25 W 2 μm Broadband Polarization-Maintaining Hybrid Ho- and Tm-Doped Fiber Amplifier

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1. Introduction

Current developments in LIDAR and atmospheric sensing experiments highlight the need for multi-watt, large bandwidth, high dynamic range polarization-maintaining optical amplifiers in the eye safe 1.9—2.15 μm band. So far, as an illustration of the previous state of the art for high power devices, multi-watt Tm-doped fiber amplifiers (TDFAs) have been demonstrated by Goodno et al. [1] with an output power of 608 W at a signal wavelength of 2040 nm. As for Ho-doped fiber amplifiers (HDFAs) Hemming et al. [2] have reported output powers of 265 W at 2110 nm. For this HDFA, a double clad Ho-doped fiber pumped by high power fiber lasers made the configuration complex and yielded an optical slope efficiency of 41%. Both of these achievements were with standard (non-polarization-maintaining) fiber.

Recently, we demonstrated a hybrid single clad-double clad TDFA with 20 W output and a dynamic range of >12 dB in the 2 μm band [3]. We have also reported single clad polarization-maintaining (PM) HDFAs with output powers of up to 6.7 W CW at 2051 nm [4], gains G as high as 60 dB, and a dynamic range of 40 dB. The scaling of output power in this amplifier is limited by the amount of pump power that can be coupled into the single clad single mode active fiber, and by the eventual onset of nonlinearities such as stimulated Brillouin scattering (SBS).

In order to scale up both output power and dynamic range performance, we propose here a new PM hybrid HDFA/TDFA with a single clad Ho-doped preamplifier followed by a double clad Tm-doped power amplifier. The role of the Ho-doped fiber preamplifier is to provide large input signal dynamic range and reasonable P_{out} over an operating bandwidth from ≈ 2—2.15 μm. The role of the Tm-doped fiber power amplifier is to offer power amplification with good efficiency, taking full advantage of 2-for-1 ion-ion interactions from 793 nm pumping, with the possibility of scaling up the output power to values much higher than 20 W. Our new hybrid Ho-Tm-doped amplifier design therefore provides a combination of large dynamic range, broad operating bandwidth, and high output power.

In this paper we report the evaluation and performance of a PM hybrid HDFA/TDFA with output power of P_{out} ≥ 25 W at 2051 nm and a high dynamic range of 34 dB. Our paper is organized as follows: first, we present the experimental setup and optical architecture of the three-stage PM hybrid HDFA/TDFA. Next, we describe the experimental performance of the amplifier with a single frequency input signal at λ_s = 2051 nm. We then compare our experimental results with a steady-state simulation of amplifier performance and demonstrate good agreement between theory and data. Finally, we discuss amplifier and performance optimization for the three-stage amplifier, and present directions for future studies.

2. Experimental Setup

The optical design of our hybrid PM HDFA/TDFA is shown in Figure 1. A single frequency input signal at 2051 nm is coupled into a preamplifier consisting of two stages: F1 (3.0 m) and F2 (2.0 m) of PM Ho-doped

