Performance Benefits of 1860 nm vs. 1940 nm Pumping of Holmium-doped Fibres with Significant Ion Pairing

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Abstract *We report a first investigation of the performance of single clad Ho-doped fibres as a function of both ion pairing and pump wavelength. Our report shows that 1860 nm yields a significant performance advantage over 1940 nm pumping for representative Ho-doped fibres with a wide range of ion pairing. We find that our simulations when compared with experiment yield an accurate value for the degree of ion pairing. Our simulations are confirmed by experimental data.*

Introduction

Recent comprehensive studies of the performance of single clad Ho-doped fibre amplifiers (HDFAs) clearly demonstrate that the degree of ion pairing in the fibres strongly affects the small signal gain and saturated output power performance of these devices [1-9]. Also, a detailed analysis of the effect of pumping wavelength on HDFA performance shows that, for representative commercially available fibres, a novel pumping wavelength of 1860 nm exhibits superior performance compared to the previous technical and industry standard pump wavelength of 1940 nm [7-9]. The quantitative advantages of 1860 nm pumping are up to 9 dB in small signal gain and up to 3-4 dB in saturated output power [7-9]. For these reasons, optimization of HDFAs with respect to both pumping wavelength and the degree of ion pairing is quite important and significant for the design of amplifiers targeting high optical-to-optical and electrical-to-optical power conversion efficiencies. In particular, the design of practical compact HDFAs with limited available pump powers on the order of 1 W or less requires careful and detailed studies of the effects of both pump wavelength and ion pairing for optimized amplifier performance.

In this paper we present a first investigation of the simulated combined effects of both novel pump wavelengths and ion pairing on the operation of practical single clad HDFAs constructed with representative doped fibres. We show that careful adjustment of the interplay between ion pairing and pump wavelength results in a clearly improved amplifier design. We then discuss future directions for the optimized design of HDFAs with available pump powers up to 3 W, and also compact HDFAs with limited pump power of 1 W or less [10]. Our simulations are confirmed by experimental results.

HDFA Architecture and Simulations

Figure 1 shows the architecture for the single clad, single stage HDFA under study. P1 is a single mode co-pump source with wavelengths between 1700 and 2000 nm and output powers from <1 W to >3 W. The signal input in the 2050 nm band passes through an input FC/APC connector, isolator I1, and wavelength division multiplexer WDM1, and is coupled into the active Ho-doped fibre F1 (iXblue IXF-HDF-PM-8-125). The amplified signal output from F1 then passes through output isolator F2 to the output FC/APC connector. Pump and signal powers are measured at the input and output of F1.

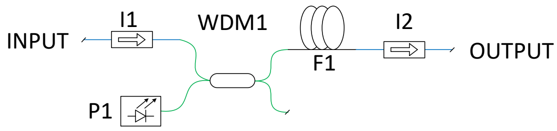

Fig. 1: Topology of the single stage HDFA under study

The performance of the amplifier is simulated with an in-house software program that employs the Giles optical amplifier model and fourth order Runge-Kutta algorithms for solving the coupled nonlinear differential propagation and rate equations [7,8]. The accuracy of the program, when compared to experimental results, is typically ± 1 dB in small signal gain and ± 0.5 dB in saturated output power [7,9].

Simulation Results with High Pump Powers

We first investigate the performance of the HDFA in Fig.1 with a pump power of 2.47 W and a pump wavelength range of 1720—2000 nm. With this pump power, the fibre length is set to its optimum value of 3.0 m. Fig. 2 shows simulated saturated output powers for an input signal of 0 dBm at 2050 nm and for four different degrees of ion pairing in the fibre.

Several conclusions can be drawn from Fig. 2

about the interplay between pump wavelength and ion pairing for this HDFA.

First, the peak optical power conversion efficiency PCE = (signal output power/pump power) increases as the ion pairing decreases. We observe PCE = 27.8% for 30% pairing, 41.5% for 13.5 % pairing, 49.8% for 7 % pairing, and 62.8% for 1 % pairing. This is the expected trend for HDFA behaviour as a function of ion pairing since each ion pair reduces the available inversion in the optical amplifier.

