Evolution of Commercial EDFAs

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Abstract: Erbium Doped Fiber Amplifiers (EDFAs) play crucial role in modern optical telecommunication networks. As the networks evolve, commercial EDFAs faces technical challenges that have to be solved within constrains of ever changing industry.
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1. Introduction

The second half of the twentieth century has seen a lot of technological advances that culminated in the creation of one of the greatest communication tool – the internet. It is hard to overestimate the importance of the internet in the modern life – it penetrates nearly every aspect of our live. While there were many technical solutions during development of the communication infrastructure, only few of those solutions were landscape changing technologies that propelled the scale of the development of the communication networks to the qualitatively new level. One of those technologies is Erbium Doped Fiber Amplifier, or EDFA.

The role of EDFA in communication networks is re-amplification of the signal. This amplification is format independent and multi-wavelength/multichannel with minimal or negligible penalties for such important effects as inta- and inter-channel cross talk, PDL/PDG and PMD. Today, we are so used to those properties of EDFA that we perceive them as something obvious, but at the time doing all that in practical and relatively cheap way allowed industry to eliminate expensive format dependent regenerators in the transmission links. That essentially made possible to have long transmission links without regeneration of the signal and significantly reduced link's price and increased flexibility.

Optical communication industry is still quite young industry, and as such significant growth and changes constantly occur in it. It is interesting to note that generally, the optical topology and technology of EDFA did not change drastically since the original use of EDFA in optical communication. One can argue, that in the past the largest changes of EDFA technology occurred in amplifier control methods and electronics, while the rest of the changes were slow evolutionary changes – the components becomes cheaper and with better characteristics. However, today the industry enters into interesting phase where 100G and higher rates may take all available spectral bandwidth and come close to Shannon's limit, and thus previously nearly exponential growth of per-fiber capacity-length product may saturate, meaning that internet capacity may not grow exponentially as it was in the past. At the same time, ROADM based networks becomes common nowadays which put additional pressure on transient performance of the system, requiring either additional margins or better performance of the subsystems with respect to transient events. These aspects points on necessity of change in the transport layer, in particular in EDFA use or design, so that future growth of the bandwidth is possible.

It is difficult to discuss EDFA amplification without mentioning Raman amplification. This is especially true because of the challenges the industry faces today where hybrid Raman/EDFA amplification has some benefits. While this work focuses primarily on EDFA, come aspects of Raman amplification use in relation to EDFA are going to be discussed as well.

Finally, there is a constant drive to reduce both size and price of EDFA either as standalone module or as part of larger module that combines several modules such as ROADMs, OCM, etc. Thus more integrated approaches for EDFA designs are constantly considered.

2. Future requirements for amplification technology

In communication links amplifiers are the dominant source of the noise. Generation of ASE (Amplified Spontaneous Emission) is physical consequence of the amplification process and as such always presents in the system where there is amplification. Typically, the channel power in the transmission system is limited by two factors. On the one hand, there are nonlinear effects that limit how large the channel power can be. On the other hand there is ASE noise generated by amplifiers, and the stronger is channel power, the better is OSNR ratio, the smaller is BER penalty due to ASE. However, the channel power can not be arbitrary large because of the mentioned above nonlinear effect; this is why ASE noise power is one of the main factor limiting link performance.

The amount of EDFA generated ASE is characterized by amplifier NF (Noise Figure). Constant pressure to build better and better systems translates to pressure of the amplifier to have smaller and smaller NF. With emergence of higher rate formats, this pressure is even stronger, because those formats are more sensitive to noise due to Shannon's theorem. More over, the higher rate systems may have dispersion and other signal distortions compensated via electronics, which works well only if nonlinearity of the system is low. In order to avoid nonlinearities, the channel power has to be reduced, which effectively decreases OSNR of the system. That means that amplifier generated noise plays even larger role for such systems and there is tremendous pressure to improve OSNR and thus NF of the amplifier. Failing to do so will limit 100G and higher bit rate systems' reach significantly.

One may ask a question, why do we worry about those formats now if their deployment will be years ahead and only sporadic to begin with? The reason is that even though there is no expectation to have 100G+ to be deployed everywhere next year, the transmission links should be feature prove, so that if or when the system is upgraded to full 100G+ system or if the system is used with multiple formats, there are sufficient margins for it.

Another major pressure on EDFA design is its performance with respect to transient events. There are two distinctive problems here. The first problem is the performance during transient event itself. Each channel that propagates through the series of concatenated spans with amplifiers should maintain its power within some range during the transient event. This may be required simply for the detectors reliability. More over, the channel power should return to the level close to the initial power in quite final time. Failing to do so may trigger protection switching. These two requirements (magnitude of channel power excursion and settling time) put rather stringent limits for the amplifier transient performance because the transient excursion is concatenated when signal travels through multiple amplifiers.

Another problem related to the transient events is the static behavior of the amplifier after the transient event and after all the processes in the amplifier are settled. Even if during the transient one may have system's bit error rate (BER) going up for short amount of time, after amplifiers are settled, the BER should return back to normal. Since both increase and decrease of channel power are bad for BER (the former is due to nonlinear effects or detector saturation and the later is due to OSNR) that puts quite stringent limits for channel power deviation. The situation is further complicated that, again, this "static offset" accumulates over multiple amplifiers. Essentially, one has to either decrease this static offset, or have additional system margin to accommodate for this, and it is much more difficult to have additional margins in the high bit rate systems.

Another pressure experienced by EDFAs is integration and size pressure. This does not necessarily relate to the new formats, but rather to the overall system becoming more complex and needing more amplification when extra losses, such as ROADMs, appear in the system. And, of course, there is always drive to reduce EDFA price despite all off the other requirements.

