**Novel Miniature 2 µm Watt-level PM Single Clad Tm-Doped Fiber Amplifier**

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## 1. Introduction and Overview

Recent developments in LIDAR [1], atmospheric sensing [2,3], and WDM transmission system experiments [4] highlight the need for large bandwidth, high dynamic range polarization-maintaining (PM) optical amplifiers in the 1.9—2.1 µm band. While some results for all-double-clad PM amplifier designs have been presented [5], single clad PM amplifiers are particularly attractive in these applications because of their potential for high gain and low noise figures approaching the quantum limit. There is also a strong and growing need for need for compact and rugged amplifiers to boost modest (1 mW CW) semiconductor laser source output powers in a space/satellite environment.

In this paper, we report first experimental results for a newly developed single clad PM Thulium-doped fiber with the parameters shown in Table 1 below and an optical signal bandwidth of > 120 nm, and then present performance of a miniature packaged optical amplifier using this new fiber.

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

Table 1. Parameters for iXblue PM Thulium-doped single clad fiber

Our goal in building a packaged PM Thulium-doped fiber amplifier (TDFA) with the fiber in Table 1 is to provide a miniaturized device with fiber coupled output powers of > 0.5 W CW, high small signal gain, low noise figure, and large OSNR that can be used as a versatile wideband preamplifier or power booster amplifier. Figure 1 shows the initial optical design of our novel miniature PM TDFA. A single frequency input signal at 1909—2004 nm is coupled through an input FC/APC connector, subminiature isolator I1, and the signal port of subminiature wavelength division multiplexer WDM1 into the PM Tm-doped fiber F1 (5.5 m length). Pump light from a multi-watt fiber laser P1 at 1567 nm (pumped itself by a multi-watt 940 nm multimode laser diode) is coupled into F1 via the pump port of WDM1 (co-propagating pump). The signal output of F1 is coupled through subminiature isolator I2 into an output FC/APC connector.

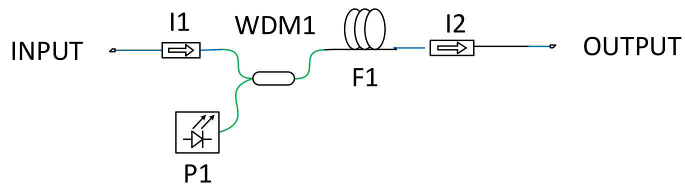


Figure 1. Optical design of co-pumped single clad polarization maintaining TDFA

In our measurements, input signal power (measured at the input of F1, for internal power measurements) is designated as $P_s$ and output signal power (measured at the output of F1, for internal power measurements) as $P_{out}$. The total pump power at 1567 nm available to couple into F1 is designated as $P_{P1}$. Linearly polarized PM signal light propagates though the fibers and components in the amplifier on the slow fiber axis.

## 2. Performance of Brassboard PM TDF Co-pumped Fiber Optical Amplifier

We first constructed a brassboard amplifier to test the subminiature optical components and multimode pump diode in our amplifier design. Figure 2 shows data on the variation of $P_{out}$ with $P_{P1}$ for $P_s$ = 0 dBm and $\lambda_s$ = 1909 nm for the brassboard co-pumped TDFA. The measured values of $P_{out}$ vary linearly with $P_{P1}$ as expected and a maximum internal output power of 1.15 W is achieved (0.81 W at the FC/APC output connector), meeting our 0.5 W fiber coupled output power goal. The optical slope efficiency is 48.6 %, and the quantum optical slope efficiency is 59.3 %. The maximum fiber coupled $P_{out}$ is limited due to (a) the use of a reduced size pump laser module that fits in the miniature PM MAKO TDFA package, and (b) the insertion losses of sub-miniature optical components used in the PM MAKO TDFA module.

