701

OPTICAL FIBRE AMPLIFIERS: DEVICES AND SYSTEMS

University of Essex Short Course

10-12 March 1993

FIBRE LASERS

A review of devices, techniques and applications

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U.K.

OVERVIEW:

- **History of fibre laser development.**

- **Fundamentals and key features of fibre lasers** - fibre amplifiers with feedback

- **Review of applications and laser wavelengths**

- **Continuous wave laser configurations**

    Power and spectral characteristics

- **Other configurations**

    Tunable lasers

    Q-switched lasers

    Mode-locked lasers

    Single-frequency lasers

    Upconversion lasers

    Superfluorescent sources

- **Some theory**

- **Summary**

HISTORY OF FIBRE LASER DEVELOPMENT 1961-1985

1961	E.Snitzer: "Proposed fiber cavities for Optical Masers", J.Appl.Phys., Jan. 1961. Advantages of strong mode selection and high gain identified. Problem: How to pump?
1964	E.Snitzer: First glass lasers and multimode fibre lasers.
1964	E.Snitzer: Neodymium-doped fibre amplifier
1965	E.Snitzer: First Er (co-doped with Yb) glass laser.
1969	E.Snitzer: Monomode Nd-doped fibre amplifier (low NA)
1973	Stone & Burrus: Longitudinally LED pumped Nd-doped fibre laser.
1985	Southampton University: High NA ($\approx$0.2) rare-earth-doped fibres Nd & Er-doped fibre lasers pumped with laser diodes
1987	Southampton University: Er-doped fibre amplifier

