Novel Single Clad Ho-doped Fiber Amplifier with High Slope Efficiency and Low Ion Pairing

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Outline

- Motivation and Objectives
- Technology and Architecture of 1860/1940 nm Pumped HDFAs
- Specifications for NRL Ho-doped Fiber
- Performance of Single Stage HDFA Using NRL Fiber
  - ✓ With 1860 nm Pumping
  - ✓ With 1940 nm Pumping
- Analysis of Experimental Data and Discussion
- Summary and Conclusions

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Motivation

- **Clear Need for High Power, High Wall Plug Efficiency, Broadband, SWaP Optimized HDFAs at 2000 –2150 nm for Communications, LIDAR, and Space Applications**
  - ✓ **Existing HDFAs: Performance is Limited by the Presence of Strong Ion Pairing for Ho Ions in the Si Host**
  - ✓ **Current Ion Pairing Values are 13-15%**
  - ✓ **Result is a Significant (~ 1—2 dB) Reduction in Power Conversion Efficiency Relative to Ideal Fiber with 0% Ion Pairing**
  - ✓ **No Systematic or Detailed Experimental Studies of Performance of Ho-doped Fibers as a Function of Ion Pairing Coefficient**

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Objectives

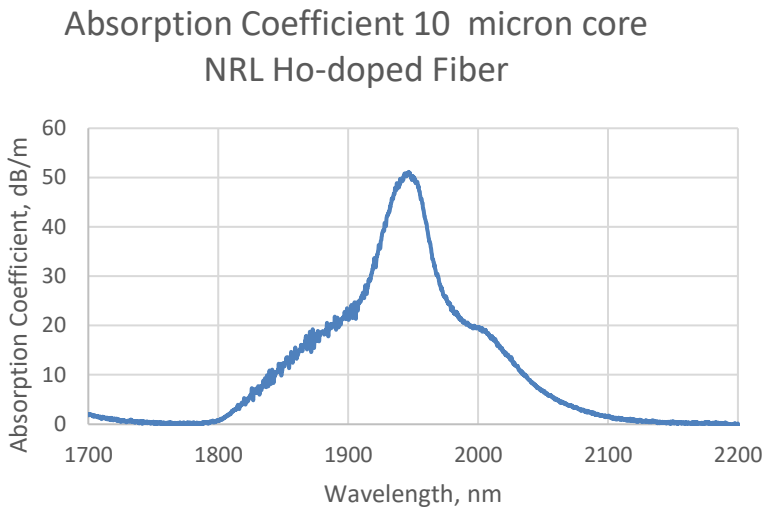
- Survey Existing and New Ho-doped Fibers Using a Nondestructive Method of Measuring the Ion Pairing Coefficient

- Using Dual Pumping Wavelengths of 1860 nm and 1940 nm Will Yield:
  - ✓ Rapid Characterization of Power Conversion Efficiency for These Two Significantly Different Pump Wavelengths
  - ✓ Straightforward Experimental Determination of Ion Pairing Coefficient Through Comparison With Simulations

- Here We Propose and Demonstrate: Successful Nondestructive Experimental Determination of Ion Pairing Coefficient for a Novel Ho-doped Fiber from NRL

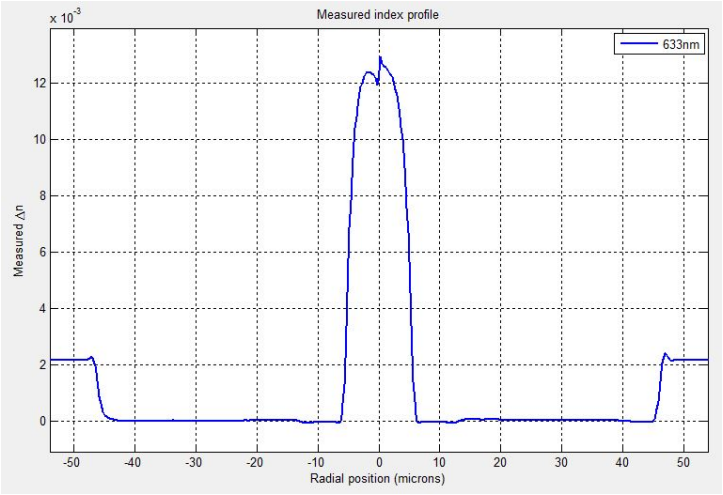
Characteristics of Novel NRL Ho-doped Fiber (1)

