Optical Amplifiers for SDM Communication Systems

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Abstract *We review recent progress on the implementation of multi-spatial channel optical amplifiers and associated passive components for SDM transmission systems.*

Introduction

Space Division Multiplexing (SDM) [1] has attracted considerable attention in the optical fibre communication community as a promising means to increase the capacity-per-fibre and, more importantly, to reduce the associated cost per-transmitted-bit.

Various SDM transmission fibres, for example, few-mode fibres (FMFs), multicore fibres (MCFs), ring-core fibres (RCF) and hollow-core photonic bandgap fibres (HC-PBGFs) have all been proposed and the possibility to support capacities beyond those possible using conventional single mode fibre technology has now been reliably proven in the laboratory. However, in order to develop practical systems and to realise the cost and performance benefits promised by SDM it is necessary to develop SDM compatible devices and components. The need for SDM amplifiers in particular is central to the SDM value proposition. In this tutorial we will review the state-of the-art in SDM optical amplifiers for the various SDM approaches under investigation – with particular focus on multi-core and few mode erbium doped fibre amplifiers.

Multicore EDFAs

To date, the greatest progress in terms of spatial channel count has been made in the area of MCF-EDFAs. Early work focused on the development of core-pumped MC-EDFAs with a limited number of cores (typically 7) [2,3]. Whilst excellent performance was reported, with gains and noise figures (NFs) comparable to those of conventional EDFA achieved, the early amplifier architectures demonstrated supported only a limited amount of cost-saving component integration e.g. each spatial channel still requiring an individual pump coupler, along with a Fan-In/Fan-Out (FI/FO) to address the individual channels [2,3]. A more attractive proposition is to use cladding-pumping as a means to simultaneously deliver the pump radiation to the individual doped cores [4,5]. Here, a multimode pump-coupler can be used to inject pump radiation from a Multimode (MM) pump diode into the fibre cladding, which is itself coated with low-index polymer to make the cladding into a MM waveguide for the pump radiation. The active rare-earth ion doped cores are bathed in pump light and gradually absorb this along the fibre length. A population inversion is thereby created providing for optical gain. To ensure efficient absorption of the pump radiation the Er-doped cores are also co-doped with a relatively high level of Ytterbium (Yb) which exhibits strong absorption for pump light around 976 nm. These excited Yb^{3+} ions then transfer their energy to the Er^{3+}-ions, resulting in gain at wavelengths around 1550 nm. The attractions of cladding pumping are multi-fold. Firstly, it allows the use of relatively low-cost, low-brightness multimode pump diodes, as well as obviating the need for multiple WDM pump combiners. Secondly, it eliminates the need for FI/FO devices allowing the development of true inline MCF-EDFAs, and finally, it allows for natural integration of other passive MCF-devices such as isolators and gain-flattening filters. The downside of using cladding pumping is that the limited pump-brightness compromises the level of inversion that can be achieved in the amplifier, resulting in a compromise in noise figure (typically an additional ~1 dB) and the optimum wavelength of operation is typically shifted to slightly longer wavelengths within the L-band. The spectral bandwidth can also be slightly compromised by the use of ytterbium and the associated glass host needed for efficient energy transfer from Yb to Er ions. One other potential drawback is that there is no option of per-core gain control through regulation of the pump power as the one (or potentially few) pump diodes energize all of the core simultaneously. The implications of this from a networking perspective have yet to be properly established, nevertheless significant progress on MCF-EDFAs has been made, with as many as 32-amplifying cores operated in a single cladding pumped device reported (see Fig.1), and the use of such an amplifier in a long haul transmission experiment over >1000 km distance demonstrated [7]. Note that 32c passive components such as isolators and filters have also now been developed [8].

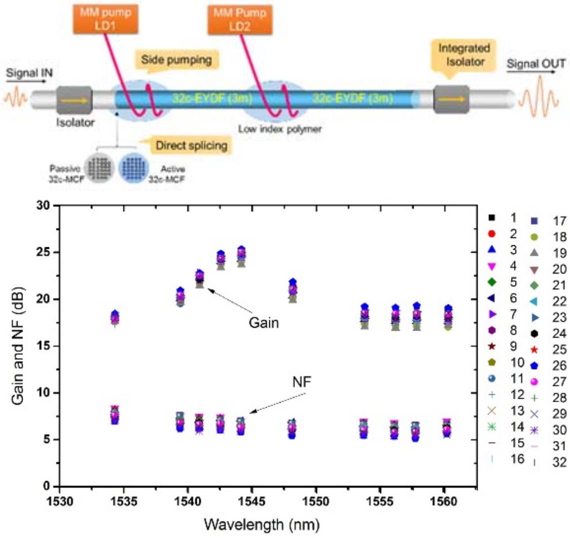

Fig. 1 Configuration, Gain and NF of 32c-MC-EYDFA for -4dBm input signal [6].

