Optical Amplifiers for Modern Networks

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ABSTRACT

Recent trends in optical networks, such as Reconfigurable Optical Add Drop Multiplexing (ROADM) and optical cross connects, require advanced optical amplifiers based on both Erbium Doped Fibre Amplifiers (EDFAs) and Raman technology. To address the dynamic nature of modern networks, EDFAs should provide broadband variable gain operation, flexible mid-stage access, fast transient response to dynamic events, and advanced spectral monitoring and control to adjust to changing spectral conditions in the network. An important supplement to EDFA technology is the use of Distributed Raman Amplification (DRA) to achieve transmission over multi-span Ultra Long Haul (ULH) links in all optical networks, as well as very high loss repeaterless links.

Keywords: Optical Amplifiers, EDFAs, Distributed Raman Amplifiers, Optical Channel Monitoring, ROADM

1. INTRODUCTION

The rapid growth of IP traffic, which now dominates most service provider networks, has placed new demands on the optical layer of the network. The unpredictable nature of the traffic, coupled with the need to provide multiple broadband services at ever decreasing cost, has led service providers to demand flexible reconfigurable optical networks which are self-managed and can seamlessly adjust to dynamic traffic conditions. In the short to intermediate term, this demand has led to the widespread interest in and deployment of Reconfigurable Optical Add Drop Multiplexing (ROADM), which allows individual wavelength to be dynamically and remotely dropped or added at sites along an optical link. In the longer term, Optical Cross Connect (OxCs), also known as high degree nodes, will be required to create all-optical mesh networks where different wavelengths traverse different and diverse paths within a multi-point mesh network. Additionally, enhanced protection and restoration capabilities are required at the optical layer to support carrier class Ethernet and other advanced services.

Being key components in any optical network, optical amplifiers need to support these new requirements. In particular, they are required to support: Broadband operation over a large dynamic range with respect to input/output power and gain: Flexible mid-stage access for advanced optical modules such as ROADM devices, Wavelength Blockers (WBs) and Dynamic Gain Equalizers (DGEs); Fast transient response to sudden dynamic changes in input power; and Detection of and adjustment to changes in spectral composition of the input signal. In addition, amplifiers should have minimum Noise Figure (NF) in order to enhance system OSNR and enable transmission over longer distances without electronic regeneration. In this respect, the use of DRA in conjunction with conventional EDFAs is a key enabler for ULH transmission and other demanding applications.

2. ADVANCED EDFA MODULES

EDFAs have been widely deployed since the early 90's, with the basic technology and components now being both mature and well understood [1]. The basic EDFA design consists of a length of Erbium Doped Fibre (EDF), pumped by a 980nm pump laser diode. The addition of input and output isolators and detectors, together with an electronic control unit, represents a single stage amplifier module, as shown in Fig. 1a. Such a module is typically operated in Automatic Gain Control (AGC) or Automatic Output Power Control (APC), where the input and output detectors supply the required feedback to the control unit, which in turn controls the pump power.

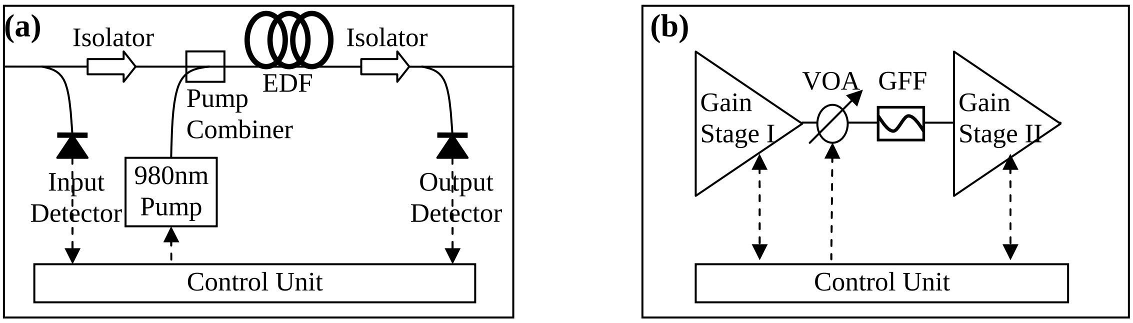

Figure 1. (a) Basic Single Stage Amplifier Module (b) Broadband Variable Gain EDFA