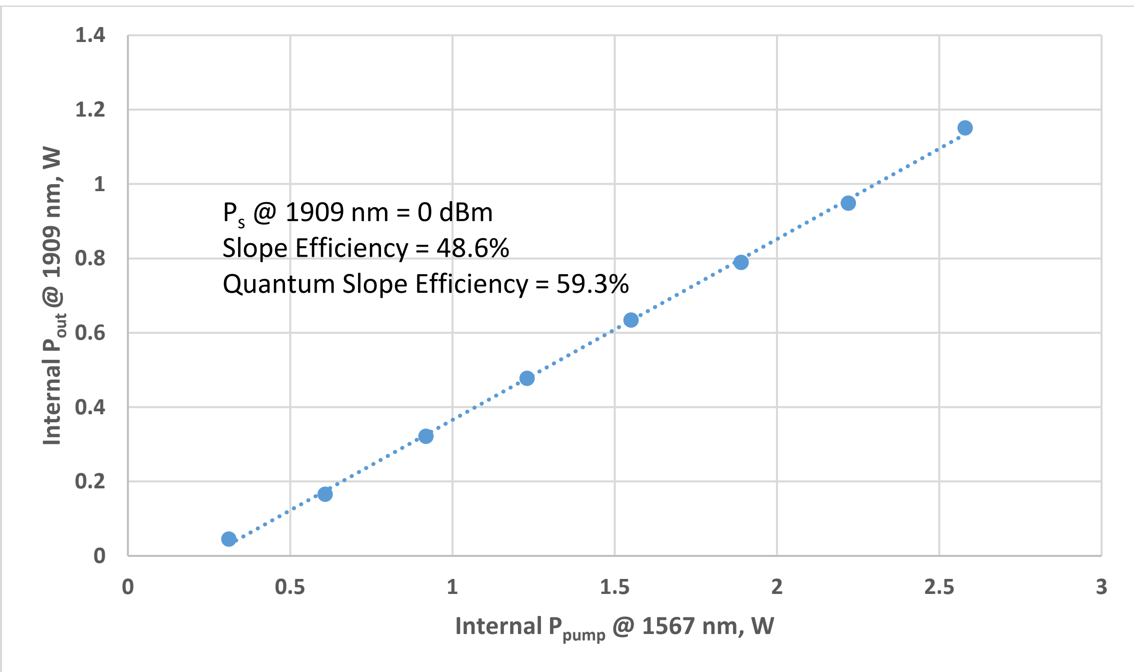


Figure 2. Internal $P_{out}$ vs. Internal $P_{P1}$ with $P_s$ = 0 dBm for brassboard co-pumped amplifier

The saturated output spectrum at $P_s$ = 0 dBm for $\lambda_s$ = 1909 nm and $P_p$ = 2.58 W is plotted in Figure 3. As illustrated by the spectral data, the estimated output power bandwidth of the saturated amplifier is 120 nm, from 1865 to 1985 nm. The measured optical signal-to-noise ratio (OSNR) is 58.1 dB/0.1 nm. This high OSNR value is desirable for applications such as LIDAR and DWDM transmission systems.