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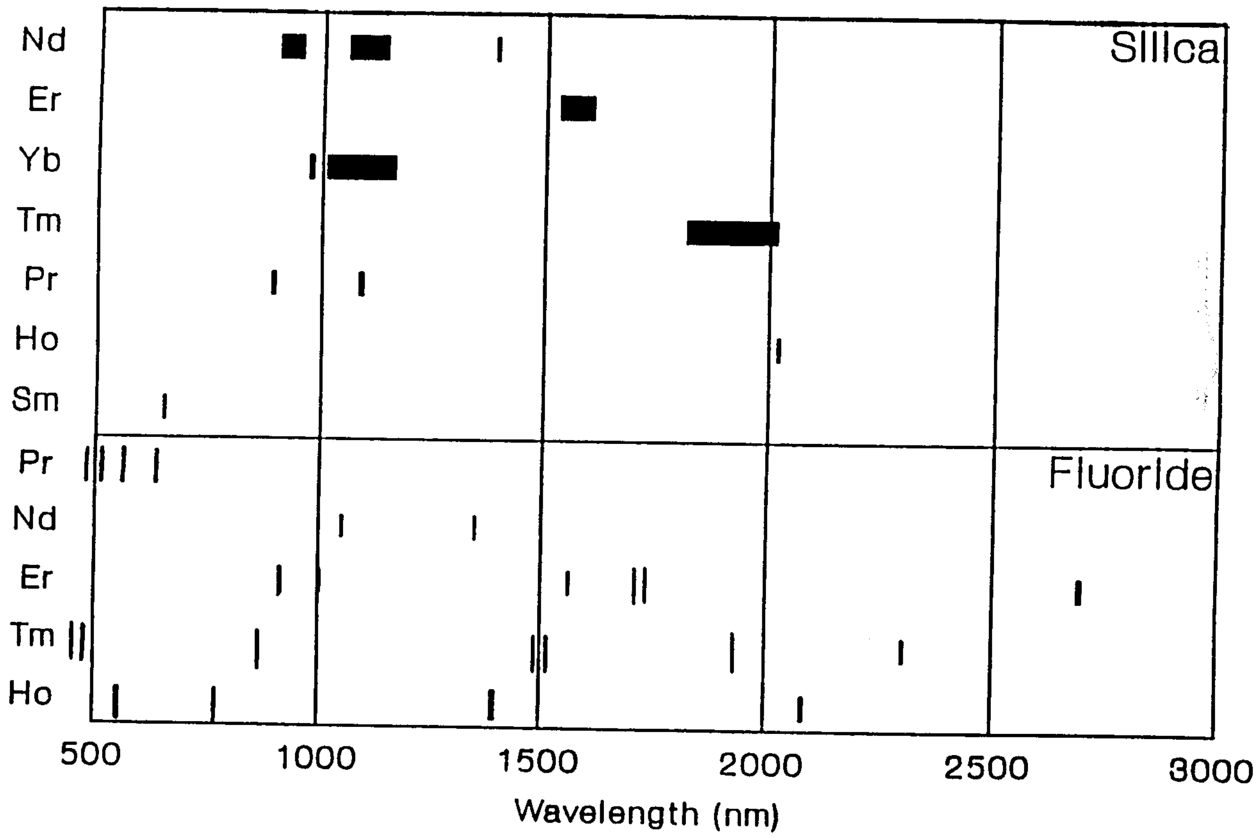
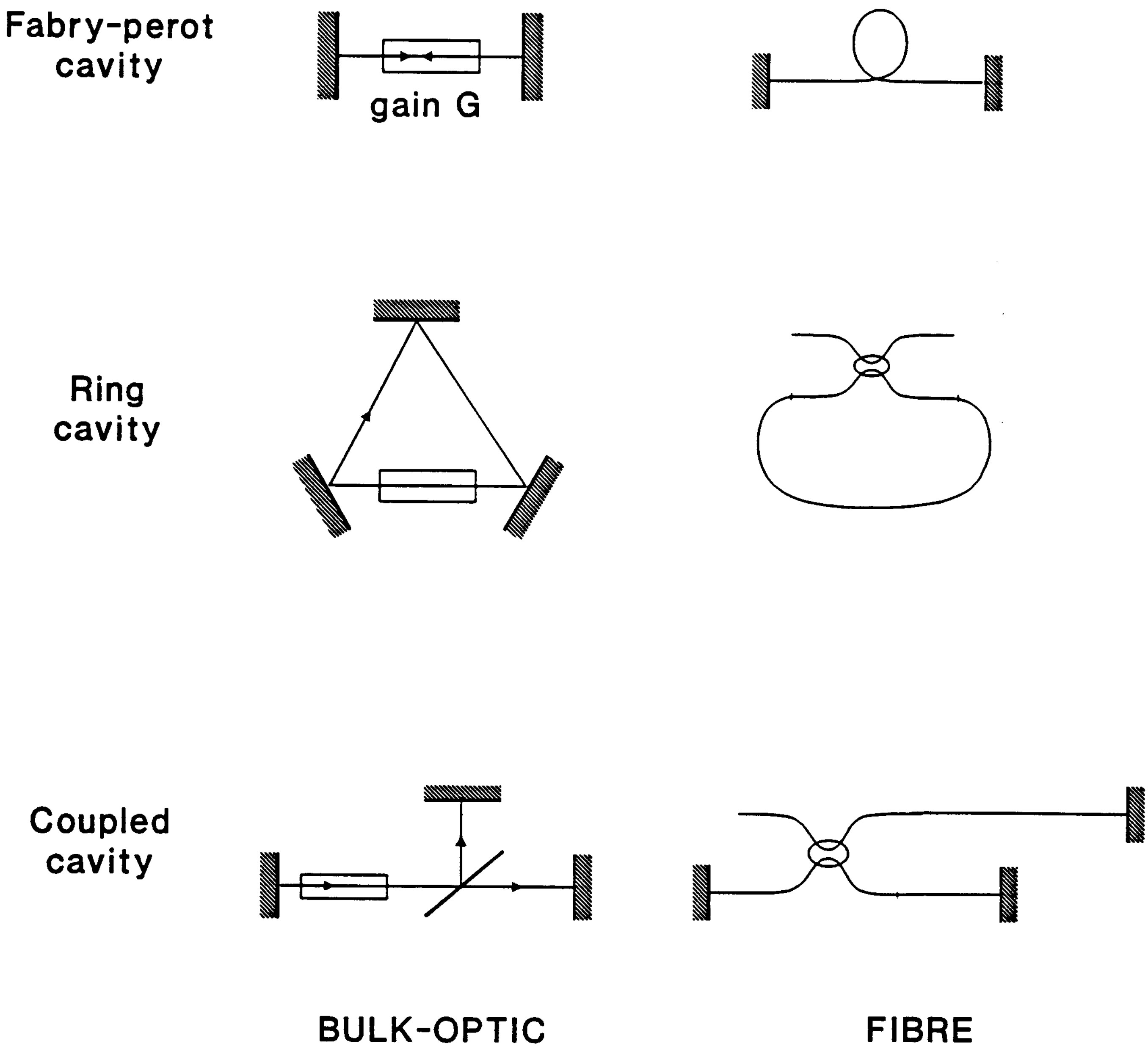
FIBRE LASER WAVELENGTHS

