ARL-TR-8375 ● MAY 2018

US Army Research Laboratory

Design, Demonstration, and Simulation of the Diode-Pumped Thulium/Holmium (Tm/Ho) Composite Fiber 2.1-µm Laser

by G Alex Newburgh

NOTICES

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
May 2018	Technical Report	May 2015–June 2017

4. TITLE AND SUBTITLE Design, Demonstration, and Simulation of the Diode-Pumped Thulium/Holmium (Tm/Ho) Composite Fiber 2.1-µm Laser	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) G Alex Newburgh	**5d. PROJECT NUMBER** 15-S&A-0551 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-SEE-L 2800 Powder Mill Road Adelphi, MD 20783-1138	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-8375
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We report on the development of the 800-nm diode-pumped thulium/holmium (Tm/Ho) 2.1-µm composite fiber laser. This technical report will detail the absorption and emission spectroscopy of Tm- and Ho-doped silicate glasses, present the lasing performance results of the Tm/Ho composite fiber laser, present analysis of the optical modes of the Tm/Ho composite fiber, and compare the results of laser simulation of the fiber laser to results from experiment.

15. SUBJECT TERMS

fiber laser, thulium, holmium, spectroscopy, mode analysis, simulation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			G Alex Newburgh
Unclassified	Unclassified	Unclassified	UU	26	**19b. TELEPHONE NUMBER (Include area code)** (301) 394-2007

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

The following report details the research and development of a diode-pumped thulium/holmium (Tm/Ho) composite fiber 2.1-µm large mode area laser for the Joint Technology Office (JTO)-funded Project 15-S&A-0551. The effort was performed over a 2-year period in which the first year's primary focus was the design, construction, and characterization of a new form of 2-µm laser based on the Tm/Ho-doped composite fiber laser. In the second year of funding, the fiber laser was numerically modeled as a means of gaining more understanding of the laser's performance observed in the Year 1 effort.

2. Project Overview

The objective in Year 1 was to design and build a 100-W Tm/Ho fiber laser using an 800-nm diode laser source to pump the Tm/Ho composite fiber manufactured by Advalue Photonics (Tucson, Arizona). It was anticipated that two fiber iterations would be required for refinement of the laser gain medium design over the course of the year. The US Army Research Laboratory's (ARL's) (Adelphi, Maryland) function was to design and characterize the fiber laser using the Tm/Ho composite fibers manufactured by Advalue Photonics.

Traditionally, to generate the 2.1-µm fiber laser wavelength, a wavelength which transmits with low loss in the atmosphere,[1] the $^5I_7$ Ho energy level has either been inverted through optical pumping by a Tm-doped fiber 1950-nm laser[2] or through energy transfer from the $^3H_4$ Tm level to the $^5I_7$ Ho level of a codoped Tm/Ho gain medium.[3] The Tm/Ho composite fiber laser functions by optically pumping the Ho core through optical overlap of the lasing Tm modes.

In Fig. 1, a dichroically coated "pump mirror" (800-nm anti-reflective (AR), high reflection (HR) 1900–2200 nm) is deposited onto a Tm/Ho composite fiber on the left-hand face while an output coupler (partially reflective (PR) coated at 2100 nm, HR at 1950 nm) is deposited onto the righthand face of the fiber. As a lasing cavity is present for both the Tm and Ho sections of the fiber gain medium, the Tm portion of the fiber will lase in a multimode fashion (green) and in so doing, optically pump the Ho core drawn (red) (see Fig. 1). In principle, this new form of 2.1-µm fiber laser combines the simplicity of the 800-nm optically pumped Tm/Ho codoped gain medium with the single-mode characteristics of the Tm fiber laser tandem pumped Ho fiber laser. A patent of the Tm/Ho composite laser was granted in 2015.[4]

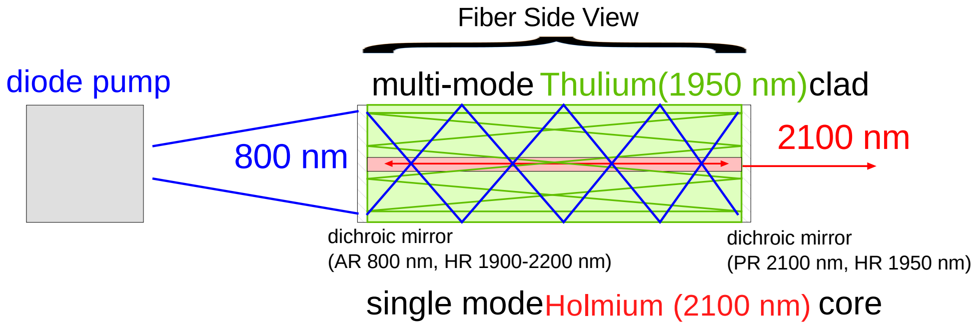

Fig. 1 Principle of the Tm/Ho composite laser

2.1 Year 1, Task 1: Design of a 100-W Tm/Ho Fiber Laser (ARL) and Manufacture of the Tm/Ho Fiber (Advalue Photonics)

The Year 1, Task 1 effort required the design and construction of the Tm/Ho composite fiber laser by ARL and manufacture of two iterations of the fiber by Advalue Photonics.

Prior to commencement of the funded portion of the research, ARL received a free composite fiber as well as two glass-doped samples: one was Tm-doped glass and the other was Ho-doped glass. ARL performed exploratory experiments to demonstrate the feasibility lasing as well as to measure the absorption and emission spectra of sample glasses provided by Advalue. As a result, the ground state absorption, σ_{GSA}, and stimulated emission, σ_{SE}, cross sections of the Advalue glasses were measured early in the program and are shown in Fig. 2.

