AFRL-AFOSR-JP-TR-2023-0069

Pushing the limits of fluoride glass transmission to create 4 micron class fibre laser systems

Stuart Jackson
MACQUARIE UNIVERSITY
BALACLAVA ROAD
NORTH RYDE, NSW, 2109
AUS

12/12/2023
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE 20231212	**2. REPORT TYPE** Final	**3. DATES COVERED** **START DATE** 20190314	**END DATE** 20220313

4. TITLE AND SUBTITLE
Pushing the limits of fluoride glass transmission to create 4 micron class fibre laser systems

5a. CONTRACT NUMBER	**5b. GRANT NUMBER** FA2386-19-1-0043	**5c. PROGRAM ELEMENT NUMBER** 61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Stuart Jackson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MACQUARIE UNIVERSITY BALACLAVA ROAD NORTH RYDE, NSW 2109 AUS	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/AFOSR IOA	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-AFOSR-JP-TR-2023-0069

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A summarization of efforts to understand and design fibre lasers for emission beyond 4 µm is provided. It is widely known that ZBLAN glass supports phonon energies that are ~560 cm-1 and it may support lasing beyond the current 4 µm limit. The important outcomes from the project include:
1) It is shown through detailed numerical modelling that pulsed pumping of Dy-doped InF3 glass fibre will create the emission at 4.3 µm
2) that doping rare earth ions into crystals and then doping the crystal into a fluoride glass could offer a solution for the future. This project is currently being funded by the Australian Government.
3) cooperative 3-ion energy transfer is operating in the Dy ion system when the concentrations are high (>3 mol.%) and the inversions are high. This may be a beneficial process for the 4 µm transition.
4) it is shown that co-doping Dy3+ with Tm3+ provides an effective route to excitation of the upper laser level of the 4 µm transition that is diode pumpable and is potentially highly efficient.
5) that effective fibre Bragg gratings can be written into InF3-glass optical fibre. This will be a key component to all future fibre 4 µm-class fibre lasers.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	SAR	130

19a. NAME OF RESPONSIBLE PERSON JEREMY KNOPP	**19b. PHONE NUMBER** *(Include area code)* 315-227-7006

Standard Form 298 (Rev.5/2020)
Prescribed by ANSI Std. Z39.18

Final Report for AOARD Grant FA2386-19-1-0043

Pushing the limits of fluoride glass transmission to create 4-µm class fibre laser systems

Date 11th April 2022

Name of Principal Investigators (PI and Co-PIs): Dr Stuart Jackson Dr Matthew Majewski and Dr Alex Fuerbach

- e-mail address : stuart.jackson@mq.edu.au
- Institution : MQ Photonics
- Mailing Address : School of Engineering, Level 1, Building E6B, Macquarie University
- Phone : +61 2 9850 9137
- Fax : +61 2 9859 7358

Period of Performance: 3/14/2019 – 3/13/2022

Executive Summary: This is the final report for the AOARD grant FA2386-19-1-0043. Here we summarise all our efforts to understand and design fibre lasers for emission beyond 4 µm. It is widely known that ZBLAN glass supports phonon energies that are ~560 cm^{-1} and it may support lasing beyond the current 4 µm limit. The important outcomes from the project include:

1) we have shown through detailed numerical modelling that pulsed pumping of Dy-doped InF_3 glass fibre will create the emission at 4.3 µm
2) that doping rare earth ions into crystals and then doping the crystal into a fluoride glass could offer a solution for the future. This project is currently being funded by the Australian Government.
3) cooperative 3-ion energy transfer is operating in the Dy ion system when the concentrations are high (>3 mol.%) and the inversions are high. This may be a beneficial process for the 4 µm transition.
4) we have shown that co-doping Dy^{3+} with Tm^{3+} provides an effective route to excitation of the upper laser level of the 4 µm transition that is diode pumpable and is potentially highly efficient.
5) that effective fibre Bragg gratings can be written into InF_3-glass optical fibre. This will be a key component to all future fibre 4 µm-class fibre lasers.

