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# Latest results and future perspectives on Few-Mode Erbium Doped Fiber Amplifiers

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ABSTRACT

Space division multiplexing has generated a lot of interest during the last five years and motivated intensive work on multicore and few-mode fibers. Whereas some concepts like multimode waveguides and mode coupling have been re-visited for mode-division multiplexing, some new problems have been addressed, as is the case for multimode optical amplifiers. This paper recalls the general context of the work on Few-Mode Erbium-Doped Fiber Amplifiers and reviews the main results reported so far on this topic.



## 1. Introduction

The need to increase the capacity of fiber optic networks in the medium term has motivated many industrial and academic players to explore new solutions for high data rate transmission in optical fibers. In this context, spatial division multiplexing (SDM) has quickly emerged as a solution with ground breaking potential similar to that offered by Erbium-Doped Fiber Amplifiers (EDFAs) and wavelength-division multiplexing (WDM) in the mid-90s, or more recently by the use of coherent detection. Demonstrations reported on SDM since 2011 have highlighted that it is possible to exploit new pathways in few-mode fibers (FMFs), multicore fibers (MCFs) and now, MCFs with few-mode cores (FM-MCFs) in a glass volume similar to that of a standard single-mode fiber (SMF). Thus, a spatial multiplicity larger than 100 was reported in 2016 by Sakaguchi et al. [1] and a total capacity as high as 2.15 Pbit/s has been recently reported [2], which largely exceeds the maximum theoretical data capacity of SMF that is about 100 Tbit/s [3]. The analysis of the work reported in recent years however shows that in addition to the optical fiber used for transport, all the fiber components that make up an optical fiber network have to be brought to a high level of performance for future implementation of an optical cable based on SDM technology. Such components include multiplexers/demultiplexers for addressing the different spatial channels (modes or cores), routing devices for extracting or adding channels and, finally optical amplifiers without which no long-haul application is possible. Whether it be a technology based on MCF or FMF, the development of such optical amplifiers poses many challenges and a maximum of 19 spatial channels have so far been amplified in a SDM optical amplifier [4]. In each case, the challenge is to amplify by a factor of 100 (20 dB) as equally as possible (a gain excursion similar to the one of conventional EDFA i.e. about 10% is targeted), different spatial channels over the entire C-band (1530–1565 nm) with an energy consumption smaller than N single-mode systems put in parallel.

In this review, we provide an overview of performances in recent reports of Few-Mode Erbium Doped Fiber Amplifiers (FM-EDFAs). Thus, having recalled some generalities on optical amplifiers for FMF, we will first detail some economical considerations on these systems. In the third section, the theoretical aspects will be discussed and we will draw up the balance sheet of the amplifying performance reported in the literature for few-mode optical amplifiers used alone or inserted in a transmission line. In the last section, we will discuss on possible developments for this technology, especially on a short-term timescale.

## 2. Key parameters of FM-EDFAs

### 2.1. Generalities on FM-EDFA

Up-to-now, EDFAs are the optical amplifiers that have demonstrated the greatest potential in the context of SDM, especially when compared to Raman amplifiers or parametric amplifiers

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[5,6]. FM-EDFAs have an architecture similar to Single-Mode Erbium Doped Fiber Amplifiers (SM-EDFAs) (Fig. 1). A pump radiation is injected in the core of an Erbium Doped Fiber (EDF) together with the signal to be amplified. This pump radiation is absorbed by $Er^{3+}$ ions which then transfer part of this energy to the signal radiation. The main difference consists in having a core that guides several modes at the signal wavelength. As a consequence, at the common pump wavelength at 980 nm, the core will guide about two times more modes at the pump wavelength than at the signal wavelength.

In the case of SM-EDFAs, especially in-line amplifiers, the challenge is to provide a flat gain over the C-band, together with a low Noise Figure (NF) and a high average gain. But in the case of a FM-EDFA, the challenge is even more complicated: the gain needs to be equalized not only over the different wavelengths used in the C-band but also over the different signal modes. Thus, when designing a FM-EDFA, one must deal with differential spectral gain (DSG, maximum difference of gain for a particular mode over spectrum) and differential modal gain (DMG, maximum difference of gain for a particular wavelength between the different signal modes), resulting in a total gain excursion $\Delta G$ (maximum difference of gain between all signal channels). These different parameters are presented in Fig. 2. As highlighted by this discussion, the situation is quite different from the one faced in early experiment on multimode EDFAs by Nykolak et al. who were working on a highly multimode fiber without a controlled modal discrimination [7].

As will be discussed in Section 3, different strategies can be implemented so as to reach low DMG and, more generally, low $\Delta G$, together with a high average gain and low NF. However, besides technical performances, the main driver of the research on FM-EDFAs is its potential to offer cost reductions compared to parallel SM-EDFAs.