Silica fibres and Fluoride fibres



BULK-OPTIC AND FIBRE LASER CONFIGURATIONS



Threshold for laser action obtained when Gain G is such that:

$$G(1-L)=1$$

where L = optical losses seen in one "round-trip" of the laser cavity

KEY FEATURES OF FIBRE LASERS

- Small modal volume gives high gain

- Broad emission and absorption lineshapes

  - wide tunability

  - short pulse mode-locking

  - wide tolerance of pump wavelength compared with crystal lasers

- Longitudinal geometry gives minimal thermal effects

- Low (potential) cost

  High manufacturing yield gain medium (doped fibre)

  Simple and rugged constructions

- Compatibility with fibre transmission media

- Strong mode selection

SOURCES FOR USE IN:

Communications:

- single frequency lasers
- soliton sources
- fibre diagnostics

OTDR type sensors:

- Q-switched lasers at 1.06μm and 1.55μm

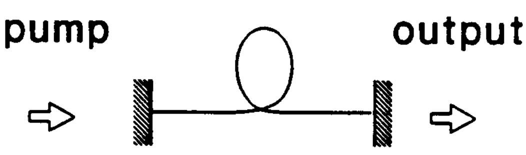
Environmental sensing:

- specific wavelength sources for gas absorption lines. eg. 1.66μm Tm^{3+} for Methane absorption.

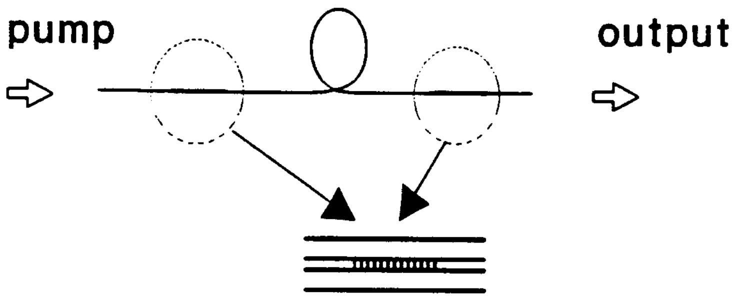
Interferometric sensors, eg fibre gyros:

- superfluorescent sources

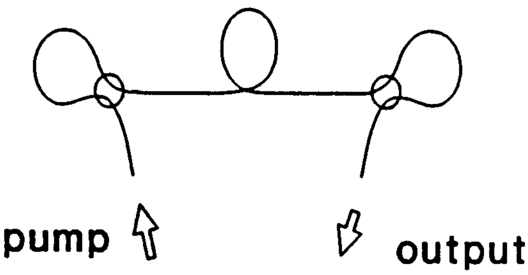
CONTINUOUS WAVE (CW) FIBRE LASER CONFIGURATIONS



