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Erbium-doped and Raman fiber amplifiers

Amplificateurs à fibres dopée erbium et à effet Raman

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Abstract

This paper provides keys to understand why erbium-doped fiber amplifiers (EDFA) have revolutionized signal transmission techniques and how they can complement with Raman amplification in the next generation of telecommunications systems. The basic physics of EDFAs is first reviewed, followed by a description of requirements for both terrestrial and submarine system applications. The related characteristics and second-order effects causing limitations in such systems are then discussed. Finally, future developments based on operation in the 'long-wavelength band' and the benefits of using distributed Raman amplification are analyzed. ***To cite this article: D. Bayart, C. R. Physique 4 (2003).***

Résumé

Cet article permet de comprendre pourquoi les amplificateurs à fibre dopée terre rare (EDFA) ont révolutionné les techniques de transmission de signaux, et comment ils peuvent être utilisés complémentairement à l'amplification Raman dans les prochaines générations de systèmes. Tous d'abord en revue les principes physiques à la base des EDFAs, puis décrivons les caractéristiques requises pour les applications aux systèmes terrestres et sous-marins. Les caractéristiques et les effets de second ordre représentant des limitations potentielles dans ces systèmes sont aussi décrits. Enfin, les développements futurs basés sur le fonctionnement en « bande à longueur d'onde étendue » et utilisant l'amplification Raman distribuée sont analysés. ***Pour citer cet article : D. Bayart, C. R. Physique 4 (2003).***

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Mots-clés : Télécommunications ; Optique ; Amplification ; EDFA ; Erbium ; Raman ; WDM

1. Introduction

In order to transmit signals over long distances, the first generation of optical systems used periodic electrical repeaters which detected, regenerated and re-transmitted the optical channel [1]. The link was thus composed of small optical transmissions segments of several tens of km length. The main constraint in terms of cost, capacity and flexibility was therefore due to the electrical regenerators. Indeed, if such regenerators could process signals with relatively high modulation speed (100 MHz–10 GHz), their cost dramatically increases with the signal bit-rate. In addition, the bit-rate, the modulation format and the data protocol are fixed for the whole system lifetime (e.g., 15–25 years). In-line regeneration by optical amplification was introduced to avoid such expensive electrical regeneration. Optical amplification also brought the potential of regenerating several WDM

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channels at once. Raman amplification in fibers was investigated first [2]. Such a non-linear process was investigated in the early 1970s as the same time as low-loss silica fibers [3]. To provide sufficient gain, Raman amplification in fibers requires long interaction distances (10–20 km) and relatively high pump powers (300 mW–1 W). Yet, Raman fiber amplifiers initially appeared as the natural candidate for fiber loss compensation. In the late 1980s, when electrical repeaters were operating at 622 Mbit/s, the emergence of erbium-doped fiber amplifiers (EDFA) with several-thousand gigahertz of bandwidth changed the paradigm [4]. The pump power required for EDFAs being one order of magnitude lower than in the Raman case, one could also use compact and efficient laser diodes for pumping. Therefore, electrical repeaters were made immediately obsolete! Another factor in favor of EDFAs is their high power-conversion efficiency. Thus EDFAs clearly appeared as the key technology to drive optical networks towards the next telecommunication revolution. Although distributed amplification theoretically provides higher system performance, erbium-doped fiber links operating at signal transparency (fiber gain = fiber loss) actually leads to a high noise penalty, due to the small degree of inversion required. Therefore, periodic loss compensation by discrete, highly-inverted EDFAs turned out to be the winning scheme.

In this paper, we shall first describe the EDFAs physics and their characteristics. The description moves on with amplified transmission-system features, related technologies, and signal-to-noise ratio (SNR) requirements. We shall also discuss the merits of using Raman amplification to complement (or even supplement) EDFAs, as well as those of the so-called long-wavelength band, for future generations of systems.

2. EDFA physics and characteristics

In this section, we review the basic physics and characteristics of erbium-doped fiber amplification (for a more detailed description see [4] for instance). An active optical media such as laser-ion-doped silica glasses can transfer energy from a pump light source to a traversing signal light through the well-known process of stimulated emission. The basis of the amplification (net signal gain) is the population inversion of the doping ions and the fluorescence lifetime of the ion's excited-state. Glasses doped with trivalent rare-earths such as Er^{3+} are good candidates for laser action in silica glasses, due to a significant lifetime (10 ms). When this effect occurs in a doped optical fiber, the pump and signal are guided near the center of the fiber core. By confining the dopant inside this core, it is possible to maximize the pump/signal interaction. Erbium ions exhibit different spectroscopic properties depending upon the glass matrix. A first property concerns the non-radiative decay from excited-state energy levels. The pump energy can be non-radiatively dissipated through optical phonons in the material. In order to bridge the energy gap, several phonons are generated during the decay from one level to the other. Therefore, the lower the phonon energy (as determined by glass composition), the more numerous the required phonons and the less likely a non-radiative transition is to occur. In Er-doped silica glasses the ${}^4I_{13/2} - {}^4I_{15/2}$ transition at 1.5 μm wavelength (see Fig. 1) is actually 100% radiative. Because of the Stark effect, the two energy levels (${}^4I_{13/2}$ and ${}^4I_{15/2}$) are split into a manifold of Stark sub-levels. The inner population of Stark levels follow a Boltzman distribution law, the levels of lowest energies being the most populated. Because thermalization by thermal phonons is a ultra-rapid process, the ${}^4I_{13/2} - {}^4I_{15/2}$ transition as a whole is effectively homogeneously broadened. Because the Stark effect is random within the glass material, different ions have different Stark-level distributions. This induces inhomogeneous broadening of the transition, resulting in broader lineshapes for the emission and absorption spectra. As will be seen later, these slight differences in the erbium energy levels may also result in a different saturation performance. This is the signature of the glass material. As seen in Fig. 1, the ${}^4I_{13/2} - {}^4I_{15/2}$ transition corresponds to a quasi two-level amplification scheme, including residual absorption by ground-state (${}^4I_{15/2}$) ions. To each signal wavelength correspond a different amount of emission from ${}^4I_{13/2}$ level and absorption from ${}^4I_{15/2}$ level. As illustrated in Fig. 2, the technique named 'optical pumping' consists in pumping the medium to excite erbium ions in the short

