Selected Papers on
Rare-Earth-Doped
Fiber Laser Sources and Amplifiers

Michel J. F. Digonnet, Editor
Edward L. Ginzton Laboratory
Stanford University

Brian J. Thompson
General Editor, SPIE Milestone Series

SPIE Milestone Series
Volume MS 37

SPIE Optical Engineering Press
A Publication of SPIE—The International Society for Optical Engineering
Bellingham, Washington USA
Selected Papers on
Rare-Earth-Doped Fiber Laser Sources and Amplifiers

Contents

xxi  Preface, Michel J. F. Digonnet

Section One
Historical Papers

3  Amplification in a fiber laser
   C. J. Koester, E. Snitzer (Applied Optics 1964)

8  Neodymium-doped fiber lasers: room temperature cw operation with an
    injection laser pump
   J. Stone, C. A. Burrus (Applied Optics 1974)

10 Mode locking in a fiber laser
    M. I. Dzhibladze, Z. G. Ésiashvilli, É. Sh. Teplitskiï, S. K. Isaev, V. R.
    Sagaradze (Soviet Journal of Quantum Electronics 1983)

12 Fabrication of low-loss optical fibres containing rare-earth ions
    S. B. Poole, D. N. Payne, M. E. Fermann (Electronics Letters 1985)

14 Neodymium-doped silica single-mode fibre lasers
    R. J. Mears, L. Reekie, S. B. Poole, D. N. Payne (Electronics Letters 1985)

Section Two
Fiber Fabrication Techniques

19 Fabrication and characterization of low-loss optical fibers containing rare-
    earth ions
    S. B. Poole, D. N. Payne, R. J. Mears, M. E. Fermann, R. I. Laming (Journal
    of Lightwave Technology 1986)

26 Solution-doping technique for fabrication of rare-earth-doped optical fibres
    J. E. Townsend, S. B. Poole, D. N. Payne (Electronics Letters 1987)

28 The fabrication and optical properties of Nd³⁺ in silica-based optical fibers

32 The fabrication, assessment and optical properties of high-concentration
    Nd³⁺- and Er³⁺-doped silica-based fibres

37 Rare-earth-doped optical fibers by the outside vapor deposition technique
    P. L. Bocko (in Optical Fiber Communication Conference Technical Digest
    1989)
Aerosol doping technique for MCVD and OVD

Fabrication of long lengths of low excess loss erbium-doped optical fibre
S. P. Craig-Ryan, B. J. Ainslie, C. A. Millar (Electronics Letters 1990)

The absorption and fluorescence spectra of rare earth ions in silica-based monomode fiber

Spectral variation of excited state absorption in neodymium doped fibre lasers
P. R. Morkel, M. C. Farries, S. B. Poole (Optics Communications 1988)

Pump excited-state absorption in erbium-doped fibers
R. I. Laming, S. B. Poole, E. J. Tarbox (Optics Letters 1988)

Characterization of Er3+-doped glasses by fluorescence line narrowing

Spectroscopy of rare earth doped fibers
R. Wyatt (in Fiber Laser Sources and Amplifiers 1989)

The effect of glass composition on the performance of Er3+ fiber amplifiers

Evaluation of 415/2 and 413/2 Stark-level energies in erbium-doped aluminosilicate glass fibers
E. Desurvire, J. R. Simpson (Optics Letters 1990)

Excited state cross sections of Er-doped glasses

Inhomogeneous line broadening of optical transitions in Nd3+ and Er3+ doped preforms and fibers

Theoretical analysis of optical fiber laser amplifiers and oscillators
M. J. F. Digonnet, C. J. Gaeta (Applied Optics 1985)

Noise figure for erbium-doped optical fibre amplifiers
R. Olshansky (Electronics Letters 1988)

Amplification of spontaneous emission in erbium-doped single-mode fibers

Analysis of transient gain saturation and recovery in erbium-doped fiber amplifiers
Large signal modelling of an erbium doped fibre amplifier

