OPTICAL AMPLIFIER IN COMMUNICATION NETWORKS. CURRENT APPLICATIONS AND PERSPECTIVES

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Abstract: Optical amplifiers may be considered one of the most significant innovation in the field of optical communication technologies, as they will allow to overcome in principle several current bottlenecks in the evolution of optical networks. In this paper, basic aspects of optical amplifier operation will be reviewed, and their use in different network applications will be discussed.[1]

Optični ojačevalnik v komunikacijskih omrežjih. Uporaba in bodočnost

Ključne besede: omrežja komunikacijska, omrežja optična, tehnologije optične, ojačevalnik optični, osnove, stanje razvoja, aplikacije praktične, EDFA ojačevalniki, SOA ojačevalniki

Povzetek: Optični ojačevalniki so ena najbolj pomembnih inovacij na področju optičnih komunikacijskih tehnologij, saj bodo v principu omogočili premagovanje nekaj ozkih grl pri razvoju optičnih omrežij. V tem prispevku smo opisali osnovne principe delovanja optičnih ojačevalnikov, kakor tudi njihovo praktično uporabo v različnih komunikacijskih omrežjih.

1. INTRODUCTION

After more than 20 years of continuous progress, optical fibre transmission systems have become the dominant technology for telecommunication networks. At present, more than 50% of long haul traffic in high developed industrial countries is routed through optical cables; the overall volume of optical fibres already installed worldwide is approximately 50 million-km.

In spite of the fact that optical communications can be considered a well established and mature technology, a strong evolution is still taking place both as regards new devices development and proposals for new system concepts; the reason is that, for the time being, only Long Distance Transmission, among the main sectors of a communication network, has been fully involved in taking advantage from optical technology; while the others (Switching and Customer Access) still remain quite far from achieving similar results, and strong interest exists to bridge this gap.

Extending the penetration of optical technologies to switching functions and access systems may in fact trigger a potential revolution in the network performance and effectiveness, resulting from a very high increase in data throughput and from an overall optical compatibility. In particular, penetration of optical fibres in the local loop will create access for everybody to a cost-effective almost unlimited bandwidth.

The ultimate objective of a fully optical network cannot be considered of course within easy reach of currently available technologies: optical switching, for instance, still requires some fundamental advance in optical processing to become a practical opportunity. Other constraints, not less important than technical problems, are limiting the growth of optical technologies in the access network, as cost, market competitions, lack of international standards, and it is beyond the scope of this paper to discuss these aspects in more detail.

Even if the progress route may be still very long, the development of the optical amplifier can be considered a major milestone along this route, similar in nature to other fundamental breakthrough, like the CW operation of the semiconductor laser and the development of a low loss optical fibre, at the beginning of years '70. The use of the Erbium-Doped-Fibre-Amplifier (EDFA) high gain and low noise properties result in a dramatic improvement in performances of optical links; but in addition the optical amplification principle makes possible to forecast

[1]This paper is the first of a series, which will be presented on MIDEM during 1994, concerning advanced topics in optical technologies and systems. The next contribution will deal with optical interconnections and integrated optics, and the last one will discuss a specific application to multiwavelength transport networks

the practical implementation of a number of optical network architectures, which were considered until now only in terms of theoretical or laboratory feasibility.

In the following, operating characteristics, design criteria and different applications for optical amplifiers will be reviewed.

2. OPTICAL AMPLIFIER CHARACTERISTICS

Optical gain in an inverted population medium is a well-known process; when the gain is controlled by the optical feedback of a resonant cavity, a laser oscillation sets up; when the feedback mechanism is suppressed, the active medium is able to amplify an incoming optical signal. The amplification process depends on several parameters: the spectral gain profile, the optical signal wavelength, the structure and relaxation time of excited levels in the active material and the excitation mechanism for the population inversion.

The structure of a very high power laser (in nuclear fusion research, for instance) is based actually on a master laser oscillator and a cascade of several bulk amplifier stages, which are able to reach optical pulse power in excess of GWatts.

