Broadband High Gain Polarization-Maintaining Holmium-doped Fiber Amplifiers

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Abstract *We report the first experimental demonstration and record performance of broadband, high gain PM HDFAs at λ_s = 2051 nm. We achieve G = 60 dB, BW = 100 nm, η = 80%, and P_{out} = 6.7 W.*

Introduction

High capacity WDM transmission system experiments in the 2000 nm band [1-4] illustrate the need for wide bandwidth, high gain optical amplifiers in this region. Holmium-doped fiber amplifiers (HDFAs) extend the bandwidth response toward long wavelengths of 2000-2150 nm for optical transmission, and also enable high energy physics experiments. Recent results have shown that with a single stage standard (non-polarization-maintaining) HDFA pumped at 1125 nm [5], G > 35 dB and P_{out} = 1 W have been achieved, while standard HDFAs pumped at ≈ 1950-2008 nm [6,7] have obtained G = 40 dB, P_{out} = 0.25 W, and noise figures NF = 7-14 dB. Also, as a reference, a single clad Holmium-doped fiber laser operating at 2090 nm and pumped at 1950 nm has shown optical-optical slope efficiencies of 87% [8]. Our investigation here presents the first experimental demonstration of polarization-maintaining (PM) HDFAs in one- and two-stage configurations for λ_s = 2051 nm and λ_p ≈ 1950 nm. The single clad PM HDFAs achieve a unique combination of record performance with gain G = 60 dB, noise figures NF = 10-14 dB, a bandwidth BW of 100 nm, an optical signal to noise ratio OSNR = 58 dB, an optical-optical slope efficiency of η = 80%, and an output power P_{out} = 6.7 W.

PM Experimental Setup

Figure 1 shows the experimental setup for the one- and two-stage PM HDFAs. A multiwatt pump P1 at ≈ 1950 nm is combined in a multiplexer (WDM1) with a 2051.45 nm single frequency input signal P_s (Δv < 1 MHz, Eblana Photonics EP2051) which is then amplified by F1. Light from another multiwatt pump P2 at ≈ 1950 nm is combined in WDM2 with the output signal from F1 which is amplified by F2. Both PM Ho-doped fibers (F1 and F2) are from IXBlue (IXF-HDF-PM-8-125) with L1 = 1.8 m or 3.0 m and L2 = 2.0 m respectively. The core diameter of the fiber is 8 µm with an NA of 0.16, the cladding diameter is 125 µm, and the absorption at 2051 nm is 14.5 dB/m. The PM fiber structure is a Panda shape with birefringence > 2 x10^{-4}. Stage 1 is a preamplifier

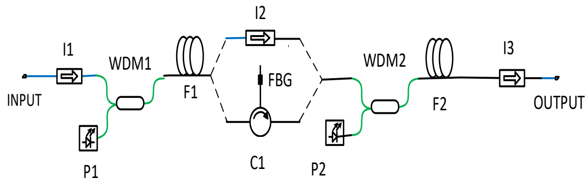

Figure 1. Two Stage PM HDFA with Multiwatt Pump Sources in the 1950 nm Band

while stage 2 functions as a power amplifier. Isolators I1 and I3 in the signal path ensure unidirectional operation and suppress backward ASE. Two interstage signal path elements are used: either an isolator I2, or an ASE filter made of a circulator C1 with a 1 nm wide reflection FBG centered at 2051.45 nm. Signal and pump powers and noise figures are measured internally, and signal and pump light propagate through the amplifier along the slow fiber axis.

Experimental Results

We first investigate amplifiers designed for high gain with L1 = 3.0 m and L2 = 2.0 m. Figures 2

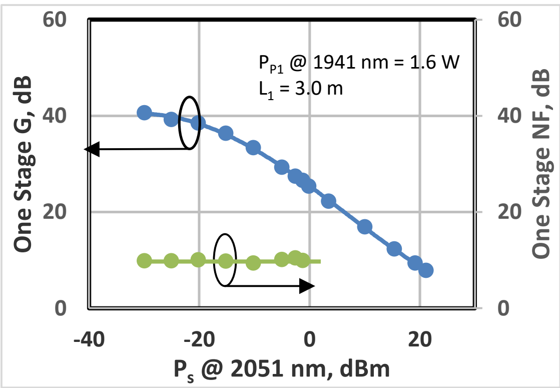

Figure 2. G and NF for One Stage High Gain PM HDFA

and 3 show G and NF for one stage and two stage amplifiers, respectively. For one stage, a maximum gain of 40 dB and an NF of 10 dB are obtained. For two stages, a record maximum gain of 60 dB is achieved with an interstage AWG and circulator (BPF). At this point P_{out} =1W (+30 dBm) is achieved for P_s = – 30 dBm. Maximum gain of 51.5 dB is obtained when an interstage isolator is used because of increased ASE. NF = 14 dB is measured for the two-stage high gain amplifier. The P_s dynamic range for both one and two stage configurations is 30 dB.