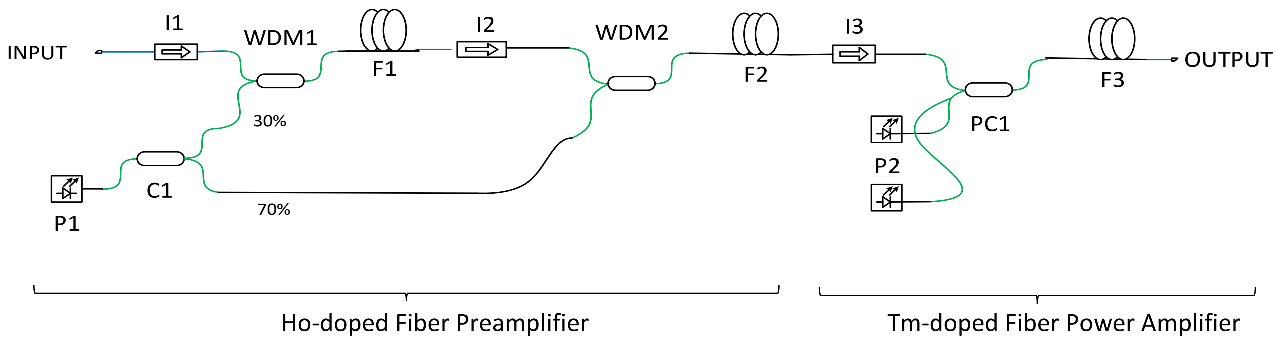

Figure 1. Optical Design of Three Stage Hybrid PM HDFA/TDFA

fiber, iXblue IXF-HDF-PM-8-125. Output from a multi-watt fiber laser P1 at 1941 nm is split by coupler C1 (30%/70%) and is sent to both F1 and F2 via the WDMs. Complete evaluation of the Ho-doped preamplifier is discussed in forthcoming papers [5,6]. The preamplifier output provides the signal input to power amplifier F3, a 5.0 m length of double clad PM Tm-doped fiber (Coherent-Nufern PM-TDF-10P/130-HE). Two multimode multi-watt 793 nm laser sources are coupled into F3 by means of the 2x1 pump combiner PC1. The total pump power at 1941 nm coupled into F1 and F2 is designated P_{P1}, and the total pump power at 793 nm coupled into F3 is designated P_{P2}. In our measurements, input signal power is designated as P_s and output signal power as P_{out}. PM signal light propagates though the fibers and components in the amplifier on the slow fiber axis. Input and output signal powers, pump powers, and noise figures are measured internally.

3. Experimental Results

Figure 2 shows the measured P_{out} as a function of P_{P2} for several values of P_s. The data are plotted in points and the dotted lines are linear fits to the data. The measured values of P_{out} vary linearly with $P_{P2.}$ A maximum optical-optical slope efficiency of $\eta = 54.9$ % is observed at the maximum input signal power $P_s = +21.1$ dBm. η is defined as the change in output power divided by the change in second stage pump power, or $\eta = \Delta P_{out}/\Delta P_{P2}$. The maximum signal output power achieved with this amplifier is 30 W, for $P_{P1} = 4.6$ W @ 1941 nm and $P_{P2} = 53.6$ W @ 793 nm. The slope efficiency η is greater than the simple quantum limit of 793 nm/2051 nm = 38.7 %, clearly indicating the presence of 2-for-1 ion-ion interactions in the double clad Tm-doped fiber in the power amplifier.

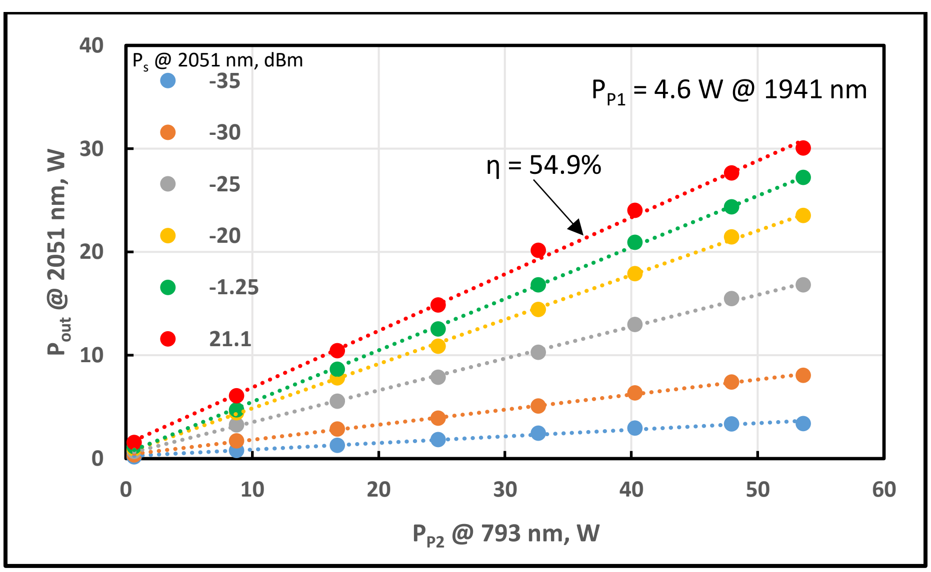

Figure 2. P_{out} vs. second stage pump power P_{P2} for different signal input powers P_s

