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Novel Highly Efficient In-Band Pump Wavelengths for Ho-doped Fiber Amplifiers

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1. Abstract We report the design and performance of Holmium-doped fiber amplifiers (HDFAs) with novel alternative in-band pump wavelengths in the 1720—2000 nm spectral region. We demonstrate through simulations that pump wavelengths of 1840—1860 nm can yield significantly improved output power (3—6 dB), gain (8—10 dB) , and optical-optical conversion efficiency compared to the previous technical and industry standard pump wavelength of 1940 nm. Experimental results fully confirm our simulations.

2. Introduction Recent development of Ho- doped optical fiber amplifiers in the 2000 nm spectral region is important for many emerging applications including LIDAR, optical telecommunications, coherent lightwave systems, and spectral sensing [1]-[7]. We have previously shown that hybrid polarization maintaining (PM) Holmium-doped fiber amplifier (HDFA) architectures exhibit low noise figure (NF), high output powers, and a large operating spectral bandwidth [8]– [13]. In all these amplifiers, the HDFA is pumped at an in- band wavelength of 1940 nm which is based on a survey of the previous literature [14]— [20] and also on previous technical results.

In this paper, we investigate the design and performance of Ho-doped fiber amplifiers with novel alternative in-band pumping wavelengths in the 1720—2000 nm spectral region. We study in detail the performance of these amplifiers as a function of pump wavelength, pump power, signal wavelength, and signal power with both co- and counter-pumping. The results of our studies show that new pumping wavelengths in the 1720-2000 nm band yield superior results for gain, output power, and optical-optical conversion efficiency in comparison to the previously selected “standard” pump wavelength of 1940 nm which up until now has been an industry norm. The clear improvements in performance with the new or alternative pump wavelengths open the possibility of novel amplifier designs and architectures which yield much better optical-to- optical power conversion efficiencies, considerably higher saturated output powers, and strongly enhanced small signal gains, among other benefits.

3. Absorption and Gain Coefficients and Single Stage HDFA Simulations We start our analysis by noting that in our research on Ho-doped fiber amplifiers to date, we have chosen an in-band pump wavelength of 1940 nm based on a survey of the previous literature [14]— [20] and also on consideration of the gain and absorption curves for the iXblue Ho-doped fiber IXF-HDF-PM-8-125 [8], [14]. Fig. 1 is a plot of these gain and absorption curves, where we see that the maximum absorption is 57 dB/m at 1945 nm. A first analysis indicates that pumping at or near 1940 nm might yield an optimum result because this is close to the wavelength for peak absorption. However, if we consider the additional effect of the gain data, we can also hypothesize that pumping at 1940 nm where the emission cross section is near its maximum value could lead to a reduction in the amplifier gain because of strong stimulated emission. This stimulated emission reduces the population inversion created for the 2000—2100 nm signal band.

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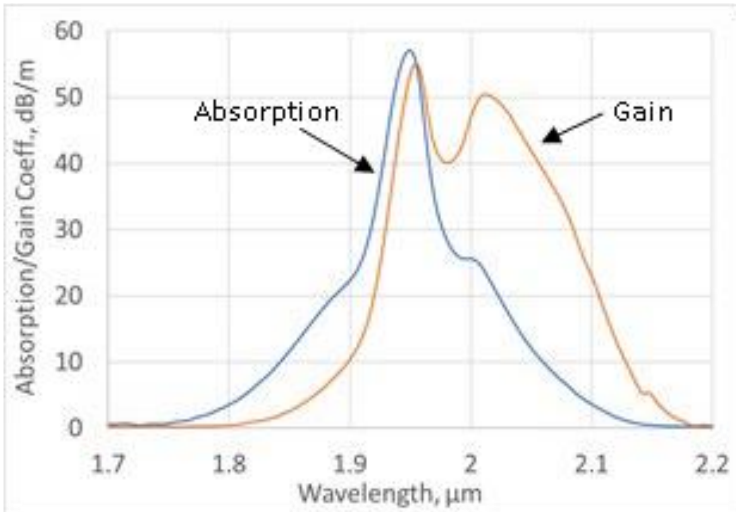

Fig. 1. Gain and absorption coefficients for iXblue PM Ho-doped fiber IXF-HDF-PM-8-125.