2.1 Broadband Variable Gain (VG) EDFAs

In order to support multi-channel dynamic reconfigurable WDM systems, optical amplifiers should provide large input and output power dynamic ranges, flat gain across the entire transmission band, and variable gain operation over a large dynamic gain range. The large power dynamic range is required to support stable operation for a single input channel up to full channel loading (about 80 channels at 50GHz spacing). Coupling this with the requirement to support a range of input and output powers per channel, broadband EDFAs should support an input and output power dynamic range of at least 30dB, with total saturated output power up to 23 dBm. Besides posing requirements on the input and output detectors and supporting electronics, this also means that the pump lasers should be able to operate over a large output power dynamic range (typically > 10dB), as well as supply total output power typically between 500 and 1000mW.

A large dynamic gain range serves two major purposes: On the one hand the same amplifier can be simply and remotely configured to support a wide range of spans with different losses, thus reducing inventory costs and simplifying installation and configuration. On the other hand, the amplifier can automatically be adjusted to account for changes in span loss due to reconfiguration of active device, for example, to perform adding or dropping of channels or protection and restoration switching. To achieve a large dynamic gain range the amplifier is typically designed to have flat gain at the top of the required gain range, using an appropriate Gain Flattening Filter (GFF), while a Variable Optical Attenuator (VOA) is used to operate the amplifier at lower gains [2]. This ensures that the amplifier exhibits flat gain over the entire gain range. However, placing the VOA at the amplifier input has an adverse affect on NF, and therefore it is necessary to place the VOA between two amplification stages, as shown in Fig. 1b. Note that the two gain stages shown in the figure may be pumped by separate pump lasers, or may use the same pump laser by splitting the pump power. The typical NF performance of a VG EDFA is shown in Fig. 2. As can be seen from the figure, placing the VOA between stages significantly reduces the NF for lower gain values, and using a stronger pump can further improve the NF performance.

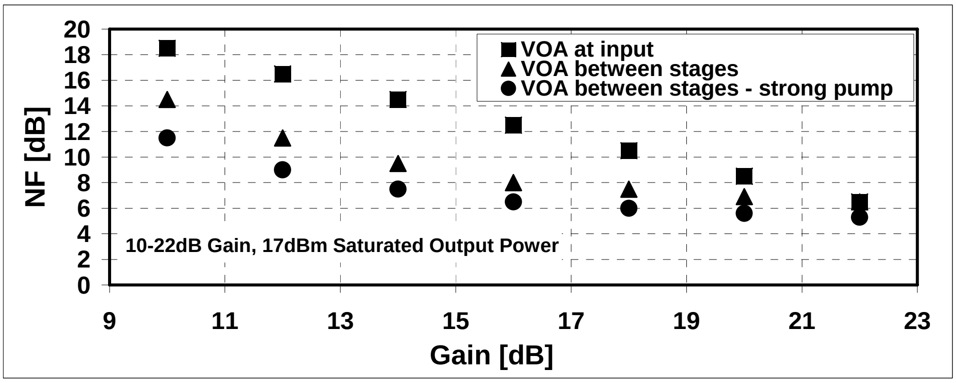

Figure 2. Example NF performance of a VG EDFA designed for 10-22 dB gain range

2.2 Dynamic Transient Control

When sudden input power changes occur in deeply saturated EDFA's, for example due to channel add/drop or protection and restoration switching, surviving channel may experience large gain transients. This issue was recognized early on in the development of EDFA technology [3], and it was later demonstrated that these gain transients may occur on a fast time scale (of microseconds), and be particularly problematic in links containing many amplifiers [4]. In order to suppress these transients, both feed-forward [3] and feed-back electronic gain control [5] have been employed. While feed-back gain control is necessary to maintain the gain at a steady-state value, it's response to fast and large changes in input power is not sufficiently rapid to suppress transient on a short time scale. To achieve this it is necessary also to employ feed-forward control to immediately detect a change in input power, and adjust the pump power accordingly even before the transient begins to develop. Thus, the feed-forward control supplies a rapid, relatively coarse initial response, while the feed-back control provides a slower and finer response. The use of digital control circuitry can further enhance the response by allowing one to fine-tune the pump power change profile in order to optimize the transient suppression.