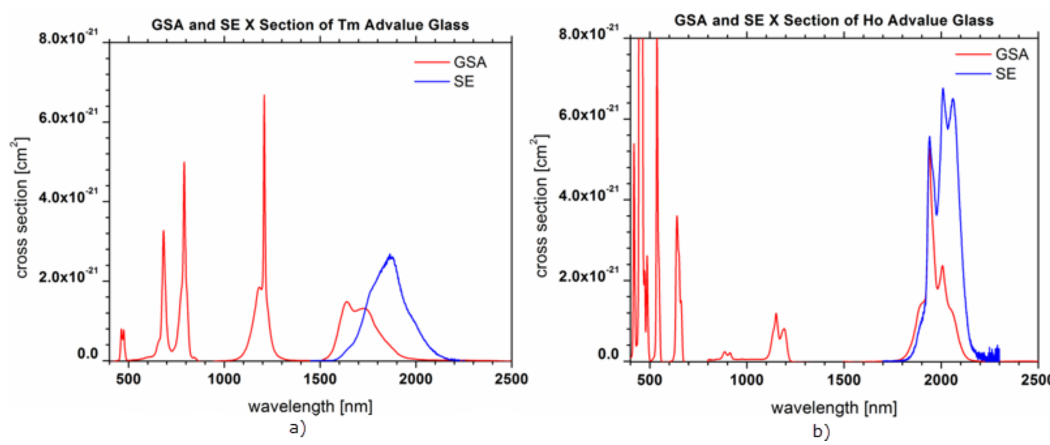

Fig. 2 Absorption and stimulated emission cross section of Tm a) and Ho b) silicate glass showing good emission cross section in Tm at around 1900 nm and emission by Ho at around 2050 nm

Using our absorption spectroscopy measurements of the $^3H_6$–$^3F_4$ transition in Tm, we determined that optical pumping at around 800 nm would allow for adequately slow longitudinal absorption given the large areal cross section of the Tm portion of the Tm/Ho fiber. As the Tm fiber was doped at around 4%, the 800-nm pumping of Tm led to a 2-for-1 cross relaxation (CR) process resulting in a population inversion of the Tm $^3H_4$ level and emission in the wavelength range of 1900–2000 nm being used to pump the Ho core. The $^3F_4$ Tm and $^5I_7$ Ho fluorescence-level lifetimes were measured to be 1.3 and 3.7 ms, respectively. Once the absorption and stimulated emission cross sections were determined, the gain cross sections, σ_{gain}, of the Tm or Ho fiber could be found as quantified by the relation,

$$\beta = \frac{N_2}{N_1 + N_2} \qquad \sigma_{gain} = \beta\sigma_{SE} - (1-\beta)\sigma_{GSA}\,, \tag{1}$$

where β is the fraction of ions in the excited level N_2, with respect to the total ion density, the sum of terminal level, N_1 plus N_2. Accordingly, it was calculated that the Tm portion of the laser would tend to lase in one of three "bands" for various β inversion values as shown in Fig. 3a due to absorption by the Ho core at 1950 nm and 2060 nm (see Fig. 2b). Calculation of the Ho gain spectrum (Fig. 3b) indicated that the Ho core was expected to lase at 2050 nm or longer.

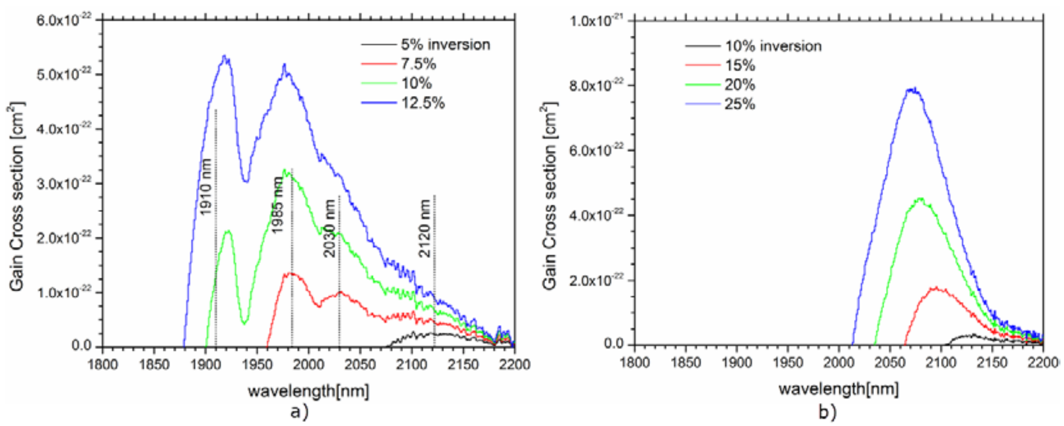

Fig. 3 Effective gain cross sections of Tm and Ho in the Tm/Ho composite fiber

2.1.1 Experimental Results Using the Advalue (23/75/187/230), NA 0.098/0.128/0.57 (Fiber no. 1)

A micrograph of ARL's first Tm/Ho composite fiber, Fiber no. 1, is shown in Fig. 4. It had a 23-µm diameter, 1% Ho core and a 75-µm diameter, 4% Tm clad surrounded by a 187-µm diameter, undoped second clad and a 230-µm diameter, undoped outer clad. The numerical apertures (NA) of Ho core, Tm clad, and undoped cladding were 0.098, 0.128, and 0.57, respectively, as provided by Advalue Photonics data.

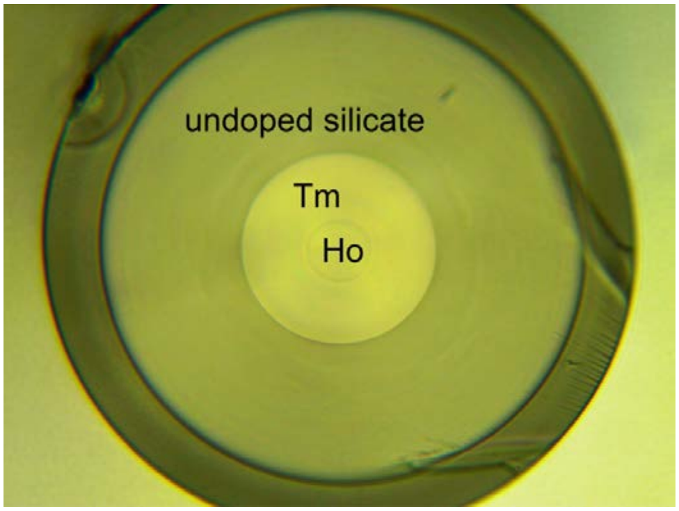

Fig. 4 Advalue Tm (4%)/Ho (1%) composite Fiber no. 1, diameter (23/75/187/230), NA (0.098/0.128/0.57)

In Fig. 5a, a LIMO (Dortmund, Germany) fiber-coupled pump, 400-µm/0.22 NA is used to deliver up to 400 W of 800-nm light through a dichroic mirror (pump mirror) butt-coupled to a 160-mm-long section of Tm/Ho Fiber no. 1. The fiber laser quasi-continuous wave performance was measured to deliver a 40% slope conversion of the pump (Fig. 5b) to 1900 nm (Fig. 5c).