Based on our inferences for stimulated emission at the pump wavelength, we hypothesize that, for Ho-doped fibers, in-band pumping at wavelengths of 1820—1900 nm might be more efficient and effective than in-band pumping at wavelengths of 1940 nm and above. From Fig. 1 we see that the stimulated emission when pumping at 1820—1900 nm is expected to be far less that for a pump wavelength of 1940 nm. We note that our hypotheses are quite similar to behavior observed with in-band pumped Er-doped fiber amplifiers for the two pumping wavelengths of 1480 nm and 1529 nm and a signal band of 1530—1610 nm [21],[22].

With these considerations in mind, we start our quantitative analysis by considering the simple single stage HDFA shown in Fig. 2. Here signal input light at 2000–2100 nm passes though isolator I1 and signal/pump wavelength division multiplexer WDM1 and is coupled into F1, a PM Ho-doped fiber (iXblue IXF-HDF-PM-8-125). The signal output from F1 is coupled through isolator I2 to the signal output port. Internal input signal power Ps is measured at the input of F1, and internal signal output powers are measured at the output of F1. In this amplifier, P1 is a multiwatt 1720—2000 nm Tm-doped fiber laser which copumps F1 through WDM1. P1 can also be a semiconductor source or a solid-state laser source. Up to 2.5 W of 1720— 2000 nm pump light is available to pump F1. Pump powers are measured at the input of F1.

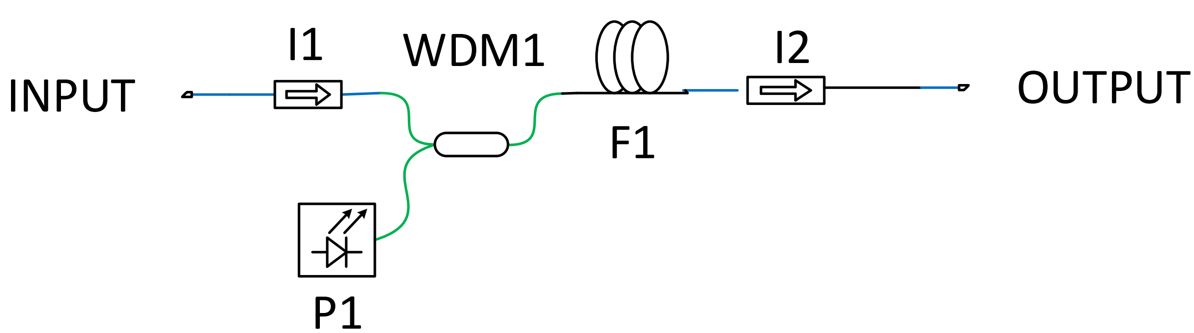

Fig. 2. Single stage co-pumped HDFA for simulation studies

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To verify our hypotheses in a systematic way, we studied through simulations [10—12] the performance of a 3 m long Ho-doped amplifier in Fig. 2 as a function of pump wavelength. 3 m length was chosen based on previous optimization studies [10—12]. The results of our first simulation analysis are presented in Fig. 3, where we plot the saturated output power at a signal wavelength of 2051 nm for a pump power of 2470 mW and pump wavelengths ranging from 1720 nm to 2000 nm. Here we see that the signal output power reaches a maximum of 1033 mW at a pump wavelength of 1840 nm and maintains a high output value over the range of 1790— 1930 nm. For all pump wavelengths, minimal pump power is left over at the end of the fiber. At 1940 nm pump wavelength, the output power is considerably reduced from the peak value to 425 mW. The numerical advantage of pumping at 1840—1860 nm relative to 1940 nm is therefore a factor of 2.43 or 3.9 dB in power. The peak optical-optical efficiency at 1840 nm is ε = 41.8 %, and the efficiency is reduced to 17.2 % for 1940 nm pumping.