Theoretical modeling of erbium-doped fiber amplifiers with excited-state absorption
P. R. Morkel, R. I. Laming (Optics Letters 1989)

Analysis of erbium-doped fiber amplifiers pumped in the $^4I_{15/2} - ^4I_{13/2}$ band

Ground-state and excited-state absorption in rare-earth doped optical fibres

Characterization and optimization of the gain in Nd-doped single-mode fibers

Analysis of noise figure spectral distribution in erbium doped fiber amplifiers pumped near 980 and 1480 nm
E. Desurvire (Applied Optics 1990)

Gain characteristics of Er$^{3+}$ doped fiber with a quasi-confined structure

A large-signal model and signal/signal ratio analysis for Nd$^{3+}$-doped fiber amplifiers at 1.3 μm
M. L. Dakss, W. J. Miniscalco (in Fiber Laser Sources and Amplifiers II 1990)

Comparison of gain dependence of different Er-doped fibre structures
S. Tammela, X. Zhan, P. Kiiveri (in Fiber Laser Sources and Amplifiers II 1990)

Modeling of three-level laser superfluorescent fiber sources

General theoretical approach describing the complete behavior of the erbium-doped fiber amplifier

Closed-form expressions for the gain of three- and four-level laser fiber devices

Section Five

CW Neodymium- and Erbium-Doped Fiber Lasers

Continuous-wave oscillation of a monomode neodymium-doped fibre laser at 0.9 μm on the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition
I. P. Alcock, A. I. Ferguson, D. C. Hanna, A. C. Tropper (Optics Communications 1986)

Device aspects of fibre lasers and amplifiers
P. Urquhart (in Fiber Laser Sources and Amplifiers 1989)
A Nd\(^{3+}\)-doped cw fiber laser using all-fiber reflectors

High-efficiency Nd-doped fibre lasers using direct-coated dielectric mirrors

Diode-laser-pumped Nd\(^{3+}\)-doped fibre laser operating at 938 nm
L. Reekie, I. M. Jauncey, S. B. Poole, D. N. Payne (Electronics Letters 1987)

Double clad high brightness Nd fiber laser pumped by GaAlAs phased array

Glass fiber laser at 1.36 \(\mu\)m from SiO\(_2\):Nd

Erbium-Doped

Low-threshold tunable cw and Q-switched fibre laser operating at 1.55 \(\mu\)m
R. J. Mears, L. Reekie, S. B. Poole, D. N. Payne (Electronics Letters 1986)

Diode-laser-pumped operation of an Er\(^{3+}\)-doped single-mode fibre laser
L. Reekie, I. M. Jauncey, S. B. Poole, D. N. Payne (Electronics Letters 1987)

Efficient operation of an Yb-sensitized Er fibre laser at 1.56 \(\mu\)m

Efficient operation of array-pumped Er\(^{3+}\) doped silica fibre laser at 1.5 \(\mu\)m
R. Wyatt, B. J. Ainslie, S. P. Craig (Electronics Letters 1988)

High-quantum-efficiency Er\(^{3+}\) fiber lasers pumped at 980 nm
W. L. Barnes, P. R. Morkel, L. Reekie, D. N. Payne (Optics Letters 1989)

Polarisation effects in fibre lasers: phenomena, theory and applications
J. T. Lin, W. A. Gambling (in Fiber Laser Sources and Amplifiers II 1990)

Nd- and Er-doped phosphate glass for fiber laser
T. Yamashita (in Fiber Laser Sources and Amplifiers 1989)

Q-Switched

Q-switched operation of a neodymium-doped monomode fibre laser

Efficient diode-pumped CW and Q-switched single-mode fibre laser
I. M. Jauncey, J. T. Lin, L. Reekie, R. J. Mears (Electronics Letters 1986)