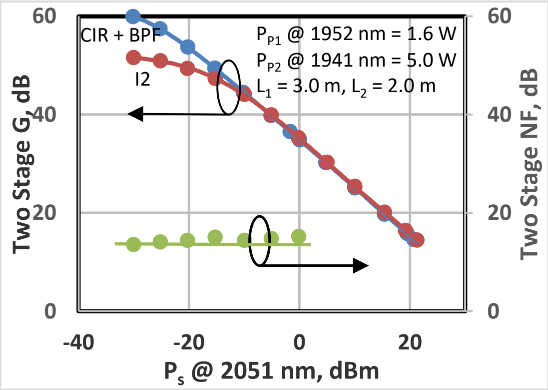

Figure 3. G and NF for Two Stage High Gain PM HDFA

We next investigate amplifiers designed for high output power with L1 = 1.8 m and L2 = 2.0 m. Figure 4 shows P_{out} for one stage vs. pump power P_{P1}, as a function of P_s with a polynomial fit. A maximum P_{out} of 3.46 W is achieved for P_s of +21.5 dBm and a 1941 nm pump power P_{P1} = 5.0 W. Figure 5 plots the evolution of P_{out} for the two-stage high power HDFA, with interstage BPF , vs. P_{P2} as a function of P_s with a linear fit. A maximum output power of 6.7 W is obtained for P_s = +21.2 dBm and a 1941 nm pump power P_{P2} = 8.0 W.

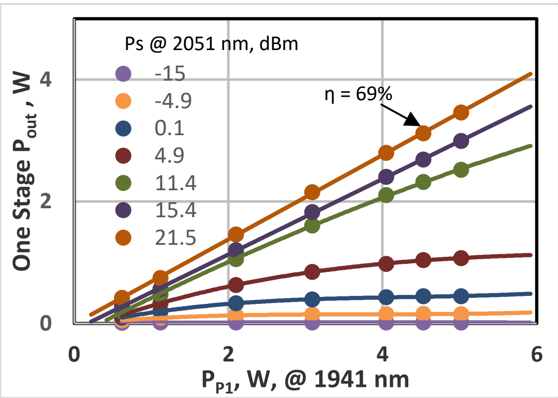

Figure 4. One Stage P_{out} vs. P_{P1} for Different P_s Levels

Output powers of 1.7 W (+32.3 dBm) can be achieved for an input of -15 dBm, demonstrating the high performance of the two-stage power HDFA. The evolution of G for one stage and two stages vs. P_s is plotted in Figure 6. A maximum G of 27 dB is observed for one stage and a maximum gain of 50.5 dB is measured for two stages. The 15 dB gain compression point for

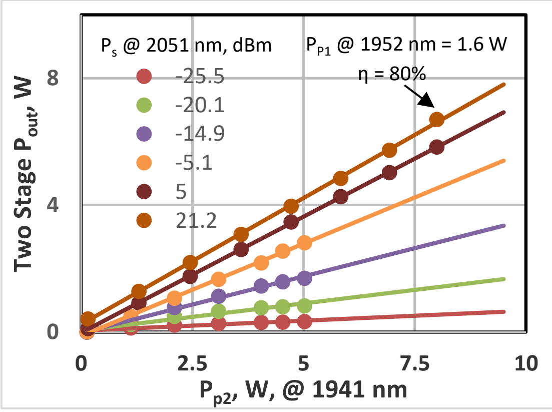

Figure 5. Two Stage P_{out} vs. P_{P2} for Different P_s Levels

the two stage HDFA occurs for P_s = 0 dBm with P_{out} = 3.2 W. Figure 7 shows the evolution of slope efficiency η as a function of P_s for one and two stages, where the optical-optical slope efficiency $\eta = \Delta P_{out} / \Delta P_p$. Slope efficiencies of η = 69 and 80% are observed for the one stage and two stage high power amplifiers, respectively.