### 2.2. Economical aspects

The economical aspect of FM-EDFAs is obviously the most important factor for evaluating the viability and the benefits of this new technology for commercial applications. However, the answer is not clear since there are currently no standardization for this new technology and several technological challenges still have to be overcome. To evaluate this point, two economical aspects can be discussed: capital expenditure (CAPEX) and operational expenditure (OPEX). Regarding CAPEX, the pooling of several components should be greatly attractive since the price of such components rises linearly in the case of SM-EDFAs in parallel. Even if a single SM-EDFA will always be less expensive than a single FM-EDFA, one may expect a FM-EDFA to become less expensive than parallel SM-EDFAs beyond a certain number of channels. At our present level of understanding of FM-EDFAs it is not possible to precisely calculate this minimum number of MDM channels. Regarding OPEX, it is possible to estimate part of it by estimating the power consumption of such an amplifier. For this purpose, a very simple model can be proposed to study the different architectures sketched in Fig. 3: several SM-EDFAs used in parallel, a single FM-EDFA with core-pumped scheme and, finally, a single FM-EDFA with double-cladding geometry. The aim of this model is to estimate the optical power budget needed for each architecture in order to then evaluate the electrical power consumption of the

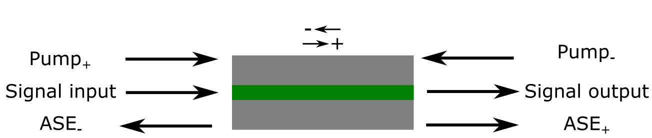


**Fig. 1.** Schematic illustration of on EDFA.

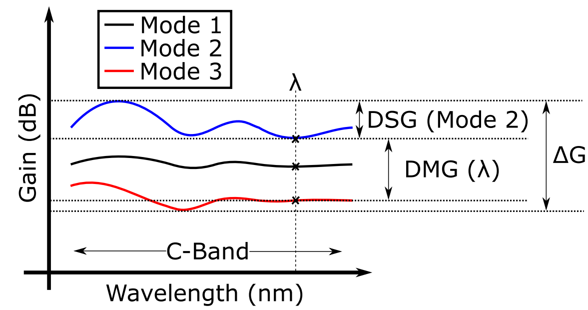


**Fig. 2.** Schematic representation of the evolution of gain as a function of signal wavelength for different modes in a non-equalized gain configuration.

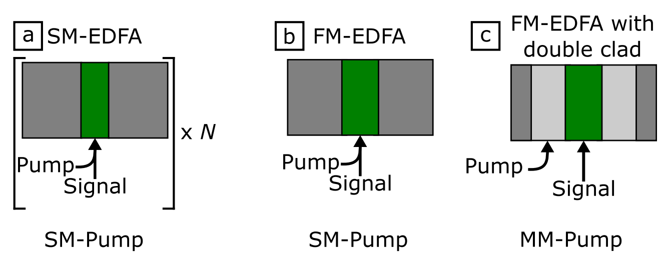


**Fig. 3.** The three different architectures that are considered in this work to estimate the power consumption of EDFAs for SDM: (a) several SM-EDFAs in parallel, (b) core-pumped FM-EDFA and (c) cladding-pumped FM-EDFA.

pump laser, which is the most important component in terms of OPEX in the amplifier.

By considering a step index fiber, with Numerical Aperture (NA) fixed at 0.16 and variable core size, optical power consumption of a FM-EDFA can be approximated, in order to compare it to parallel SM-EDFAs. First, the optical power consumption of $N$ SM-EDFA can be easily obtained by $N \times P^0_{op}$, where $P^0_{op}$ is the optical power consumption of a single SM-EDFA (arbitrarily set at 50 mW for this study). This linear behavior is depicted in Fig. 4.

Secondly, in the case of a core-pumped FM-EDFA, the average gain produced by the amplifier is fully determined by pump input power (if fiber length and signal power are fixed). It can be easily demonstrated that the same pump power per unit area should be injected in a FM-EDFA core in order to obtain a gain level similar to that of a SM-EDFA. In other words, the average intensity of the pump radiation should be equal in SM-EDFA and core-pumped FM-EDFA.

$$I_p = \frac{P^0_{op}}{S^0} = \frac{P'_{op}}{S'}$$

where $I_p$ is the average intensity of the pump radiation, $P^0_{op}$ and $P'_{op}$ are the pump optical power of SM-EDFA and FM-EDFA respectively, $S^0$ and $S'$ are the core area of SM-EDFA and FM-EDFA, respectively. Note that, in this simple model, we do not consider the gain equalization issues, which is a much more complicated problem. The core cross-section ratio between SM-EDFA and FM-EDFA is given by the squared ratio between normalized frequencies ($V = \frac{2\pi R_c}{\lambda} NA$).

$$P'_{op} = \frac{S'}{S^0} P^0_{op} = \frac{V'^2}{2.405^2} P^0_{op}$$

The number, $N$, of core-guided spatial modes for the FM-EDFA as a function of the normalized frequency $V$ can be easily computed by using a mode-solver or could be found in the literature (see for example Ref. [8]). It is then possible to plot the optical power consumption as a function of the number of guided modes (see Fig. 4).