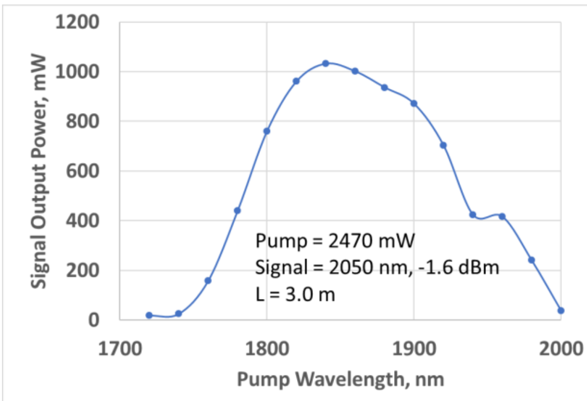

Fig. 3. Signal output power vs. pump wavelength for L = 3 m and λ_S = 2050 nm.

Based on the results in Fig. 3, we then investigated the small signal gain and noise figure for the 3 m HDFA as a function of signal wavelength for the two selected pump wavelengths of 1860 nm and 1940 nm. Fig. 4 shows the simulated values of G and NF as a function of λ_s for an input power of P_s = -31.6 dBm. The advantage of pumping at 1860 nm is clear, where the peak gain at this pump wavelength is 54 dB in comparison to a peak gain of 45 dB for 1940 nm pumping. The simulated noise figures for the two pump wavelengths track one another closely with maximum noise figures of 10 dB at 1990 nm signal wavelength and minimum noise figures of 6.8 dB at 2110 nm.

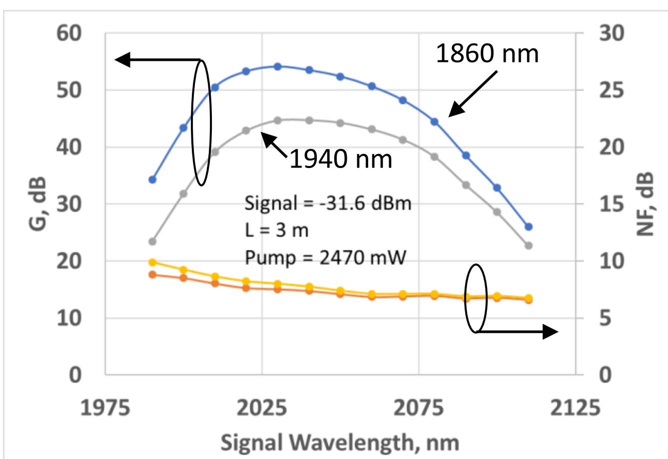

Fig. 4. Gain and noise figure vs. signal wavelength for L = 3 m and pump wavelengths of 1860 nm and 1940 nm.

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We also simulated the saturated output power as a function of signal wavelength for the two selected pump wavelengths. Fig. 5 plots output power vs. λ_s from 1990 to 2110 nm. Here we see again the effectiveness of pumping at 1860 nm relative to 1940 nm, with an increase in peak power between the two pump wavelengths of 3.8 dB.

The signal output power with an 1860 nm pump is 1016 mW, corresponding to ε = 41.1%. At 1940 nm pump peak power is 426 mW corresponding to ε = 17.2 %.

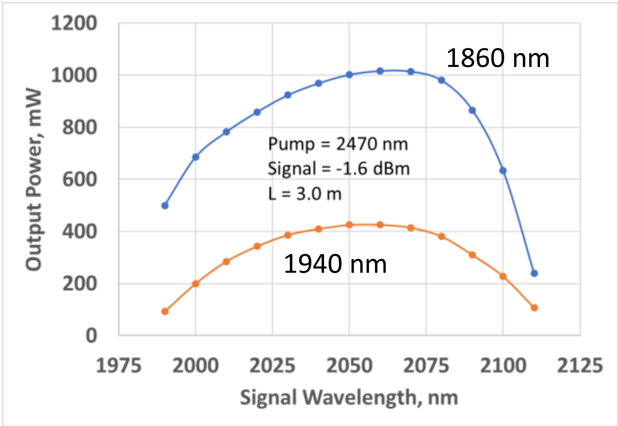

Fig. 5. Output power vs. signal wavelength for L = 3 m and pump wavelengths of 1860 nm and 1940 nm.

In summary, for all the configurations studied through simulations, we find that 1860 nm pumping is far more efficient than 1940 nm pumping, verifying our hypotheses based on the gain and absorption curves of Fig. 1.

