Experimental Performance of a Broadband Dual-Stage 1950 nm PM Single-Clad Tm-Doped Fiber Amplifier

Robert E. Tench, *Senior Member, IEEE*, Alexandre Amavigan, Ken Chen, Jean-Marc Delavaux, *Senior Member, IEEE*, Thierry Robin, Benoit Cadier, and Arnaud Laurent

***Abstract*— We report the experimental performance of a packaged dual-stage all-single-clad broadband polarization maintaining (PM) Tm-doped silica fiber amplifier (TDFA) with a high signal output power of 2.2 W at 1909 and 1951 nm. Our novel design incorporates an uncooled 940 nm multimode semiconductor pump laser source. Combined high gain of >46 dB, wide operating bandwidth of 1875–2000 nm, low noise figure of 7 dB, high OSNR of >54 dB/0.1 nm, and a PER of >20 dB are achieved with our TDFA.**

***Index Terms*— Doped fiber amplifiers, infrared fiber optics, optical fiber devices, Thulium, 2 microns.**

I. Introduction

Two μm high power and high performance amplifiers are needed for applications such as LIDAR, remote sensing, and WDM transmission systems [1]–[4]. We have recently demonstrated that single clad Tm-doped amplifiers (TDFAs) can offer large bandwidth, high dynamic range, and multi-watt output power from 1.90 to 2.05 μm [5]–[7]. More recently, we have presented the results of a miniature, high gain, low noise figure, broadband single stage PM amplifier using a newly developed single clad PM Tm doped fiber [8]. The development of the amplifiers in [5]–[8] naturally lead us to consider the possibility of designing and testing an all-single-clad amplifier with multiple stages to improve and enhance the achievable performance characteristics.

In this paper we report the design and experimental evaluation of the performance of a fully integrated, compact, two stage, broadband multi-watt amplifier [9] using the same PM single clad Tm-doped fiber employed in [8].

The new two stage amplifier consists of a preamplifier stage followed by a booster stage, with both stages being pumped by an L-band pump at 1567 nm. Our novel TDFA uses an uncooled 940 nm multimode semiconductor laser source for the L-band pump which is of great practical advantage in amplifier design. In this paper, we report first experimental results and performance of the two stage packaged optical amplifier using the newly developed PM Tm-doped fiber. Our design exhibits a saturated output power > 2 W at 1909 and 1951 nm, an optical bandwidth from 1875 to 2000 nm, high gain > 46 dB at 1909 nm, a low noise figure of 7 dB, a large output OSNR (> 54 dB/0.1 nm), and a PER > 20 dB.

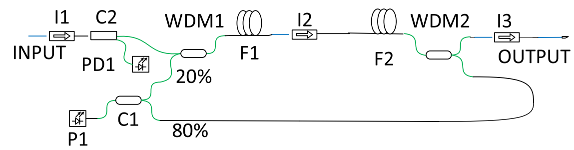

Fig. 1. Two stage PM single clad TDFA configuration.

II. Experimental Setup and Amplifier Packaging

Figure 1 shows the optical architecture of the two stage TDFA. Signal light from a single frequency discrete mode laser (DML) source (Eblana Photonics) at 1909–2004 nm is coupled into the first stage TDF F1 through the input FC/APC connector, isolator I1, tap coupler C2 and wavelength division multiplexer WDM1. The amplified signal output from F1 passes through I2 and is then coupled into the second stage TDF F2. The amplified signal from F2 passes through WDM2 and isolator I3 to the output fiber FC/APC connector. P1 is a 1567 nm multiwatt Er-Yb fiber laser that is itself pumped by a multiwatt multimode 940 nm semiconductor laser diode. As shown in Figure 1, coupler C1 splits the 1567 nm output of P1 with 20% of the pump light coupled to F1 (copumped preamplifier stage) and 80% of the pump light coupled to F2 (counterpumped power amplifier stage). Tap coupler C2 splits off a small portion (5%) of the input signal light which is subsequently monitored by photodiode PD1. Input and output optical signal powers are measured at the FC/APC connectors (packaged amplifier performance.)