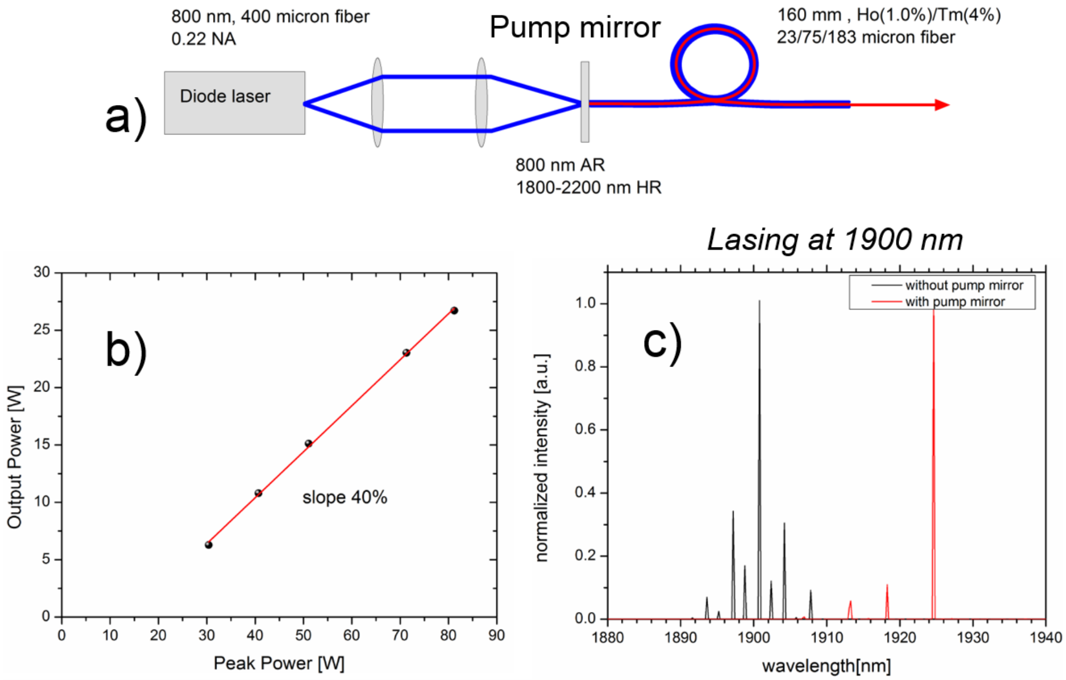

Fig. 5 Tm/Ho composite fiber laser setup a) and performance b) and output wavelength c) using Fiber no. 1. Spectra in black taken without a pump mirror and in red with pump mirror. Laser performance used a pump mirror.

After verifying that the Tm section of the fiber would lase, an output coupler (HR coated for 1850–1975 nm, PR reflective coating 95% for 2060–2100 nm [Lattice Electro Optics, Fullerton, CA]) was butt-coupled to a 300-mm-long length of fiber. (See Fig 6b for outcoupler transmission curve.) As expected, lasing of the Ho ion was observed at approximately 2080 nm (Fig. 6a) due to optical pumping of the Ho core by the lasing Tm medium. Also note that despite the HR coating at 2000 nm, leakage of the Tm-lasing wavelength is evident. While this result was seen as a successful demonstration of the principle of lasing of the Tm/Ho composite fiber, the lasing efficiency (~2% optical-to-optical) left much to be desired (Fig. 7). It should be pointed out that previous authors experimented with the Tm/Ho composite fiber as well, a fact unknown to us before this effort. They attained similar slope and lasing characteristics as we did.[5]

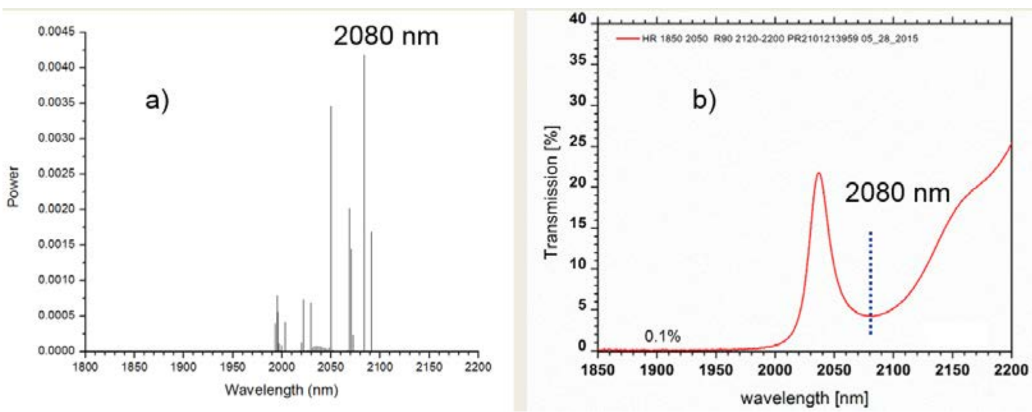

Fig. 6 Demonstration of Tm/Ho fiber lasing a) output spectrum and b) output coupler transmission spectrum

In retrospect, it became clear that the Tm portion of the laser naturally selected a wavelength that minimized its loss due to absorption by the Ho ion. In other words, the Tm portion of the fiber tended to lase where absorption by the Ho core was minimized (as can be seen in Fig. 2b at around 1980 nm). This tendency of the Tm to lase where it met the “least resistance” was repeatedly observed and in agreement with Year 2’s laser simulations.