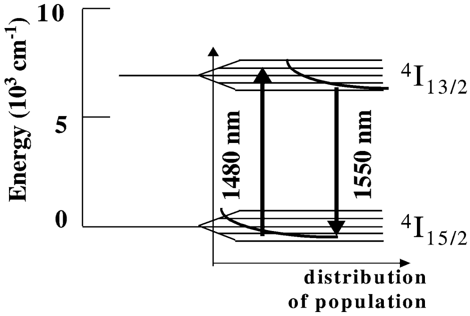

Fig. 1. Simplified energy diagram for erbium ions showing the Boltzman population distribution of the Stark sub-levels.

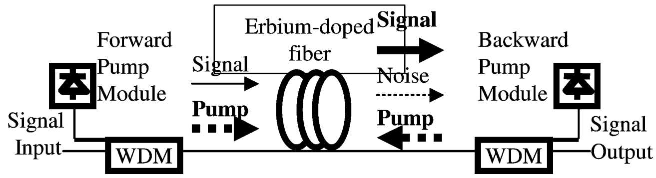

Fig. 2. Schematic illustrating pumping scheme for erbium-doped fiber amplifiers.

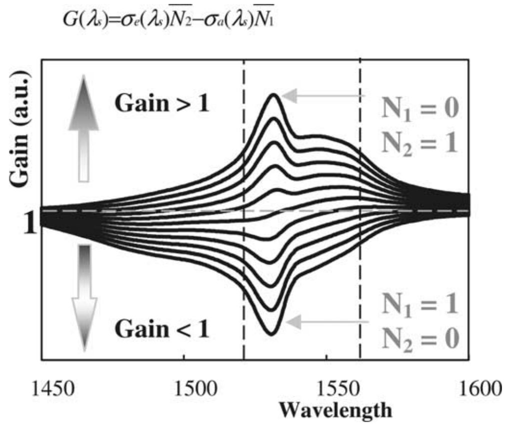

Fig. 3. Normalized calculated gain spectra $G(\lambda_s)$ for erbium ions in silica glass host as a function of signal wavelength λ_s (nm) for different ground (N_1) and upper-level ($N_2 = 1 - N_1$) population in the amplifier.

wavelength band of the absorption spectrum of the ${}^4I_{13/2} - {}^4I_{15/2}$ transition, namely at 1480 nm wavelength. Pumping can also be performed at 0.98 µm wavelength, corresponding to the ${}^4I_{11/2}$ level. When sufficient population inversion is achieved, signal amplification is obtained between $\lambda = 1525$ nm and $\lambda = 1565$ nm wavelengths, typically. Therefore, the medium behaves like a three-level laser system at shorter wavelengths (near $\lambda = 1530$ nm) with significant residual ground-level absorption and like a four-level laser system at longer wavelengths (from $\lambda = 1560$ nm and up). Depending on the local population inversion in the doped fiber, signals are amplified or absorbed, as illustrated by the gain curves shown in Fig. 3. The net signal gain $G(\lambda)$ can be defined from the average population $\overline{n_i}$ of ions in excited-state or ground-state levels as integrated over the fiber length, giving:

$$G(\lambda) = \exp\bigl[\Gamma(\lambda) \cdot \bigl(\sigma_\mathrm{e}(\lambda) \cdot \overline{n_2} - \sigma_\mathrm{a}(\lambda) \cdot \overline{n_1}\bigr) \cdot L\bigr], \tag{1}$$

where $\Gamma(\lambda)$ is the overlap coefficient of the guided-mode field with the doped core and σ_a, σ_e the absorption and emission cross-sections, respectively. The overlap coefficient reduces to the ratio between the mode-field area and the doped-core area. Increasing the cut-off wavelength of the fiber increases the coefficient. Its wavelength dependency over the gain bandwidth is, however, weak.

At low signal powers (< -30 dBm, i.e., <1 µW) the fiber inversion is not affected by signal amplification, corresponding to the unsaturated gain regime. High dB/mW gain efficiencies can then be achieved (several dB of gain per mW of pump power). When the signal input power is higher, the medium inversion is reduced because stimulated emission de-populates the excited states, leading to gain saturation. One defines then the power conversion efficiency (PCE) of the amplifier as

$$PCE = \frac{P_\mathrm{out} - P_\mathrm{in}}{P_\mathrm{p}} \tag{2}$$

where P_out and P_in are the output and input signal powers launched in the doped fiber and P_p is the launched pump power. The highest PCE is near 80–90% with 1.48 µm pumping (close to 98% as the ratio of the signal and pump photon energies) and near 55–60% with 0.98 µm pumping (close to 63% energy ratio).