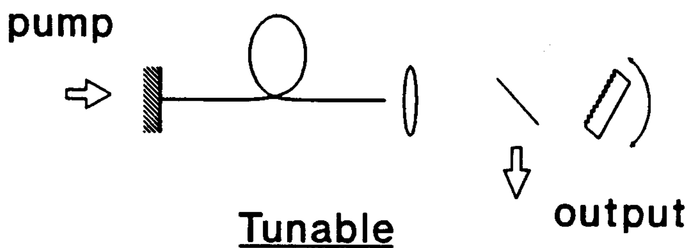
Simple Fabry-Perot



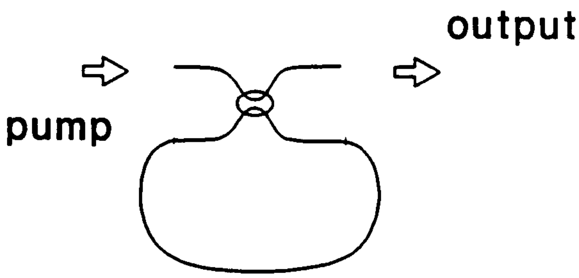
Fibre grating Fabry-Perot



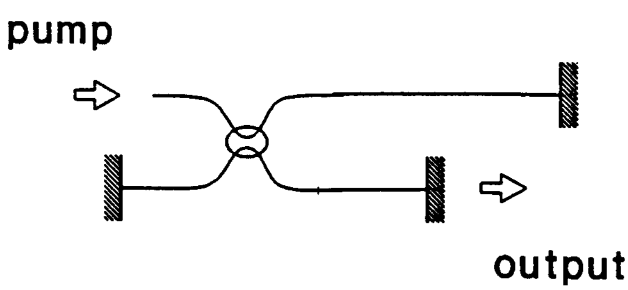
Fibre mirror Fabry-Perot



Tunable



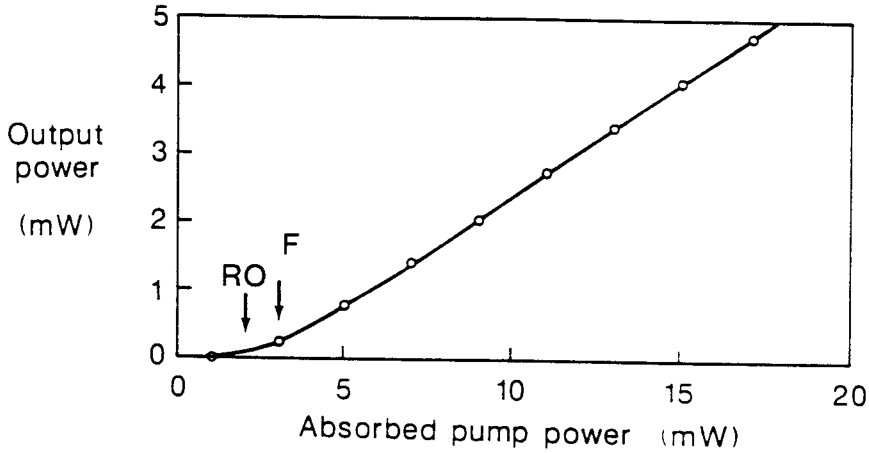
Ring



Coupled cavity

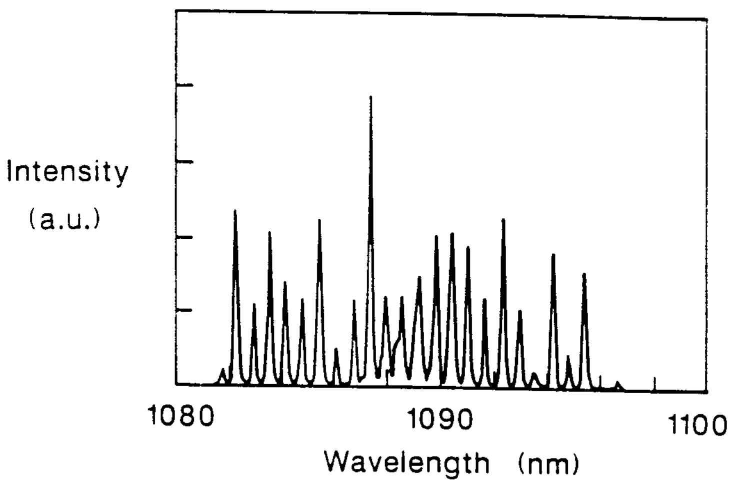
CW FIBRE LASER OUTPUT CHARACTERISTICS

Barnes et al, Opt. Comm, **82**(3), p.282, 1991



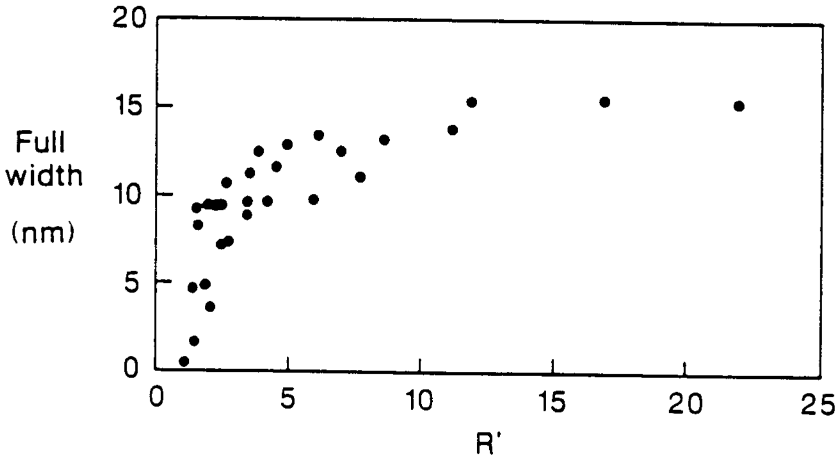
Nd-doped GeO_2/SiO_2 fibre laser characteristic