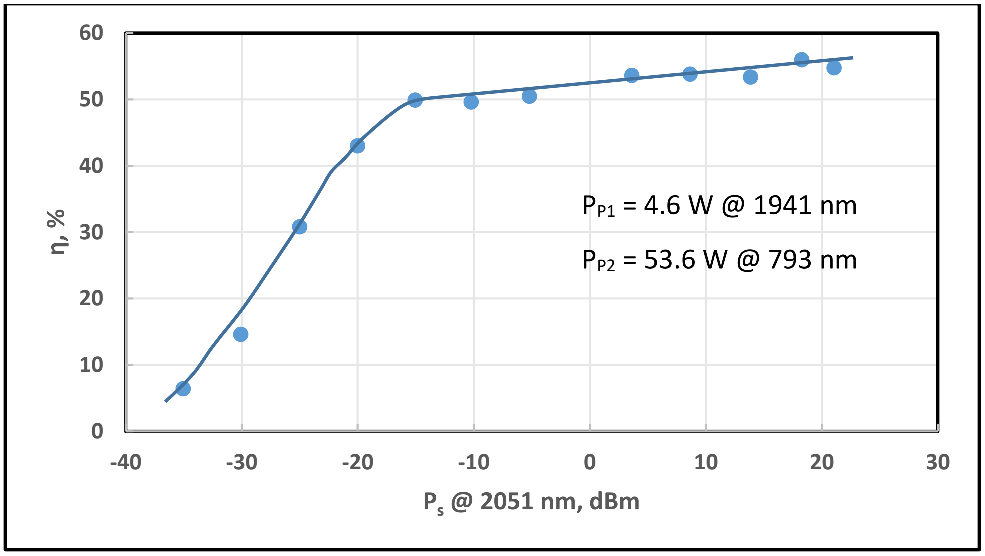

Figure 3. η vs. P_s for P_{P2} = 53.6 W

Figure 3 plots the measured values of optical-optical slope efficiency η. The points are the data, and the solid line is a fit to the data. The rapid increase in η as P_s increases is caused by the high gain compression of the three-stage amplifier. For P_s > -10 dBm, η is seen to exceed 50%, demonstrating the high efficiencies and high dynamic range that can be achieved with the PM HDFA/TDFA configuration.

Figure 4 shows the measured values of experimental gain G vs. signal input power P_s (points) and calculated values of gain (dotted line) for an output power P_{out} of 20 W. For these data, P_{P1} was fixed at 4.6 W @ 1941 nm. In order to achieve P_{out} = 20 W, P_{P2} was adjusted individually for each value of P_s. For P_s < -26 dBm, an output power of 20 W could not be achieved, thus P_{P2} was set to its maximum value of 53.6 W. Here we measure a signal dynamic range for the amplifier of 43 dB for an output power of 20 W.

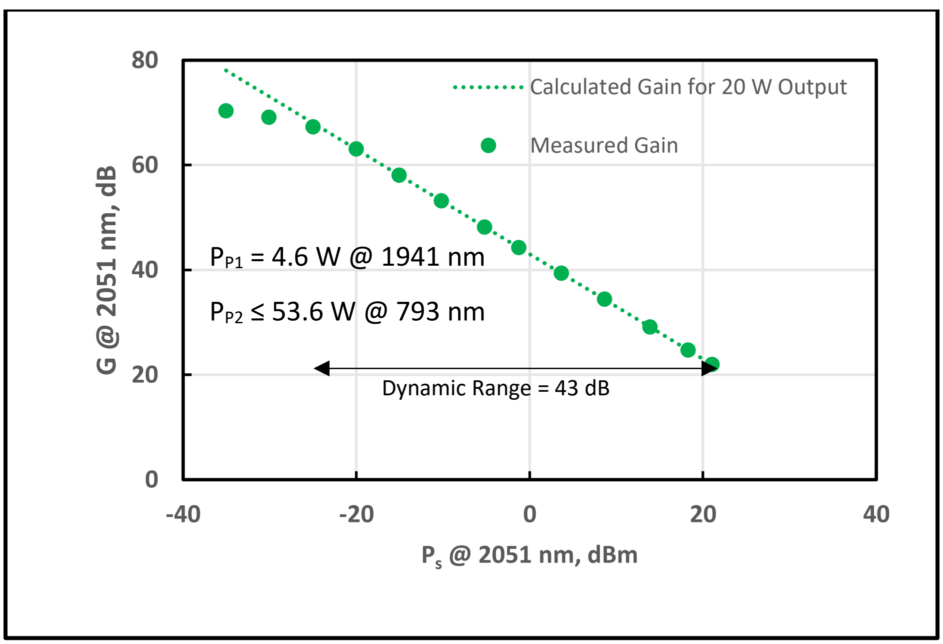

Figure 4. Measured and Calculated G for 20 W Output Power

Figure 5 plots the dynamic range as a function of P_{out}. The data are plotted in points and the dotted line is a polynomial fit to the data. Each point was obtained by measuring the dynamic range at different output powers as described for 20 W P_{out} in Figure 4. At 25 W output power the dynamic range has the relatively high value of 34 dB, and this rises monotonically to 52 dB for an output power of 5 W. Such high values of dynamic range are important for successful amplifier operation over wide variations in input signal power.