In the saturation regime, the gain decreases as the signal is increased. This difference in dB between unsaturated and saturated gains is referred to as gain compression (ΔG). This gain compression is defined with respect to the gain level obtained in the small-signal regime (e.g., -30 dBm), or formally:

$$\Delta G_\mathrm{dB} = G_\mathrm{dB}(P_\mathrm{in} = -30 \text{ dBm}) - G_\mathrm{dB}(P_\mathrm{in} = P_s), \tag{3}$$

where P_s is the nominal amplifier total input power.

To increase amplification efficiency, it is possible to play on the fiber guiding parameters, which increases the pump/signal overlap with the doped area. The intrinsic background loss of doped fibers (5–10 dB/km at $\lambda = 1200$ nm) does not impact the performance, due to the short lengths used (a few tens of meters). One can also increase the doping concentration to shorten the fiber length. Cut-off wavelengths that enable single-mode operation at the pump wavelength are near $\lambda = 800$ nm for 0.98 µm pumping and near $\lambda = 1200$ nm for 1.48 µm pumping. The refractive-index difference between 15×10^{-3} and 20×10^{-3} is then used (corresponding numerical apertures between 0.2 and 0.25). This yields core mode-field diameters of 6–8 µm, compared to 10 µm for conventional single-mode fibers. This choice of parameters ensures large manufacturing capability with high yield.

We shall consider next some important physical characteristics of EDFAs.

2.1. *Dynamics behavior*

When the signal modulation frequency is increased above a few kHz, the gain stabilizes itself at a steady-state value defined by the mean signal power. The output signal does not experience then any nonlinear distortion. It is fortunate that the low-frequency data streams used in the telecom protocols stand above this frequency level. The time behavior of EDFAs is however dependent upon the pump and signal powers and wavelengths.

2.2. *Spontaneous emission noise*

In optically-amplified transmission, accumulation of amplifier noise along the link is an important issue. This noise generation is linked with the spontaneous de-excitation of the erbium ions. The resulting photons experience gain as they travel through the amplifier. This amplified spontaneous emission (ASE) noise then accumulates through the link. In a single EDFA, the output ASE power can be written as:

$$Pase = 2 \cdot \frac{n_{\mathrm{eq}}}{C_1} \cdot G \cdot h\nu \cdot B_f, \tag{4}$$

where n_{eq} is the equivalent input noise parameter and determines the level of noise generated by the amplifier for a given gain value (G), C_1 is the amplifier input coupling loss, $h\nu$ is the photon energy at the related frequency and B_f the optical bandwidth in which this noise falls. We define the corresponding EDFA noise figure through

$$NF = \frac{1}{C_1}\left(\frac{1}{G} + 2n_{\mathrm{eq}}\right). \tag{5}$$

At high gains ($G \gg 10$ dB) and negligible coupling loss ($C_1 \approx 1$), we have $NF \approx 2n_{\mathrm{eq}}$. Full inversion yields ‘quantum limited’ noise performance ($n_{\mathrm{eq}} = 1$), and mimimum noise figures of $NF \approx 2$ (or 3 dB). In practical amplifiers, the input loss is typically 1 dB (as due to the input coupler loss, and the pump-to-signal multiplexer, see Fig. 2). Values of n_{eq} around 1 dB and 0.5 dB should be considered for 1.48 µm pumping and 0.98 µm respectively, leading to NFs ranging between 4.5 dB and 5.5 dB. The parameter n_{eq} is higher at shorter wavelengths compared to longer wavelengths, with higher wavelength dependence when n_{eq} increased in average. It also increases with amplifier saturation, due to either excessive signal power or ASE power. It is clear that the best EDFA design consists in minimizing the noise figure under the system constraints of signal power and wavelength.

3. Requirements for amplified transmission systems

In order to ensure high signal to noise ratios (SNR) at the link output, it is crucial to keep the signal power at a relatively high level throughout the link. This means using relatively short fiber spans between two successive amplifiers, which minimizes the span loss and hence, the gain and resulting ASE noise. In terrestrial systems the amplifier span is typically 80–120 km (loss of 20–25 dB, a function of connection loss), while in submarine systems, it is typically 40–60 km (10–15 dB). The actual choice depends upon the total system length and the signal output power that is allowed by non-linear effects. Indeed, nonlinear Kerr-like effects (self-phase and cross-phase modulation and four-wave mixing) confine the maximum per-channel powers to the range 0–5 dBm, corresponding to EDFA output powers between +14 dBm and +23 dBm (depending upon the number of channels, e.g., 16 to 80 channels).

The impact of ASE noise on the output SNR can be calculated by summing up the contributions of each amplifiers in the chain. Since each amplifier contribution (expressed in dBm) is a linear function of the amplifier’s NF, a NF increase of 1 dB reduces the link output SNR by the same amount.