The optical amplifier for communication applications is based on the same principles, but includes a specific important feature, which makes possible to control very precisely the amplification parameters like gain and noise with high overall efficiency. This result has been obtained by using a dielectric waveguide for optical confinement of the active medium. In particular the waveguide can be realised by an optical fibre or by the active region of a semiconductor laser. The optical confinement in the core region of the waveguide is very effective in allowing a high degree of control in the design parameters of the amplifier, like the active material volume, the overall gain, the coupling of the excitation pump. Moreover, the nearly ideal matching of the active fibre with the fibre used in the communication network makes almost straightforward the add-on of this new device into the existing equipment.

The careful optimisation and matching of these parameters, which has been the subject of an intense development activity in the past 5 years /1/ /2/, has given finally to the communication engineers the real opportunity to achieve, for the first time, the control of the optical carrier in the electromagnetic regime, without being obliged to step back and forth to the low frequency scalar components of the field (voltage and current) for signal amplification purposes. This is the real meaning of the conceptual innovation introduced by the guided optical amplifier, which opens the way to implement a wide range of new data processing methods in the optical domain.

To discuss the amplifier characteristics in more detail let focus on the fibre structure first.

2.1 Fibre amplifier

The structure of an Optical Fibre Amplifier (OFA, Fig. 1) is very simple in principle; it includes a short length (a few meters) of active fibre, a wavelength division multiplexer to couple into the active fibre the signal optical carrier and the pump intensity, an optical isolator on the output port, in order to avoid any parasitic light reflection which may cause spurious laser oscillation in the active medium and a pump source; due to the high gain available, isolation in the range of 50 ÷ 60 dB is usually required, and therefore the isolator is quite critical for a correct operation of the amplifier.

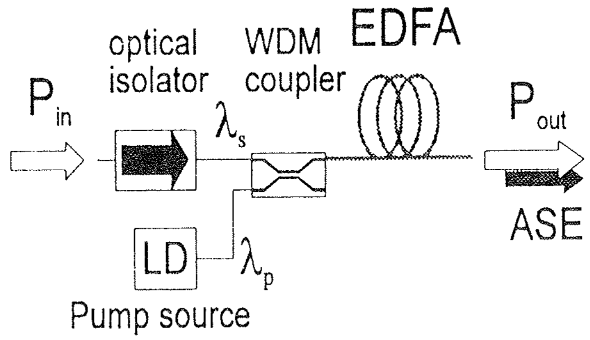

Fig. 1: Optical fibre amplifier: schematic block diagram

Let discuss in some detail the OFA components:

– active fibre

The principle of using a guided structure for increasing the efficiency of the optical gain in an inverted medium is indeed very old. As early as in 1963 /3/, for instance, well before the introduction of fibres for communication purposes, a Nd doped fibre was realised to demonstrate the possibility of high optical gain at λ = 1060 nm.

At present, two wavelength bands are considered for optical amplifiers, at λ = 1300 and 1550 nm; a number of so called Rare Earth Elements in the Periodic Table can have the appropriate electronic levels structure to allow for stimulated emission at the required wavelengths: most popular examples are Praseodymium for the 1300 nm band and Erbium for the 1550 nm band. Efficient doping with Er has been achieved in silica-based fibre /4/, while fluoride glasses /5/, of the so called ZBLAN family, have been investigated for Praseodymium doping. Optical amplifiers with Erbium doped fibres have become available commercially since 1991, while Praseodymium doped fibres still remain at the stage of a research product. Only very recently (at the Optical Fibre Communications Conference, February 1994) Hewlett-Packard has announced the first commercial amplifier for the 1300 nm optical band. In the following discussion only Erbium doped amplifiers will be considered.

Even for the relatively well known Erbium Doped Fibre Amplifier (EDFA), quite a work for optimisation of fibre material characteristics and structure is currently under way; the objectives of this work are the increase of the saturated power and saturated gain, a wider and flat spectral gain profile and a better pump efficiency. Methods to achieve these results may involve the use of co-dopants, like Al and Yb, to increase the spectral bandwidth and the pump energy transfer, an increase of the fibre Numerical Aperture and a reduction of the core diameter in order to increase the power density along the signal path. Process technology still needs definite improvements to control these effects (In particular co-doping), in order to satisfy design specifications and achieve a good level of reproducibility .