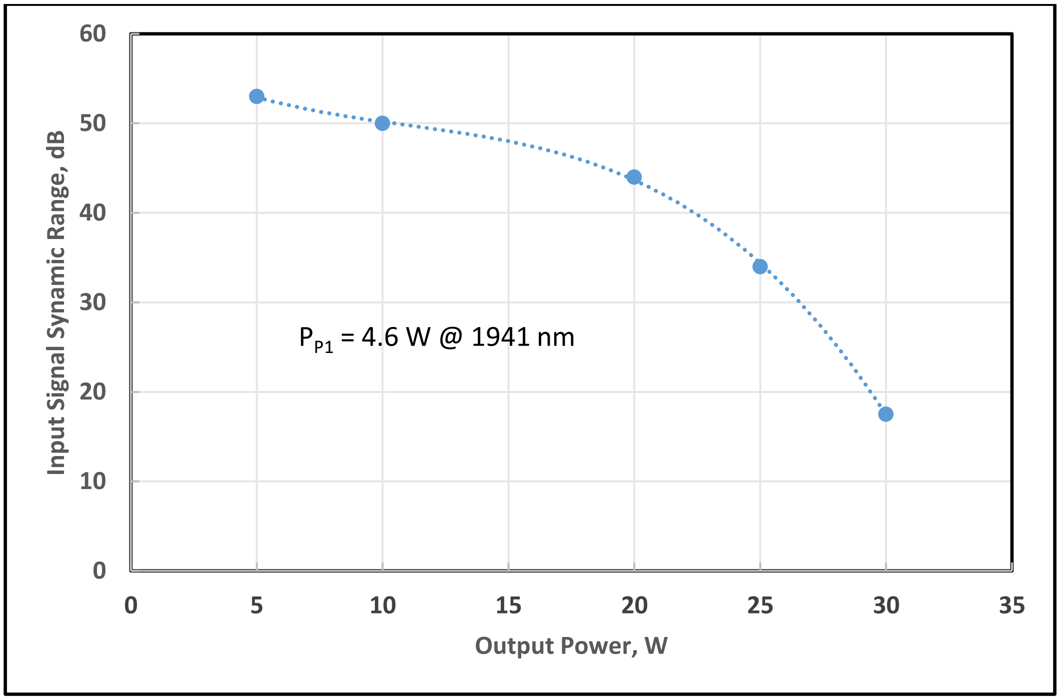

Figure 5. Signal Input Dynamic Range vs. P_{out}

Figure 6 shows the output optical spectrum for P_s = -5 dBm. Here the optical signal to noise ratio (OSNR) is 50.3 dB/0.1 nm. An estimate of the amplifier bandwidth made from the -10 dB values of the background ASE spectrum yields BW = 80 nm. Measured values of OSNR vs. P_s are plotted in Figure 7. Here we see that the OSNR increases monotonically from 21.2 dB/0.1 nm at P_s = -35 dBm to 53.5 dB/0.1 nm at P_s = -1.3 dBm.