Gain switching of a Nd\(^{3+}\)-doped fiber laser

Q-switching in fibre lasers
Mode-Locked

311 Q-switching, mode-locking and tunable operation around 0.9 μm of a neodymium-doped monomode fibre laser

315 Neodymium-fibre laser with integrated-optic mode locker
   G. Geister, R. Ulrich (Optics Communications 1988)

318 High-power, mode-locked Nd:fibre laser pumped by an injection-locked diode array

320 Frequency-modulation mode locking of a Nd³⁺-doped fiber laser

323 Mode-locked, long-cavity, erbium fiber lasers with subsequent soliton-like compression

326 Mode-locked erbium-doped fiber laser with soliton pulse shaping
   J. D. Kafka, T. Baer, D. W. Hall (Optics Letters 1989)

329 All-solid-state passively Q-switched mode-locked Nd-doped fiber laser

332 Diode-pumped FM modelocked fibre laser with coupled cavity bandwidth selection
   M. W. Phillips, A. I. Ferguson, D. B. Patterson (Optics Communications 1990)

337 Integrated-optical Q-switch/mode locker for a Nd³⁺ fiber laser

340 30 GHz picosecond pulse generation from actively mode-locked erbium-doped fibre laser
   A. Takada, H. Miyazawa (Electronics Letters 1990)

342 Controlled amplifier modelocked Er³⁺ fibre ring laser
   D. Burns, W. Sibbett (Electronics Letters 1990)

Section Seven
Tunable Fiber Lasers

347 Tunable single-mode fiber lasers
   L. Reekie, R. J. Mears, S. B. Poole, D. N. Payne (Journal of Lightwave Technology 1986)

352 Tunable, continuous-wave neodymium-doped monomode-fiber laser operating at 0.900-0.945 and 1.070-1.135 μm

355 Tunable Nd³⁺-doped fibre ring laser
   C. Yue, J. Peng, B. Zhou (Electronics Letters 1989)
Section Eight

Single-Frequency Fiber Lasers

357 Narrow linewidth tunable operation of Er\textsuperscript{3+}-doped single-mode fibre laser

359 High-power broadly tunable erbium-doped silica fibre laser
   R. Wyatt (Electronics Letters 1989)

361 Electronically tunable, 1.55-μm erbium-doped fiber laser

367 Narrow-linewidth fibre laser with integral fibre grating

369 Narrow-linewidth fiber laser operating at 1.55 μm
   I. M. Jauncey, L. Reekie, R. J. Mears, C. J. Rowe (Optics Letters 1987)

371 Single-longitudinal-mode operation of an Nd\textsuperscript{3+}-doped fibre laser

373 Fiber Fox-Smith resonators: application to single-longitudinal-mode operation of fiber lasers
   P. Barnsley, P. Urquhart, C. Millar, M. Brierley (Journal of the Optical Society of America A 1988)

381 Er\textsuperscript{3+}-doped fiber-ring-laser with less than 10 kHz linewidth

385 Travelling-wave erbium fibre ring laser with 60 kHz linewidth
   P. R. Morkel, G. J. Cowle, D. N. Payne (Electronics Letters 1990)

Section Nine

Broadband Fiber Sources

389 Broadband diode-pumped fibre laser

391 Analysis of a 1060-nm Nd:SiO\textsubscript{2} superfluorescent fiber laser

398 Erbium-doped fibre superfluorescent source for the fibre gyroscope
   P. R. Morkel (in Optical Fiber Sensors Conference 1989)

403 Fiber superfluorescent sources for fiber gyro applications

408 High-power superfluorescent fiber source

411 Wavelength stability of Nd\textsuperscript{3+}-doped fibre fluorescent sources

413 Broad-spectrum, wavelength-swept, erbium-doped fiber laser at 1.55 μm

416 Excess noise in fiber gyroscope sources
1.55 μm broadband fiber sources pumped near 980 nm

Spectral thermal stability of Nd- and Er-doped fiber sources

Section Ten
Fiber Amplifiers

Low-noise erbium-doped fibre amplifier operating at 1.54 μm
R. J. Mears, L. Reekie, I. M. Jauncey, D. N. Payne (Electronics Letters 1987)