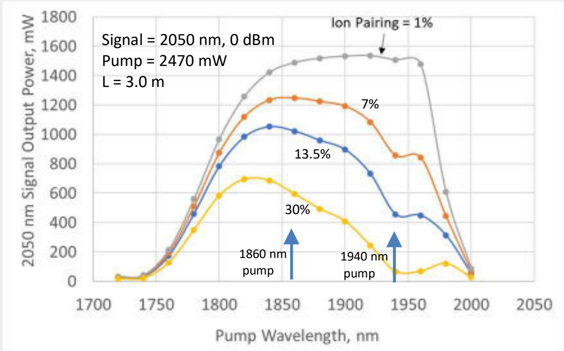

Fig. 2: Saturated output power of the HDFA as a function of pump wavelength and ion pairing

Second, we observe that the 1 dB or 79% width of the saturated output power curves around the maximum values is quite broad, with a width of 105 nm (1805—1910 nm) for the fibre with 13.5% ion pairing. The width increases significantly as the ion pairing decreases. Physical reasons for this behaviour will be discussed at the conference. This indicates that it is beneficial to use a novel pump wavelength around 1860 nm for typical fibres with ~15% ion pairing where the wavelength tolerance is broad, rather than the previous technical and industry standard of 1940 nm where the tolerance is narrow and output power changes rapidly with variations in pump wavelength.

To determine the behaviour of the amplifier with signal wavelength, we consider the plot in Fig. 3 where simulated PCE is studied as a function of λ_s for ion pairing of 13.5%. We see that 1860 nm pumping yields output powers about 2.4 times or 3.8 dB greater than 1940 nm pumping, as expected from the analysis and results in [7-9]. Peak output power is reached for a signal wavelength of 2070 nm at 1860 nm pumping, and 2060 nm for 1940 nm pumping. The 3 dB or 50% width of the OCE curves is about 1990—2105 nm or 115 nm, indicating a wide operating output power bandwidth for the HDFA.

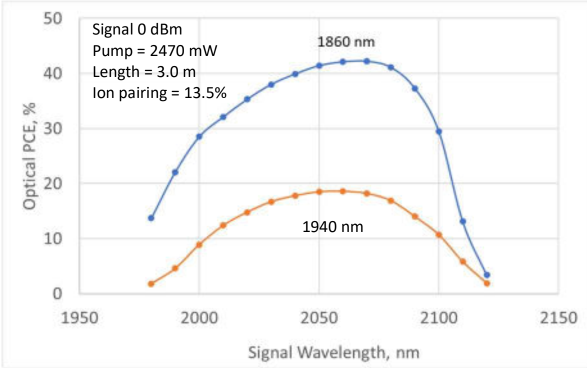

Fig. 3 Optical PCE as a function of signal wavelength for ion pairing of 13.5%

Simulation Results with 1 W Pump Power

We next simulate the performance of the HDFA with a pump power of 1 W which is the level of pump that can be generated in a compact HDFA packaged unit used for preamplifier and moderate output power booster amplifier applications [10]. For this pump power, the fibre length is set to its optimum value of 2.0 m.

Fig. 4 shows the simulated saturated output powers as a function of ion pairing for an input signal of 0 dBm at 2050 nm and for two pump wavelengths of 1860 nm and 1940 nm. Here we see that the behaviour of the amplifier with the ion pairing parameter is quite different for the two pump wavelengths considered. For 1940 nm pumping, the output power decreases rapidly and almost exponentially with increased ion pairing. For 1860 nm pumping, the decrease is slightly sublinear and much slower with ion pairing. We see that for most of the parameter space on the plot, 1860 nm pumping holds a strong advantage over 1940 nm pumping.

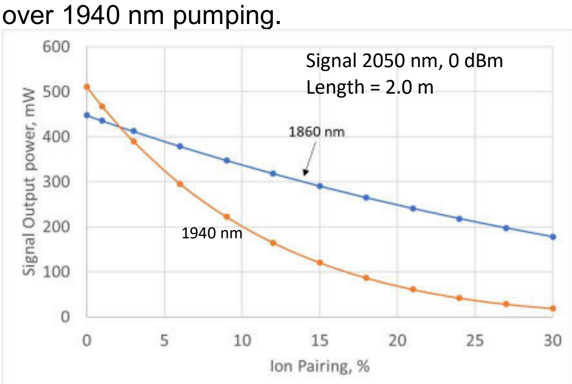

Fig. 4: Saturated output power vs. ion pairing for 1860 nm and 1940 nm pump wavelengths and a pump power of 1W

To quantify this observation, the ratio of saturated output powers for the two pump wavelengths as a function of ion pairing is plotted in Fig. 5. Here we see that for ion pairing of greater than 2%, 1860 nm pumping holds a definite power advantage over 1940 nm pumping. Since typical values for commercially available Ho-doped