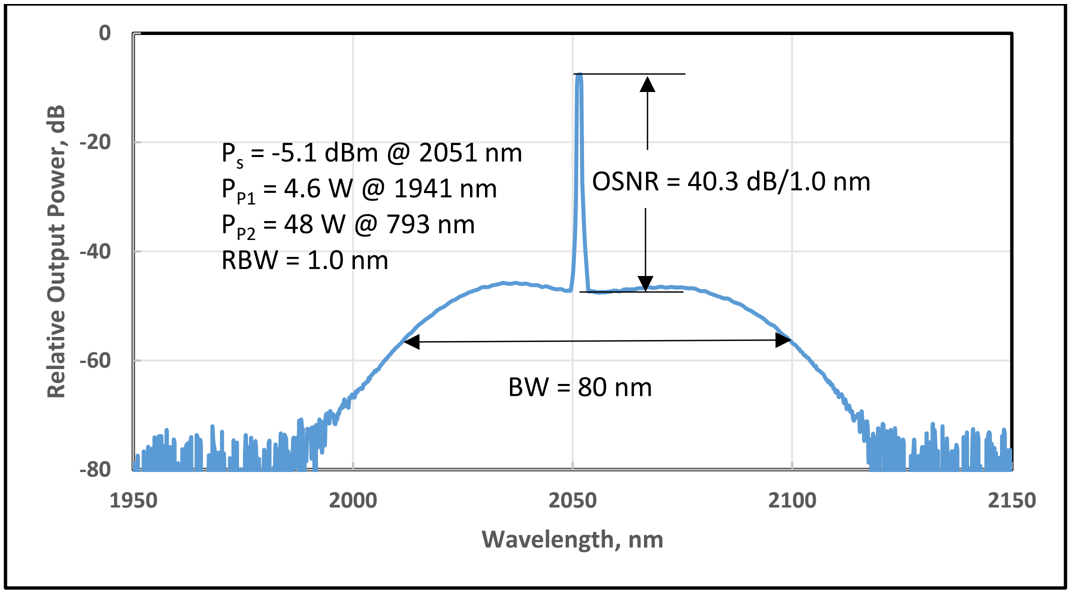

Figure 6. Output Optical Spectrum for P_s = -5 dBm. RBW = 1.0 nm.

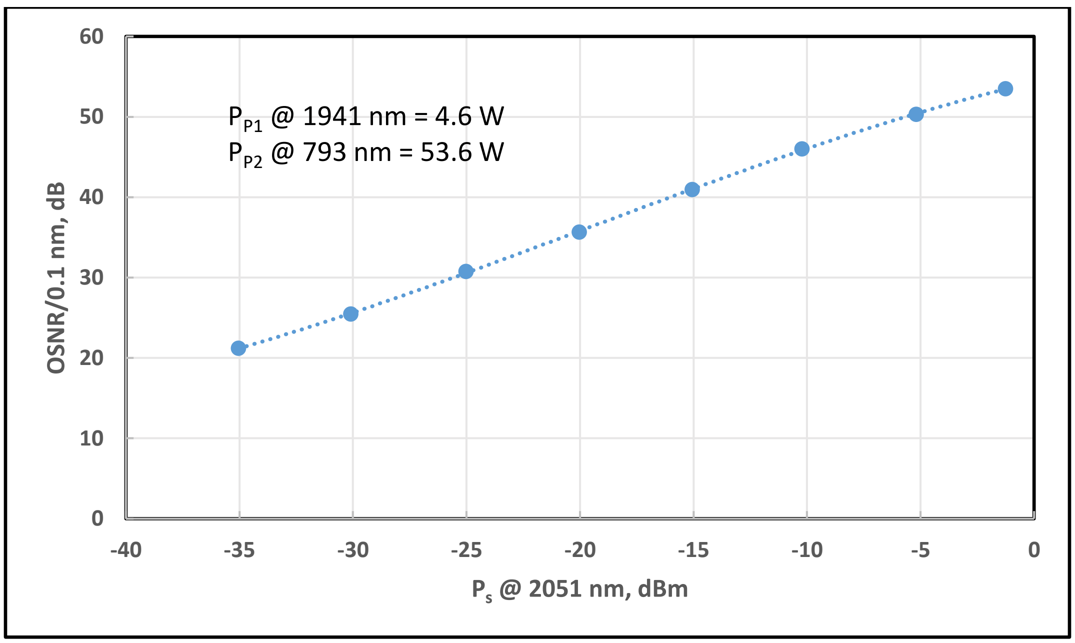

Figure 7. OSNR vs. P_s. Data: points. Dotted line: Fit to data.