Few Mode EDFAs

Likewise there have been significant advances in the development of few mode amplifiers capable of simultaneously amplifying signals propagating on the multiple modes of a few mode fibre. Initial work focused on core-pumped amplifiers supporting 2 mode groups and a total of 3 distinct spatial modes, with good overall gains and noise figures demonstrated that were sufficient for early transmission experiments [9,10], A critical issue in few mode amplifiers is the minimization of Differential Modal Gain (DMG) between all the supported modes which can directly affect the outage probability of a few mode transmission system and substantially limit system reach. These early experiments suffered from reasonably high values of DMG in the range 3-5 dB for an overall gain of order 25 dB. Various strategies to help overcome DMG have been developed (see Fig.2) these include: the use of complex refractive index and rare earth dopant distributions designed to equalize the modal overlap with the inverted ion population and the use of higher-order mode pump beams (either in isolation or in combination) to again equalize the modal overlap of the guided modes with the population inversions that these more complex pump modes create. Using this approach DMG values of <2 dB have been achieved, initially in amplifiers supporting as many as 6 distinct spatial modes [11], and more recently with amplifiers supporting as many as 10 modes [12]. Such amplifiers have been successfully used in a number of FMF transmission experiments [13-14].

As with MC-EDFAs, the adoption of cladding-pumping provides significant practical advantages, in particular in terms of facilitating fully-integrated amplifier devices without the requirement for mode multiplexing and demultiplexing devices and providing significant component sharing opportunities and hence cost reduction, Initial results in this direction have now been reported [15] and associated system experiments demonstrated [16]

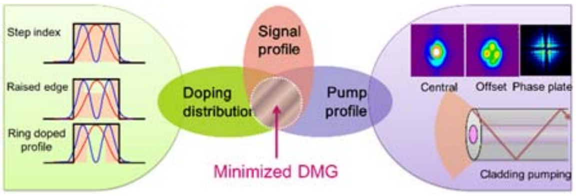

Fig. 2. Strategies to minimize DMG in few-mode EDFAs. The DMG can be engineered by: i) tailoring the radial erbium-doping concentration profile of the erbium doped fibre, ii) controlling the pump field intensity distribution and (iii) controlling the signal mode profile.

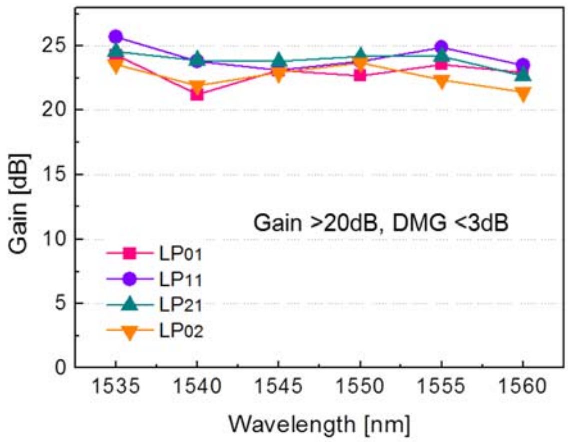

Fig. 3. Performance of a core-pumped 6M-EDFA showing the low values of DMG possible for an optimized system by implementing index profiling and selective mode pumping [11].

Conclusions

Significant advances have been made in the development of SDM amplifiers both of MCF and FMF designs, and their combination, with comparable gains and NFs per spatial channel to conventional SM-EDFAs. Moreover, in-line pump coupling approaches have been shown, along with integrated passive components such as isolators and filters, which promise significant cost savings relative to the use of an equivalent numbers of conventional SM amplifiers. However, although very good performances have been shown, both from a device and system perspective, the impact of the associated loss of independent control per spatial channel has yet to be properly assessed and the envisaged cost and power savings have yet to be properly quantified. This will need to become a major focus of research in the coming years.

Acknowledgements

The authors gratefully acknowledge support from the EU-Japan coordinated R&D project on "Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI)" commissioned by the Ministry of Internal Affairs and Communications (MIC) of Japan and EC Horizon 2020. DJR gratefully acknowledges support from the Royal Society through provision of a Royal Society Research Merit Award.

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