– WDM coupler

To couple into the active fibre the pump power, a wavelength sensitive coupler is required to achieve a minimum signal loss at λ_{sig} , and a maximum power transfer at the pump wavelength. In the most widely used configuration, the coupler is based on the directional coupler principle /6/; two fibres are fused together and pulled apart in order to bring in a close proximity the fibre cores for a well defined coupling length. A coupled mode propagation regime takes place, which causes a periodic power transfer back and forth between the fused fibres. As the transfer period (beat length) depends on the wavelength, it is usually possible to find a coupling length at which the required power transfer takes place with defined transfer ratio for two selected wavelengths.

Very good and reproducible results are usually obtained by a real time monitoring of the power transfer at the specific wavelengths during the fibre fusion process. The fused fibre Wavelength Division Multiplexer is a simple, reliable and inexpensive solution, fully adequate for 1550 nm EDFA amplifiers operating with 980 nm pump wavelength, with insertion loss of the order of 0,2 dB and extinction ratio better than 20 dB. Less satisfactory performance is available for operation with 1480 nm pump, rather close to the signal wavelength: in this case, to achieve the required extinction ratio a cascade of two or more identical WDMs may be necessary.

– optical isolator

Optical isolation is increasingly important in many fiber applications, as laser sources may show instabilities and intensity noise, if even a negligible fraction of the optical power is reflected back into the laser optical resonator. To avoid these parasitic effects, optical isolators are needed with an isolation ratio ranging from 30 to 60 dB.

The Faraday rotation (e. g. the non reciprocal rotation of the polarisation plane when the light propagates through certain crystals placed in a magnetic field, with the Poynting vector aligned to the field) is the effect on which most of optical isolators are based. The isolator basic structure includes at the input port a linear polariser, a Faraday rotator which rotates the polarisation plane by 45° and an output polariser aligned with this direction; any reflected light will be polarised at 90° with respect to the input polariser and not transmitted. The actual structure of an optical isolator is much more complex, in order to compensate for the dependence on temperature, wavelength and input light polarisation state. Other critical parameters are the extinction ratio of the polariser, the Verdet constant of the material for the Faraday rotator and finally the permanent magnet for the magnetic field. Therefore, a good isolator still remains quite an expensive component, and its cost account for a sizeable part of the full cost of the amplifier.

– pump sources

High power laser diodes are used as pump sources for optical amplifiers. Pump wavelengths can be chosen at 800, 980 and 1480 nm for the Er doped amplifier. Initially the 1480 pump wavelength was preferred because laser diode reliability was better assessed for the already developed InGaAsP/InP heterostructure system. Better performance may be achieved with pumping at 980 nm, as far as noise figure and efficiency are concerned /7/; moreover, 980 nm InGaAs/GaAs quantum well strained-lattice laser diodes with output power in excess of 250 mW are becoming available with increasing confidence about their reliability. Both 980 and 1480 nm pump wavelength are still used with increasing interest for the 980 nm operation.

At present, the choice of a specific pump wavelength imposes a number of compromises on other parameters of amplifier components (for instance, on the WDM coupler and on the fundamental mode cut-off of the active fibre and related bend losses), and a comprehensive evaluation of the best compromise is still under investigation.

2.2 Semiconductor optical amplifier

The Semiconductor Optical Amplifier (SOA, Fig. 2) is a basically different device with respect to the OFA, both in terms of its fabrication technology, and for its rather long term application potential.