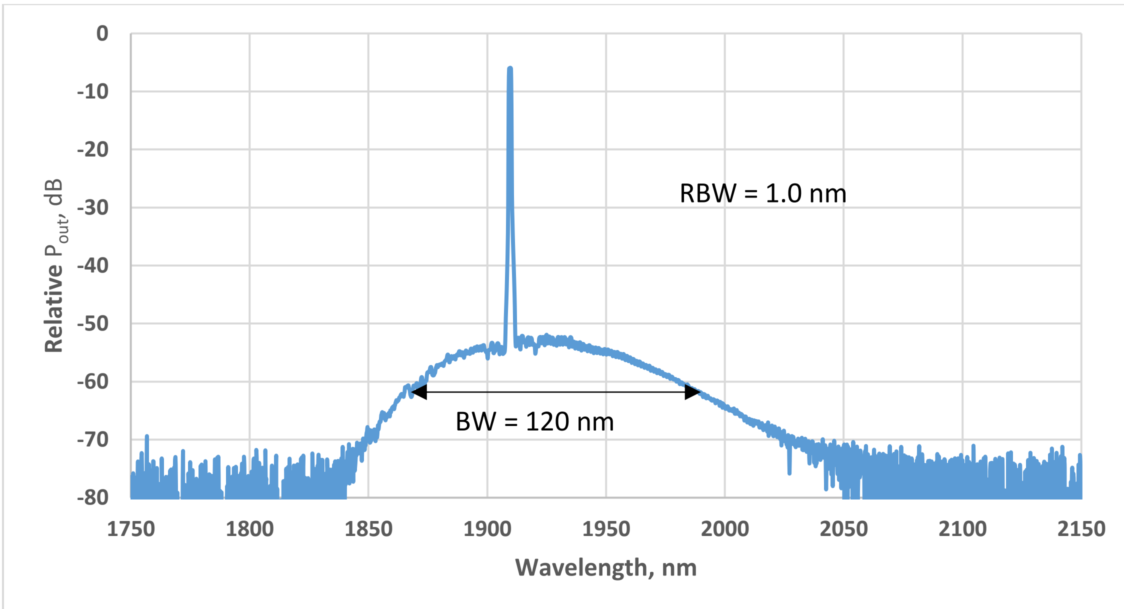


Figure 3. Single Stage Co-pumped PM TDFA Output Spectrum with $P_s$ = 0 dBm at 1909 nm for brassboard co-pumped amplifier.

In Figure 4 we plot the gain and noise figure of the brassboard co-pumped amplifier as a function of $P_s$ for $P_{P1}$ = 1.55 W @ 1567 nm. dBm. We see that the maximum small signal gain G reaches the high value of 46 dB, and the small signal noise figure is approximately NF = 4.0 dB. As expected, G decreases with increasing $P_s$ and trends to a linear asymptote. The measured NF rises to approximately 5.5 dB for the maximum input signal power of – 1.5 dBm. The high gain and low noise figure indicate that this TDFA will function very well as an optical preamplifier.

