Low Cost Solution for Super L-Band Fiber Amplifier based on Single-mode and Multi-mode Hybrid Pumping Scheme

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Abstract: A super L-band amplifier (21 dB gain over 1575~1626 nm) is demonstrated using two types of erbium doped fibers designed for single-mode and multi-mode pumping. Noise figure, power consumption and fabrication cost are analyzed.

1. Introduction

Wideband amplifiers are among the main building blocks for future telecom systems [1]. Apart from the extensive investigations on amplifiers for S- [2], E- [3], O- [4] and U- [5] bands, much effort is being devoted on further extending the bandwidth of existing commercialized erbium doped fiber amplifiers (EDFA), especially in the L-band. EDFs that are able to support amplification beyond 1620 nm ("super" L-band) were reported recently [6], [7]. In addition to the bandwidth, the cost of the amplifier is also a major concern. In conventional EDFAs, the 980 nm single-mode (SM) pump diodes represent over 50% of the overall amplifier cost. Considering that high-power but low-brightness multimode (MM) diodes are much cheaper than their SM counterparts in $/W, the integration of MM pumping in EDFA architectures could therefore enable a significant cost reduction, provided that the performance remains comparable with that of SM pumping. Super L-band EDFs are especially well suited for the MM cladding pumping scheme because they are mainly based on the phosphor-silicate glass, which is almost the only material that ensures a quick energy transfer from the ytterbium ions to the erbium ions. Until now, super L-band EDFs and amplifiers using MM pumping have not yet been reported. Therefore, the performance, cost and power consumption of amplifiers that implement SM-MM-hybrid pumping remain to be investigated.

In this paper, we report two types of "super" L-band EDFs, one designed for SM pumping and the other for MM pumping, and demonstrate super L-band fiber amplifiers that provide 16 ~ 21 dB gain in the 1575 ~ 1626 nm spectral region for input powers between -1 to 4 dBm, respectively. Compared to pure-SM pumping, hybrid pumping can lower the fabrication cost of L-band amplifiers, especially in future multi-fiber-based space division multiplexing (SDM) amplifier arrays. Meanwhile, the performances, including the gain level, the NF and the electrical power consumption, can be kept the same or even be better.

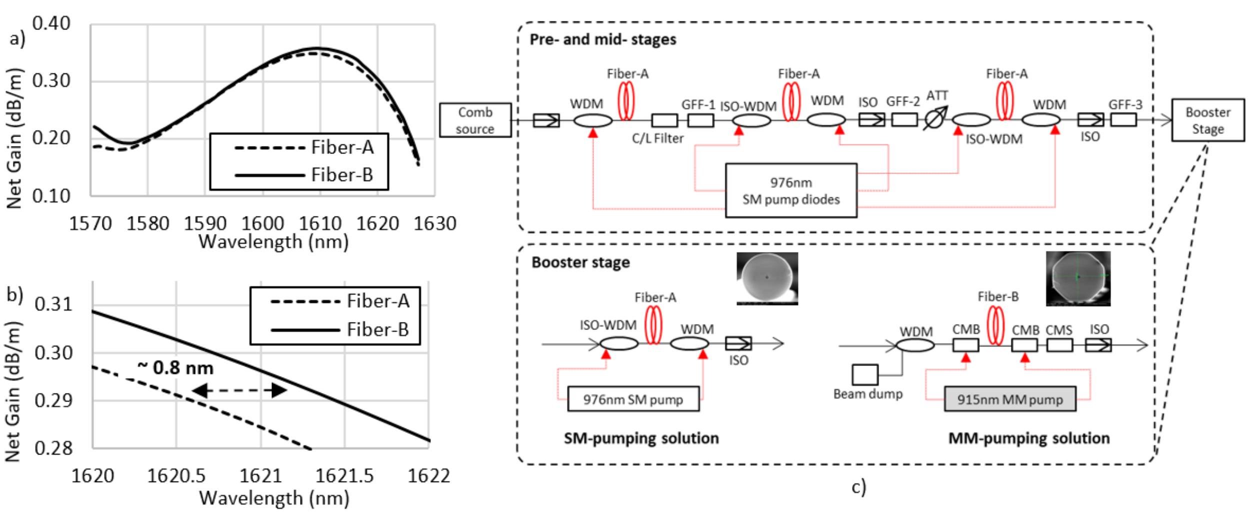


Fig. 1. a) The gain shapes of Fiber-A and Fiber-B under a similar Er^{3+} inversion level; b) a zoom in of the gain shapes in the vicinity of 1621 nm; c) a schematic diagram of the super L-band fiber amplifier. Two schemes were tested: pure SM-pumping and hybrid SM and MM pumping. *Insert*: SEM pictures of Fiber-A and Fiber-B.WDM: wavelength-division multiplexer; GFF: gain flattening filter; ISO-WDM: isolator-WDM hybrid; ISO: isolator; ATT: tunable attenuator; CMB: signal/MM-pump combiner; CMS: cladding mode stripper.