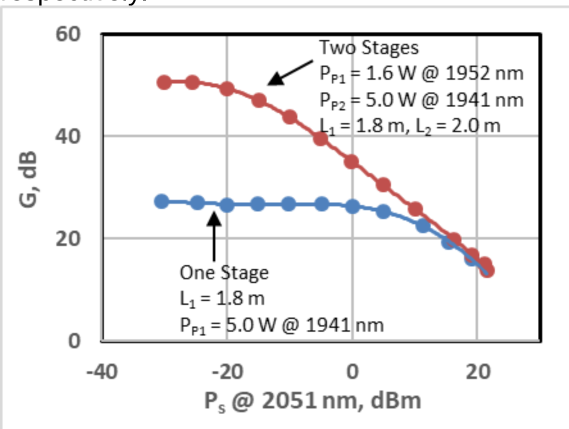

Figure 6. G vs. P_s for One and Two Stages with Different P_p Levels

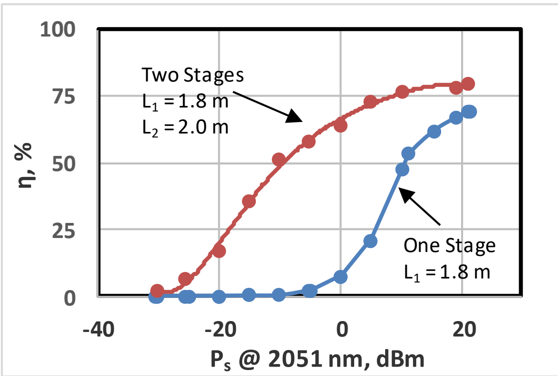

Figure 7. η vs. P_s for One and Two Stage Configurations

In Figure 8 we plot the long-term stability of P_{out} for an elapsed time of six hours. The observed p-p fluctuation in P_{out} is 2% illustrating excellent long-term stability of the two-stage amplifier. No evidence of SBS or other nonlinear effects was observed in our experiments.

Figure 9 shows the output spectrum of the high power two- stage amplifier with an interstage isolator for P_{out} = 6.7 W. An OSNR of 58 dB/0.1 nm is obtained, and the estimated operating bandwidth of the amplifier (at 15 dB down from the ASE peak) is 100 nm (2005-2105 nm). The output polarization extinction ratio (PER) of 20 dB is determined by isolator I3.

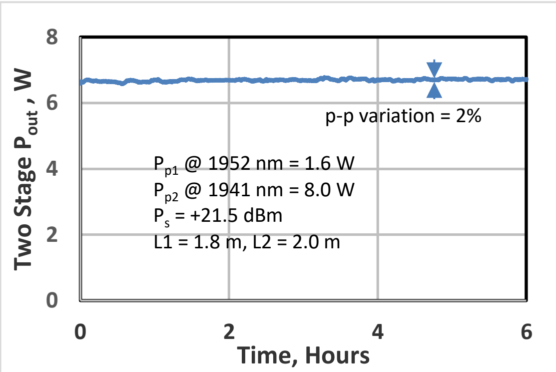

Figure 8. Long-Term Stability of P_{out}.

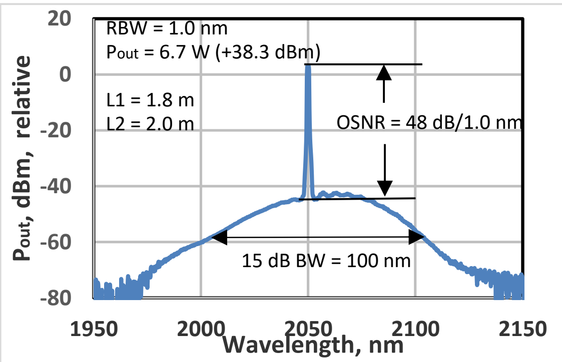

Figure 9. Saturated Output Spectrum of the Two Stage High Power HDFA.

Summary

We have reported the design and experimental behavior of one- and two-stage PM HDFAs at 2051 nm signal wavelength. Our high gain HDFAs achieved G = 40 dB for one stage and G = 60 dB for two stages, P_{out} = 1 W (+30 dBm) for P_s = -30 dBm, NF = 10-14 dB, and a dynamic range of 30 dB. Our high power HDFAs achieved G = 27 dB and P_{out} = 3.4 W for one stage, G = 50.5 dB and P_{out} = 6.7 W for two stages, a long-term variation in P_{out} of 2%, a slope efficiency η = 80%, and BW = 100 nm using an interstage isolator. Our next studies will be to model the one and two-stage amplifiers and optimize their performance with respect to λ_s, P_{out}, and NF. The high performance and design flexibility of the two-stage PM HDFA make it useful for many applications such as LIDAR, high energy physics experiments, and DWDM lightwave transmission systems.

Acknowledgement

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