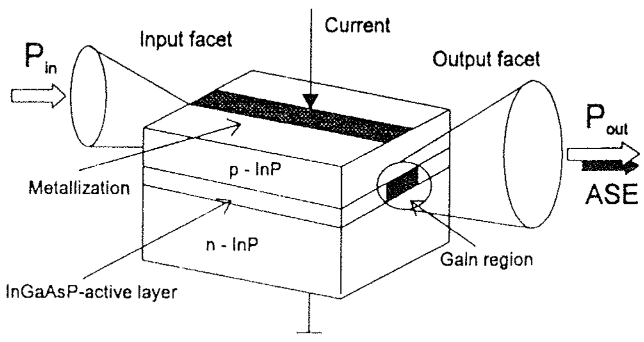

Fig. 2: Semiconductor optical amplifier: schematic block diagram

In practice, a semiconductor optical amplifier is basically built with the same technology required for a semiconductor laser, with one non trivial addendum: the need for a full suppression of the optical cavity feedback, which may be obtained by an efficient AR coating and by a tilting of the cavity axis with respect to the mirror facets. At present the SOA can not be considered as a practical alternative to the fibre amplifier, due to several disadvantages in its operation: among them the gain sensitivity to the polarisation of the input signal, the ripple in the spectral gain profile due to the residual reflectivity of the chip mirrors, which still can not be controlled to the required extent, and the high insertion losses due to the fibre pig-tailing, which negatively affects the amplifier noise figure. Moreover, the SOA may be affected by cross-talk effects from different wavelength channels and in the case of high speed modulation data transmission, due to the very short (1 ns) carrier lifetime. (In the case of the OFA, the equivalent parameter is of the order of several ms). A comparison between the two devices' characteristics is reported in the following table (Tab.1):

	SOA	EDFA	
GAIN	> 30 dB	> 40 dB	
PUMP EFFICIENCY	> 0,5 dB/mA	10 dB/mW	@ 980 nm
		5 dB/mW	@ 1480 nm
EXCITED STATE LIFETIME	1 ns	10 ms	
WAVELENGTH RANGE	700 - 1600 nm	1520 - 1580 nm	
INSERTION LOSS	5 - 6 dB	0,5 dB	
OPTICAL BANDWIDTH	> 40 nm	> 20 nm	
NOISE FIGURE	5 - 6 dB	3 dB	@ 980 nm
		6 dB	@ 1480 nm
SATURATION POWER	> 10 dBm	> 27 dBm	
POLARISATION SENSITIVITY	YES	NO	
CROSS-TALK SENSITIVITY	YES	NO	
OEIC CAPABILITY	YES	NO	

Tab. 1 - Performances of Semiconductor Optical Amplifier and Erbium Doped Fibre Amplifier

Perhaps, the most interesting potential feature of the SOA is its full integration compatibility with a monolithic Opto Electronic Integrated Circuit (OEIC); even if this potential could only be exploited in the long term, the possibility of optical signals amplification is a necessary condition for considering photonic circuits a feasible target. Other interesting intrinsic features of the SOA are the high speed direct current modulation capability (which may be used for optical signal processing), the wide band (0,5 GHz) photodetection capability, which may be used to sample the data of the optical carrier being amplified. By using a diffraction grating on the active region (like in a DFB laser structure) a narrow band active optical filter can be also implemented.

Feasibility of all these features has been already experimentally demonstrated and offers a wide range of interesting opportunities in the future development of advanced optoelectronic components and system, not only for telecommunication applications, but also for optical sensors and measurement's techniques. More details on SOAs can be found in /8/.

2.3 Operating characteristics and noise properties

One of the distinct advantages of optical amplifiers is their full transparency to the optical carrier modulation format, and the possibility to operate in a multiwavelength environment (Fig. 3). This flexibility is a key factor for understanding the impressive growth of commercial applications, in a very short time with respect to the R&D results. In fact, the EDFA is suitable for immediate upgrading of an existing optical communication link, and can easily accommodate future upgrading of the link as far as bit rate or data format are concerned. These are

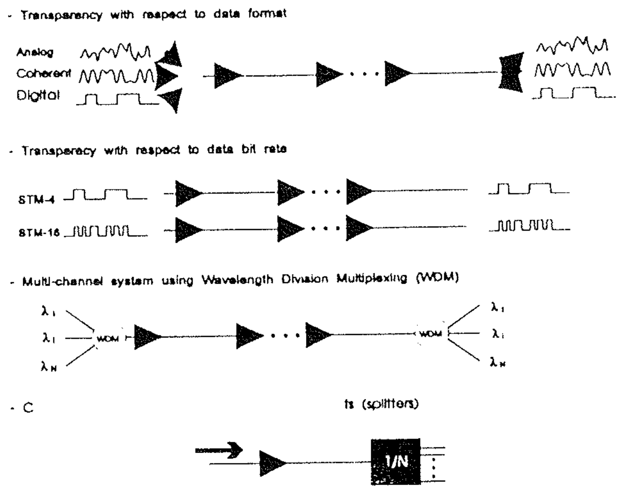

Fig. 3: Some peculiar characteristics of optical amplifier

valuable assets for Telecommunication Operators, that are always very conservative about any innovation that may cause a premature obsolescence of the huge investments already made in a network.