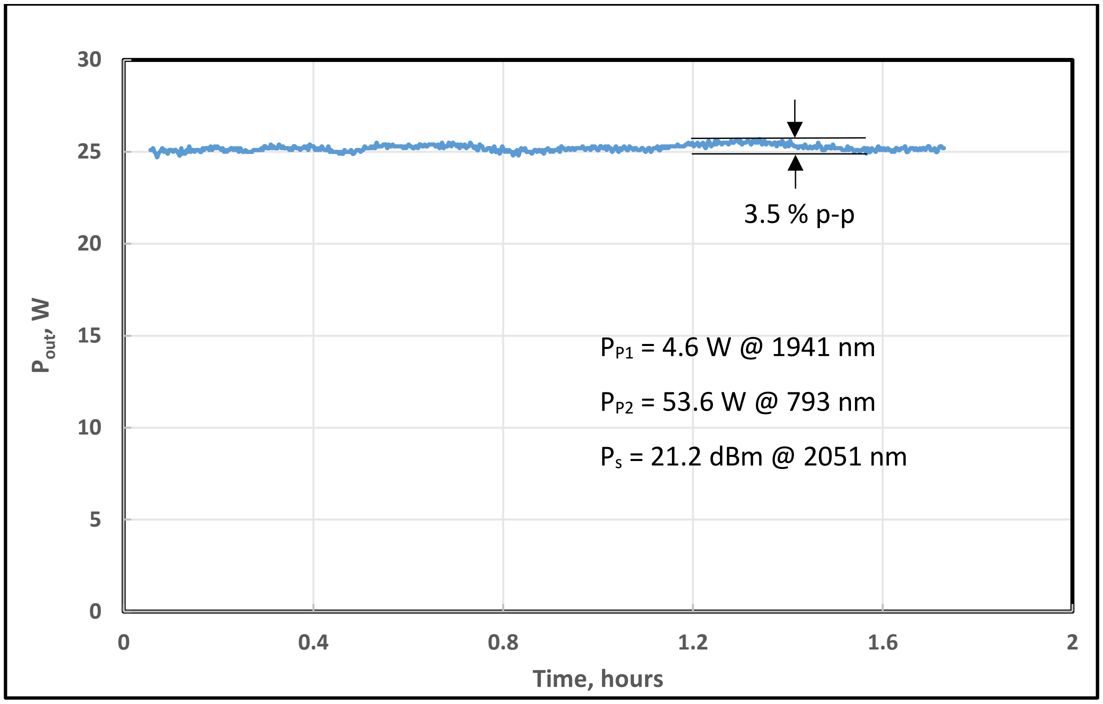

Figure 8. P_{out} as a function of time (in hours)

Figure 8 shows the long term stability of the amplifier output at an average value of P_{out} = 25 W. From these data we see that the variation in P_{out} over a time period of > 1.5 hours is 3.5% p-p or 1.25% rms. The data show that the amplifier output is stable for high powers over time and demonstrate good stability.

4. Comparison of Simulation and Experiment

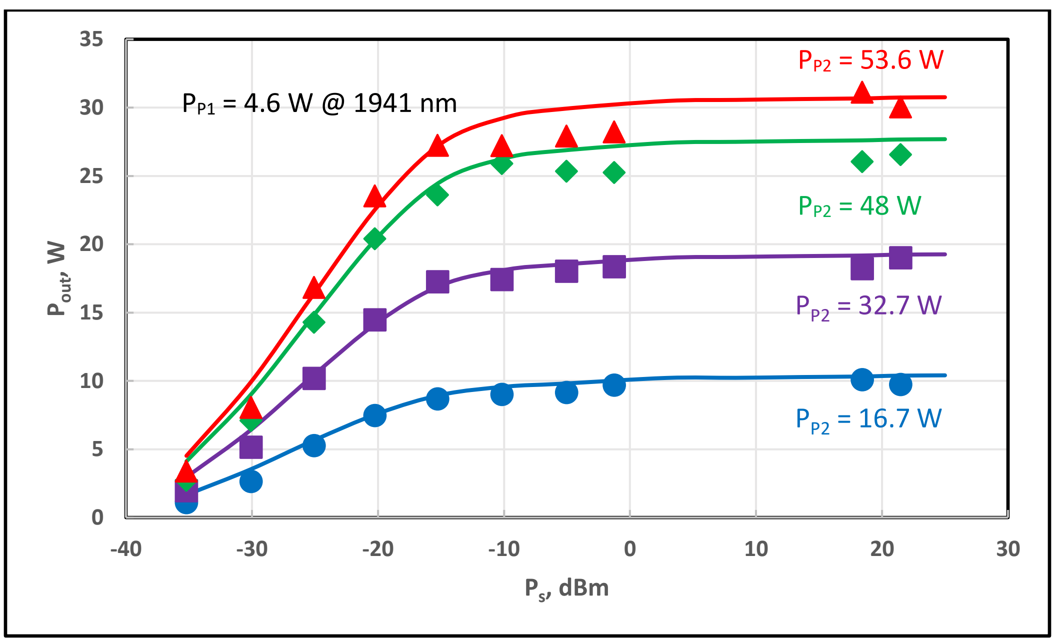

Figure 9. Experimental (points) and simulated (lines) P_{out} vs. P_s for the parameter of P_{P2}

We begin our comparisons of experiment and simulation by plotting P_{out} as a function of P_s for P_{P1} = 4.6 W and four different values of P_{P2}. These data (points) and simulations (solid lines) are shown in Figure 9, where the simulations are carried out using the techniques detailed in Ref. [3] for the double clad TDFA output stage and experimentally measured output powers and output spectra for the single clad HDFA preamplifier stage. As Figure 9 demonstrates, agreement between experiment and simulation is good over the measured range of input signal powers and output powers.

