Evaluation of Potential Optical Amplifier Concepts for Coherent Mode Multiplexing

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Abstract: Fiber capacity increase by coherent mode multiplexing requires inline optical amplification for cost and energy efficiency. Erbium doped and distributed Raman fiber amplifier concepts are evaluated concerning their suitability for this function with promising perspectives.

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1. Introduction

Data traffic in long haul networks has grown with an increase of 60 % per annum in recent years and will most likely continue to grow exponentially [1]. The potential of concepts to increase the capacity of optical transport systems based on wavelength division multiplexing (WDM) and single mode fiber (SMF) such as enhanced bandwidth efficiency enabled by higher order modulation formats and wider wavelength bands will be exhausted in a few years from now. Other cost and energy efficient approaches to increase the capacity per fiber have to be found to open a path for continued exponential growth of data traffic in the next ten to twenty years.

Spatial mode multiplexing in multimode fibers has been proposed as an additional dimension to increase fiber capacity [2,3]. For best use of this concept, each eigenmode capable of propagating in the fiber should carry its own individual signal. Unavoidable coupling of modes during propagation will require coherent techniques to separate the channels after transmission. Multiple input / multiple output (MIMO) techniques can be considered being a promising approach [4]. Two different concepts have been proposed to realize transmission of multiple modes in a single fiber as depicted in Fig. 1. The first one relies on a single core with a doping profile enabling propagation of multiple eigenmodes (SCM). The second one features multiple single mode cores in the same cladding (MSC).

Cost and energy efficiency of single mode WDM transmission benefits significantly from simultaneous processing of multiple wavelength channels in a single optical amplifier. Increased fiber capacity enabled by multimode transmission can achieve similar cost and energy efficiency only, if the channels are not just transmitted in multimode fiber spans but also optically amplified by multimode inline amplification. Therefore, multimode amplification with equal gain and equal noise performance for all modes is an important function to enable multimode operation of the entire link.

Lumped amplification in erbium doped fibers and distributed Raman amplification in the transmission fiber are the most commonly used amplifier concepts for single mode long haul WDM transmission. In this contribution, we evaluate the potential of these two concepts to provide multimode amplification for fiber capacity increase by coherent mode multiplexing. The ability to realize cost and energy efficient multimode amplification will have an important impact on the suitability of the SCM and the MSC fiber concept as a solution for increased fiber capacity of long haul WDM transmission systems.

2. Erbium-doped fiber amplifiers

Single mode erbium-doped fiber amplifiers are deployed for optical signal amplification in the majority of commercial long haul (LH) WDM systems due to their excellent compatibility with fiber based transmission, high pump power efficiency, small noise figure, and low cost. It would be highly desirable to refine this amplifier concept towards multimode operation. The potential to use erbium-doped active fibers for multimode amplification has already been demonstrated [5]. However, research on optical amplification in multimode fibers has mainly focused on very high output powers in recent years [6].

One important aspect of inline amplification is low noise operation with similar noise figures of all channels. Decent noise performance requires much higher probability of photon creation due to stimulated emission than photon annihilation due to absorption. For wavelengths around 1550 nm, this can only be achieved by strong inversion of erbium ions. The population density of the upper laser level has to be considerably higher than the population density of the ground state. As high pump spatial power densities are required to achieve strong inversion, the ability to achieve them will be a crucial criterion for the cost and energy efficiency of multimode amplification concepts.

The pump spatial power density required for strong inversion can be estimated from a simplified rate equation model for the Er^{3+} ions in a silica host matrix. Fig. 2 shows the energy levels considered in the model – the ground state $^4I_{15/2}$, labeled "1", which coincides with the lower laser level, the upper laser level $^4I_{13/2}$, "2", and the pump level $^4I_{11/2}$, "3". Absorption of pump radiation around a wavelength of 980 nm results in the transition "1" -> "3" depicted by the solid arrow. Depopulation of the pump level occurs either by a nonradiative transition "3" -> "2" depicted by the dotted arrow or a spontaneous radiative transition "3" -> "1" depicted by the dashed arrow. The signal radiation around a wavelength of 1550 nm can stimulate the transition "1" -> "2" (absorption) or the transition "2" -> "1" (stimulated emission). Depopulation of the upper laser level also occurs due to the spontaneous radiative transition "2" -> "1".