The EDFA can be designed for several specific functions in an optical link. It can be used as a booster on the transmitter side, to achieve high fibre input power, not available by standard semiconductor laser sources, as high gain preamplifier in front of a PIN photodetector on the receiver side, or as a line repeater. The noise figure is the relevant parameter that set a limit to the amplifier performance, at least as optical preamplifier or as line repeater.

Factors affecting the noise figure of an optical amplifier are due to the spontaneous emission, to the population inversion mechanism and to the signal losses (for coupling, residual reflectivity, absorption and scattering in the active medium). In particular, the amplified spontaneous emission (ASE), due to its wide spectral bandwidth, is causing a beat-noise in the optical detection process, due both to the signal-ASE beat and ASE- ASE beat, which set a fundamental limit of 3 dB for the noise figure of the amplifier /9/.

The noise figure (NF) is defined as the ratio between the amplifier input and output signal to noise (SNR) ratio, and is always greater than unity; in the limit of large amplified signals, NF can be written /10/ as

$$NF = \frac{2\,N(\nu_s) + |\eta_C \eta_D \eta_F(\nu_s)|^{-1}}{G(\nu_s)}$$

where η_C, η_D and η_F are the fibre-detector coupling efficiency, the detector quantum efficiency and the transmission (at ν_s) of an optical filter placed in front of the detector to limit the ASE spectral bandwidth; G is the EDFA gain and N the ASE noise, that can be written as a function of the spontaneous emission

$$N(\nu_s) = n_{sp}(\nu_s)\,(G(\nu_s) - 1)$$

where the spontaneous emission factor n_{sp} can have different expressions depending on the excitation mechanism, but it is unity when a full population inversion is achieved.

In ideal conditions for the detection process (η_C, η_D and $\eta_F = 1$), and in the high gain regime (G >> 1), from the above expressions results $NF \approx 2n_{sp}$; therefore, as much as full population inversion is achieved, as in the case of 980 nm pumping, the noise figure is near its limit of 3 dB. The simple concepts outlined here are very useful as practical amplifier's design rules for specific applications.

3. TECHNOLOGY AND DESIGN

A fiber optic amplifier can be designed with different criteria depending on the specific application. For digital communications saturated power is the main parameter for a booster amplifier, while small signal gain and noise figure are most important for a preamplifier and all these characteristics are relevant for a device used as line amplifier. Polarization sensitivity and polarization mode dispersion (PMD) shall also be considered, specially for analog applications, where distortion becomes the limiting factor. Gain equalization across the optical spectrum is evidently of primary importance for multiwavelength applications.

Some of these characteristics, as for example gain equalization, depend on the intrinsic properties of the active fiber. In aluminosilicate fibers for instance, due to homogeneous line broadening, the saturation spectrum is substantially broader and flatter than in other kinds of fibers /11/.

Amplifier's different architectures essentially reflect different pumping schemes (Fig. 4). Co-propagating pumping gives the best performances in terms of noise figure, as gain is higher in the first portion of the active medium, while counter-propagating and bidirectional pumping provide higher output power. With counter-propagating pumping moreover, especially in the case of 1480 nm pump wavelength, the residual pump power does not need to be filtered out from the signal line.

More sophisticated architectures can also be implemented: as an example, cascading of two stages with diffe-

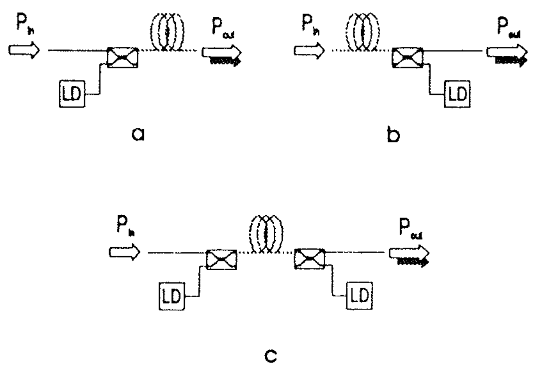

*Fig. 4: Pumping schemes for EDFAs.
a) co-propagating; b) counter-propagating;
c) bidirectional*

rent gain and insertion of filters and optical isolators within the amplifying stages allow for shaping of the gain spectrum and provide improvement to the noise figure.