The fully packaged and integrated amplifier (SCIROCCO Skyline) incorporates electronic control circuits for the pump laser and for monitoring the signal input power, has dimensions of 200 × 150 × 43 mm^3, and a mass of 600 g.

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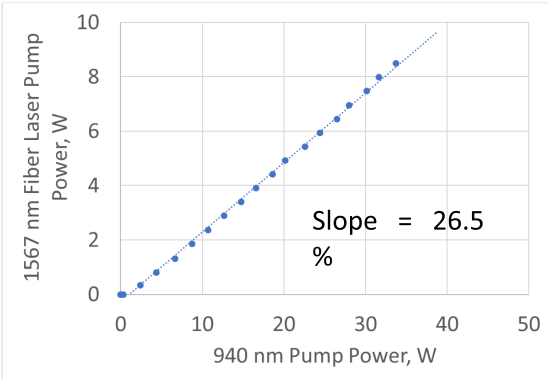

Fig. 2. Output of 1567 nm fiber laser as a function of 940 nm semiconductor laser power.

TABLE I
DATA FOR NEWLY DEVELOPED PM TM-DOPED FIBER

Parameter	Value
Fiber ID	IXF-TDF-PM-5-125
Core Diameter, µm	4.5
Fiber Structure	Single Clad PANDA
Estimated Core Absorption at 790 nm, dB/m	134
Estimated Core Absorption at 1180 nm, dB/m	33.5
Peak Core Absorption at 1650 nm, dB/m	114
Birefringence	$> 1.5 \times 10^{-4}$
Numerical Aperture	0.25

Communication and control are via USB and RS232 interfaces. Electrical power consumption for the packaged device is 66 W at full optical output power.

III. DATA FOR NEWLY DEVELOPED SINGLE CLAD PM TM-DOPED FIBER

Table I shows summary data for the newly developed PM Tm-doped fiber from iXblue. We note that the core diameter is 4.5 microns and the NA is 0.25. Splice losses to a standard undoped single clad PM fiber (Coherent/Nufern PM1950) are measured to be less than 0.1 dB. The peak absorption of the iXblue fiber in the pump band is 114 dB/m at 1650 nm. At the pump wavelength of 1567 nm, the absorption is 69 dB/m. Using this pump absorption value, fiber lengths of 4 m for F1 and 2 m for F2 are chosen for the packaged TDFA.

IV. EXPERIMENTAL RESULTS

Figure 2 shows the measured output of the 1567 nm Er-Yb fiber laser as a function of its multimode 940 nm pump power input. Here the points are data and the line is a linear fit to the data. We see that the maximum 1567 nm power available to pump the TDFA is 8.5 W at a 940 nm power of 33.5 W. The 1567 nm laser output follows a linear trend with 940 nm input and exhibits a slope of 26.5 %.

In Figure 3, we plot output signal powers at 1909, 1952, and 2004 nm as a function of 1567 nm pump power. The points are data, and the lines are linear fits to the data. For these data, the 1909 nm signal power was 0 dBm, the 1952 nm power was 3 dBm, and the 2004 nm power was 5 dBm. At all three wavelengths, the signal output powers follow a linear trend with pump power, with slopes ranging from 34.9% to 41.5% as indicated on the plot. The low slope measured at 2004 nm is caused by the roll off of the gain coefficient of the Tm-doped fiber at this high wavelength [10]. A maximum external signal output power of 2.2 W is measured at 1952 nm. When we account for the output signal coupling loss of 1.63 dB between the output of F2 and the output FC/APC connector in Figure 1, the maximum internal signal output power is 3.2 W and the internal slopes range from 50.8% to 60.4%. These high internal slope values indicate that the amplifier makes efficient use of the available 1567 nm pump power.

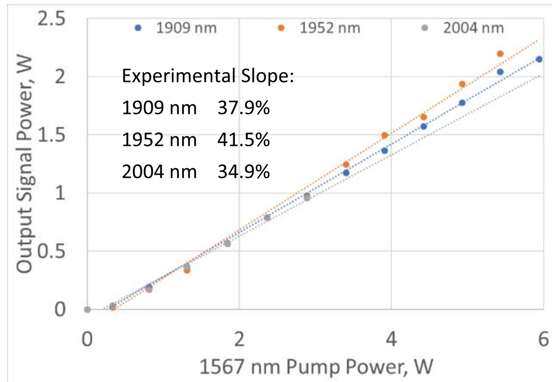

Fig. 3. External output signal power vs. 1567 nm pump power for wavelengths of 1909, 1952, and 2004 nm.