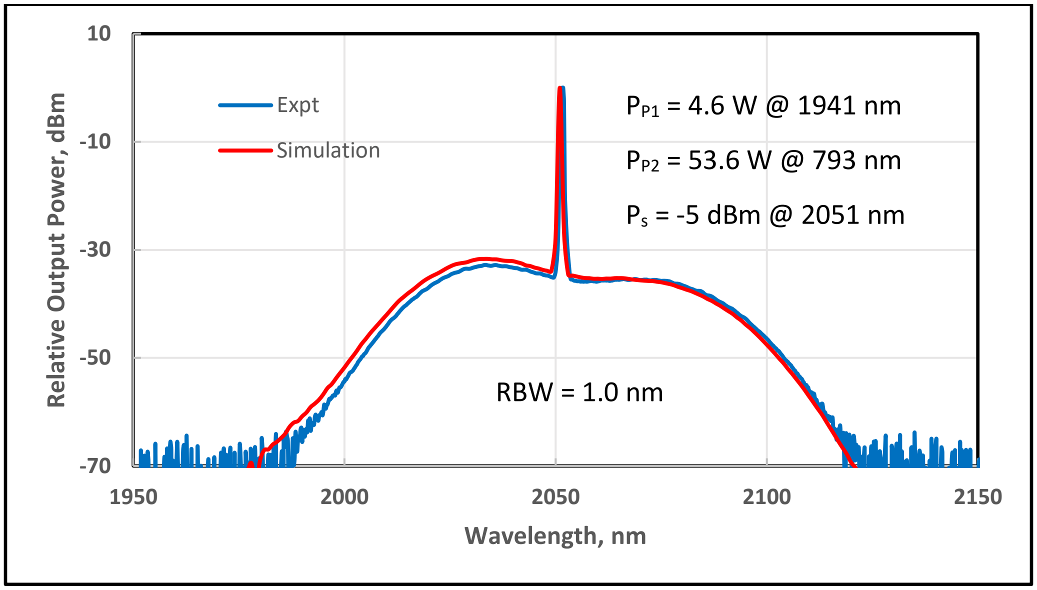

Figure 10. Experimental and Simulated Output Spectra for P_s = -5 dBm

In Figure 10, we show the experimental (blue) and simulated (red) output spectra for the three-stage PM HDFA/TDFA for P_s = - 5 dBm. The agreement between data and theory is excellent, confirming the accuracy of our spectral simulations for this amplifier.