There are some technological limiting factors to the performances attainable from fiber optic amplifiers to date. For instance, even though it is possible in principle to increase the saturated power by cascading several amplifying stages, reliability assessments require to limit the number of pump sources, which are the most critical components from this point of view. With the most widely used pumping techniques, based on single mode laser diode sources which can provide about 150 mW from the chip at most, this sets a limit of 15-17 dBm to the power attainable from an amplifier. Losses in efficiency are caused essentially by the pigtailing of the laser with the fiber, with almost 50% coupling loss, by the intrinsic fiber efficiency (around 50% with the most recently developed active fibers) and by the insertion losses of passive components like couplers and isolators.

For high power amplifiers, a cladding pumping technique has been recently developed /12/. The radiation from the pump source is injected into a large diameter

(50 μm or more) guiding cladding sorrounding the active core. In this way high power (half watt or more) laser sources can be used.

To increase the absorption of pump radiation, Ytterbium-Erbium codoping has also been developed /13/. Ytterbium ions show a strong absorption band around 980 nm, more than 100 nm wide and excitation in this band is followed in phosphate glasses by efficient energy transfer to the resonant level of Erbium ions. The Erbium absorption cross section is therefore substituted by an effective cross section proportional to the ratio of Ytterbium to Erbium concentrations.

This mechanism is not effective in pure silica or aluminosilicate glasses, therefore a compromise between spectral characteristics and power shall be accepted. In addition the broad absorption spectrum allows for less stringent requirements on pump wavelength stability.

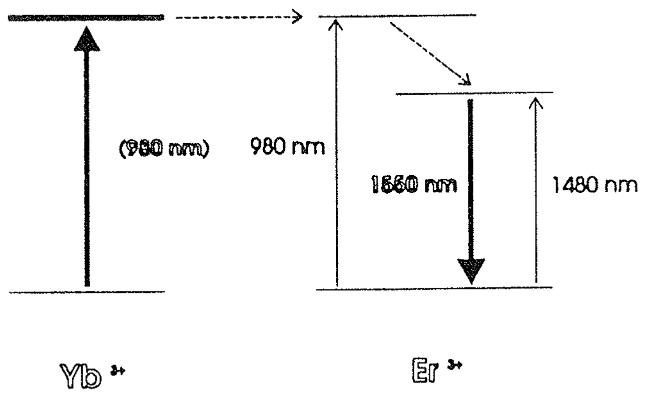

Fig. 5: Sensitization by Ytterbium-Erbium co-doping

4. APPLICATIONS AND TRENDS

4.1 Long haul

A few application schemes for long haul communication networks are illustrated in Fig. 6. Application of the EDFA to end functions (booster or optical preamplifier, Fig. 6b), in a point to point link, does not change the system design criteria. Only the use of the EDFA in a multi-repeater network application (Fig. 6d,f) affects the fundamental system characteristics and design rules. In a conventional (3R) electronic repeater technique, reshaping, retiming and regeneration functions are necessary which strictly depends on modulation formats and bit-rate. The 1R (Reshaping with available bandwidth up to 15 GHz) characteristics of the optical repeater make possible the direct handling of a full range of signals, with some care (optical band pass filters) to avoid the accumulation of ASE noise and saturation effects in a cascade of line repeater. In fact the noise figure optimisation may become the critical parameter for optical line repeater design, since for this application, both low noise and high output power capabilities are required. Other important system design aspects concern the position of the repeater along the link, which should be selected according to the best compromise between linear and saturation regime, in order to take the best advantage from the available NF of the amplifier. In the following table (Tab. 2) are reported results of a few experiments on long distance transmission with optical repeaters.