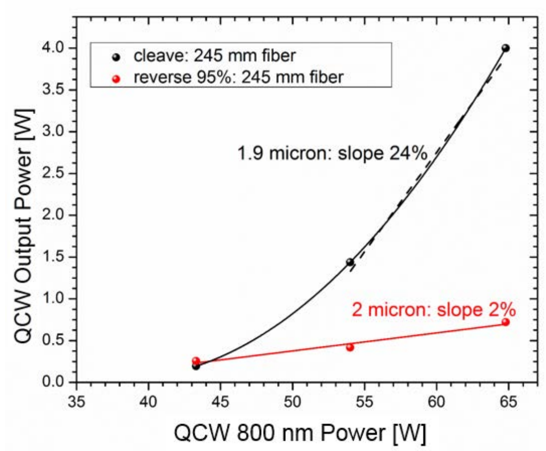

Fig. 7 Performance of the Ho/Tm laser using Fiber no. 1: only 2% optical-to-optical conversion of 800-nm pump to 2080 nm

2.1.2 Experimental Results Using the Advalue (20/60/185/230), NA 0.05/0.14/0.57 (Fiber no. 2)

Based on the results of experiments using Fiber no. 1 it was hoped that laser performance would improve with a fiber redesign, assuring the greater overlap of the Tm laser modes with the Ho core. Consequently, a second Tm/Ho composite fiber design was ordered from Advalue Photonics that increased the ratio of the Ho core to Tm clad cross-sectional area (60-µm Tm clad/20-µm core). The Ho core was also placed 15–20 µm off-center so as to further increase the Tm lasing mode's interaction with the Ho core. Shown in Fig. 8 are micrographs of Fiber no. 2 as provided by Advalue (Fig. 8a). Note that the core perimeter is not well distinguished from the Tm cladding areas. ARL conducted a test of the transmission of a 1339-nm wavelength through the Ho core to see if the Ho core was effectively guiding light (Fig. 8b). The 1339-nm wavelength was chosen as Ho and Tm have minimal absorption at that wavelength. A comparison of the spectral output of the laser using Fiber no. 2 with and without an output coupler is presented in Fig. 9. Unfortunately, the laser performance of Fiber no. 2 was inferior to Fiber no. 1, probably due to the weak guiding of the Ho core (overly low NA).

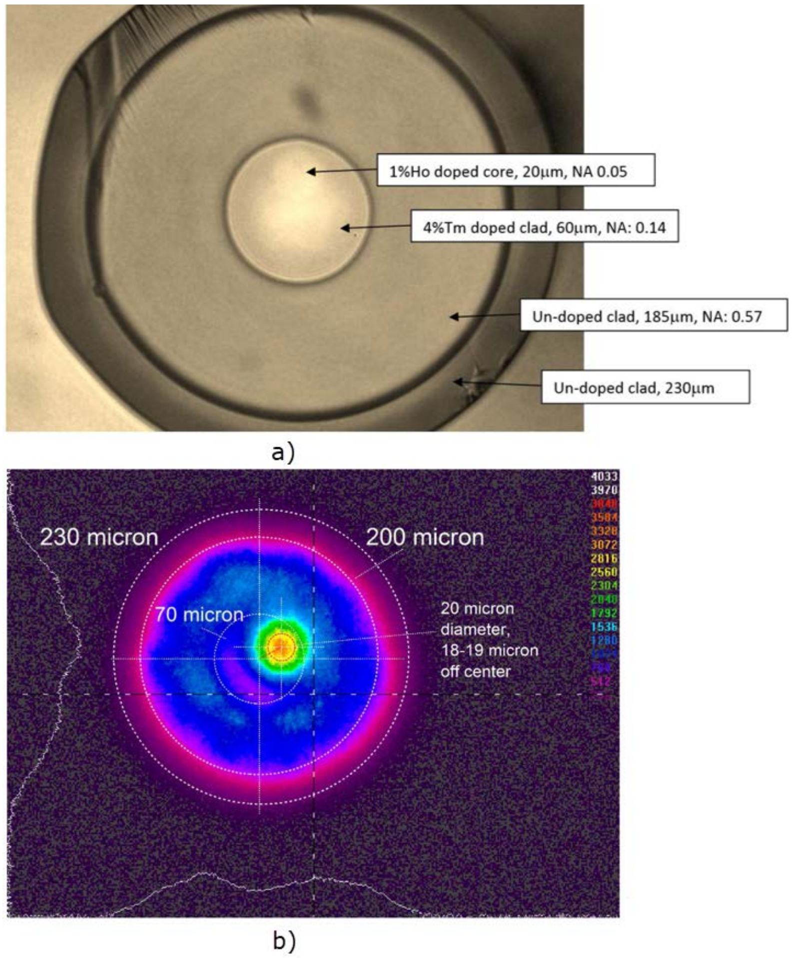

Fig. 1 Micrograph of Fiber no. 2 a) and image b) of off-center Ho core as illuminated by 1339-nm source

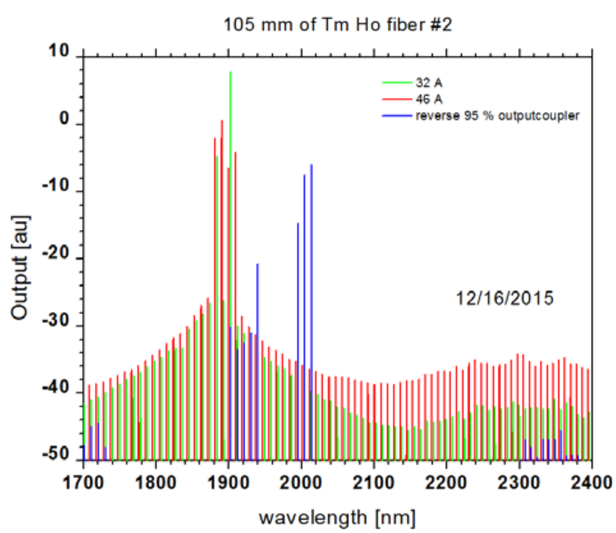

Fig. 2 Spectral output of the Tm/Ho fiber laser using Fiber no. 2 with and without a mirror output coupler

2.2 Year 2, Task 1: Model Multimode Distribution in the Triple Clad Tm/Ho Fiber

The second year's effort was intended to investigate causes for the low lasing efficiency of the Tm/Ho composite fiber using simulation of the laser. The earliest and simplified continuous wave (CW) modeling of the laser performance predicted a 40% optical-to-optical efficiency, that is, the efficiency of converting an 800-nm pump wavelength to a 2-µm lasing emission. As results of the Year 1 effort were analyzed, it became evident that new explanations for the low performance had to be considered. The explanations were that: 1) the Tm laser modes were not overlapping well with the Ho core and 2) the Tm clad was lasing at a wavelength least likely to be absorbed by the Ho rare earth ion. Modeling to test these two hypotheses required modal analysis of the fibers used in the experiment and expansion of the earliest, and oversimplified, laser model to a newer model that included the entire absorption and emission spectroscopy of the Tm and Ho ions rather than preselected lasing wavelengths.