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fibres are in the range of 13.5-30 % [6-9] we find that 1860 nm yields a clear power gain over 1940 nm pumping for most practical applications.
The quantitative advantage for 15% ion pairing is a factor of 2.4 or 3.8 dB for 1860 nm pumping over 1940 nm pumping, which is a significant technical and practical advantage for the

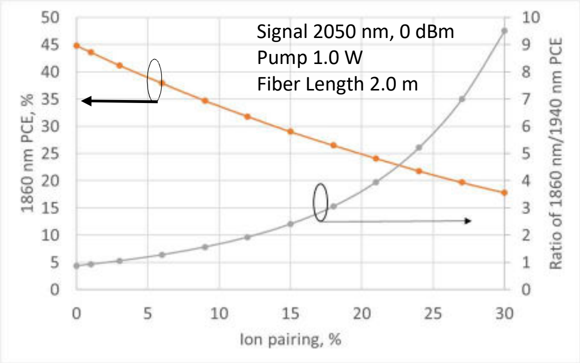

Fig. 5: Ratio of Saturated Output Powers for 1860 nm Pumping to 1940 nm Pumping, for 1 W Pump Power

construction of compact HDFAs with available pump powers limited to 1 W. The advantage increases to a factor of 9.5 for 30% ion pairing. PCE for 1860 nm pump wavelength is also plotted in Fig. 5 for reference, and decreases with increasing ion pairing as expected. The physical reasons for the behaviour of the curves in Fig. 5 will be discussed at the conference.

Comparison of Simulations with Experiment

To compare the results of our simulations with data, we first turn to an experimental measurement of the output power from a PM Ho-doped fibre with 1860 nm pumping. The single stage experimental setup for this measurement has the following parameters: Pump power = 2.0 W at 1860 nm, signal input = 0.8 dBm at 2092 nm, F1 = 3.0 m, and a counter-pumped configuration [7,8]. We have carried out simulations for both co-pumped and counterpumped amplifiers and we find that the trends for both are quite similar.
The experimentally measured output power from the counterpumped amplifier under these conditions is found to be 840 mW ± 15 mW, corresponding to a power conversion efficiency of 42%. 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 with 1860 nm pumping.
Similar agreement is observed between simulation and experiment for 1940 nm pumping [7-9].

By carrying out parametric studies, we find that the best agreement between our experiments and simulations is achieved for an ion pairing of 13.5 ± 1% for both co and counter-pumping [7-9]. We therefore take this as our estimate of the experimental value for the iXblue Ho-doped fibre under study. An independent measurement of ion pairing in [6] by measuring the ratio of saturable to non-saturable absorption at 1908 nm yields an experimental value of 15 ± 1% for the fibre under study. Our estimated experimental value for ion pairing and the value obtained by LeGouet et al. in [6] therefore match to within the stated measurement uncertainties, indicating good agreement of our results with an independent measurement of ion pairing.

Discussion

In our current research we find that performance of HDFAs with 1860 nm pumping either significantly exceeds or is quite comparable with amplifier performance with 1940 nm pumping. For example, the quantitative benefit of 1860 nm pumping for 1 W pump power is as high as a factor of 9.5 or 9.8 dB for the ion pairing value of 30%. So, we observe that for all values of ion pairing, 1860 nm is the clear choice for a practical pump wavelength. Also, as predicted by theory, reductions in the ion pairing coefficient lead directly to higher PCEs. At the conference we will discuss in detail the implications of our results for the physical and material design of single- and double-clad Ho-doped fibres.
Additional experimental and simulation results for several newly developed Ho-doped fibres with anticipated ion pairing coefficients that are significantly lower than 13.5 % will also be presented at the conference.

Conclusions

We have reported a novel detailed analysis and optimization of the performance of single clad Ho-doped fibres as a function of ion pairing and pump wavelength. Our simulations and experiments demonstrate that, with this new method of analysis, the degree of ion pairing is accurately determined by comparing simulations with experimental data for 1860 nm and 1940 nm pumping. We have also demonstrated that for existing Ho-doped fibres with 13.5—30% ion pairing, 1860 nm pumping has many practical and scientific advantages over the previous industry standard of 1940 nm. Future work will address these issues in more detail including comprehensive studies of newly developed Ho-doped fibres with significantly lower anticipated ion pairing coefficients.

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