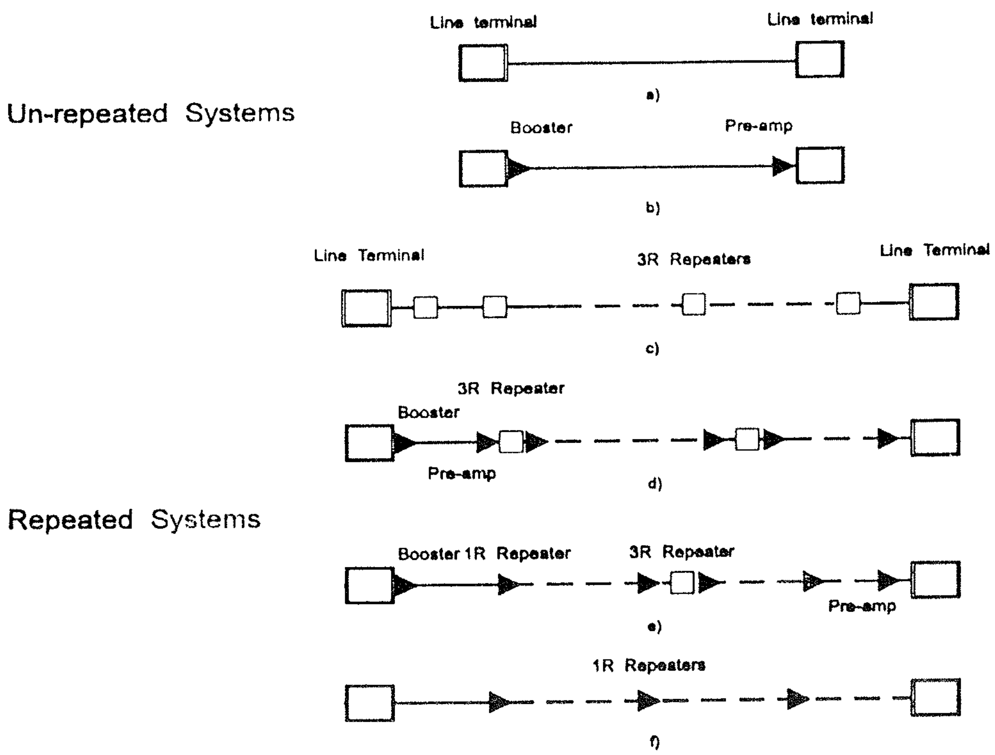

Fig. 6: Examples of application of OFAs in long haul links

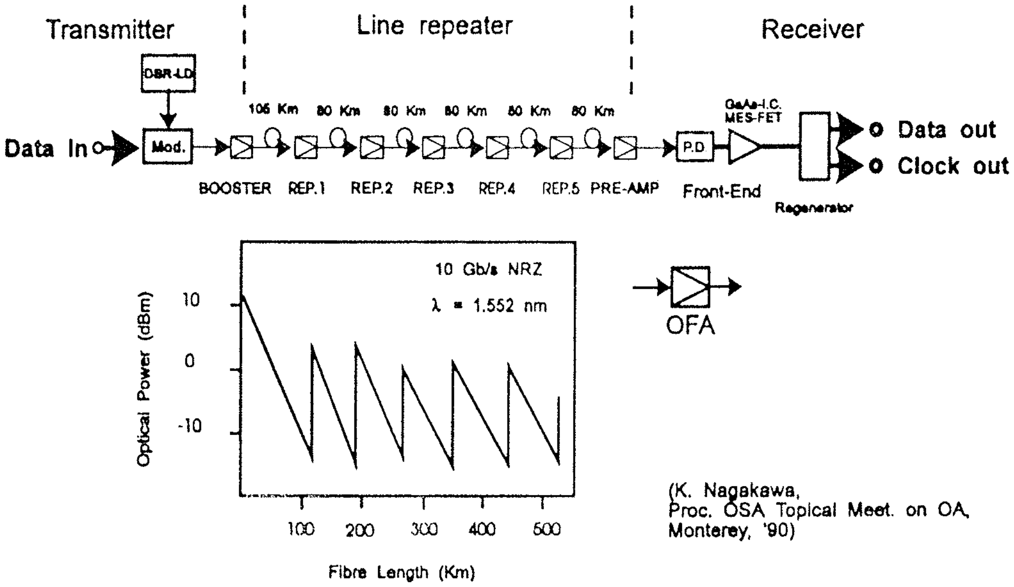

Fig. 7: *Example of application of OFAs in a multi-repeater system operating at 10 GBit/s*

Bit Rate (Gbit/s)	Link length (km)	N. Repeaters	Laboratory
2,5	1316	26	ALCATEL
2,5	2500	24	NTT
2,5	4500	48	NTT
5	14300	4*116 (loop)	AT & T
10	1500	22	KDD

Tab. 2 - Transmission experiments with optical repeaters

A typical layout for a multi-repeater system is presented in Fig. 7, with total link span of 505 km and 5 intermediate repeaters 80 km spaced /14/. The most likely candidates for commercial applications of optical repeaters are the undersea communications: two sub-marine links equipped with EDFA both in the Atlantic (TAT-12) and Pacific (TPC-5CN) oceans, are already planned in 1995-96.