Introduction:

Fluoride glass fibre is the dominant and most widely used glass in mid-IR fibre laser research, but there has been no demonstration of lasing beyond 4 µm using this glass. The aim of this project was to investigate the potential of a new type of fluoride glass based on InF_3 precursor material for emission at 4 µm and beyond. This glass supports lower phonon energies compared to other fluoride glasses and hence has better infrared transmission. We are exploring the 4 µm transition of the Dy^{3+} and Ho^{3+} ions in the project as they show the greatest potential for high power output, and they can be excited using direct diode laser pumping.

Fibre lasers are the ideal platform for the emission of high power cw light because the light is tightly confined within a core and the large surface area to volume ratio effectively removes any heat created. This makes fibre lasers such a disruptive technology particularly in the near-IR but emission in the mid-IR is much more of a challenge because the glasses used have weak thermomechanical properties and they harder to handle. To date, the longest emission wavelength from a fibre laser is 3.9 µm, with only 0.2 W emitted.

The aims (as originally stated in the white paper) are:

1. Room temperature emission from a 4 µm class fibre laser. This is significant because all previous demonstrations have been at cryogenic temperatures.

2. The first directly diode pumped 4 µm class fibre laser. This will be the most convenient method of generating high power 4 µm light.
3. The first cascade laser with 3 µm and 4 µm emission. This is significant because dual wavelength emission opens many new applications.
4. The first 4 µm class ultrafast fibre laser. Currently, mode locked mid-infrared fibre lasers are limited to emission wavelengths <3 µ

Table: Specific milestones of the project as stated in the original White Paper and 2019-2020 annual report

Milestone	Progress	Our Future Work (as stated in	Completion Date	Complete
First room-temperature 3.9 µm laser using Ho^{3+} fibre	Accomplished by a competing group in Canada in 2019	Completely simulate this system and optimize it using a detailed numerical model.	2020	NO – a number of other groups have already published in this area
First diode pumped Ho^{3+} fibre laser emitting 3.9 µm	Accomplished by a competing group in Canada in 2019	Combine our numerical model + our in fibre Bragg gratings for the demonstration of the first all fibre version of this system	2021	INCOMPLETE – we have decided not to pursue this as many groups working in this area now
First fibre laser emitting beyond 4.0 µm, using Dy^{3+} fibre	Numerical model being developed and spectroscopy measurements being designed	Publish results of numerical model and spectroscopy measurements	2020	COMPLETE
First diode pumped Dy^{3+} fibre laser emitting in the mid-IR	COMPLETE	Examine alterative pump wavelengths to help quantify energy transfer upconversion	2020	COMPLETE
Demonstrate lower laser level de-excitation using excited state absorption	Numerical model being developed	Publish results from numerical model + demonstration change in optical gain	2020-2021	PARTIALY COMPLETE
First short-pulse fibre laser above 3 µm	COMPLETE	Extend pulse generation to nonlinear polarization technique for the 3.5 µm transition of Er^{3+}	2020	
Probe the mid-IR nonlinear optical properties of new nanomaterials	INCOMPLETE	Intend to seek funding for ultrashort-pulsed MIR fibre laser for these measurements	2020	Funding unsuccessful
Demonstrate stable 4-µm-class pulse	INCOMPLETE	The milestone is dependent on the	2021-2022	INCOMPLETE

sources using nanomaterials		completion of a number beforehand.		

List of Publications and any Significant Collaborations that resulted from your AOARD supported project:

a) **papers published in peer-reviewed journals**

1. MR Majewski, MZ Amin, T Berthelot, SD Jackson, "Directly diode-pumped mid-infrared dysprosium fiber laser," Optics letters 44 (22), 5549-5552 (2019)
2. O Henderson-Sapir, N Bawden, MR Majewski, RI Woodward, DJ Ottaway, SD Jackson, "Mode-locked and tunable fiber laser at the 3.5 µm band using frequency-shifted feedback," Optics Letters 45 (1), 224-227 (2020)
3. MR Majewski, RI Woodward, SD Jackson, "Dysprosium Mid-Infrared Lasers: Current Status and Future Prospects," Laser & Photonics Reviews 14, 1900195 (2020)
4. MZ Amin, MR Majewski, RI Woodward, A Fuerbach, SD Jackson, "Novel near-infrared pump wavelengths for dysprosium fiber lasers," Journal of Lightwave Technology 38 (20), 5801-5808 (2020)
5. SD Jackson, RK Jain, "Fiber-based sources of coherent MIR radiation: key advances and future prospects," Optics Express 28 (21), 30964-31019 (2020)
6. M Pawliszewska, MR Majewski, SD Jackson, "Electronically tunable picosecond pulse generation from Ho^{3+}-doped fluoride fiber laser using frequency-shifted feedback," Optics Letters 45 (20), 5808-5811(2020)
7. MR Majewski, G Bharathan, A Fuerbach, SD Jackson, "Long wavelength operation of a dysprosium fiber laser for polymer processing," Optics Letters 46 (3), 600-603 (2020).
8. MR Majewski, M Pawliszewska, SD Jackson, "Picosecond pulse formation in the presence of atmospheric absorption," Optics Express 29 (12), 19159-19169 (2021).
9. MR Majewski, SD Jackson, "Numerical Design of -Class Dysprosium Fluoride Fiber Lasers," Journal of Lightwave Technology 39 (15), 5103-5110 (2021).
10. SD Jackson, MR Majewski, "Role of energy transfer in concentrated Dy^{3+}-doped fibers," OSA Continuum 4 (10), 2591-2597.

b) papers published in peer-reviewed conference proceedings

1. MZ Amin, MR Majewski, SD Jackson, "Yellow emission from dysprosium-doped ZBLAN fiber laser," Fiber Lasers XVII: Technology and Systems 11260, 112601K (2020)
2. MZ Amin, MR Majewski, RI Woodward, A Fuerbach, SD Jackson, "New excitation wavelengths for dysprosium-doped mid-infrared fiber lasers," Fiber Lasers XVII: Technology and Systems 11260, 112601R (2020)
3. MR Majewski, MZ Amin, T Berthelot, SD Jackson, "Diode pumped dysprosium fiber laser," Fiber Lasers XVII: Technology and Systems 11260, 112601P (2020)
4. G Bharathan, X Jiang, H Zhang, F Chen, Z Li, SD Jackson, A Fuerbach," Mode-locked mid-IR fibre laser based on 2D nanomaterials," AOS Australian Conference on Optical Fibre Technology (ACOFT) and Australian 11200 112002B (2019)
5. MZ Amin, MR Majewski, SD Jackson, "GaN laser diode pumped dysprosium doped ZBLAN fibre laser for yellow emission," AOS Australian Conference on Optical Fibre Technology (ACOFT) and Australian 11200 1120017 (2019)
6. Nathaniel Bawden, Ori Henderson-Sapir, Matthew R Majewski, Robert I Woodward, Stuart D Jackson, David J Ottaway, "Q-switched and Mode-locked 3.5 µm Fiber Laser," 2020 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)
7. Gayathri Bharathan, Luyi Xu, Xiantao Jiang, Han Zhang, Matthew Majewski, Stuart D Jackson, Alex Fuerbach, "All-fibre Ultrafast Mid-infrared Laser," Conference on Lasers and Electro-Optics/Pacific Rim (2020)
8. MR Majewski, MZ Amin, T Berthelot, SD Jackson, "Diode pumped dysprosium fiber laser," Fiber Lasers XVII: Technology and Systems 11260, 112601P (2020)
9. M Pawliszewska, MR Majewski, SD Jackson, "Picosecond Pulse Generation from a Wavelength

Tunable Er: ZBLAN Mid-Infrared Fiber Laser, "The European Conference on Lasers and Electro-Optics, paper cj_7_1 (2021).

c) papers published in non-peer-reviewed journals and conference proceedings,
NIL
d) conference presentations without papers,
NIL
e) manuscripts submitted but not yet published, and

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

Attachments: Publications a), b) and c) listed above if possible.