(800nm laser diode pump)



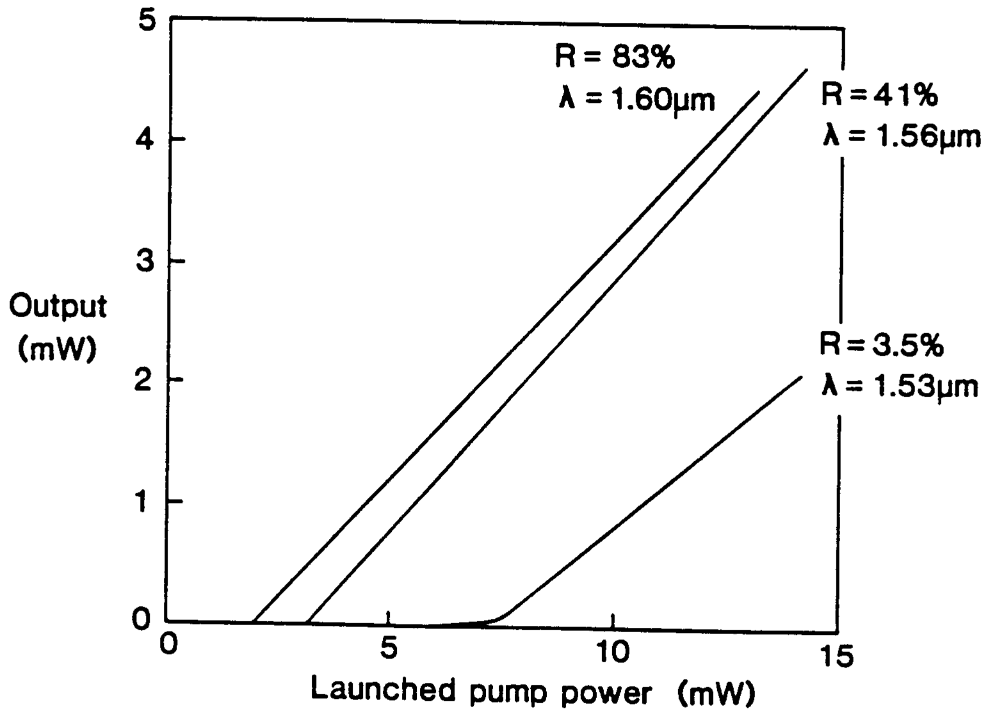
Nd-doped GeO_2/SiO_2 fibre lasing spectrum

CW FIBRE LASER OUTPUT CHARACTERISTICS



Nd-doped GeO_2/SiO_2 fibre spectral width variation with pump power

(normalised to threshold power)