2. Characterization of SM- and MM- pumped super L-band Erbium Doped Fibers

Two erbium doped fibers (EDFs) were designed and fabricated at the *Center for Optics, Photonics and Lasers (COPL), Université Laval, Canada*. The fibers were fabricated using the conventional MCVD process, combined with the solution doping technique, and the glass composition was optimized to provide sufficient gain beyond 1620 nm. Fiber-A is designed for 980 nm SM pumping, while, in Fiber-B, ytterbium ions were added so as to enable Er^{3+} excitation through 915 nm MM pumping. The SEM pictures of the two fibers can be found in the insert of **Error! Reference source not found.**(c). The cladding of Fiber-B was made to be octagonal so as to increase the MM pump absorption.

The gain shapes of the two fibers were evaluated in a single-stage amplifier setup. The pump wavelength was chosen to be 1480 nm so that the pumping conditions were the same for both fibers. **Error! Reference source not found.**(a) plots the gain shapes which were obtained under similar Er^{3+} inversion levels. Both Fiber-A and Fiber-B can support super L-band amplification. There exists a slight difference in the gain shapes between Fiber-A and Fiber-B, which is believed to be induced by the additional ytterbium ions in Fiber-B. As seen in the zoom in of the gain shape in **Error! Reference source not found.**(b), Fiber-B can provide ~ 0.8 nm more bandwidth than Fiber-A in the L-band.

3. Fiber Amplifier Setup and Experimental Results

Using the two fibers, we made a super L-band fiber amplifier with a hybrid pumping scheme, *i.e.* SM pumping for the first three stages and MM pumping for the last booster stage. In comparison, an amplifier based on pure-SM pumping was also built and tested. The schematic diagram of the experimental setup is shown in Fig. 1. The signal source is an amplified spontaneous (ASE) generated from a section of Fiber-A which was then filtered by two cascaded interleavers with ~ 100 GHz spacing. The total signal power was tuned from -1 to 4 dBm by an optical attenuator. The architecture of the first three amplification stages is identical for both pumping schemes under investigation. It contains three sections of Fiber-A, pumped by several 976 nm SM semiconductor diodes so as to guarantee the best NF performance. In the hybrid pumping scheme the booster stage utilized Fiber-B and 915 nm MM pumping. The backward ASE generated by the ytterbium ions, located in the 1 μm region, was eliminated by an additional thin-film WDM filter and absorbed by a beam dump. In the pure-SM pumping scheme, Fiber-A (bi-directionally pumped) was used in the booster stage. Three chirped fiber Bragg grating (FBG)-based GFFs were inserted to flatten the gain curve.

Fig. 2(a) compares the gains obtained with both pumping schemes under investigation. A gain tilt with a few dBs was intentionally induced for the compensation of the stimulated Raman scattering in the passive transmission fiber. It can be seen that there is a relatively large gain ripple, ~ 8 dB, in the gain curve. This ripple is related to the fact that the GFFs used in the experiment were designed for the previous iterations of the EDFs and were not perfectly adapted for Fiber-A and Fiber-B. Nevertheless, an averaged gain level of 16 dB and 21 dB is achieved with an input signal power of 4 dBm and -1 dBm, respectively. To this extent, an attenuation of 5 dB was added with the VOA in-between the 2nd and the 3rd stages for the 16 dB gain setting so as to get the same gain tilt. Averaged NFs of ~ 6.5 dB (for 21 dB gain level) and ~ 7.9 dB (for 16 dB gain level) can be reached for both the hybrid and the pure-SM pumping schemes, see Fig. 2(b).