Output spectra for wavelengths of 1909, 1952, and 2004 nm are shown in Figure 4. Here the input signal powers are the same as in Figure 3. The measured optical signal-to-noise ratios are all greater than 54 dB/0.1 nm for these output spectra. Such high values of OSNR are desirable for many applications including LIDAR, spectral sensing, and coherent lightwave systems. From the background widths of the ASE spectra below the signals, we estimate the 3 dB power bandwidth of the amplifier to be 1875–2000 nm or 125 nm.

Figure 5 plots the measured values of G and NF as a function of P_{in} over a range of -22 dBm to $+2$ dBm for a signal wavelength of 1909 nm. The small signal noise figure is 6.9 dB, and the maximum measured gain is 46.6 dB at $P_{in} = -22$ dBm. The total pump power for these measurements is 2.5 W at 1567 nm. The high small signal gain and low noise figure indicate that our amplifier design will work well in applications such as a preamplifier for an optical receiver or as an amplifier for pulsed input signals with a low duty cycle and a correspondingly low average optical power.

In Figure 6, we show the measured stability of output power as a function of time for 1952 nm and 1909 nm signal wavelengths. These data are taken after a 30 minute warmup period for the amplifier. As shown in the plot, the measured stability at 2W output power is $< 4\%$ p-p over a period of two hours. This small long term variation indicates that our packaged amplifier design is robust and stable with time.

The polarization extinction ratio (PER) at the output of the PM amplifier is determined by isolator I3 and is > 20 dB.

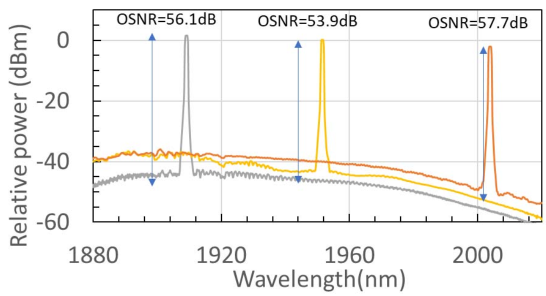

Fig. 4. Output spectra for signal wavelengths of 1909, 1952, and 2004 nm.

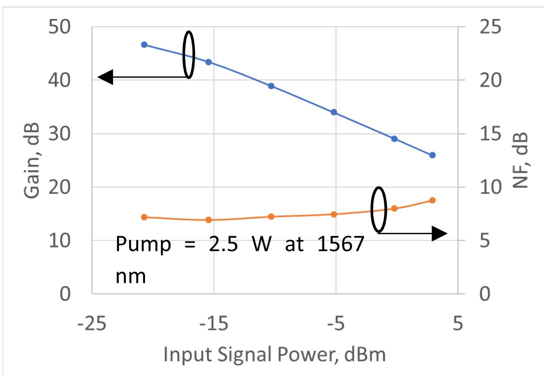

Fig. 5. G and NF vs. input signal power for a signal wavelength of 1909 nm.

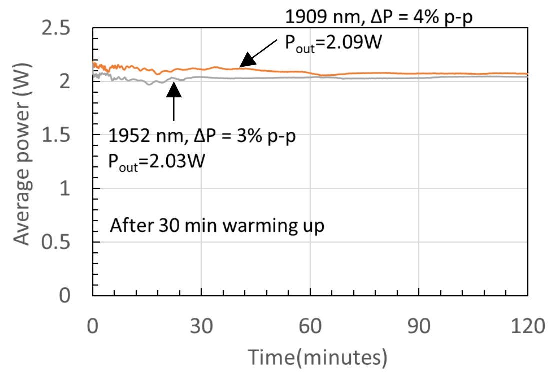

Fig. 6. Output power stability vs. time. $P_S = 0$ dBm.