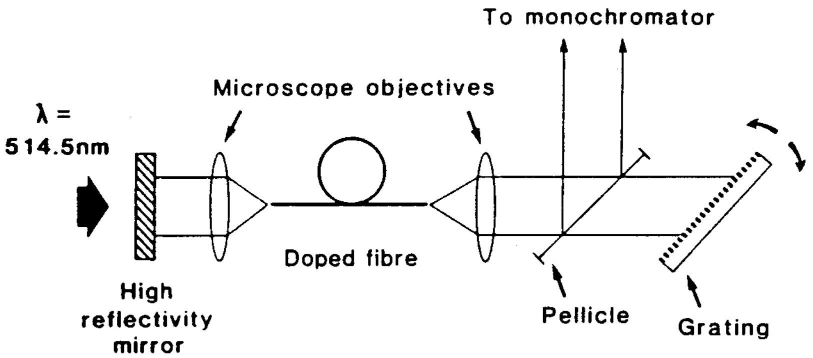


Er-doped Al_2O_3/SiO_2 fibre 980nm pumped laser characteristics

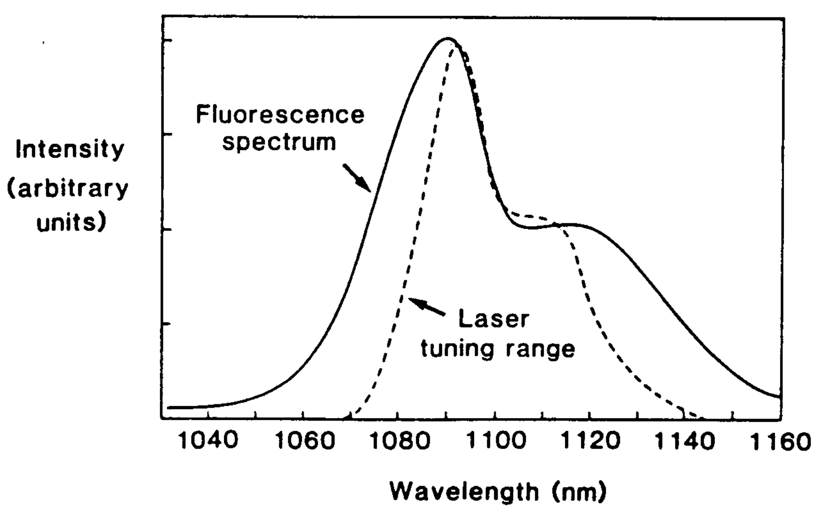
TUNABLE LASERS

Tunable neodymium-doped fibre laser

L.Reekie et al., Journal of Lightwave Technology, **LT-4**(7), July 1986.



Tunable laser configuration

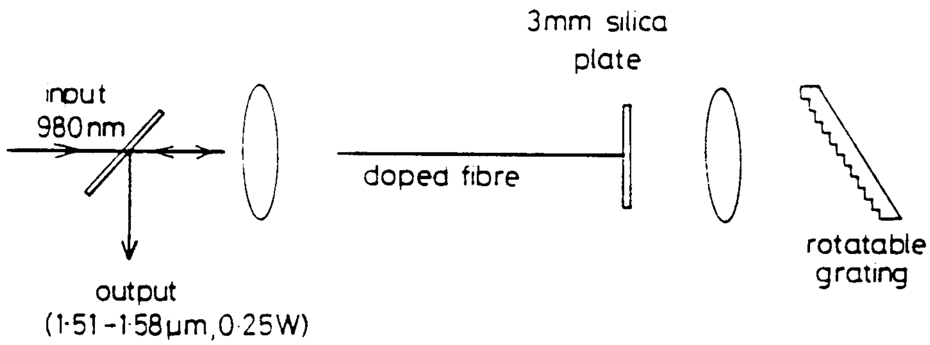


Laser tuning range and fluorescence spectrum

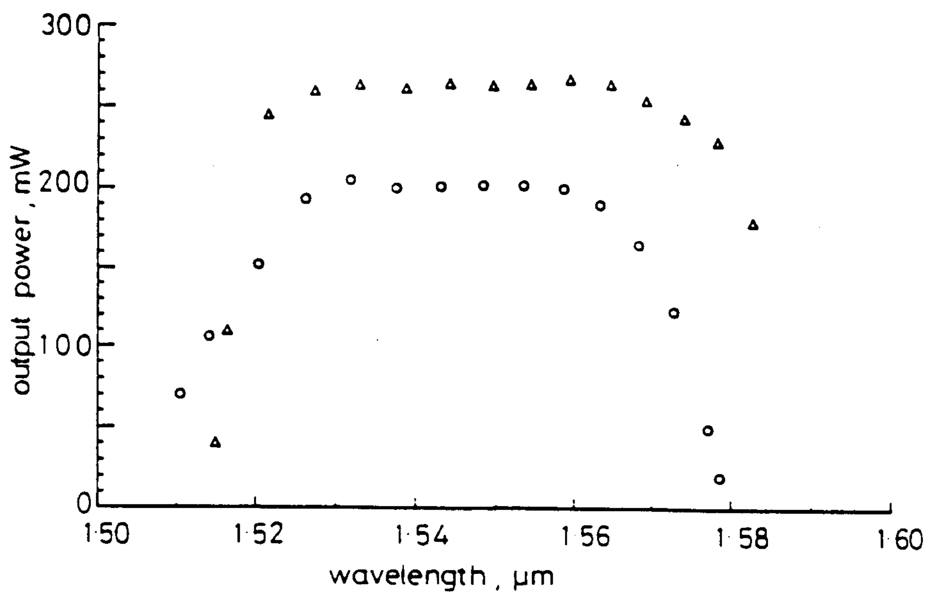
TUNABLE LASERS

High power tunable erbium-doped fibre laser

R.Wyatt, Electronics Letters, 25(22), Oct 1989



Tunable Er-doped fibre laser configuration



Erbium fibre laser tuning characteristic. 540mW pump power at 980nm. 1100ppm Er^{3+}-doped fibre lengths of 5.5m (○) & 9.5m (△).