4. Experimental Verification of Simulations

To compare the results of our simulations with data, we first turn to an experimental measurement of the output power from the PM Ho-doped fiber with 1860 nm pumping. The single stage experimental setup for this measurement is shown in Fig. 6, with the following parameters: Pump power = 2.0 W at 1860 nm, signal input = 0.8 dBm at 2092 nm, and F1 = 3.0 m. The amplifier is counterpumped instead of copumped as in Fig. 2.

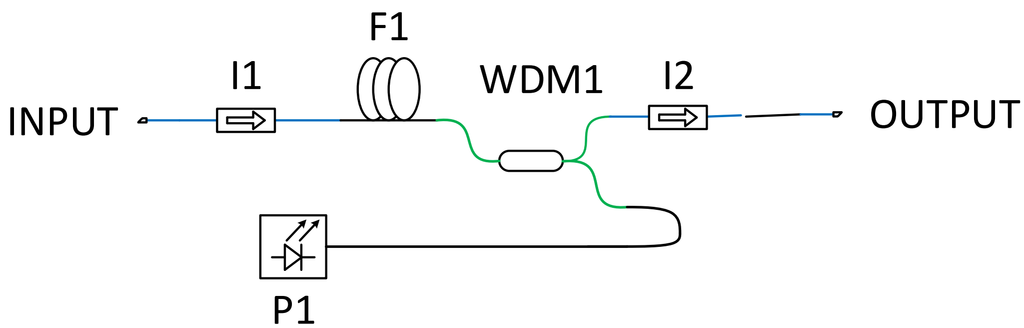

Fig. 6. Counterpumped Single Stage PM HDFA

The experimentally measured output power from the amplifier in Fig. 6 under these conditions is found to be 840 mW ± 15 mW, corresponding to a power conversion efficiency of 42%.

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The simulated output power for this configuration is found to be 907 mW, which is 0.33 dB or 8% greater than the measured output power. This indicates excellent agreement between simulation and experiment for 1860 nm pumping.

We next study the variation in 2092 nm signal output power for this amplifier as a function of 1860 nm pump power. Fig. 7 plots the measured (points) and simulated (solid line) signal output power at 2092 nm as a function of pump power at 1860 nm with pump powers ranging from 0.26 W to 2.32 W. We see that the agreement between experiment and simulation is quite good, with typical variations between data and simulations of 0.5 dB or less. The optical-optical conversion efficiency slope for the simulated amplifier output is η = 37.3 %.

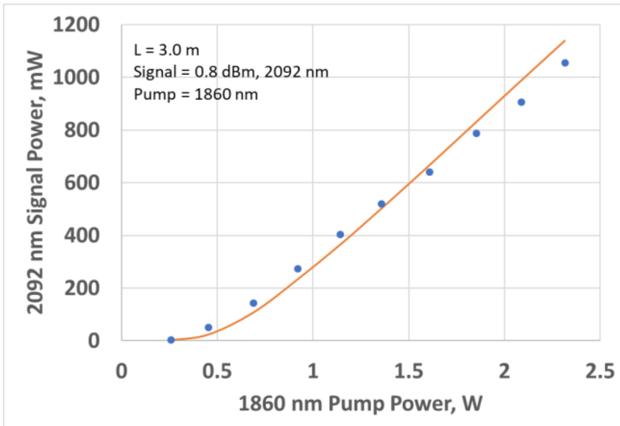

Fig. 7. Signal Output Power vs. Pump Power for Counterpumped Single Stage PM HDFA

Fig. 8 gives a comparison of simulation and experiment for the optical signal to noise ratio (OSNR) for the amplifier signal at 2092 nm as a function of pump power. Here the experimental data are points and the simulation is a solid line. The simulated spectrum for a signal wavelength of 2092 nm and a pump power of 2.32 W is shown in Fig. 9. Here the gain peak is at 1940 nm and the 10 dB bandwidth is about 90 nm. As the plot in Fig. 8 indicates, the simulations and the experimental data agree well over the measured pump range of 0.26—2.09 W at 1860 nm.