4.2 Distribution network

Characteristic topology of a distribution network is based on a point to multipoint architectures, which are schematically shown in Fig. 8. In many cases this implies that the signal power is splitted during transmission and distributed to each receiver. Therefore the available optical power is the factor which limits the maximum number of subscribers.

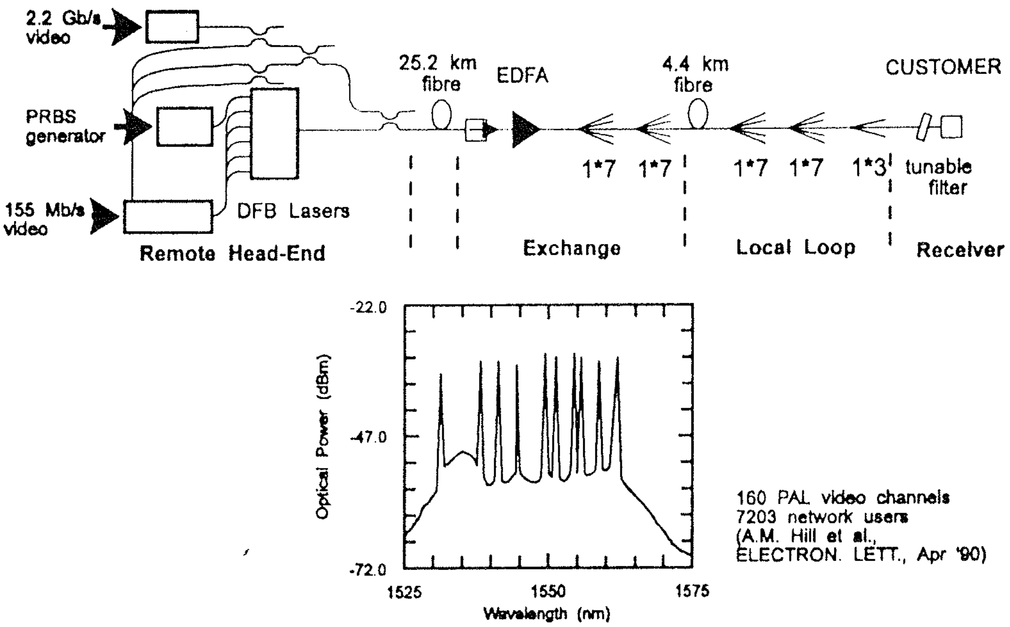

Fig. 8: *Example of application of OFAs in a broadband distribution network*

The high power EDFA is the natural solution to remove this limit; in principle, a 20 dB gain amplifier can increase the number of subscriber by a factor of 100, and it can be applied many times in the network when required. The low harmonic distortion and cross-modulation distortion characteristics of the EDFA are also very interesting for multiwavelength and multichannel transmission formats, which would be implemented in the future broadband distribution network. The combination of WDM techniques and multistage optical amplification has been already demonstrated /15/ potentially suitable for distributing more than 600 TV channels to more than 40 million users. Even if practical implementations of these applications still remain a quite long term target, a bright future is foreseen for the optical amplifier in the local loop.

5. CONCLUSIONS

A broad survey on optical amplifier characteristics and application features in telecom-munication networks has been presented. A wide range of very appealing opportunities for upgrading existing system performance have been already well demonstrated by field trials and laboratory experiments, but also are strongly supported by an increasing number of commercially available equipments.

While a basic understanding of optical amplifier operation has been achieved, many improvements in the fibre materials and guiding structure and in passive optical components are still actively under investigation, which may allow better performances, new design criteria and overall cost reduction. Cost is actually a limiting factor for a widespread use of optical amplifier in communication networks.

Still in the background, as far as practical applications are concerned for the time being, the semiconductor optical amplifier should not be neglected; in the medium term it may offer the right solutions for optical switching systems, where the monolithic integration of complex optical functions could be the only way for a practical system implementation.

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