2.2.1 Fiber Modal Analysis

To model the Tm/Ho composite laser accurately, we need to know to what extent the multimode Tm laser modes overlap with the Ho-doped core. The earliest modeling efforts assumed that the fraction of overlap of the Tm lasing mode with the Ho core was a simple area ratio of the Ho-doped core area to the area encompassed by the Tm-doped ring. These assumptions were inaccurate in two aspects: first, not all modes comprising the Tm laser profile overlap equally with the Ho core, and second, the NA of the core influences the degree to which the Tm mode will overlap the Ho core. The only accurate way to predict the degree of overlap requires calculation of the individual modes of the Tm/Ho fiber system.

We commenced the calculation by finding the eigenvectors of the Hemholtz equation describing the transverse magnetic field,[6]

$$\nabla_T X \frac{\nabla_T X \boldsymbol{H_T}}{\epsilon_r} - \frac{\nabla_T(\nabla_T \cdot \boldsymbol{H_T})}{\epsilon_r} + \left(\beta^2 - \frac{k^2}{\epsilon_r}\right)\boldsymbol{H_T} = 0\,, \qquad (2)$$

where ε is the relative permittivity of the medium ($n^2 = \varepsilon$), H_T is the transverse magnetic field, k is the wavevector in free space and β is the propagation constant. The solutions to Eq. 2 were found using a finite element analysis (FEA) method as calculated by the software package FlexPDE. For example, in the case of a core of 20-µm (NA=0.057) clad diameter of Fiber no. 3 of 40 µm (NA=0.15) imbedded in a second clad, 12 modes are supported at a wavelength of 1.9 µm. Once the mode's distributions are known, the degree to which the 12 modes overlap the Ho core may be calculated. In the case of the lowest order linearly polarized (LP) mode, LP_{01} overlaps 60% with the Ho core, while the LP_{11} only overlaps 25%. A plot of the fractional overlap of the various modes with the Ho core is shown in Fig. 10. The FEA mode method is valuable as it allows us to design a fiber structure that assures *all* modes overlap with the Ho core such that *all* Tm laser modes interact with the Ho core.

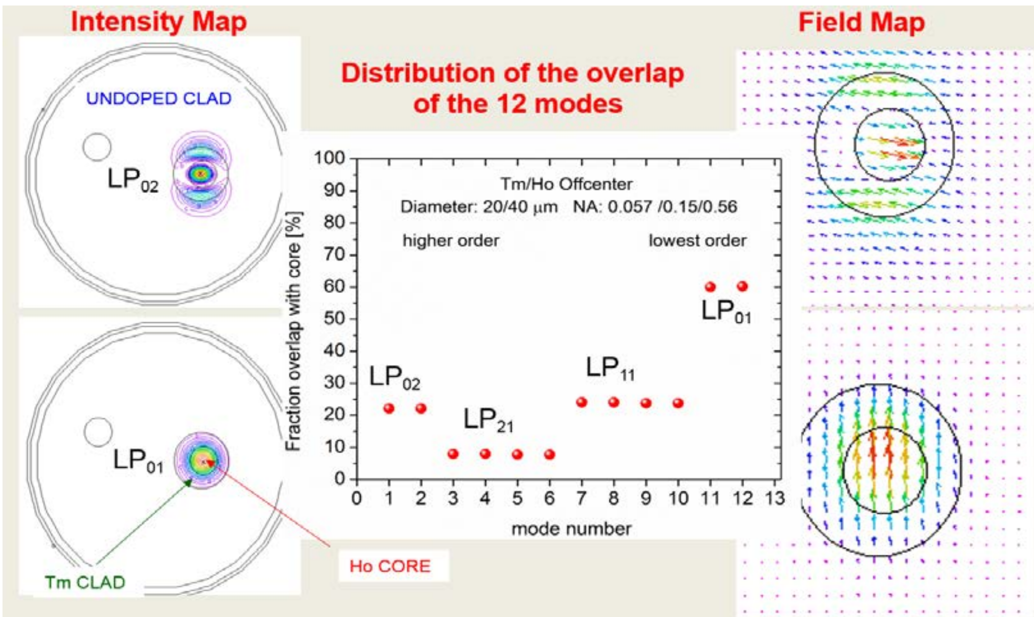

Fig. 10 Mode distribution example of Advalue Fiber no. 3 (30/40/180 [0.057/01.5/0.56 NA]) inclusive of low index region for 800-nm pump homogenization

2.2.2 Time- and Wavelength-Dimensioned Laser Simulation Equations

In an attempt to further investigate the causes for low laser efficiency performance, a Fortran program was written to simulate the Ho/Tm composite laser using the ARL-measured spectroscopy of Tm and Ho in a silicate glass. Unlike the earliest modeling efforts where Tm and Ho lasing wavelengths were chosen a priori, the model was rewritten to include the entire absorption and emission cross section spectra from 1800 to 2200 nm. Starting from an initial condition where the Ho and Tm was populated only in a ground state, the laser model was allowed to evolve from a nonlasing condition to lasing over the course of the 1-ms simulation interval. The simulation basis governing the evolution of Tm and Ho ions is based on the energy-level schemes, reproduced in Fig. 11, where both the linear and nonlinear transitions are such that the CR and upconversion (UC) processes are included. The UC process in Tm is responsible for the so-called “2-for-1” conversion of one 800-nm photon to two electrons in the $^3H_4$ level in Tm ion.