Erbium fiber laser amplifier at 1.55 μm with pump at 1.49 μm and Yb sensitized Er oscillator

Efficient pump wavelengths of erbium-doped fibre optical amplifier

High-gain, broad spectral bandwidth erbium-doped fibre amplifier pumped near 1.5 μm

Highly efficient 978 nm diode-pumped erbium-doped fibre amplifier with 24 dB gain

High-gain and high-efficiency diode laser pumped fiber amplifier at 1.56 μm

Efficient erbium-doped fiber amplifier at 1.53-μm wavelength with a high output saturation power

46.5 dB gain in Er³⁺-doped fibre amplifier pumped by 1.48 μm gain GaInAsP laser diodes

Gain saturation effects in high-speed, multichannel erbium-doped fiber amplifiers at λ = 1.53 μm

Er³⁺-doped fiber amplifier pumped by 0.98 μm laser diodes

Optimal pump wavelength in the ⁴I₁₅/₂⁻⁴I₁₃/₂ absorption band for efficient Er³⁺-doped fiber amplifiers
480 Very high gain Er$^{3+}$ fiber amplifier pumped at 980 nm
W. J. Miniscalco, B. A. Thompson, E. Eichen, T. Wei (in Optical Fiber
Communication Conference Technical Digest 1990)

481 A distributed erbium doped fiber amplifier
J. R. Simpson, L. F. Mollenauer, K. S. Kranz, P. J. Lemaire, N. A. Olsson,
H. T. Shang, P. C. Becker (in Optical Fiber Communication Conference
Technical Digest 1990)

484 Gain and noise figure variations of an erbium doped fiber amplifier for
pump wavelengths between 1460 and 1510 nm
R. S. Vodhanel, A. Yi-Yan, B. Enning, R. I. Laming (in Optical Fiber
Communication Conference Technical Digest 1990)

486 Noise characteristics of Er$^{3+}$-doped fiber amplifiers pumped by 0.98 and
1.48 μm laser diodes
M. Yamada, M. Shimizu, M. Okayasu, T. Takeshita, M. Horiguchi, Y.

489 Pump wavelength dependence of the gain factor in 1.48 μm pumped Er$^{3+}$-
doped fiber amplifiers

492 Highly efficient integrated optical fibre amplifier module pumped by a 0.98
μm laser diode
M. Shimizu, M. Horiguchi, M. Yamada, M. Okayasu, T. Takeshita, I. Nishi,

494 High gain Er$^{3+}$-doped fibre amplifier pumped by 820 nm GaAlAs laser
diodes

496 Feasibility demonstration of low pump power operation for 1.48 μm diode-
pumped erbium-doped fibre amplifier module
1990)

498 Efficient, high power, high gain, Er$^{3+}$ doped silica fibre amplifier
J. F. Massicott, R. Wyatt, B. J. Ainslie, S. P. Craig-Ryan (Electronics Letters
1990)

500 0.98-μm laser diode pumped erbium-doped fiber amplifiers with a gain
coefficient of 7.6 dB/mW
M. Shimizu, M. Yamada, T. Takeshita, M. Horiguchi (in Optical Amplifiers
and Their Applications 1990)

503 Saturated erbium-doped fibre amplifiers
R. I. Laming, D. N. Payne, F. Meli, G. Grasso, E. J. Tarbox (in Optical
Amplifiers and Their Applications 1990)

507 Spectral gain hole-burning in an erbium-doped fiber amplifier with
GeO$_2$:SiO$_2$ core
J. L. Zyskind, E. Desurvire, J. W. Sulhoff, D. J. DiGiovanni (in Optical
Amplifiers and Their Applications 1990)
Temperature variation of gain in a 1480-nm pumped erbium-doped fibre amplifier
M. Suyama, R. I. Laming, D. N. Payne (in Optical Amplifiers and Their Applications 1990)

Noise characteristics of rare-earth-doped fiber sources and amplifiers
P. R. Morkel, R. I. Laming, G. J. Cowle, D. N. Payne (in Fiber Laser Sources and Amplifiers 1990)