Ideally, the transient control of an amplifier should deal with extreme events such as sudden drop of all but one channel, or sudden addition of many channels to a single pre-existing channel. As switching technologies progress and network dynamics become faster, these events as well as protection and restoration events will occur with microsecond time scales. This requires a sharp and large change in the amplifier operating conditions, and thus poses a challenge to the transient control mechanism. Fig. 3 shows example transient responses to 15 dB add/drop events, corresponding to add/drop of 31 channels. The Figure shows that the transient control is able to stabilize output power of the Pre-existing/Remaining channel within ~100μs, and suppress the transient overshoot/undershoot to less than 1dB relative to the initial output power. This high level of transient control is necessary to deal with the dynamic nature of modern reconfigurable optical networks.

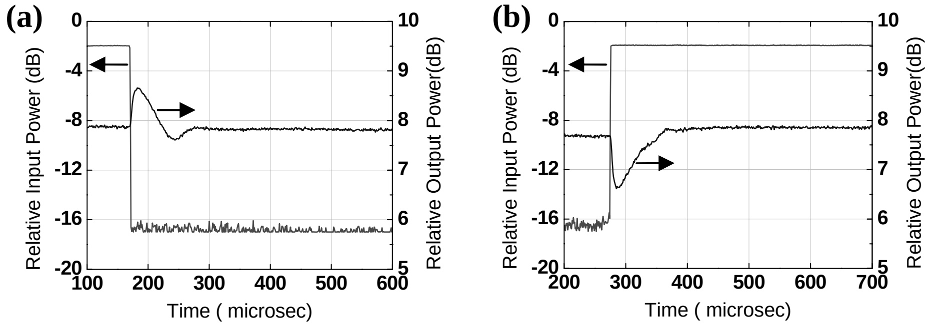

Figure 3. Transient response of an amplifier with 14-26 dB dynamic gain range and 20dBm saturated output power (a) Response of existing channel to 15dB Drop (b) Response of remaining channel to 15dB Add

2.3 Flexible Mid-Stage Access (MSA)

With the transition to 10Gb/s transmission rates in the late 90's, dispersion compensation has become a necessary requirement for optical networks [6]. To overcome the high insertion loss of Dispersion Compensating Modules (DCMs), initially as high as 10dB for every 80-100km of transmission fiber, additional optical amplification is required. The generally accepted solution is to use multi-stage EDFAs with Mid-Stage Access (MSA) for the DCM. Such EDFAs comprise a Pre-amplifier stage to amplify the input signal, followed by MSA for the DCM, then a Booster stage to re-amplifier the signal to the required output power. For VG EDFAs with MSA, the pre-amplifier itself typically comprises two sub-stages as in Fig. 1b, thus providing the VG functionality, whereas the booster comprises a single stage and is designed to operate at a fixed gain.

While recent advances in DCM technology have resulted in decreased insertion loss, typically less than 5dB for every 80-100km transmission fiber, modern optical networks also have to deal with the insertion loss of dynamic modules providing the reconfigurable functionality, such as WBs, ROADM modules and DGEs. Thus, modern EDFAs with MSA typically should provision up to 15 dB for mid-stage insertion loss. However, the dynamic modules not only require MSA with larger insertion loss provisioning, they also require a much more flexible design of the amplifiers themselves. To illustrate this point consider a ROADM device placed at mid-stage, such that channels are dynamically added and dropped between the two amplifier stages. For complete control for all added, dropped and pass-through channels, it is necessary that not only the pre-amplifier provide VG functionality, but the booster amplifier should provide such functionality as well. Ideally, both amplifier stages should operate independently of one another, and over a wide dynamic range of input and output powers, and gain values. In addition, each amplifier stage should provide independent state of the art transient control.