The EDFA requirements for terrestrial and submarine applications are quite different, corresponding to two different amplifier products (see [5,6] and references herein for a detailed description). First, the reliability of terrestrial (land-based) equipments is somewhat relaxed, corresponding to a 15-year operation lifetime. In contrast, submarine systems are designed for 25-year operation lifetimes and a minimum of ship repair that imply reliability and redundancy of all critical components. On the other hand, terrestrial equipments should work over a wide temperature range, namely $[-5; +70\,^{\circ}\mathrm{C}]$ and support $[-40; +85\,^{\circ}\mathrm{C}]$ range in certain storage conditions. This makes it necessary to implement cooling circuits for the highest temperatures and temperature-compensation means for sensitive devices. In submarine amplifiers, heat is dissipated, from the outer shell of the repeater's container, into the sea [$+10\,^{\circ}\mathrm{C}$ down to $+5\,^{\circ}\mathrm{C}$, function of depth]. The containers themselves are designed to achieve moderate temperature in all their inside points. Special care is given to repeaters located at coast or in shallow water (higher temperature) in order to guarantee no pump failure. This constant device/doped-fiber temperature makes it possible to precisely tailor the EDFA gain spectra of the submerged repeaters through accurate gain-equalizing filters (GEF). This would not be possible for terrestrial amplifiers whose gain cannot be specified within better than 1 dB for a 30 nm bandwidth, partly due to temperature change, to compare with a few tenths of dB for in the submarine case. An other important difference is that for economical reasons, the same type of terrestrial amplifier must be used along non-uniform, evolutive land-based links. In submarine systems, the amplifiers are designed together with the link, and are therefore optimized accordingly.

4. EDFA-related technologies

In order to keep complexity at low levels and ensure high reliability, one should minimize the number of optical components in optical repeaters as well as the impact of their non-ideal characteristics. While land-based applications typically use two-stage EDFAs with midway access for channel add-and-drop functions, submarine EDFAs are single-stage. The stages consists of one or two pieces of doped fiber, one or two pump/signal multiplexer, power-monitoring tap couplers and input/output optical isolators. Submarine amplifiers use as twice less components as terrestrial ones; their relatively low gains ($\cong 12$ dB) even alleviate the use of an output isolator.

The first generation of EDFAs relied upon 1.48 µm pumping, due to the more mature technology of InGaAsP semiconductors. Optical power conversion efficiency was around 40–50%, when used in a high population inversion level. Also, pumping at 1.48 µm does not allow one to achieve full inversion, leading to noise factor increase (about 0.5 dB at $\lambda = 1560$ nm, and 1 dB at $\lambda = 1.53$ µm). Pumping at 0.98 µm pumping allows one to achieve full inversion. While the associated power conversion efficiency is smaller (63% maximum), the actual PCE lies between 40 and 50% along with a better electrical efficiency. Due to the impossibility of bi-directionnal pumping (no optical isolator to protect 0.98 µm pumps), the first generation of land-based EDFAs was based upon a hybrid configuration, using both 0.98 µm and 1.48 µm pumping (e.g., 160 mW, 0.98 µm forward pumping in stage 1 or pre-amplifier stage, and 2×180 mW, 1.48 µm bidirectionnal pumping in stage 2 or power stage). Recently-developed high-power (300 mW) reliable 0.98 µm pumps have allowed their use in EDFA second stage as well. Before being usable in submarine systems, reliability of 0.98 µm pump technology had to be improved in order to comply with the 25-year system target lifetime (instead of 15-year in land-based systems). With 0.98 µm pumping, the NF improves by about 0.5 dB for both submarine and terrestrial applications (compared to 1.48 µm in stage 2 configuration). Cladding-pumping of the doped fiber by using spatially multi-mode pumps is also a promising technique to reach high output power with reduced power consumption and cost [5]. Characteristics of other devices incorporated in the amplifier should also ensure negligible polarization dependency, high reliability, low-sizing/cost and reduced power consumption. Such features also concern new devices like gain slope compensators and active spectral gain equalizers.

5. Characteristics of EDFAs in WDM transmission systems

When concatenating several EDFA ($\geqslant 5$) to form a link, the evolution of the amplifier total output power (signal + noise) rapidly levels off, due to intrinsic saturation. The saturated output power is mainly determined by the available pump power. The signal output power is therefore weakly dependent of the signal input power. After several amplifiers, the total output power is thus determined, the total input power and corresponding gain are then also determined, the difference between output and input (in dB) corresponding to the amplifier-span loss. As further described later, the gain coefficient increases with the population inversion and is wavelength-dependent. As seen in Fig. 3, the spectral shape of this coefficient is function of the inversion, favoring shorter wavelengths with higher gains (near $\lambda = 1.53$ µm) at high inversion. Lower inversion favors longer wavelengths (near $\lambda = 1.56$ µm and up). When several amplifiers are concatenated, optical channels experiencing gains lower than the span decreasing in power along, and thus in SNR. While in single-channel operation, the amplifier gain adapt to the span loss due to intrinsic gain compression, this is not the case in WDM operation. In WDM, the gain adapts to span loss only *in average* (average gain being defined as the ratio of total output power to total input power). Thus, the power of most-favored WDM channels increases along the link, introducing higher penalties from non-linearity. The power of less-favored channels decreases along the link, corresponding to SNR decrease. Beside in-line filtering, one can use as a means for passive