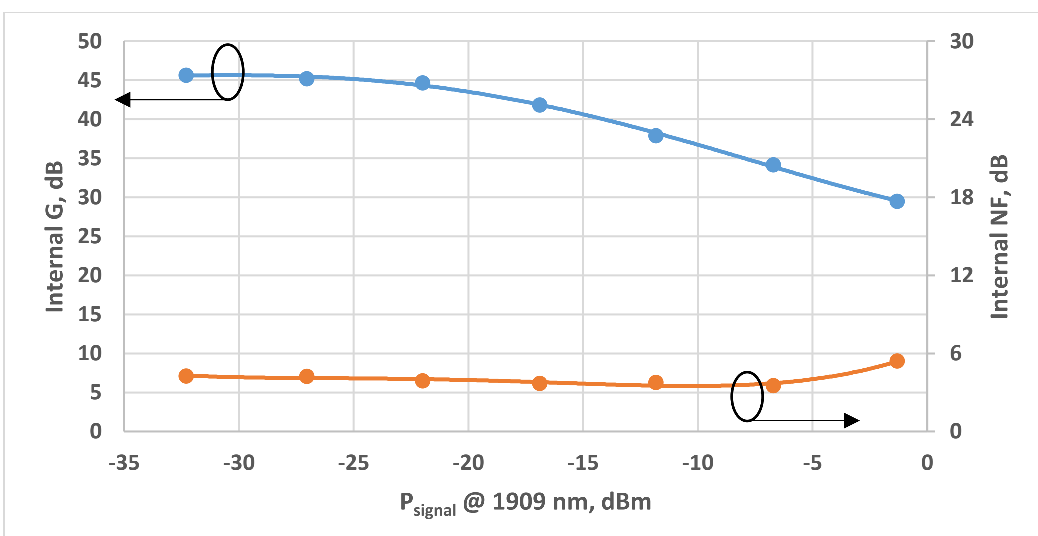


Figure 4. Internal G and NF for the Co-pumped Brassboard PM TDFA

## 3. Performance of Fully Integrated and Packaged MAKO+ Miniature PM TDFA

The miniature PM MAKO+ TDFA was then assembled, packaged, and tested at a signal wavelength of 1909 nm in a co-pumping configuration. Figure 5 is a photograph of the MAKO+ unit which has dimensions of $97 \times 78 \times 15$ mm$^3$, incorporates full pump control electronics, and communicates via an RS232 interface. The mass of the packaged amplifier including fiber pigtails and connectors is 180 gm.

Figure 6 plots the output power of the co-pumped MAKO+ TDFA as a function of drive current to the 940 nm multimode pump laser in the miniature package. The maximum internal output power was measured to be 0.654 W, which corresponds to a fiber coupled output power (external) of 0.50 W, meeting the stated output power target for the miniature MAKO+ package.

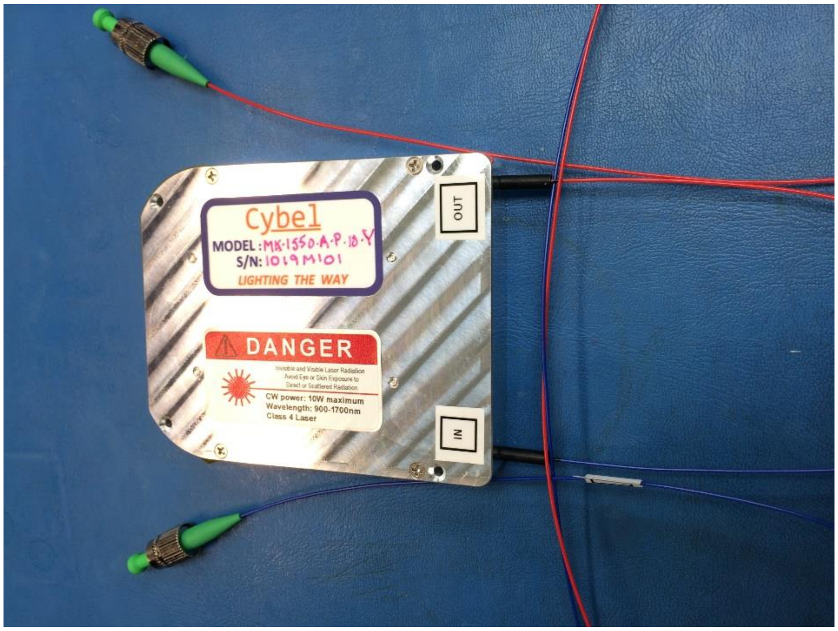


Figure 5. Miniature Packaged PM MAKO+ TDFA with Dimensions of $97 \times 78 \times 15$ mm$^3$ and Mass of 180 gm