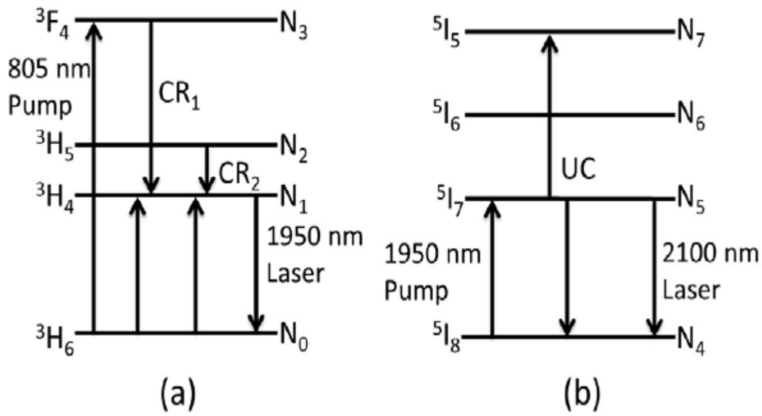

Fig. 11 Energy-level scheme of the Tm a) and Ho b)

The laser model was based on the rate and power propagation equations of Eqs. 3 and 4,[7] where N_i specifies the energy level density of level i, the coefficients A_{ij} define the fluorescence rate from level i to j, k_{ij} are the nonlinear coupling coefficients involved in CR and UC, σ_a and σ_e are the absorption and emission cross sections at a particular selected wavelength, and P_r^{Tm} and P_f^{Tm} are the backward and forward propagating Tm light intensities at the Tm lasing wavelength, and A_{eff}^{Tm} and A_{eff}^{Ho} are the effective spatial cross sections of the Tm-doped ring and Ho-doped core, respectively. The simulation also included an intrinsic glass loss due to scattering, α_{glass}, (not shown in equation 4)

$$N_0 = N_{Tm} - N_1 - N_2 - N_3$$

$$\begin{aligned}\frac{dN_1}{dt} &= -A'_{10}N_1 + A'_{21}N_2 + A_{31}N_3 \\ &+2\left(k_{31}N_3N_0 - k_{13}{N_1}^2\right) + 2\left(k_{21}N_2N_0 - k_{10}{N_1}^2\right) \\ &- \frac{\lambda_{Tm}}{hcA_{eff}^{p}}\left[P_f^{Tm}(z) + P_r^{Tm}(z)\right]\left[\sigma_e^{Tm}(\lambda_{Tm})N_1 - \sigma_a^{Tm}(\lambda_{Tm})N_0\right]\end{aligned}$$

$$\frac{dN_2}{dt} = A'_{32}N_3 - (A'_{21} + A_{20})N_2 - \left(k_{21}N_2N_0 - k_{10}{N_1}^2\right)$$

$$\begin{aligned}\frac{dN_3}{dt} &= \frac{\lambda_p}{hcA_{eff}^{Tm}}\sigma_a^{Tm}(\lambda_p)\left[P_f^p(z) + P_r^p(z)\right]N_0 \\ &- (A'_3 + A'_{32})N_3 - \left(k_{31}N_3N_0 - k_{13}{N_1}^2\right)\end{aligned} \quad (3)$$

$$N_4 = N_{Ho} - N_5 - N_7$$

$$\frac{dN_5}{dt} = -A'_{54}N_5 + A'_{75}N_7 + \frac{\lambda_{Tm}}{hcA_{eff}^{Tm}}\sigma_a^{Ho}(\lambda_{Tm})[P_f^{Tm}(z) + P_r^{Tm}(z)]N_4 - 2k_{57}N_5{}^2 - \frac{\lambda_{Ho}}{hcA_{eff}^{Ho}}[P_f^{Ho}(z) + P_r^{Ho}(z)][\sigma_e^{Ho}(\lambda_{Ho})N_5 - \sigma_a^{Ho}(\lambda_{Ho})N_4]$$

$$\frac{dN_7}{dt} = -(A'_{75} + A_{74})N_7 + k_{57}N_5{}^2$$

Ho and Tm rate equations

$$\frac{dP_{f,r}^{p}(z)}{dz} = \mp P_{f,r}^{p}(z)[\sigma_a^{Tm}(\lambda_p)N_0\Gamma_p^{Tm} + \alpha_p]$$

$$\frac{dP_{f,r}^{Tm}(z)}{dz} = \pm P_{f,r}^{Tm}(z)\{[\sigma_e^{Tm}(\lambda_{Tm})N_1 - \sigma_a^{Tm}(\lambda_{Tm})N_0]\Gamma_{Tm}^{Tm} - \sigma_a^{Ho}(\lambda_{Tm})N_4\Gamma_{Tm}^{Ho} - \alpha_{Tm}\} \pm \sigma_e^{Tm}(\lambda_{Tm})N_1\Gamma_{Tm}^{Tm}h\upsilon_{Tm}\Delta\upsilon_{Tm}$$

$$\frac{dP_{f,r}^{Ho}(z)}{dz} = \pm P_{f,r}^{Ho}(z)\{[\sigma_e^{Ho}(\lambda_{Ho})N_5 - \sigma_a^{Ho}(\lambda_{Ho})N_4]\Gamma_{Ho}^{Ho} - \alpha_{Ho}\} \pm \sigma_e^{Ho}(\lambda_{Ho})N_5\Gamma_{Ho}^{Ho}h\upsilon_{Ho}\Delta\upsilon_{Ho} \qquad (4)$$

Power propagation equations

The simulation was carried out by dividing the laser gain medium into a set of *N* equally divided wide sections (cells) along the dimension, *z*, and then calculating the time evolution of the rate equations for each n-gain sections over a small time interval. The time interval was determined by the time it would take for light to propagate across one gain section, typically defined in tens of picoseconds. After calculating the level densities, the 800-nm pump, Tm and Ho light intensities (both forward and backward propagating) were advanced from one gain section to another (Fig. 12). The cycle was then repeated. At the mirror boundaries, a wavelength-dependent reflectivity profile was used to reflect/transmit the Ho and Tm light intensities as a function of their wavelengths.