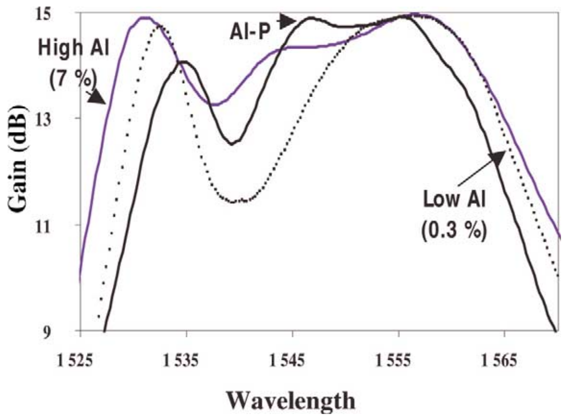

Fig. 4. Calculated EDFA gain spectra with gain excursion over the range [1530–1560 nm] minimized (gain peaks balanced) as function of signal wavelength (nm) for three different glass host compositions including low (0.3%) and high (7%) aluminum concentration and aluminum (3%)–phosphorus (3%) composition.

gain equalization some special glass compositions with the appropriate choice of population inversion, as also illustrated in Fig. 3. For a given population inversion, the gain excursion scales with the gain peak level. For a given gain peak level and wavelength range, the lowest normalized gain excursion achievable is only a function of glass composition and is given by the optimal average population inversion. The result is independent of other parameters such as the doped-fiber length, the pump wavelength or the total output power. Doped-fibers with high aluminum (Al) co-doping provide the lowest gain excursion, representing 14% of the gain peak between $\lambda = 1528$ nm and $\lambda = 1562$ nm, as illustrated in Fig. 4. For a gain of 28 dB, for instance, the lowest gain excursion is 4 dB. Alternative glass co-doping compositions, such as based upon phosphorus did not show clear advantages over Al for gain broadening for this conventional amplified band (referred to as C-band). In addition, Al allows for high erbium-ion concentrations while avoiding pair-induced effects due to ion-clustering, which is explained by improved ion solubility in the glass. Regardless of gain-equalization strategies (glass composition and/or passive filtering), gain excursion should always be minimized. The gain excursion resulting from imperfect equalization (ΔG, expressed in dB) is a key limiting factor for the minimum achievable SNR at link output. This feature can be formally expressed as follows [5]:

$$SNR_N^{\min} = \frac{Ps}{Bo + NF \cdot h\nu \cdot B_f \cdot \frac{10^{(\Delta G \cdot N)/20} - 1}{10^{\Delta G/20} - 1}}. \tag{6}$$

For instance, assume a 130-amplifier chain (6500 km length with 50 km spans) with -9.5 dBm channel input power (corresponding to an output power of $+14.5$ dBm with 16 channels and 12 dB gain), with amplifiers having a $NF = 4.5$ dB. In this case, the SNR at the chain output is 16.64 dB (expressed in 0.1 nm bandwidth), assuming ideal flat-gain amplifiers. With a gain excursion as low as 0.01 dB, the SNR penalty would be of only 0.33 dB (after (6). However, if the excursion increases to 0.1 dB/0.15 dB, this penalty becomes 3.6/5.7 dB.

The above result is somewhat pessimistic since signal pre-emphasis (power increase at transmitter level) can compensate partly this penalty, but it illustrates the need for high-quality gain-flattening filtering. In land-based applications, the span loss between amplifier site makes that the amplifiers are not operated with a gain level that corresponds with their best equalization spectrum, thus inducing extra gain excursion (sometimes of several dBs). The use of mid-stage voltage optical attenuators (VOA) may help to adapt the amplifier gain level by keeping the same erbium gain and playing on the internal loss value (issue of impact on noise figure). While the gain spectrum can be equalized with 0.2–0.3 dB at room temperature, when the EDFA is operated over the [$-5\,^\circ$C;$+70$] range, the gain excursion increases to 1–1.5 dB, as due to changes in Boltzman populations of Stark erbium sub-levels, thus in macroscopic cross-section spectra. Some techniques to compensate this effect have been proposed [5]. The temperature of submerged/submarine equipment is constant (between $+5\,^\circ$C and $+10\,^\circ$C), making easier to achieve almost perfect gain flattening. The required filter accuracy can be met by specific equalizing-filters technologies, although within some limits. Gain filtering ensures a flattened gain spectrum with moderate penalty on the required pump power, due to their low insertion loss and contrast provided by careful amplifier design. Since such filters are placed within the amplifier or at its output, the noise penalty by the use of filters is minimized. Next generations of transmission systems will be implemented over bandwidth over 30 nm (potentially 40 nm) and possibly over, owing to such filtering technologies and using increased pump power for higher filter contrast (several dBs versus a few dBs in first generations). This near-perfect gain equalization allied to a highly reproducible process for doped fiber manufacturing are key elements that made possible broadening of the amplifier bandwidth and hence, the addition of more wavelength channels. Such an outstanding performance is, however, allowed by the control of all limiting effects which may prevent systems from working with the nominal characteristics, as described next.