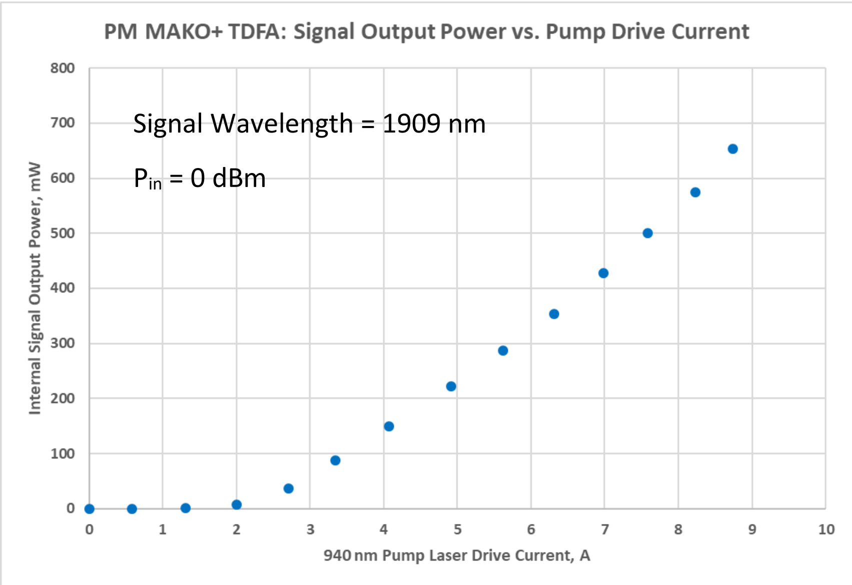


Figure 6. L-I Data for the Miniature MAKO+ PM TDFA

The maximum internal output power of 654 mW is reduced from the value obtained with the brassboard co-pumped amplifier for various reasons, including the center wavelength of the 940 nm pump laser diode in the MAKO+, routing of optical fibers, and available drive current for the 940 nm pump in the packaged amplifier. With modifications to these and other areas, we anticipate results for future MAKO+ amplifiers to approach the data shown in Figures 2, 3, and 4.

Figure 7 shows the output spectrum of the PM MAKO+ TDFA for a 940 nm multimode laser drive current of 5.6 A. The output OSNR is measured to be 54 dB/0.1 nm, which is a highly desirable value for WDM and LIDAR system applications.

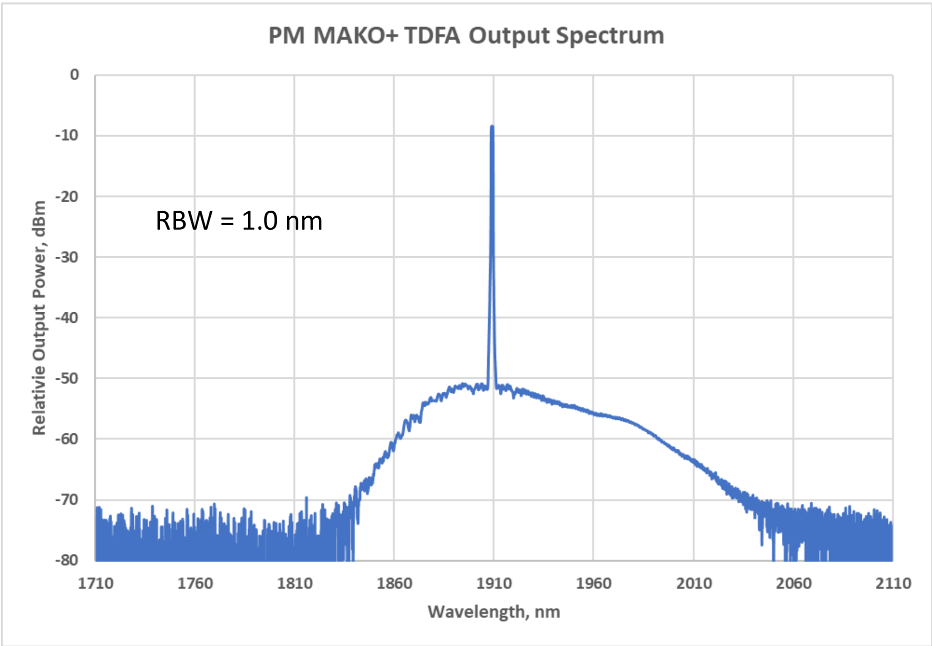


Figure 7. Measured Output Spectrum of the PM MAKO+ TDFA at 5.6 A Drive Current.

Data on the parametric variation of G with $P_P$ and $P_s$, as well as other measurements of the performance of the brassboard and miniature PM TDFAs (such as operating bandwidth evaluations and long-term output power stability) will be presented at the conference.

## 4. Acknowledgement

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