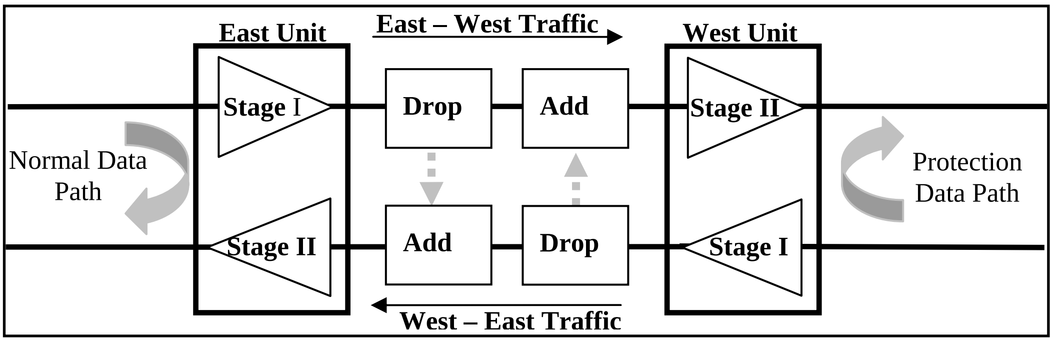

Figure 4. East/West separation for amplifiers with Add/Drop at MSA

An additional requirement for modern amplifiers with MSA is East/West separability, referring to the need to avoid a single point of failure when traffic is dropped and added at mid-stage. East/west separability requires that the booster and pre-amplifier of a given transmission direction not belong to the same physical unit, as illustrated in Fig. 4. In practice, this also means that the pre-amplifier and booster of an amplifier unit should operate independently, as just described, since they are not both part of the same transmission direction.

2.4 Optical Channel Monitoring

As the optical layer becomes more complex and intelligent, so the need for optical monitoring increases [7]. In previous point to point optical links, the optical power and ONSR levels were set at link design, and changed little (with the exception of aging effects) during the lifetime of the system. In modern reconfigurable multipoint systems, with constantly changing conditions, it is highly desirable to be able to monitor the power and OSNR of each channel at all sites along the link. A particularly efficient, cost-effective, and space saving method for achieving this is to embed an Optical Channel Monitor (OCM) within each amplifier along the link. This also allows the amplifier to make direct use of the information provided by the OCM, thus providing enhanced functionality that wouldn't otherwise be possible. Example applications include: Self-setting of amplifier gain and gain tilt to achieve a required output power per channel: Optimizing performance according to the spectral loading at amplifier input; And automatic start-up and shut-down based on direct detection of existence or non-existence of transmission channels (as opposed to loss of total input power). In addition to enhanced functionality of the amplifier itself, an embedded OCM can also provide spectral feed-back to dynamic devices deployed at amplifier mid-stage, such as ROADM modules, DGE's and WB's.

OCMs can be implemented using either diffraction gratings combined with detector arrays, or a scanning tunable filter combined with a single detector. The former is generally considered more reliable and can provide a faster update rate, while the latter provides more flexibility, requires less space, and is more cost-effective. Since space and cost requirement are major factors when integrating an OCM within an amplifier, a tunable filter based OCM appears to be the optimal choice. However, due to the space limitation, it is not feasible to include a separate wavelength referencing element to calibrate the wavelength measurement of the OCM. To address this issue the tunable filter should be inherently reliable, ideally without moving parts or based on MEMs technology. In addition, it is possible to implement a sharp well defined feature (notch) in the GFF, such that the ASE generated by the amplifier has a sharp spectral signature outside the transmission band. This spectral signature can be used to provide wavelength calibration for an embedded tunable filter based OCM.

3. DISTRIBUTED RAMAN AMPLIFICATION (DRA)

In recent years DRA has emerged as an important technology for modern optical networks [8], typically used to supplement EDFA technology for demanding applications where OSNR is a limiting factor. Three such applications are: Long repeaterless links, typically 150-350km, where DRA at the terminal sites negates the need for in-line EDFAs; Multi-span links where some of the spans are longer than normal (i.e. 100-150 km) and can be managed using DRA; and ULH links requiring DRA on all spans to allow longer link length and/or higher link capacity. The latter application is particularly important for next generation all-optical mesh networks, where signals may be required to traverse long distances from one point of the mesh to another. In addition, the increased OSNR budget provided by DRA allows greater network flexibility and reconfigurability, including higher channel capacity, the ability to transmit 40Gb/s channels, and greater distance between repeaters.

4. CONCLUSIONS

Dynamic reconfigurable optical networks require advanced EDFA modules with large dynamic power and gain ranges, flexible mid-stage access, high level transient control, and spectral monitoring. For particularly demanding applications, DRA can be used in conjunction with EDFA's to provide critical OSNR enhancement.

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