6. EDFAs impairments and technology limitation

First, polarization effects like PMD (polarization mode dispersion) and PDL (polarization-dependent loss) of devices incorporated in the EDFAs (isolators or gain-equalizing filters) or polarization-dependent gain (PDG, also named *polarization hole burning* is intrinsic to the doped fiber medium and related to signal-induced saturation) have been avoided. The use of high channel counts (having different polarization states) implies that PDG induced by different channels averages itself out and thus relaxes the need for signal-polarization scrambling. Also due to a signal-induced saturation in the doped fiber medium, spectral hole burning (SHB) is a limitation of amplified WDM system with high channel counts. The main reason lies in the fact there is no possibility to compensate for this effect. In addition, accurate predictions are of most difficult to carry out. SHB acts as a spectrally-selective over-saturation of specific erbium ion classes, due to a precise matching of the signal wavelength with their corresponding Stark sub-levels. The gain contribution from a given ion class depends upon the energies of its Stark sub-levels (as determined by random variations of the local electric field in the glass, unlike in defect-free crystals), and of their population density (i.e., of the related induced saturation). The overall gain spectrum is therefore distorted by SHB. The distortion takes the form of a hole in the gain spectrum centered about the saturating channel wavelength. During propagation over a long-haul link, the most favored channels experience a slightly lower gain due to self-induced SHB. However, the correcting effect is much less important than the effect creating SHB. The detrimental effect actually comes from distortions induced in the gain spectrum due to homogeneous broadening. Other channels located few nm away from the most favored ones also experience gain reduction, while being not favored like the channels generating SHB. The neighboring channels thus experience SNR degradation.

Other well-known parameters such as noise figure or power consumption are also limiting parameters in system performance. It is not possible to significantly decrease the EDFA noise figure (already close to the 3 dB quantum limit by use of 0.98 μm pumping). Another significant limitation comes from fluctuations between the different devices and doped-fiber characteristics. This may causes variations in total loss of all incorporated devices representing several tenths of dB. In addition, non-uniformity of erbium concentration along the doped fiber length causes gain deviations, depending upon the point where the fiber is sampled from the manufacturer’s spool. By a tight control of the manufacturing process and accurate characterization of the doped fiber, erbium quantities incorporated in an EDFA may be precisely determined and adjusted (through doped fiber length modification) so that the observed difference in insertion loss of passive devices does not impact on the resulting inversion in the doped fiber at fixed input/output powers. It is also crucial to achieve closely reproducible Al-concentrations in order to ensure that the nominal inversion provides the same target gain spectrum, matching the equalizing-filters transfer function. With high technology and engineering skills, all the above requirements can be fulfilled. The effects of non-linearities in the amplifier (four-wave mixing, cross-phase modulation) or even PMD (not a linear effect) can also be avoided through proper design. To summarize, system performance is not strongly affected by amplifier technologies when the highest possible care is given to amplifier design and manufacturing. Clearly, non-linearities caused by passive propagation in the transmission link are for more limiting impairments.

7. Operation with L-band EDFAs

As seen from Fig. 3, the gain profile of EDFAs shifts toward longer wavelengths when the degree of inversion in reduced to a value close to 40% of inverted ions. In this case, the amplifier become absorbent in the conventional or C-band [1530–1560 nm] while gain is provided at longer wavelengths or L-band [1560–1610 nm], as limited by signal excited-state to $^4I_{9/2}$ level. It is worth emphasizing that L-band amplification involves different Stark sub-levels and cross-section spectra, as compared to C-band amplification. At long wavelengths, the set of pump/signal transitions closely emulates that of a 4-level laser system, i.e., with minimal population for the terminating level of the signal transition. Since there is almost zero signal re-absorption by the ground level, the EDFA exhibits low NFs even if the (average) inversion is relatively low.

7.1. System performance

Forward pumping at 0.98 μm yields the lowest noise figure, owing to the high inversion made possible at the amplifier input. This is however at the expense of a high gain peak near $\lambda = 1.53$ μm in the first meter the doped fiber length. This leads to significant loss of pump power by conversion in C-band ASE and to a self-saturation effect by such a noise, thus degrading the amplifier NF. Specific techniques can be implemented in order to guarantee near-quantum-limited NF, but at the expense of increased complexity. Actually, WDM amplifiers are operated under significant saturation induced by the signal power. Higher NFs are then observed (+0.5 dB) compared to C-band EDFAs. Pumping at 0.98 µm being less efficient (only 25% PCE compared to 40% minimum for practical 0.98 µm/C-band EDFAs), a shift of the pumping wavelength may improve the efficiency, but this also leads to somewhat higher NFs. Using a backward additional pump at 1.48 µm is an efficient means of reaching high output powers. The higher efficiency or 1.48 µm pumping ($\geqslant$60%) enables one to use relatively low pump powers (only several tens of mW). Gain equalization can be provided by a single Bragg-grating filter for 30 nm bandwidth (2–3 dB contrast) against several filters (3–5 dB contrast) in case of larger bandwidths. In order to reduce fiber length and its related possibly loss or non-linear effects, doped fibers used for L-band require Er concentrations nearly four times higher than for C-band. Strong Al-codoping is then used in order to allow high Er-concentrations without suffering from noise penalties. Other co-dopants such as Yb (with 1.48 µm pumping), or La, or Bi (see [5]) permit one to spread the gain bandwidth towards longer wavelengths or to increase the Er concentration for shorter fiber lengths (and reduced non-linearity). L-band EDFAs have been intensively investigated in conjunction with C-band EDFAs for terrestrial WDM system experiments. Although SHB is three times higher and broader in the L-band, the implementation of L-band EDFAs in long-haul experiments has proven successful. The choice of whether or not to implement L-band in parallel with C-band or as a stand-alone band alternative is in fact driven by other considerations, which involve economical aspects and cable-management issues. In case of limited-bandwidth operation (smaller than 40 nm), a single EDFA operating over a seamless bandwidth will be cheaper than two used in parallel as far as it can comply with system specifications over such a bandwidth.