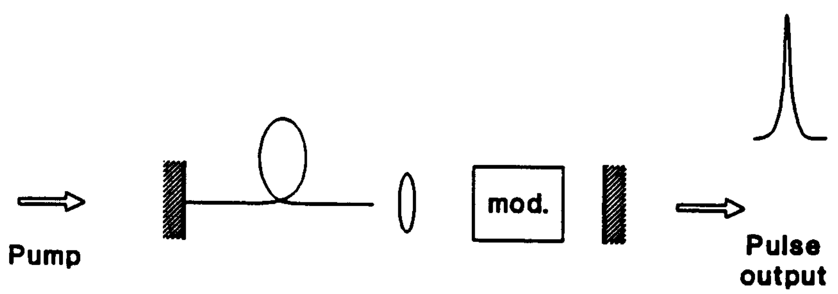
Q-SWITCHED LASERS

Principle:

Population inversion allowed to build up in a fibre laser amplifier medium by preventing feedack (holding cavity in a high-loss state)

Rapidly switching the cavity to a low-loss state allows rapid increase in the laser intensity and saturation of the gain medium to produce a high power pulse.

Q-switched laser schematic:



Q-SWITCHED LASERS

Features of Q-switched lasers:

- Energy stored in the gain medium due to the long lifetimes associated with the rare-earth media.

- Energy extracted in a short time scale to produce a pulse output power orders of magnitude ($\sim 10^5$) greater in power than that of a CW laser.

- Pulse durations $\approx$ 1ns demonstrated for Nd doped fibres

  $\approx$ 10ns for Er doped fibres.

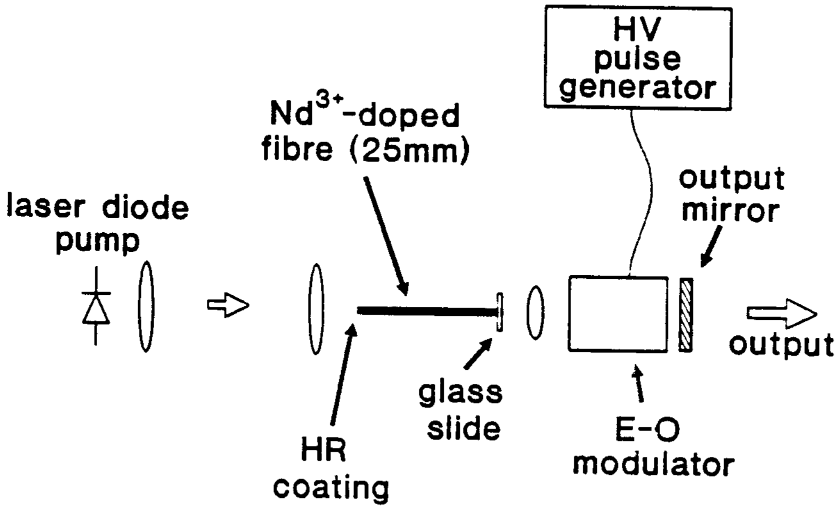
- Repetition rate determined by the fluorescence time constant of the material.

- Applications in Optical Time Domain reflectometry (OTDR) and time division multiplexed sensor systems.