- Core Diameter = 10 µm
- Cladding Diameter = 92 µm
- Refractive Index Difference Between Core and Cladding = 1.2×10^{-2}
- Numerical Aperture = 0.186
- Ho+ Ion Concentration in Core = 0.7%-wt
- Peak Absorption = 51 dB/meter



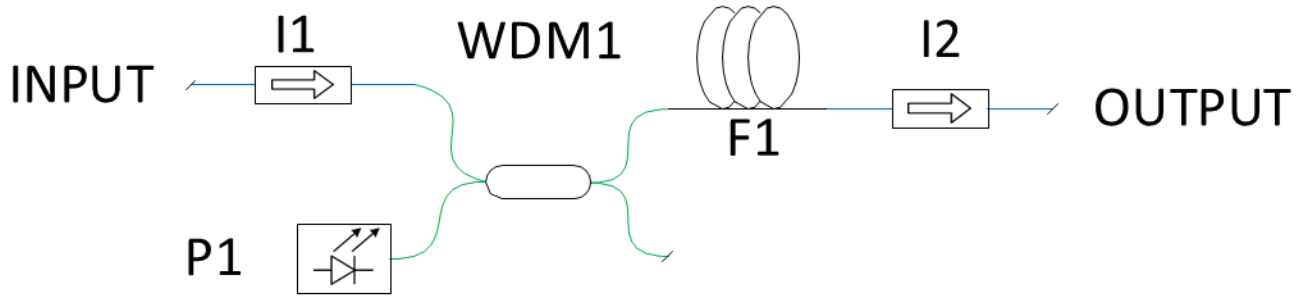
Characteristics of Novel NRL Ho-doped Fiber (2)

- Core Diameter = 10 µm
- Cladding Diameter = 92 µm
- Refractive Index Difference Between Core and Cladding = 1.2 x 10^{-2}
- Numerical Aperture = 0.186
- Ho+ Ion Concentration in Core = 0.7%-wt



Measured Refractive Index Profile of Novel NRL Fiber

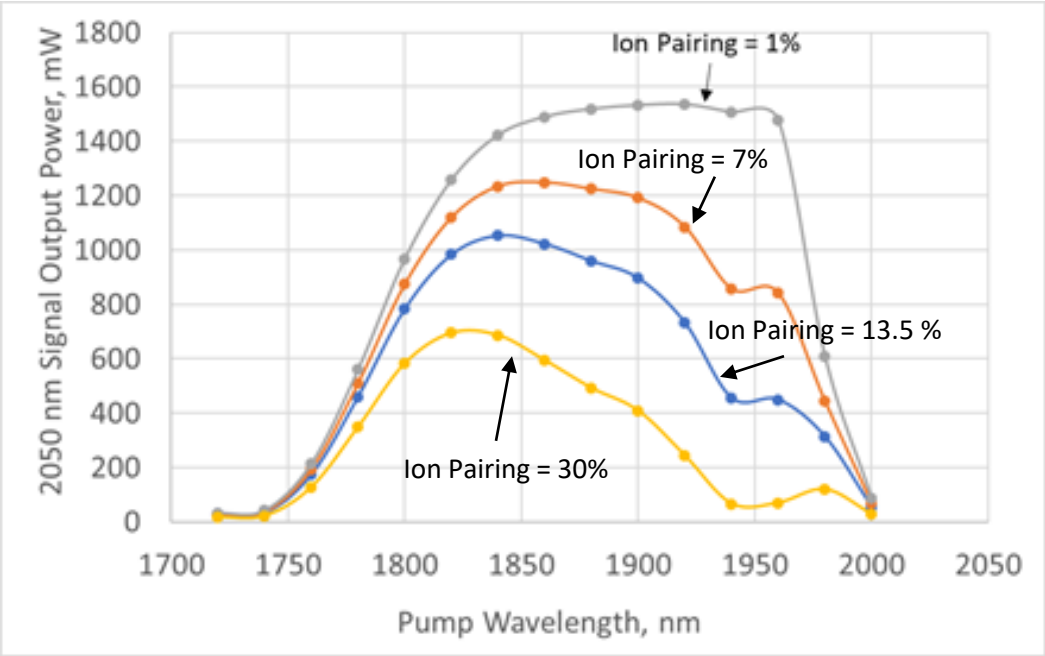
Optical Architecture for NRL Ho-doped Fiber Amplifier



- F1: Novel NRL Ho-doped Fiber, Length = 2.5 meters
- I1, I2, WDM1: 2000 nm Band SM Isolators/WDM
- P1: 1760—1940 nm Multiwatt Fixed Wavelength Fiber Laser or Tunable TENOR Pumped by a 940 nm Diode Laser
- Input Signal: 2050 nm, 0 dBm (1.0 mW)
- Input and Output Pump and Signal Powers: Measured at Input and Output of F1

R. E. Tench et al, Journal of Lightwave Technology, vol. 39, no. 11, pp. 3546-3552, June 1, 2021, doi: 10.1109/JLT.2021.3067600.