Erbium-doped fibre amplifiers with an extremely high gain coefficient of 11.0 dB/mW

Neodymium-Doped Fluoride Fiber Lasers

Neodymium-doped fluoro-zirconate fibre laser
M. C. Brierley, P. W. France (Electronics Letters 1987)

1.3 |m fluoride fibre laser

Efficient semiconductor pumped fluoride fiber lasers
M. C. Brierley, M. H. Hunt (in Fiber Laser Sources and Amplifiers 1989)

Erbium-Doped Fluoride Fiber Lasers

Continuous wave lasing at 2.7 |m in an erbium-doped fluorozirconate fibre
M. C. Brierley, P. W. France (Electronics Letters 1988)

Erbium-doped fluorozirconate single-mode fibre lasing at 2.71 |m

Lasing at 1.00 |m in erbium-doped fluorozirconate fibres

Narrow linewidth tunable cw and Q-switched 0.98 |m operation of erbium-doped fluorozirconate fibre laser

Diode-pumped single-mode fluorozirconate fiber laser from the \( ^4I_{11/2} \rightarrow ^4I_{13/2} \) transition in erbium

Erbium doped fluorozirconate fibre laser operating at 1.66 and 1.72 |m

Neodymium-Doped Fluoride Fiber Amplifiers

Amplification and lasing at 1350 nm in a neodymium doped fluorozirconate fibre
M. C. Brierley, C. A. Millar (Electronics Letters 1988)
1.31-1.36 μm optical amplification in Nd³⁺-doped fluorozirconate fibre

Amplification in the 1300 nm telecommunications window in a Nd-doped fluoride fibre
M. Brierley, S. Carter, P. France, J. E. Pedersen (Electronics Letters 1990)

High saturation output power from a neodymium-doped fluoride fibre amplifier operating in the 1300 nm telecommunications window
J. E. Pedersen, M. Brierley (Electronics Letters 1990)

**Erbium-Doped Fluoride Fiber Amplifiers**

Diode-laser pumped erbium-doped fluorozirconate fibre amplifier for the 1530 nm communications window

Erbium-doped fluoride fibre optical amplifier operating around 2.75 μm

Characterisation of diode-pumped erbium-doped fluorozirconate fibre optical amplifier

Section Twelve

**Fibers Doped with Other Rare Earth Ions**

563 Pulsed laser emission at 2.3 μm in a thulium-doped fluorozirconate fibre
L. Esterowitz, R. Allen, I. Aggarwal (Electronics Letters 1988)

564 CW diode pumped 2.3 μm fiber laser

566 Efficient high-power continuous-wave operation of monomode Tm-doped fibre laser at 2 μm pumped by Nd:YAG laser at 1.064 μm

568 Tunable cw lasing around 0.82, 1.48, 1.88 and 2.35 μm in thulium-doped fluorozirconate fibre

570 Blue upconversion fluorozirconate fibre laser

572 Efficient and tunable operation of a Tm-doped fibre laser
D. C. Hanna, R. M. Percival, R. G. Smart, A. C. Tropper (Optics Communications 1990)

576 CW diode-pumped operation of 1.97 μm thulium-doped fluorozirconate fibre laser
Highly tunable and efficient diode pumped operation of Tm$^{3+}$ doped fibre lasers

W. L. Barnes, J. E. Townsend (Electronics Letters 1990)

**Holmium**

Lasing at 2.08 μm and 1.38 μm in a holmium doped fluorozirconate fibre laser


Continuous-wave oscillation of holmium-doped silica fibre laser


Efficient cw operation of a 2.9 μm Ho$^{3+}$-doped fluorozirconate fibre laser pumped at 640 nm

