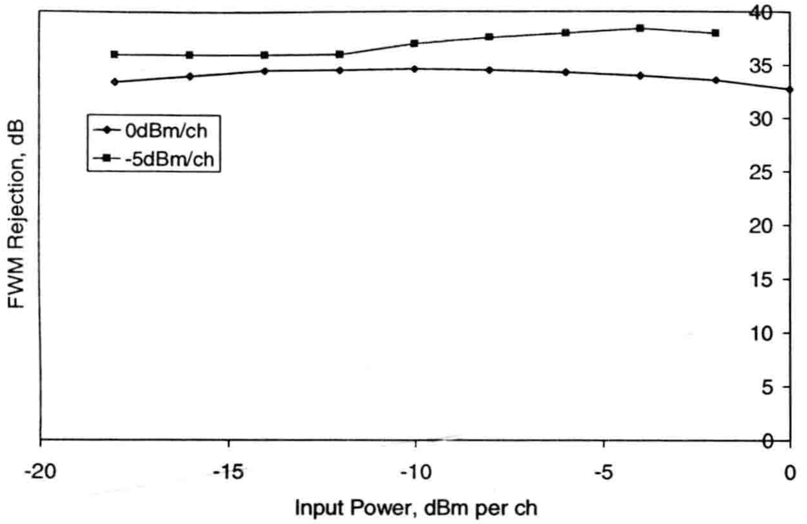


Fig. 6: Four Wave Mixing products as a function of channel input power

In all circumstances, the channel bit error rate is the key measurement of system integrity. Figure 7 displays the power penalty associated with multi channel transmission on one of the channels from a total of four (at 0dBm per channel) being amplified by the OLA has been measured. No significant power penalty was recorded compared to the back-to-back performance.

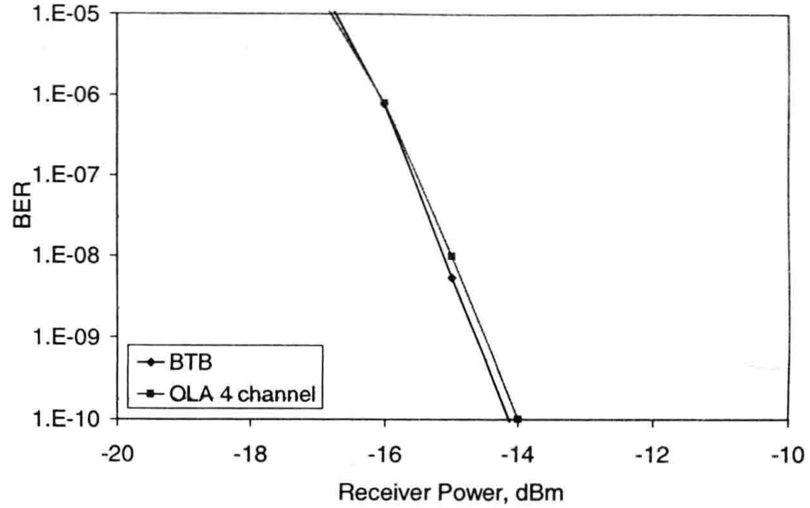


Fig. 7: Channel bit error rate for four signals (at 0dBm) being amplified by the OLA.

5. Conclusions

There is a growing need to increase loss budgets associated with Metro Networks, and the introduction of optical nodes which facilitate and promote dynamic wavelength routed networks. These nodes are complex at the optical level and in order to control costs, first generation implementations are focussing on geometries that rely on the manipulation and switching of low channel count bands of wavelengths. SOA's provide a low cost route to providing amplification in such scenario's. In addition, it is advantageous on many occasions to embed the amplification within the node to enhance integration levels which then translates into smaller footprint, more cost effective solutions. In this respect SOAs have a clear advantage over alternative solutions such as EDFA's.

The use of SOAs in multi-wavelength amplification applications requires linear operation. Dependent on the particular system design there are three routes to providing acceptable use of SOA in this roles;

- SOA; managing the power levels of the input multiplexed signal to ensure operation in the linear portion of the gain characteristic. A cost effective solution which has ramifications with respect to channel power monitoring.
- GC-SOA; providing an extended linear regime at a fixed gain. Higher output saturation powers are achieved but the gain is fixed, a significant restriction with respect to flexibility. A price premium results for increased output powers due to the added complexity of the SOA design.
- OLA; providing extended linear operation at high output saturation powers with variable gain. The most versatile alternative with an additional price premium for the flexibility it provides system architects.

This paper has summarised the data recorded from the first set of experimental characterisations of the OLA. The measurements have shown that variable linear gain is achievable up to the saturated output power of the signal SOA (in this case around 9 dBm). FWM measurements have been undertaken and these show that the OLA suffers minimal cross channel interference even up to high input powers. These measurements are supported with BER measurements on the OLA where multi-channel operation without significant power penalty has been demonstrated with 8 channels separated by 200 GHz and input amplitudes of up to 0 dBm.

Invited Paper

Linear optical amplifier and its applications in optical networks

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Genoa Corporation

ABSTRACT:

The Linear Optical Amplifier (LOA) is a chip-based amplifier that was developed to meet the optical amplifier requirements for emerging optical networks. The requirements include operating at wide range of bit rates and protocols, varying number of channels, as well as reduced cost and size. In this work, LOA performance characteristics are measured and its linearity characterized under both static and dynamic switching environments. The LOA performance is also shown in three key applications: transmitter boost, receiver pre-amplification, and in an in-line, cascaded metropolitan ring.