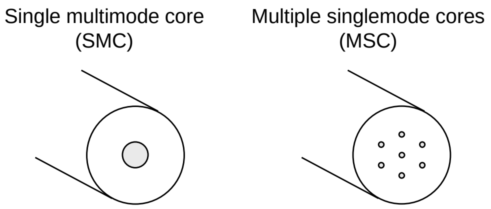

Fig. 1: Fiber types for multimode transmission

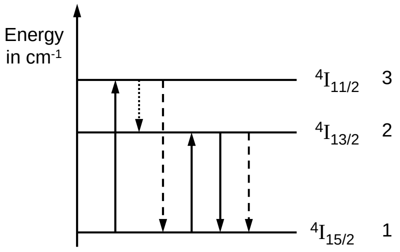

Fig. 2: Simplified energy level diagram of Er^{3+}

The time derivatives of the population densities N_i in m^{-3} with i = "1", "2" or "3" of the three levels can be described by the following set of rate equations: $dN_1/dt = - W_{13}N_1 - A_{31}N_3 - W_{12}N_1 + W_{21}N_2 + A_{21}N_2$, $dN_2/dt = A_{32}N_3 + W_{12}N_1 - W_{21}N_2 - A_{21}N_2$, and $dN_3/dt = W_{13}N_1 - A_{31}N_3 - A_{32}N_3$, where A_{ik} denotes the spontaneous transition rate in s^{-1} from level i to level k and W_{ik} the transition rate in s^{-1} from level i to level k stimulated by radiation. The stimulated emission rate W_{ik} is related to the spatial power density S in W/m^2 at a given wavelength, the absorption or emission cross section σ_{ik} in m^2 of the given transition, Planck's constant h and the frequency ν in Hz of the radiation by $W_{ik} = \sigma_{ik}{:}S / (h\nu)$.

For low noise figures, strong inversion has to be achieved especially in the input section of the active fiber. In this section, the signal power is usually not strong enough to cause saturation, i. e. the spontaneous transition rate dominates over the stimulated ones: $A_{21} >> W_{21}$ and $A_{21} >> W_{12}$. In silica glass, the nonradiative depopulation of the pump level dominates over the radiative one: $A_{32} >> A_{31}$. The requirement that a given ion has to be either in state "1", "2", or "3" leads to the completeness condition for the population densities and the Er^{3+} ion concentration N_t: $N_t = N_1 + N_2 + N_3$. With these approximations, the following equation for the excitation ratio of the upper laser level η as a function of the spatial power density of the pump radiation S_p in W/m^2 can be derived:

$$\eta = \frac{N_2}{N_t} = \frac{S_p}{S_p + h\nu A_{21} / \sigma_{13}} \tag{1}$$

Decent noise performance close to the quantum limit can be achieved with an excitation ratio η around 0.95. With a typical spontaneous emission rate $A_{21} = 83\ s^{-1}$ and absorption cross section for the pump radiation $\sigma_{13} = 2.3 \times 10^{-25}\ m^{-1}$, this leads to a required spatial pump power density $S_p = 1.6\ GW/m^2$. In order to keep the pump power which is necessary to achieve such high spatial power densities low, typical single mode active fibers feature a small effective mode area A_{eff} around 20 µm^2. Such an Er^{3+}-doped fiber can be strongly inverted with pump powers around 32 mW.

The pump power required to achieve the same level of inversion in a multimode active fiber depends on the concept used for guiding the pump radiation. In case of multicore fibers, guiding the pump radiation by a double cladding can ease the generation of the strong pump radiation and the coupling into the active fiber. However, sufficient spacing between the double cladding interface and the outer ring of cores has to be provided to avoid additional loss of the signal radiation. The required spacing will be similar to the spacing between the cores which is necessary to avoid excessive coupling of the radiation guided by the cores. This results in large effective areas of the pump radiation in the inner cladding. For instance, with a total number of 7 cores and a spacing of 20 µm between them, the inner cladding needs an outer diameter of 80 µm, corresponding to an effective mode area around 5,000 µm^2. In this fiber, a pump power of 8 W is necessary to achieve the above mentioned spatial power density required for strong inversion.

Much better pump power efficiency can be realized, if the pump radiation is guided by the same single mode cores as the signal radiation. This concept reduces the required pump power, but it complicates the coupling of the pump radiation into the active fiber. Fig. 3 depicts a potential solution for the pump and signal radiation combiner.

The dichroic mirror provides the core function. Its dielectric coating strongly reflects the pump radiation around 980 nm and is transparent for the signal radiation around 1550 nm. The fiber taper and gradient index (GRIN) lens arrays are required to transform the field distributions from the signals in the multicore fiber to parallel collimated beams. Pump radiation is generated by laser diodes with single mode pigtails, which are combined to a fiber bundle to realize the appropriate arrangement of parallel beams. With such a pump signal combiner, the total pump power required for high inversion in the cores of the active fiber can be reduced to 7 x 32 mW = 224 mW