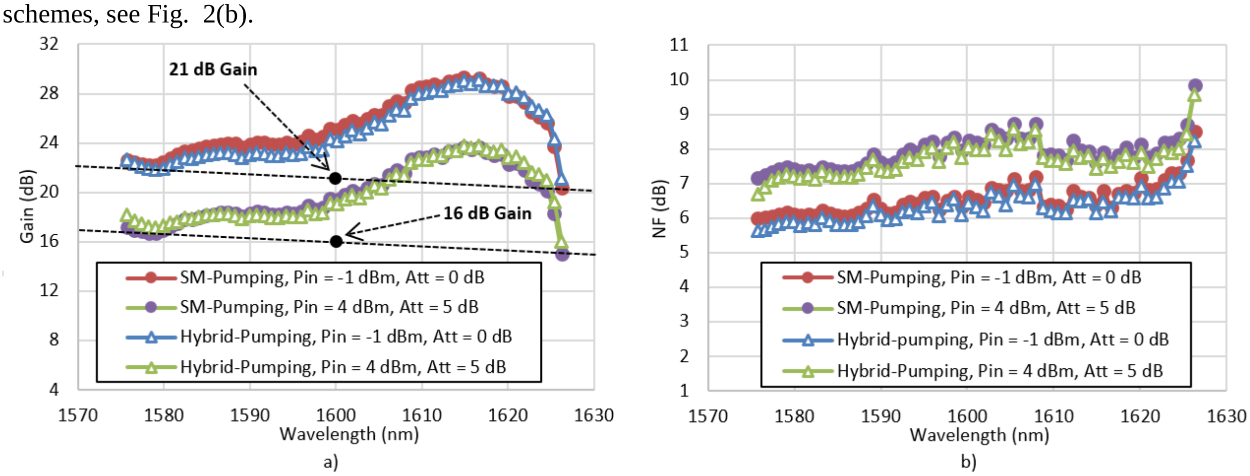
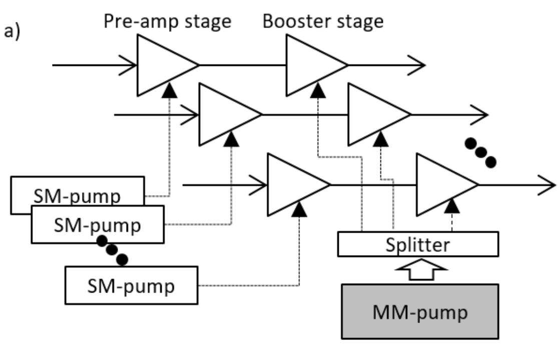


Fig. 2. a) Gain and b) NF comparison between the SM-pumping and SM-MM-hybrid-pumping super-L-band fiber amplifier.

4. Analysis of Cost and Power consumption

Can a hybrid pumping amplifier provide a similar electrical power consumption compared to the pure-SM pumping scheme? To answer this question, the optical and electrical power consumptions of the SM and MM pumped booster stages have been tested under different signal input power levels, as shown in Fig. 1. During the experiment, whenever the input signal power was changed, the SM and the MM pump powers were adjusted accordingly in order to reach the same gain level and shape as shown in Fig. 1(a). The results are plotted in Fig. 3(b). The green circles represent the optical power consumption ratio between the MM and SM pumps. The MM optical power consumption is generally 1.7 ~ 3 times that of the SM pumps. This is explained by the fact that, in Fiber-B, MM pump energy is converted into the parasitic 1 µm ytterbium ASE which increases as the input L-band signal power decreases. The purple triangles show the electrical power consumption ratio, calculated using the E/O efficiencies of the commercial MM (~ 29%) and SM pump diodes (~13%) [8]. The electrical power consumption ratio becomes lower than unity when the signal input power is above ~ 11 dBm. This means that MM pumping can be more power efficient than SM pumping provided that the signal input power is high enough, *i.e.* the MM pumping stage is placed further downward in the amplification chain.

The cost of a commercially available 10 W 915 nm MM pump diode is only ~ 10% that of a W-level 976 nm SM pump diode. Replacing part of the SM pump by MM pump can obviously reduce the amplifier's fabrication cost. Of particular interest are the case of future multi-fiber-based SDM amplifiers where, as seen in Fig. 3(a), a 10W MM pump diode would be able to boost 4~5 L-band amplifiers at a negligible cost. Generally speaking, several tens of percent of cost saving in pump diodes is foreseeable. Considering that the input signal power of the booster stage is typically above 10 dBm (the gray region in Fig. 3(b)), there is plenty of room for an amplifier designer to play with the trade-off between the fabrication cost and the wall-plug power consumption.



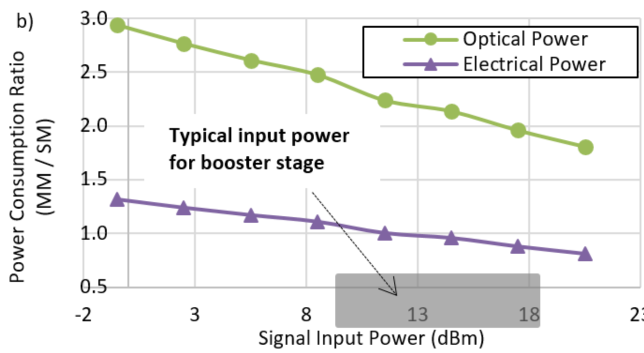


Fig. 3. a) Schematic diagram of the fiber line amplifier array using the SM-MM-hybrid pumping scheme; b) the ratio of MM power consumption over SM power consumption, both optical and electrical, under different input signal power levels.

5. Conclusion

It is technically feasible to design super L-band EDFs for either SM or MM cladding pumping. Compared to the pure-SM pumping scheme, the super L-band fiber amplifier based on hybrid pumping can achieve the same gain and NF performances, while, the electrical power consumption can be comparable or even lower. Therefore, the hybrid pumping scheme has the potential to significantly reduce the amplifier's cost in future super L-band, multi-fiber-based SDM amplifiers.

6. References

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