1. INTRODUCTION

Optical amplifiers, specifically Erbium doped fiber amplifiers (EDFAs), dramatically changed the economics of optical networking in the 1990s. This technology, coupled with DWDM, enabled the huge increase in network core capacity required by the emergence of the internet. As optical systems move closer to the end-user, optical amplification will continue to play a key role in enabling network capacity, flexibility and scalability. In long haul systems, the primary consideration in designing an optical system is performance. In designing metropolitan and access optical systems today, the primary considerations have become cost, size and power consumption. In the 1960's the electronics industry, much like the photonics industry today, faced the challenge of reducing the size, cost and power consumption of its products. The path the electronics industry selected was one of integration, shrinking systems onto a single chip, increasing the functionality of individual components as the way to meet its goals. The photonics industry must follow in the footsteps of the electronics industry and leverage the power of integration to reduce cost size and power consumption of components in order to meet the emerging, demanding requirements of system OEMs and service providers.

In order to effectively achieve significant levels of integration, many optical functions must be combined into a single package. In today's optical systems, every function in the optical layer creates loss except the optical amplifier. In addition, as signal processing migrates from the electronic layer to the optical layer, more gain will be required to offset the increased loss. For example, replacing fixed optical add drop multiplexers (OADMs) with reconfigurable OADMs in a simple four node optical network can increase the system loss by 25 to 30 dB. Without amplification, the amount of integration achievable is limited by the total amount of loss that can be tolerated at any one location in the network. To increase sub-system functionality, optical amplifiers must be integrated within optical modules after each significant loss element. An integratable, chip-based optical amplifier is necessary for integrated optical modules to their performance, size and cost goals.

Evolving optical networks will simultaneously transport data rates ranging from Kbps to multiple Gbps and utilize many types of protocols. Channel counts will range from one to dozens, and wavelengths will dynamically be added and dropped as networks are constantly reconfigured. To effectively operate in this environment, an optical amplifier must be able to handle any data rate, be protocol independent, operate in single channel and multi-channel environments and not create unwanted power transients regardless of real-time changes in the network.

Historically, chip based optical amplifiers such as semiconductor optical amplifiers (SOAs), have had problems such as crosstalk and limited output power, while erbium-based amplifiers create unwanted power transients during network reconfiguration.

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The linear optical amplifier (LOA) was developed to overcome these deficiencies and meets the emerging requirements for optical networks. The LOA overcomes both the intersymbol interference and WDM crosstalk of the SOAs, as well as the dynamic transient difficulties of EDFAs, while maintaining the required optical performance. In this paper we describe how the LOA works, and show for the first time its performance parameters as a function of power and wavelength. We also demonstrate the use of the amplifier in several key applications. Based on these results, we believe that the LOA is an amplifier with the performance, size and cost required for integration in the next generation of optical networks.

2. BACKGROUND: Non-linearities

2.1 ISI and WDM crosstalk

The SOA has been in existence for many years. It has some key attributes needed for next-generation networks: small size and cost, and the capability of being integrated with other functions in a single package. In addition, other technical hurdles such as polarization sensitivity have been resolved. Yet, with all of these positive attributes, it is not suitable for broad scale adoption in optical networks due to its non-linear performance at even moderate output power levels.

The non-linearity of the SOA is caused by dynamic gain variations due to gain saturation. In the SOA, the active region reacts rapidly to signal input conditions (nano-second reaction time); therefore, as the power through the semiconductor changes, the gain also changes. These dynamic gain changes show up as inter-symbol interference (ISI) in a single channel system, and as WDM crosstalk or cross-gain modulation (XGM) in multi-channel systems. The SOA dynamic gain changes are shown graphically in figure 1. These non-linearity issues must be resolved before semiconductor-based optical amplifiers are adopted broadly in optical systems [1].

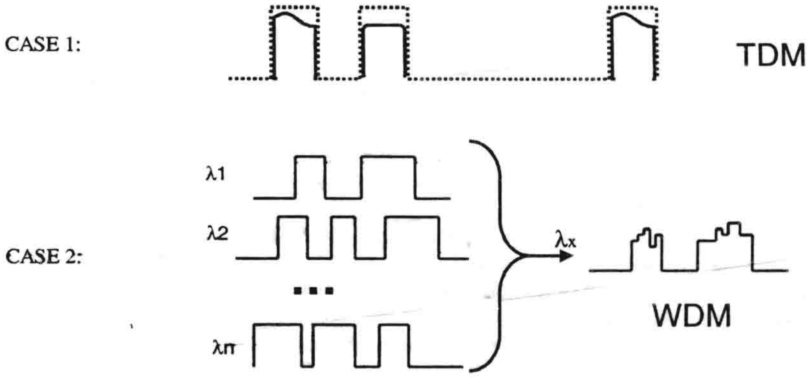

Fig. 1 An SOA's gain medium has the speed to react to individual bits. In Case 1, trailing bits see different gain than leading bits (inter-symbol interference or TDM crosstalk). In Case 2, the gain in one channel depends on other channels through the amplifier (WDM crosstalk).

2.2. Dynamic gain transients

Amplifier non-linearities in SOAs, as described in the previous section, are high speed non-linearities. Non-linearities are also seen at slow speeds (in the KHz range). These slow speed non-linearities are described as gain transients. Gain transients affect a system when it is switched or reconfigured dynamically. The slow "reaction" speed of the EDFA has allowed it to operate quite well in static, long haul optical links as it does not suffer from ISI or WDM crosstalk.