Basis of Non-destructive Analysis of Ion Pairing in Ho-doped Fibers



- **Degree of Ion Pairing Strongly Affects the Signal Output Power as a Function of Pump Wavelength**
- **Output Power Decreases as Ion Pairing Increases**
- **1860 nm Pump Wavelength is Close to Optimum for Most Ion Pairing Values**

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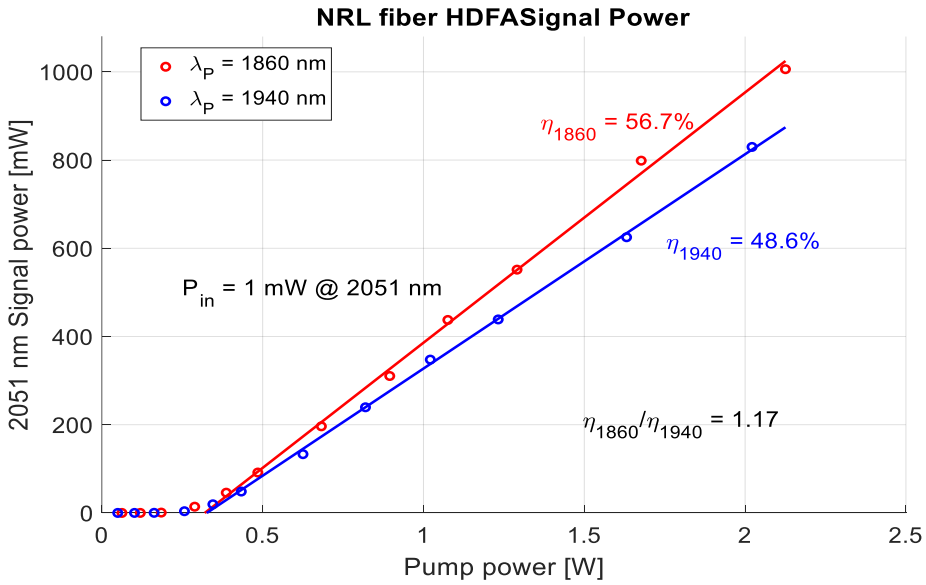
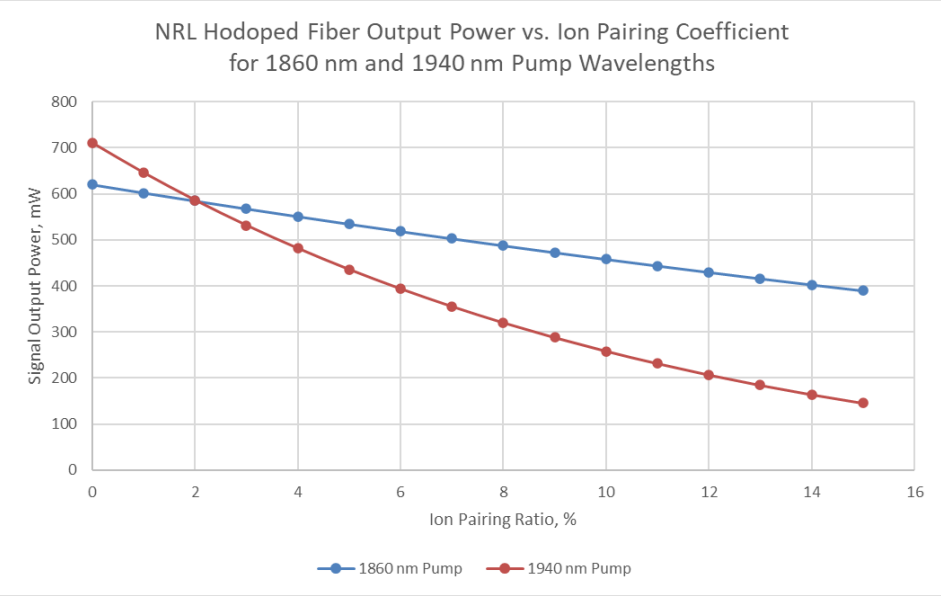
Comparison of Experimental NRL HDFA Performance with 1860 nm and 1940 nm Pumping