8. Implementation of Raman amplification

Following earlier studies [2,4], Raman fiber amplifiers (RFA) have been recently re-investigated for providing distributed amplification (as opposed to discrete or lumped amplification with EDFAs). Progress on pump technology, driven by EDFA development, and the benefit of smoothly compensating fiber attenuation made RFAs beneficial to improve the link SNR and reduce its non-linearity.

8.1. Principle of Raman amplification

Raman amplification is based on a stimulated Raman scattering process involving pump and signal photons on one hand, and optical phonons of the glass material, on the other hand. This is a non-linear effect, therefore polarization-dependent (which requires polarization-multiplexed semiconductor or de-polarized fiber-laser pumps) and requiring relatively high pumping powers. This inelastic process converts one pump photon into a signal or noise photon of longer wavelength, the difference being absorbed by the creation of an optical phonon (excitation of a vibrational state of Si-0 molecular bonds). Due to intrinsic glass inhomogeneity, the phonon energy corresponds to a broad and continuous range of signal wavelengths or Stokes shifts [2]. In Si-Ge glasses, the Raman spectrum exhibits a peak at a 13.2 THz frequency shift, giving a 1 dB bandwidth of 3 THz for a 20 dB peak gain. Fig. 5 shows the coefficient C_R ($C_R = g_R/A_{eff}$, with g_R = Raman gain coefficient and A_{eff} = effective

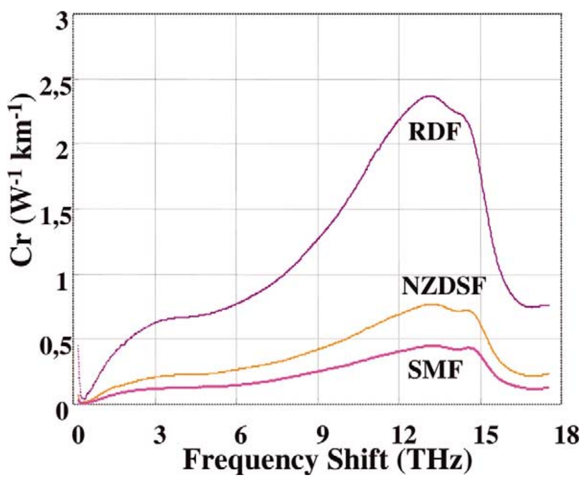

Fig. 5. Raman gain coefficient Cr ($W^{-1} \cdot km^{-1}$) measured with a 1486-nm pump wavelength in the case of a reverse-dispersion fiber (RDF), a standard single-mode fiber (SMF), and a negative non-zero dispersion fiber (NZDSF) as a function of the frequency shift (THz) of the signal channel with the pump channel.

interaction area) as a function of frequency shift in the case of non-zero-dispersion-shifted fibers (NZDSF), single-mode fibers (SMF, having 1.3 µm zero-dispersion wavelength), and reverse-dispersion fibers (RDF, which are SMFs of opposite dispersion sign). The effective interaction area, A_{eff}, takes into account the modal overlap between the pump, the signal and the fiber core (Ge) profile. It is close to the core cross-sectional area and increases with signal/pump wavelength, which reduces the Raman scattering efficiency. Therefore, the observed differences between the three curves in Fig. 5 are mainly due to variations of their effective areas and of their Ge concentration. When such curves are normalized to unity, the spectra are nearly identical, except for a small peak at $f = 15$ THz due to silica. This shows that Ge does not strongly distort the Raman gain profile. The gain spectrum is only dilated when pump power is increased, resulting in a scale factor effect. Over a given wavelength range, a twice higher gain peak therefore yields a twice-higher gain excursion. As far as its spectral gain is concerned, implementation of Raman amplification in practical systems is relatively simple. The normalized gain profile is indeed the same for any gain levels in a given fiber, and exhibits very slight differences from two fibers of different index profile, core sizes or Ge concentrations. In addition, there is no energy storage involved. The phonons energy is rapidly dissipated in the glass, making negligible the probability of the reverse absorption process, i.e., signal photons re-conversion into a pump photons, called anti-Stokes scattering. This feature leads to quantum-limited noise operation, like in a 4-level laser system. Depending upon the fiber characteristics in C_{R} coefficient or attenuation (particularly at the pump wavelength), the pump power requirements to achieve a given gain may strongly vary. In any case, RFAs are far less power-efficient in comparison to EDFAs. Furthermore, the pump power required in distributed amplification, is much higher than the signal power. Therefore, the amount of pump energy transferred in the process is relatively low. As a result, the RFA gain is only weakly dependent on the total signal power load, i.e., the channel count. This is advantageous in practical implementation, as long as the pump power can be closely regulated. Backward pumping (in the fiber direction opposite to the signal) is usually implemented to average the effects of pump instabilities and its relative intensity noise (RIN).