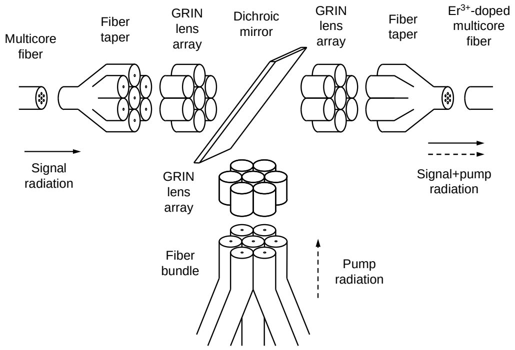

Fig. 3: Pump signal combiner for multicore fibers

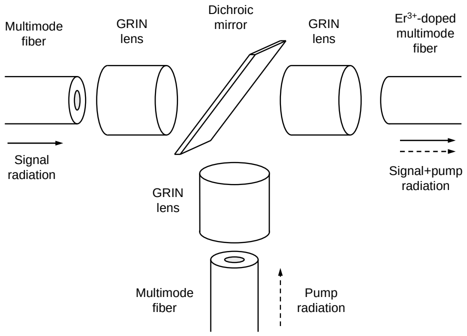

Fig. 4: Pump signal combiner for multimode fibers

A much simpler approach can be realized for the pump signal combiner for multimode fibers as shown in Fig. 4. The arrangement resembles the single mode version. An Er^{3+}-doped fiber enabling propagation of up to 9 modes can be realized with a numerical aperture NA = 0.23 and an effective mode area of A_{eff} = 85 μm^2. For this fiber, around 136 mW of total pump power are required for high inversion levels – significantly less than for the multicore fiber.

3. Distributed Raman amplifiers

Distributed Raman amplification is the second most frequently deployed amplifier concept for terrestrial LH WDM systems. Its applicability to coherent mode multiplexing would be desirable due to its noise reduction capabilities. Required pump powers can be estimated from analogies. A flat Raman gain of 10 dB across the C-band can be achieved in standard single mode fibers (A_{eff} = 80 μm^2, peak Raman coefficient $g_R = 2.4 \times 10^{-14}$ m/W) with two pump wavelengths with a total pump power around 550 mW, corresponding to a spatial pump power density S_p = 6.9 GW/m^2.

In case of direct pumping of multiple cores with the combiner concept depicted in Fig. 3, the required pump power scales linearly with the number of cores, resulting in 3.9 W for a 7 core fiber. A double cladding pump approach with A_{eff} = 5000 μm^2 would need around 34 W of total pump power. For a single core multimode fiber capable of transmitting up to 9 modes with a numerical aperture NA = 0.1 and A_{eff} = 440 μm^2, the required spatial pump power density can be achieved with a total pump power of 3.0 W. Again, the single core multimode fiber achieves better power efficiency than the multicore fiber. The larger A_{eff} compared to the multimode erbium-doped fiber was chosen, because the distributed Raman amplification is induced in the transmission fiber of a span where nonlinear interactions between signals have to be avoided.

4. Summary and conclusions

Prospects of realizing lumped erbium-doped and distributed Raman amplifiers capable of providing inline multimode amplification for coherent mode multiplexing transmission were evaluated. Pump powers required for sufficient gain and decent noise performance are challenging, especially in the distributed Raman case, but should be feasible. Multimode fibers with a single core were found to require less pump power than directly pumped multicore fibers. Double cladding pump approaches for multicore fibers need excessive pump powers and cannot be considered being energy efficient.

5. References

[1] A. Chraplyvy: "The Coming Capacity Crunch" 35th European Conference on Optical Communication (ECOC 2009), paper 1.0.2
[2] S. Berdaguè, P. Facq: "Mode Division Multiplexing In Optical Fibers", Applied Optics (1982), Vol. 21, No. 11, pp. 1950 – 1955
[3] M. Koshiba, K. Saitoh, Y. Kokubun: "Heterogeneous multi-core fibers: proposal and design principle", IEICE Electronics Express (2009), Vol. 6, No. 2, pp. 98 - 103
[4] A. R. Shah, R. C. J. Hsu, A. Tarighat, A. H. Sayed, B. Jalali: "Coherent optical MIMO (COMIMO)", Journal of Lightwave Technology (2005), Vol. 23, No. 8, pp. 2410- 2419
[5] G. Nykolak, S. A. Kramer, J. R. Simpson, D. J. DiGiovanni, C. R. Giles, H. M. Presby: "An Erbium-Doped Multimode Fiber Amplifier", IEEE Trans. Phot. Technol. Lett. (1991), Vol. 3, No. 12, Dec., pp. 1079 – 1081
[6] C. D. Stacey, J. M. Jenkins: "Demonstration of fundamental mode propagation in highly multimode fibre for high power EDFAs", Conference on Lasers and Electro-Optics Europe (CLEO 2005), Munich, Germany, June 17, p. 558