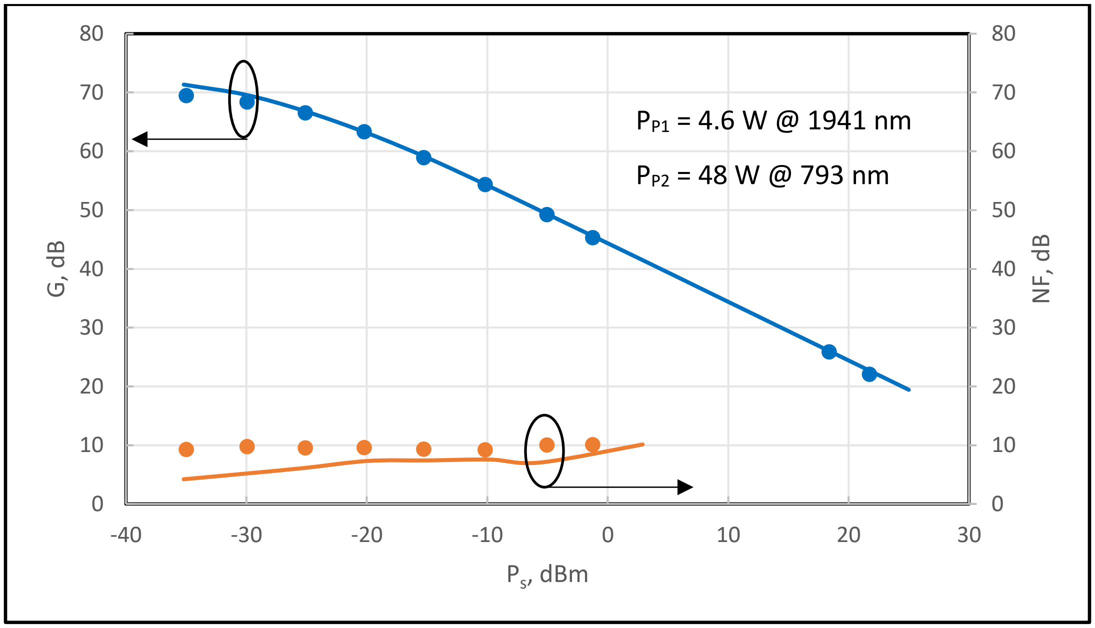

Figure 11. Experimental and simulated G and NF vs. P_s

In Figure 11 we plot G (in blue) and NF (in orange) vs. P_s for the indicated values of P_{P1} and P_{P2}. The data are given in points and the simulations are plotted with solid lines. The comparison of data and theory shows that the simulations predict the measured G quite well, and that the predicted values of NF are slightly less than the experimental values. This discrepancy for NF results is under active investigation.

Overall, we find that the agreement between simulation and experiment for the three-stage PM HDFA/TDFA is good, indicating that our simulation capabilities accurately represent the physical performance of the multistage optical amplifier.

5. Discussion

The results presented in sections 4 and 5 indicate that our three-stage PM HDFA/TDFA design is a simple and efficient means to achieve a high slope efficiency of $\eta = 55\%$ (Figure 2) for the power amplifier configuration with $P_s = +21$ dBm. For high gain applications, the three-stage architecture is quite appropriate, and yields small signal gains in excess of 70 dB. These high gains are important for future applications employing pulsed input sources whose average input power is typically – 20 dBm or less. For high input power applications with $P_s >$ 0 dBm, the amplifier topology may possibly be simplified to two stages (one Ho-stage preamp and one Tm-stage power amp) to reduce the cost and complexity of the design.

The high dynamic range of 34 dB at 25 W P_{out}, which rises to 52 dB for P_{out} = 5W, is advantageous in applications using low input powers, e.g. CW preamplifiers and future pulsed source amplification. We believe that the measured NF of 10 dB can be improved by optimizing the design of the Ho-doped fiber in the preamplifier, and by optimizing the preamplifier architecture. This topic will be discussed at length in future publications.

The maximum achieved P_{out} of 30 W at 2051 nm is limited only by the power of the 793 nm multimode pump sources in our experiments. We believe that output powers of 50—100 W are readily achievable with higher power pump sources.

From the 10 dB bandwidth of the ASE spectrum underneath the amplified peak signal in Figures 6 and 10, we estimate the effective operating bandwidth of the hybrid PM HDFA/TDFA to be 80 nm. Future work will concentrate on extending this effective operating spectral band to signal wavelengths $\lambda_s > 2100$ nm, a region where there is considerable current interest in atmospheric propagation and directed energy weapons.

Using the parameters for the double clad Tm-doped fiber in the output power amplifier, with a core diameter of 10 µm and a core NA of 0.15, we estimate the M^2 value for the PM HDFA/TDFA to be $M^2 < 1.3$. Future work will directly measure this value to confirm our preliminary estimate.

6. Summary

We have proposed and experimentally demonstrated a new three-stage PM hybrid HDFA/TDFA design exhibiting 30 W output power at 2051 nm. The output power of the existing amplifier is pump power limited, indicating that future output powers of 50-100 W should be readily achievable. Our amplifier also exhibits a small signal gain > 70 dB which is the highest value so far reported for fiber optical amplifiers operating in the 2000 nm region of the spectrum.

A dynamic range of 34 dB at 25 W P_{out} was achieved, rising to 52 dB for P_{out} = 5W. The measured noise figure of the amplifier is 10 dB over an input power range P_s = -35 to -1 dBm. The estimated 10 dB operating bandwidth of the amplifier is 80 nm, and M^2 is estimated to be < 1.3. Measured long term stability at P_{out} = 25 W is 3.5% p-p (1.25 % rms), illustrating good long term performance of our amplifier topology.

Comparison of simulations and experiment shows good agreement between theory and data for multiple amplifier operating parameters, validating our approach to calculations of amplifier performance.

Our novel amplifier design points the way toward future applications requiring compact, efficient, high gain, and high output power fiber amplifiers in the important 2000-2150 nm region of the spectrum.

7. Acknowledgements

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