Formally, the gain experienced by a signal channel due to distributed Raman amplification can be expressed as follows:

$$G_{\text{ON/OFF}}(\text{dB}) = \frac{10}{\ln 10} \cdot \frac{g_{\text{R}}}{A_{\text{eff}}} \cdot \frac{1 - \text{e}^{-\alpha_{\text{p}} \cdot L}}{\alpha_{\text{p}}} \cdot P_{\text{p}}, \tag{7}$$

where $G_{\text{ON/OFF}}(\text{dB})$ is the gain at the signal wavelength, P_{p} (mW) is the pump power, A_{eff} is the Raman effective area of the fiber, L is the fiber length. The effective interaction length, $L_{\text{eff}} = (1 - \text{e}^{-\alpha_{\text{p}} \cdot L})/\alpha_{\text{p}}$, where α_{p} is the fiber attenuation coefficient (m^{-1}) at the pump wavelength, can be approximated by $1/\alpha_\rho$ (absorption length) if the fiber length L is much higher than L_{eff}. This is the case for distributed Raman amplification ($L = 50$–100 km, $L_{\text{eff}} \approx 20$ km). As defined above the gain $G_{\text{ON/OFF}}(\text{dB})$ is also called the ON/OFF gain, because it accounts only for gain due to stimulated emission and not for signal attenuation in the link fiber. It therefore corresponds to the increase in signal output power when pump light is ON. The fiber attenuation at the pump wavelength strongly impacts this ON/OFF gain. With a pump attenuation of 0.2 dB/km, for instance, a pump power of 300 mW yields a maximum ON/OFF gain of 16 dB, while with 0.25 dB/km this gain is reduced to 13 dB (NZDSF with $A_{\text{eff}} = 67\ \mu\text{m}^2$).

8.2. RFA implementation as EDFA pre-amplifiers

RFAs can be implemented as periodic pre-amplifiers before EDFA amplification. To achieve this, some pump power is launched into the fiber span in the direction opposite to the signal, owing to a pump multiplexer located at the EDFA input. The Raman gain provided increases the signal power at the EDFA input. If one overlooks the spontaneous Raman emission noise, this resulting distributed ON/OFF gain is equivalent to decrease of span loss between two EDFAs, and could result in an improvement of the SNR at the link output of same value. However, spontaneous Raman emission is not negligible although being locally emitted at quantum limit. This nearly reduces by one half the SNR improvement due to the distributed Raman gain. In addition, EDFAs see a total input signal power increase of several dBs, which is at the expense of their NF. The EDFA output power must also be reduced in order to keep the same the total non-linear effects seen by the channel over a given span of the link, resulting then in link SNR decrease (however improved in comparison to the Raman 'OFF' mode). Pure distributed RFA-based systems (i.e., without any line EDFAs) have been also investigated, bringing up new issues. Those related to gain stability can be solved relatively simply, owing to a high control of the pump power level. But the gain required to compensate span loss is about 20–25 dB, which changes considerably the required (Raman) pump power compared with a few dB extra gain provided as Raman pre-amplification in EDFA systems. If pump power efficiency is clearly lower than for EDFAs, the use of several wavelength-division-multiplexed pumps enables one to broaden the usable amplification bandwidth without requiring gain-equalizing filters with high contrast at each span. The gain bandwidth may therefore be increased at will towards shorter or longer wavelengths just by the implementation of enough pump channels (four pumps are enough for providing a nearly flat bandwidth of 26 nm, and eight ones may be used to give a 65 nm bandwidth), and not necessary linked with the location of the erbium gain spectrum. If problems linked with EDFAs SHB vanish (there is no SHB in RFAs), other issues to be addressed appear like double Rayleigh scattering leading to incoherence interference. An other issue concerns interactions between pumps, whose total power required to compensate for a a full span loss is quite high (several hundred mW required). Pump channels of shorter wavelength will be absorbed more rapidly in the link due to a slightly higher link attenuation, and also because they will be depleted at the benefit of pump channels of longer wavelengths (and thus will provide a less distributed gain). The gain for the related signal channels will therefore be lowered, thus reducing their related SNR. Increasing the short-wavelength pump power may help to compensate this gain deficit, but care must taken that this added pump power is not totally transferred to the other pump wavelengths (due to Raman scattering). This Raman pump interaction can be compensated only to some extend, and raises crucial issues for implementing practical wideband ($\geqslant$40 nm) RFAs. Using short pump wavelengths in forward pumping while using long pump wavelengths in backward pumping may help to address this issue, but at the expense of impairments linked with pump RIN or other instabilities. Further investigation should reveal whether such limitations can eventually be overcome. Foreseen advantages procured by an all-Raman amplification approach (no gain distortion or increased noise with signal saturation, high aggregate bandwidths without requiring tight filtering, and more) should be assessed with consideration to the noise penalty introduced by double Rayleigh scattering, and extra cost/power-consumption due to the lower pumping efficiency. In addition, the improvement in noise performance of distributed-gain links compared to lumped-gain links remains to be qualified when operating at the same levels of cumulated non-linearity.

9. Further amplification perspectives

Owing to their outstanding characteristics and adaptation possibilities to further increase throughput capacities, EDFAs have revolutionized transmission systems. The ultimate utilization of their bandwidth potential is still quite far from being fully exploited. In parallel, the proliferation of new active devices offered by recent technologies provides new degrees of freedom for designing transmission systems. The future availability of variable attenuators, dynamic gain-slope compensators, and dynamically-adjustable gain equalizers will help to relax the requirements put on all-passive devices and provide new system margins. The implementation of 2R or 3R regeneration, which could one day complete '1R' optical amplifier regeneration is still not mature, due to their relatively high technology cost and issues with massive WDM implementation. As a matter of fact, optical fiber amplification with EDFAs and RFAs will continue to run the show in next-generations systems!

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