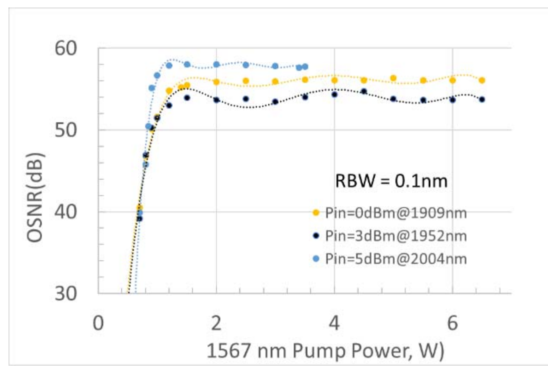

Fig. 7. OSNR for signal wavelengths of 1909, 1952, and 2004 nm vs. 1567 nm fiber laser pump power.

Finally, in Figure 7, we plot the measured values of OSNR at the output of the amplifier as a function of 1567 nm fiber laser pump power. Here the points are data and the lines are polynomial fits to the data. The data for 2004 nm are limited to 3 W pump power because of the appearance of parasitic lasing in the amplifier above this pump level. From these overall data we see that the measured OSNR values reach their asymptotic values of > 54 dB/0.1 nm at pump powers as small as 1 W. This shows that the amplifier has a very wide dynamic range of 1567 nm pump powers ranging from 1–6 W, and output signal powers ranging from 0.25–2 W, over which the measured output OSNRs achieve their high limiting values. This wide dynamic range behavior with pump power and output signal power is a desirable feature in a high performance fiber optical amplifier.

V. Discussion

To our knowledge, the data presented here are the first reported experimental measurements of the performance of a multistage Tm-doped fiber amplifier using polarization-maintaining single clad fibers.

The high measured gain of > 46 dB at 1909 nm represents an improvement over results previously reported [8] for single stage PM TDFAs. Such a high small signal gain is promising for preamplifier, repeater, and low noise applications. The bandwidth and noise figure of the two stage amplifier are comparable to the single stage results in [8].

The high observed external slope efficiencies of 35-42 % and external output power of 2.2 W also show significant improvement over previously reported PM TDFA performance [8]. Internal slope efficiencies ranged from 51–60%. Internal slope efficiencies of this magnitude indicate that the 1567 nm pump power in the amplifier is used quite efficiently.

The experimental SNRs of 54–57.7 dB/0.1 nm for a saturated amplifier output are important for applications such as booster amplifiers and coherent lightwave systems.

The usable 50% output power operating bandwidth of the two stage PM TDFA, measured from the width of the ASE curve below the spontaneous emission peak (Figure 4), is estimated to be 125 nm (1875–2000 nm). This value agrees with previous work [5]–[8] on both non-PM and PM TDFAs and is fully consistent with the output power measurements reported in Figure 3.

Future work will involve changing the doping level and material compositions of the PM TM-doped fiber, as well as the selected pumping wavelength, to extend the operating band toward lower signal wavelengths of 1600–1850 nm [10], [11]. These lower signal wavelengths are important for spectral sensing and WDM transmission applications. Future work will also involve the insertion of a mid-stage gain shaping filter after F1 and before F2 to significantly increase the operating bandwidth of the dual stage amplifier.

VI. Summary

We have reported the design and experimental performance of a novel two stage polarization maintaining TDFA using new single clad Tm-doped fiber and an uncooled 940 nm pump source. The TDFA exhibits small signal gain of > 46 dB, noise figure of 7 dB, an output power of 2.2 W at 1909 and 1952 nm, output OSNR values of > 54 dB/0.1 nm, a long term output power stability of $< 4\%$ p-p, and a PER of > 20 dB. Our packaged amplifier has dimensions of $200 \times 150 \times 43$ mm^3, a mass of 600 g, and communicates via RS232 and USB interfaces. The use of a 940 nm uncooled semiconductor pump laser results in a highly stable, practical, and robust design. We believe that the efficiency of the amplifier can be improved with new fiber designs, and that output powers of 5–10 W can be achieved in the future. Applications for the 2000 nm band PM TDFA include avionics, space, LIDAR, spectral sensing, coherent lightwave systems, and WDM transmission.

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