NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

AC/323(SET-170)TP/600

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STO TECHNICAL REPORT **TR-SET-170**

Mid-Infrared Fiber Lasers

(Lasers à fibre fonctionnant
dans l'infrarouge moyen)

Final Report of Task Group 095.

Published April 2015

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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List of Acronyms

AFB	Air Force Base
AFRL	Air Force Research Laboratory
ALLS	Advanced Laser Light Source
AOM	Acousto-Optic Modulator
AR	Anti-Reflection
ASE	Amplified Spontaneous Emission
BYF	Barium Yttrium Fluoride
CFBG	Chirped Fiber Bragg Grating
COTS	Commercial-Off-The-Shelf
CW	Continuous Wave
DEU	Germany
DFB	Distributed Feedback
DFG	Difference Frequency Generation
DIRCM	Directed Infrared Countermeasures
DRDC	Defence Research and Development Canada
Dstl	Defence Science and Technology Laboratory
EDFA	Erbium-Doped Fiber Amplifier
EOM	Electro-Optic Modulator
ESA	Excited State Absorption
ET	Exploratory Team
ETU	Energy Transfer Up-conversion
EYDFA	Erbium-Ytterbium-Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FFI	Forsvarets Forskningsinstitutt (Norwegian Defence Research Establishment)
FTIR	Fourier Transform Infrared Spectrometer
FWHM	Full-Width Half Maximum
GaAs	Gallium Arsenide
GaP	Gallium Phosphide
GSML	Gain-Switched Mode-Locked
GVD	Group Velocity Dispersion
HIP	Hyperspectral Image Projector
HNLF	Highly Non-Linear Fiber
HR	High Reflector
HVPE	Hydride Vapor Phase Epitaxy
INO	Institut National d'Optique
IR	Infrared
IRCM	Infrared Countermeasures
IRP	IR Photonics
ISL	French-German Research Institute Saint-Louis
LMA	Large-Mode-Area
LVF	Le Verre Fluoré
LWPF	Long Wave Pass Filter

MI	Modulation Instability
MIR	Mid-Infrared
ML	Mode-Locking
MLR	Mode-Locking Resembling
MOPA	Master Oscillator Power Amplifier
MOPAW	Master Oscillator with Programmable Amplitude Wavefront
MUT	Military University of Technology
NA	Numerical Aperture
NIR	Near Infrared
NRL	Naval Research Laboratory
OC	Output Coupler
OPA	Optical Parametric Amplifier
OPGaAs	Orientation-Patterned Gallium Arsenide
OPGaP	Orientation-Patterned Gallium Phosphide
OPO	Optical Parametric Oscillator
OSA	Optical Spectrum Analyzer
PCF	Photon Crystal Laser
PL	Programmable Laser
PM	Polarization Maintaining
PPLN	Periodically-Poled Lithium Niobate
PRF	Pulse Repetition Frequency
QCL	Quantum Cascade Laser
QML	Q-switched Mode-Locked
QPM	Quasi-Phasematching
RTG	Research Task Group
SC	Supercontinuum
SET	Sensors and Electronic Technology
SIF	Step Index Fiber
SMF	Single-Mode Fiber
SPL	Synchronised Programmable Laser
SPM	Self-Phase Modulation
SSFS	Soliton Self-Frequency Shift
TDF	Thulium-Doped Fiber
TDFA	Thulium-Doped Fiber Amplifier
TDFL	Thulium-Doped Fiber Laser
TPA	Two-Photon Absorption
USA	United States of America
UV	Ultraviolet
VBG	Volume Braggs Grating
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation
YAG	Yttrium Aluminum Garnet
ZBLAN	Family of glasses containing ZrF_4-BaF_2-LaF_3-AlF_3-NaF
ZDW	Zero-Dispersion Wavelength
ZGP	Zinc Germanium Phosphide

Preface

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Fiber lasers	Infrared spectroscopy	Non-linear frequency conversion
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Fiber optics	Laser modelling	Optical parametric processes
Fluoride fiber	Laser spectroscopy	Optical resonators
Fluoride glass	Lasers	Rare earth lasers
Guided wave sources	Mid-infrared	Supercontinuum generation

14. Abstract

The objective of SET-170 was to advance the state-of-the-art in mid-IR fiber lasers, to support development of active sources primarily for countermeasures and remote sensing applications. The Task Group made significant advances in each of the three areas of its program of work. (1) In direct-lasing fibers, we identified trivalent holmium operating ~ 3.9 µm as the active ion most likely to result in a successful laser; and fluoroindate fiber as the most promising host material. Spectroscopic analysis and modelling were used to evaluate feasibility and to calculate fiber specifications, and led to demonstration of lasing in a sample of Ho-doped glass. (2) Supercontinuum work focused on increasing output power and especially extending the output spectrum and improving efficiency at longer wavelengths. Results include power scaling demonstrations in fluoride and chalcogenide fibers; demonstration of efficient power distribution at wavelengths longer than 3 µm; and a comparison of different fiber-based pumping techniques. (3) As an intermediate step to all-fiber mid-IR sources, SET-170 considered how best to use fiber lasers to pump bulk non-linear ($\chi^{(2)}$) devices. Pumping strategies were investigated and demonstrated for ZGP, PPLN, and OPGaAs, representing the current spectrum of birefringent, poled ferroelectric, and orientation-patterned non-linear materials.

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