L. Wetenkamp (Electronics Letters 1990)

**Ytterbium**

Continuous-wave oscillation of a monomode ytterbium-doped fibre laser


Highly efficient 980 nm operation of an Yb$^{3+}$-doped silica fibre laser


Efficient superfluorescent emission at 974 nm and 1040 nm from an Yb-doped fiber


**Samarium and Praseodymium**

The properties of the samarium fibre laser

M. C. Fairies, P. R. Morkel, J. E. Townsend (in Fiber Laser Sources and Amplifiers 1989)

Characterization of spontaneous and stimulated emission from praseodymium (Pr$^{3+}$) ions doped into a silica-based monomode optical fiber


Pr$^{3+}$-doped fluoride fiber amplifier operating at 1.31 μm


Amplification and lasing at 1.3 μm in praseodymium-doped fluorozirconate fibres


Amplification at 1.3 μm in a Pr$^{3+}$-doped single-mode fluorozirconate fibre

Section Thirteen

Applications to Fiber Telecommunication Systems

Solitons

615 Subpicosecond soliton amplification and transmission using Er\textsuperscript{3+}-doped fibers pumped by InGaAsP laser diodes

618 Femtosecond soliton amplification in erbium doped silica fibre

620 Automatic optical soliton control using cascaded Er\textsuperscript{3+}-doped fibre amplifiers
K. Suzuki, M. Nakazawa (Electronics Letters 1990)

622 Observation of multi-wavelength soliton collisions in fiber amplifier based systems

626 Soliton transmission in a distributed, dispersion-shifted erbium-doped fiber amplifier
M. Nakazawa, Y. Kimura, K. Suzuki (in Optical Amplifiers and Their Applications 1990)

Transmission Systems

629 An over 2,200 km coherent transmission experiment at 2.5 Gbit/s using erbium-doped-fiber amplifiers

632 12300 ps/nm, 2.4 Gbit/s optical fiber transmission experiment using Er-doped fiber amplifiers and penalty due to transmitter phase noise

636 3.2-5 Gb/s, 100 km error-free soliton transmissions with erbium amplifiers and repeaters

640 2.55 \textmu m, 400 Mbit/s transmission experiment with single-mode fluoride optical fibre
T. Komukai, Y. Miyajima, Y. Katsuyama (Electronics Letters 1990)

642 A 17 Gb/s long-span fiber transmission experiment using a low-noise broadband receiver with optical amplification and equalization
K. Hagimoto, Y. Miyamoto, T. Kataoka, K. Kawano, M. Ohhata (in Optical Amplifiers and Their Applications 1990)

646 100-channel common amplification using an Er\textsuperscript{3+}-doped fiber amplifier
Field demonstration of FSK transmission at 2.488 Gbit/s over a 132 km submarine cable using an erbium power amplifier

1.7 Gb/s - 419 km transmission experiment using a shelf-mounted FSK coherent system and packaged fiber amplifier modules

Distribution Networks

658 FM microwave multiplexed broad-band distribution systems using Er3+ fiber amplifiers and preamplifiers

661 Simultaneous distribution of AM/FM FDM TV signals to 65,536 subscribers using 4 stage cascade EDFAs
K. Kikushima, E. Yoneda, K. Suto, H. Yoshinaga (in Optical Amplifiers and Their Applications 1990)

665 Demonstration of a distributed optical fibre amplifier BUS network
T. J. Whitley, C. A. Millar, S. P. Craig-Ryan, P. Urquhart (in Optical Amplifiers and Their Applications 1990)

Section Fourteen
Applications to Fiber Sensors

671 Fiber optic rare earth temperature sensors

674 Distributed temperature sensor using Nd3+-doped optical fibre
M. C. Farries, M. E. Fermann, R. I. Laming, S. B. Poole, D. N. Payne, A. P. Leach (Electronics Letters 1986)

676 Fabrication and properties of large core, high NA, high Nd3+ content multimode optical fibres for temperature sensor applications

678 All-fibre, diode-pumped recirculating-ring delay line
P. R. Morkel (Electronics Letters 1988)

680 Fibre gyro experiment using fibre laser source

682 Stable fiber-source gyroscopes

685 Author Index
689 Subject Index