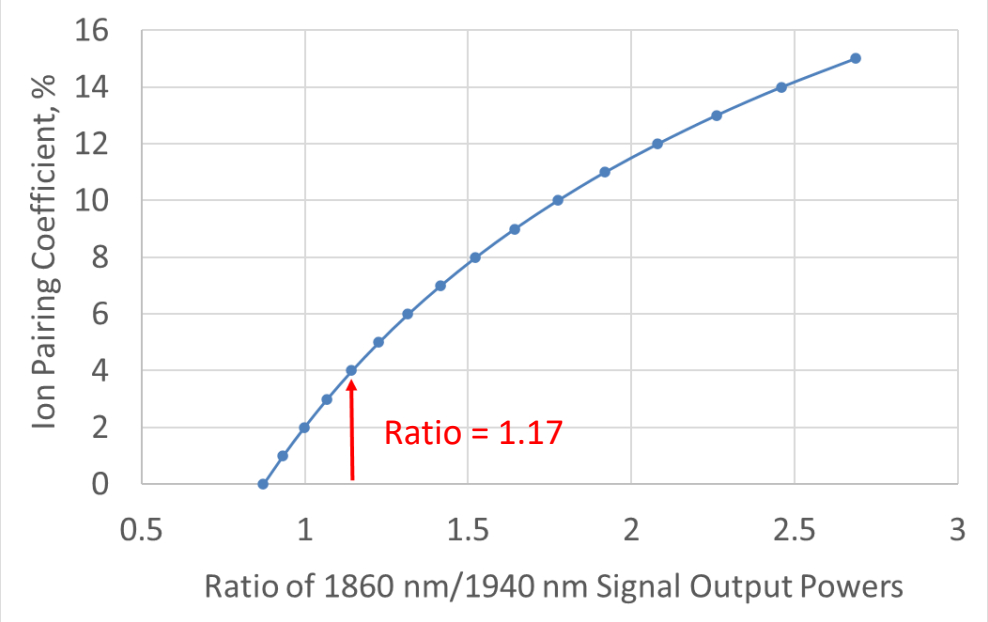
- Input Signal is 1 mW at 2050 nm
- Ratio of 1860 nm to 1940 nm Power Conversion Efficiencies = 1.17
- 1860 nm Pumped Power Conversion Efficiency is 42% greater than for Typical Existing Ho-doped fibers from Other Sources
- Highest Power Conversion Efficiency Experimentally Observed to Date for Single Clad Ho-doped Fibers

Comparison of Simulated NRL HDFA Performance as a Function of Ion Pairing with 1860 nm and 1940 nm Pumping



- **Input Signal is 1 mW at 2050 nm**
- **Pump Power = 1.5 W**
- **Fiber Length = 2.5 meters**
- **Ratio of 1860 nm to 1940 nm Power Conversion Varies Strongly with Ion Pairing Coefficient**

Simulated Ion Pairing Coefficient vs. Experimentally Measured Ratio of 1860 nm/1940 nm Output Power Conversion Efficiency



- **Input Signal is 1 mW at 2050 nm**
- **Ratio of 1860 nm to 1940 nm Power Conversion Efficiencies = 1.17**
- **Derived Ion Pairing Coefficient = 4 % (Lowest So Far Experimentally Observed)**
- **Typical Ion Pairing Values for Today's Commercial Fibers = 13—15%**

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Summary

- We Have Proposed and Demonstrated A Non-destructive Evaluation of the Ion Pairing Coefficient for a Novel NRL Ho-doped Fiber
- Using This New Method, We Experimentally Determined an Ion Pairing Coefficient of 4% for the Novel NRL Fiber
- The Experimentally Determined Value of 4% is the Lowest Ion Pairing Measured to Date for Single Clad Ho-doped Fibers
  - ✓ Typical Ion Pairing for Today's Commercial Ho-doped Fibers is 13—15%
- With This Novel Ho-doped Fiber Design from NRL, We Achieve 40% Greater Power Conversion Efficiency for 1860 nm Pumping than with Today's Commercially Available Fibers

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Conclusions and Directions for Future Work

- Our Research and Development of Novel Ho-doped Fiber Designs Yields Significant Improvements in SWaP for HDFAs in Commerical, Defense, and Space Venues
- Good Performance with Existing Ho-doped Fiber Core Diameter = 10 µm
- Future Ho-doped Fiber Core Diameters of 15—25 µm Will Yield Improved High Power Performance and Higher Nonlinear Thresholds in Pulsed HDFAs
- Immediate New Practical Applications in Communications, LIDAR, and Space Arenas

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Thank You For Your Attention!