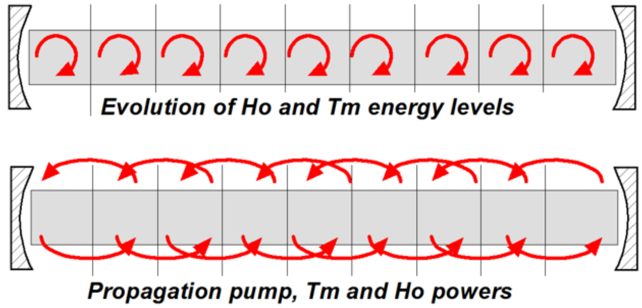

Fig. 12 Steps used by laser simulation to calculate laser performance: calculate the energy level evolution in each cell based on the rate equations (top) and propagate pump and laser powers to neighboring cell (bottom)

2.2.3 Laser Simulation Results

As a simulation example of the Tm/Ho fiber laser (Fig. 13), we calculated the temporal intracavity intensity and Tm- and Ho-lasing wavelengths of an 800-nm, 100-W high-loss pumped (α_{glass} = 4.34 dB/m) 0.5-m-long fiber. The measured reflectivity (green trace in Fig. 13) of the output coupler used in the experiment was included in the laser model. The simulation predicted that 17 W of intracavity, 1900-nm Tm laser, and 4 W of Ho 2100-nm intracavity power would be produced at the output coupler. Since the output coupler allowed only 20% power to exit, we would expect only 1 W of 2100-nm power to be produced for this particular experiment. Clearly demonstrated in the simulation is that the Ho portion of the fiber laser requires about 60 µs of pumping by the Tm portion of the laser before it begins to lase. Also note that given the uniform reflectivity of the output coupler between 1800 and 1975 nm, the Tm portion of the laser "chooses" to function at 1920 nm, well off the peak absorption by Ho at 1950 nm.

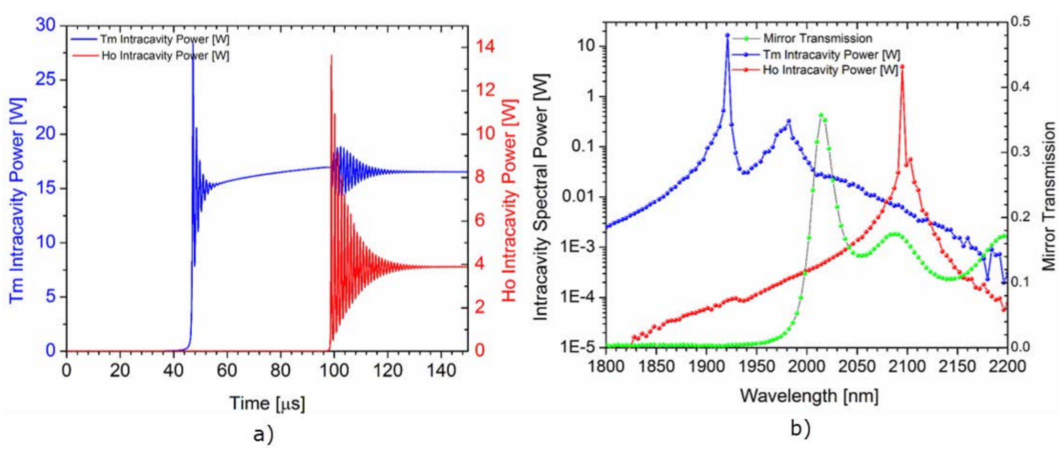

Fig. 13 a) Evolution of the Tm (blue) and Ho (red) laser intracavity power over a 150-µs interval and b) spectral output of the Tm (blue) and Ho (red) laser powers at the end of the 150-µs period. Note the transmission spectra (green) of output coupler used in simulation.

2.2.4 Self–Pulsing as Observed and Modeled

We observed under certain experimental conditions that laser output pulsed at roughly a 3-MHz frequency. We attributed this to interaction of the Tm laser with the Ho-absorbing core. Assuming that the Ho core served as a dynamic absorber, that is, that the Ho core acted as a gain medium that could go undergo relaxation oscillations as it was pumped by the Tm laser, it is reasonable to assume that the Tm and Ho portions of the fiber would exhibit a synchronized relaxation oscillation behavior. An estimate of the expected damping time constant, τ, of the Tm laser can be estimated as,

$$\tau = \frac{2L}{c\left(1 - R_1 R_2 + L\left(\alpha_{glass} + N_{Ho}\sigma_{Ho\ abs}\gamma\right)\right)}, \tag{5}$$

where R_1 and R_2 are the reflectivities of the output coupler and pump dichroic at the Tm-lasing wavelengths, α_{glass} is the scattering/absorption loss of the medium, c is the speed of light, L is the length of the fiber, N_{Ho} is the ion density of the Ho medium, $\sigma_{Ho\ abs}$ is the absorption cross section of the Ho core at the lasing Tm wavelength and Υ is the fraction of Tm-lasing power seen by the Ho core. Using τ, the relaxation frequency, f, of the Tm laser can be calculated[8] as

$$f = \frac{\sqrt{\frac{\sigma_{SE} I}{\tau h \upsilon}}}{2\pi}, \tag{6}$$

where σ_{SE} is the stimulated emission cross section of the Tm medium, I is the intracavity Tm laser intensity, h is the Planck's constant, and v is the Tm optical frequency. Using Eqs. 5 and 6, we expected to see a relaxation frequency of 600 kHz, whereas a detail of the Fig. 13 simulation shows a relation frequency of 1 MHz (Fig. 14).

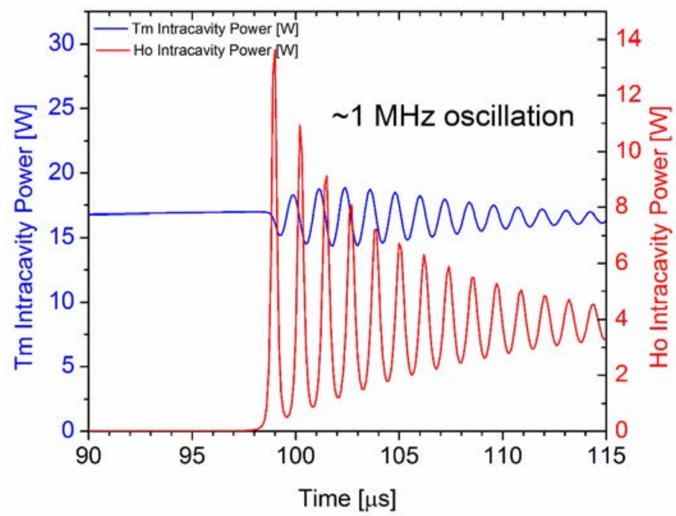

Fig. 14 Detail of Fig. 13: illustration of the synchronized relaxation oscillation between the Tm and Ho portions of the simulated laser

Experimental observation of the laser self-pulsing differed from what was modeled in two ways: the pulsing was persistent and it was more chaotic than the simulation predicted. Using the experimental setup shown in Fig. 15, which allowed for the Tm and Ho laser wavelengths to be separated by an optical grating and observed concurrently, we measured the 1.95-µm and 2.1-µm temporal output (Fig. 16).