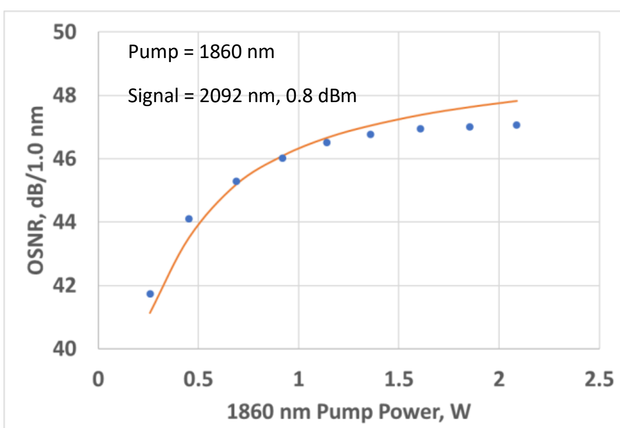

Fig. 8. Experimental and simulated OSNR for counterpropagating PM HDFA.

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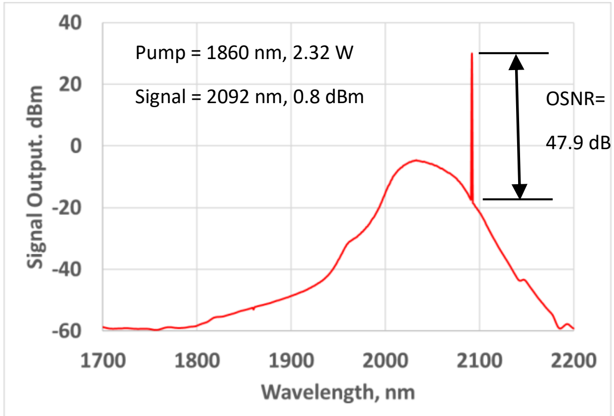

Fig. 9. Simulated spectrum for counterpropagating PM HDFA

In Fig. 10 we graph the simulated vs. experimental values of output signal power vs. input signal power for an 1860 nm pump power of 1.262 W. The plot demonstrates that agreement between simulation and experiment is relatively good over the full range of input powers studied. The differences for lower input powers are under study. We will address this subject more fully in a future publication.

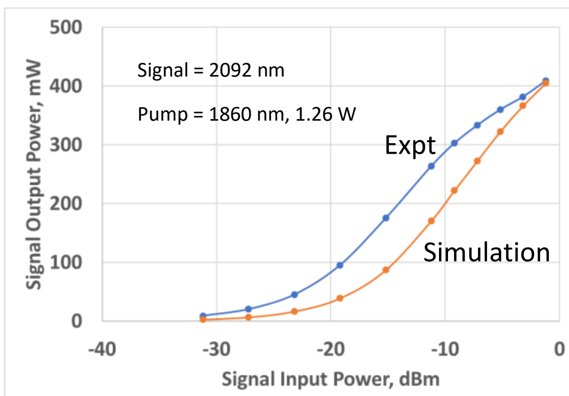

Fig. 10. Output signal power vs. input signal power at 2092 nm for counterpropagating HDFA

Additional simulations and experimental data will be presented at the conference.

5. Summary and Conclusions

We have presented a novel and innovative in-band pumping wavelength of ~1860 nm for Ho-doped fiber amplifiers operating in the 2000—2100 nm signal region. The strong performance advantages of this new pumping wavelength are verified both through simulations and experiment. Compared to the previous industry and research standard pumping wavelength of 1940 nm, we have demonstrated that 1860 nm pumping can yield significantly higher output powers, small signal gains, and power conversion efficiencies in current amplifier architectures. In the case of single stage designs, the advantages in output power are typically 3-4 dB, and the advantages in small signal gain are found to be as great as 8—10 dB. Our findings will apply to single- and double-clad fiber amplifiers and also to fiber lasers.

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Taken together, our results clearly demonstrate the strong advantages of this novel ~1860 nm pumping approach for HDFAs. We anticipate immediate applications in the design and manufacture of single and multi-stage HDFAs and ASE sources for LIDAR, lightwave communications systems, coherent lightwave systems, and spectral sensing applications.

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