Finally, we are now seeing the requirement of having more and more channels transmitted through EDFA, meaning EDFA wavelength band is increasing. This usually complicates all of the problems discussed above.

Not all of the requirements for new, faster formats translate to more stringent requirements for EDFAs. Most of the 100G and higher rate formats rely on coherent detection and electronic compensation and because of that some of the penalties introduced by amplifiers become less important. This is true for any "linear" type of penalty, such as PMD. The most stringent requirements in this respect are given by non-coherent 40G systems and they are not expected to become significantly more stringent for higher rate formats in future.

3. Future evolution of EDFA design

Given all those limits put forward by future formats and looking at general direction of the communication system evolution, how much EDFA of tomorrow will differ from EDFAs of today and yesterday?

The requirement of having better and better NF translates to several things for EDFA. The most significant is the wide use of Raman amplification together with EDFAs. It is quite feasible economically to have hybrid EDFA/Raman system where Raman pump is launched to the fiber preceding the amplification node for counter-pumping Raman amplification, producing the benefit of roughly 5dB in effective NF, which is very desirable. While hybrid EDFA/Raman systems are not new, what is new is the penetration of this technology in the coming years. Because of this we expect to have fully integrated hybrid amplifiers (either on module level or on circuit pack level). This integration is important not only from the size and cost saving point of view, but from the control point of view – there are synergies between EDFA and Raman amplification that can be exploited in hybrid Raman/EDFA control and provide superior performance in terms of control accuracy and transient control. This is partly due to the fact that the Raman portion of the hybrid amplifier can be used as very fast, low resolution DGE for EDFA. This gives perfect opportunity for hybrid amplifier to be able to compensate those static offsets mentioned in the previous section.

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Raman amplification by itself also is not immune to similar problems described above. That includes the problem of transient control and of static offset, now originated in the Raman portion of the hybrid amplifier. The problems are complicated by the fact that in distributed Raman amplifier the only accessible measurement points for amplifier control are those at the amplifier node itself. Despite of that, due to commonality of the problems, there are similar ways to solve many of the problems for both EDFA and Raman portions of the amplifier.

Another way to improve NF of EDFA or of hybrid Raman/EDFA is the traditional way of using better components including pumps with higher pump power. However there is only so much that can be done here without making amplifiers extremely expensive.

At the same time, the importance of the EDFA design itself should not be overlooked. A computer assisted optimization of multiple parameters in EDFA design related to optical topology, control parameters and electronics design parameters, becomes more and more important. EDFA design, especially combined now with Raman amplification, becomes more and more complex due to the need to optimize it nearly perfectly to work under many different conditions, including different gains, channel load, temperature, aging and transient events. All of those conditions have to be accurately simulated/estimated during EDFA design. The optimization is especially difficult because of the interplay of various specifications (e.g. steady state vs. transient) and interaction of optical design with control algorithms and their implementation in digital and analog electronics. All of that creates huge number of possibilities and variables that should be optimized.

In order to compensate the mentioned above static offsets it is not sufficient just to have “low resolution DGE” provided by Raman portion of the hybrid amplifier. One also needs to control this “low resolution DGE”, meaning that one needs to measure spectral characteristics of incoming light, so that the right correction can be computed and applied to DGE. These measurements and reactions should be very fast, on the order of or faster than 1ms, which is problematic with existing OCMs. There are couple approaches to overcome this problem. One of them relies on the presence of the “monitoring” channels and detection of the powers of just those channels. Another approach is the use of additional detectors for monitoring of the light passed through specially designed optical filters. While these approaches are currently not used, it seems as a likely possibility that something like this will be used in future in order to diminish the problems related to variable channel load.

The mentioned above integration of EDFA and Raman amplifiers should not stop at just integration of those amplifiers. There is an incentive to have many devices, including OCMs, ROADMs, optical switches, etc. in addition to the amplifiers, to be integrated on the same device, usually on a card level product. Combination of all those devices in the single product gives additional optimization parameters, which can result in better optical performance of the whole module and better, finely tuned control. This is also a good opportunity to use PLC optics instead of bulky optical components. PLC gives an opportunity to have next level of integration, provided that penalties associated with PLC optics are small enough or absent. One of the interesting opportunities is to be able to create a “field reprogrammable OA”, which is to have topology of EDFA reconfigurable via the use of optical switches for both pump and signal. This can give extra adaptively and optimality of the amplifier depending on conditions it has to operate in. Highly reconfigurable EDFA can be practical only with the use of PLC optics, where adding extra components does not dramatically change the price of the whole device.

While discussing all those new techniques, there is one parameter, which is never forgotten in commercial amplifiers: price. Every decision about EDFA design comes through the “price filter”. Even though due to renewed importance of having amplifier performance and flexibility, the price pressure is not as strong, as it was, say, 5 years ago, the pressure always is there. Thus it is important to have the amplifier cost as one of the parameters of the computer assisted optimization of EDFA design.

On should note that the above discussion is mostly related to the high performance EDFA amplifiers. There is also important segment of low performance, cheaper amplifiers that work typically with either single channel or limited number of channels. They do not have the same pressure of performance improvement; however, they do have much stronger pressure of higher integration, smaller size and lower price. One of the options for addressing all of those items is, again, PLC integration of multiple amplifiers, where possible. Such integration, together with some pump sharing techniques, can be further expanded to circuit pack level products that include ROADMs or other devices.

In conclusion, the communication industry passes through interesting times with various challenges related to the per-fiber capacity limits. These transformational challenges will change EDFAs as well. It is interesting to see which of the mentioned above techniques become standard for EDFAs and which are not. One thing is still for certain, Erbium Dopped Fiber is unique amplification media, well suited for communication technologies, and will be used in foreseeable future with some modifications and improvements in EDFA design.