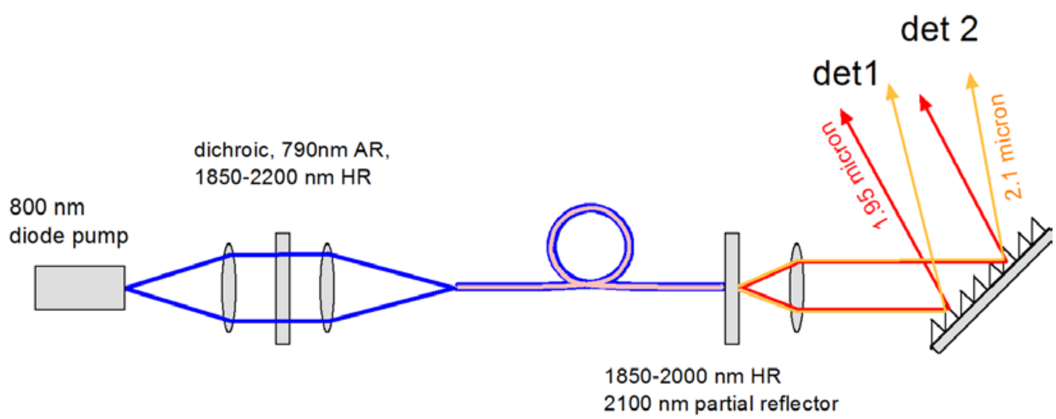

Fig. 15 Experimental setup used to observe the high frequency self–pulsing output of the Tm/Ho composite laser

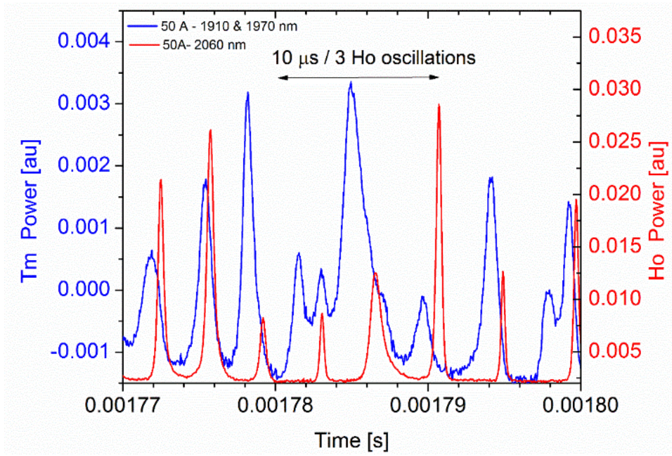

Fig. 16 Self–pulsing of the Tm/Ho fiber laser showing that Tm (blue) and Ho (red) wavelengths pulsed in rough coordination with each other at ~3.3 MHz

2.2.5 Potential for Improved Laser Efficiency

Using the laser simulation program developed at ARL, we were able to explore variations to the Tm/Ho composite fiber laser design. We found that by replacing the output coupler "single band" profile (see Fig. 13b), as manufactured with the ideal "2-band" profile of Fig. 17a, we could force the Tm portion of the laser to operate at 1950 nm and optimally pump the Ho core. The simulation indicated that a 12% optical-optical (Fig. 17b) slope efficiency could be achieved through this switch of output coupler designs. Unfortunately, manufacture of such an output coupler would be challenging due to the large number of dielectric layers required for the coating, but not impossible.

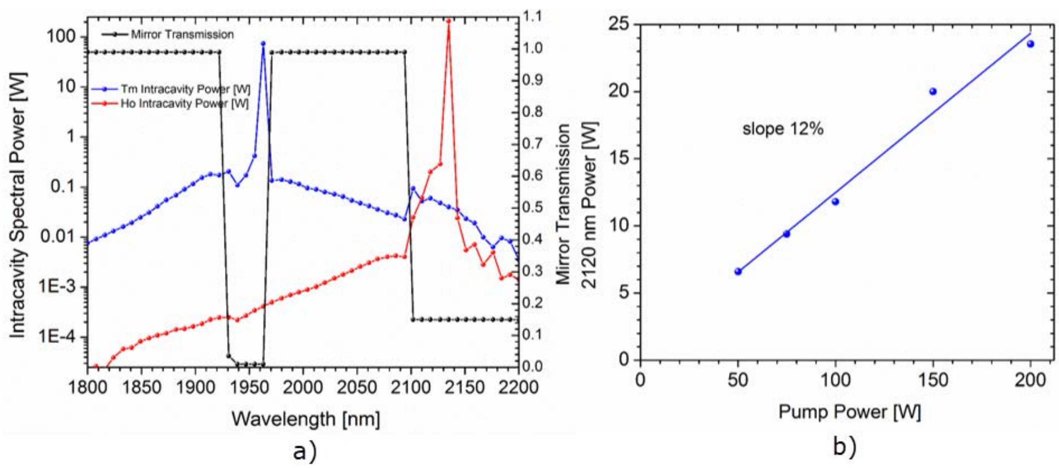

Fig. 17 a) Calculated laser performance of a Tm/Ho composite laser using a 2-band output coupler reflectivity profile and b) calculated performance showing 12% slope efficiency and emission at 2120 nm

3. Conclusion

Through funding by the JTO, we presented the principle and reported the performance of the Tm/Ho composite Tm/Ho fiber laser as optically pumped at 800 nm and lased at 2.1 µm using fiber produced by Advalue Photonics (also JTO-funded). During the two-year effort we tested three different fiber geometries, measured the absorption and emission spectroscopy of the Tm and Ho silicate glasses used in the fiber, and showed a 2% optical-to-optical slope efficiency is possible. We also developed a time-dependent, wavelength-dimensioned laser model of the Tm/Ho composite fiber laser and determined that at least a 12% slope efficiency should be possible using an optimized output coupler design.

4. References

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List of Symbols, Acronyms, and Abbreviations

AR	anti-reflective
ARL	US Army Research Laboratory
CR	cross relaxation
CW	continuous wave
FEA	finite element analysis
Ho	holmium
HR	high reflection
JTO	Joint Technology Office
LP	linearly polarized
NA	numerical apertures
PR	partially reflective
Th	thulium
UC	upconversion

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