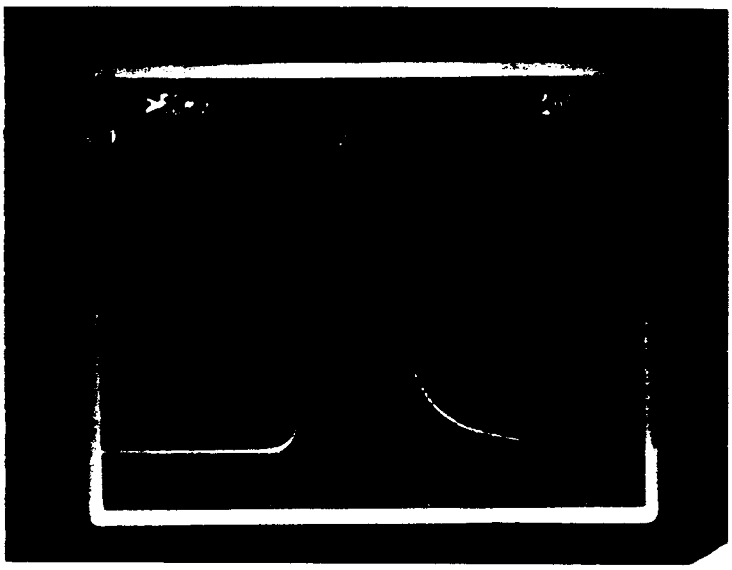
Q-SWITCHED LASERS

Q-switched Neodymium-doped fibre laser

Morkel et al, IEEE Photonics Tech. Lett., 4(6), p.545, 1992



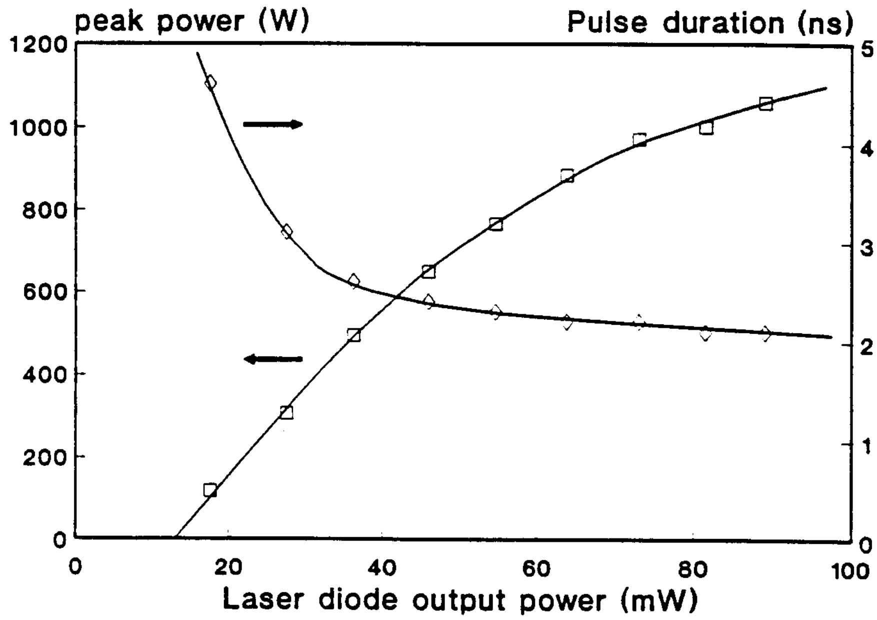
Experimental Q-switched Nd-doped fibre laser cavity



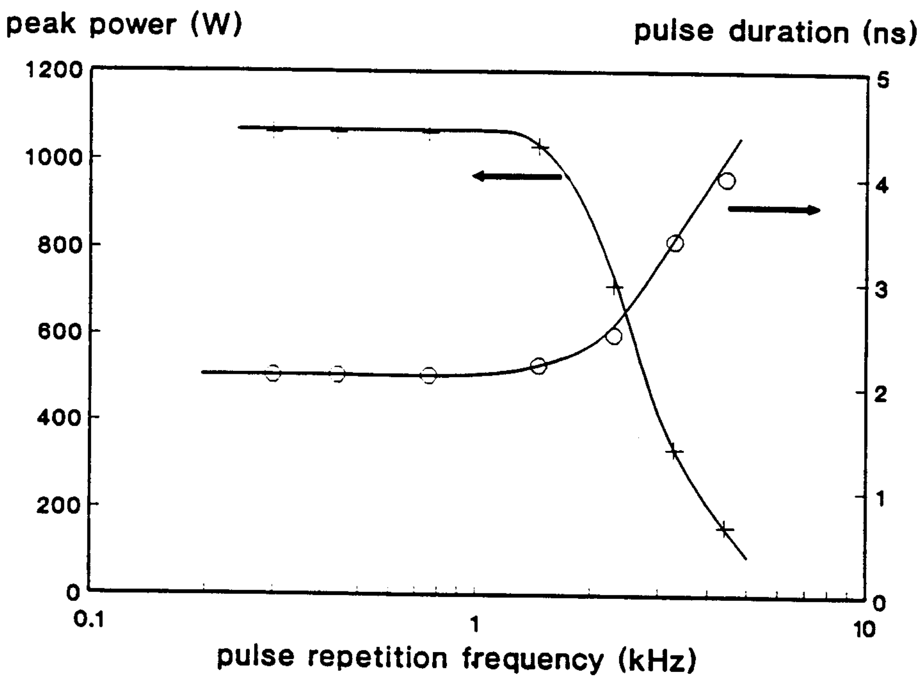
Pulse characteristic obtained at 1.05μm

Q-SWITCHED LASERS

Q-switched Neodymium-doped fibre laser



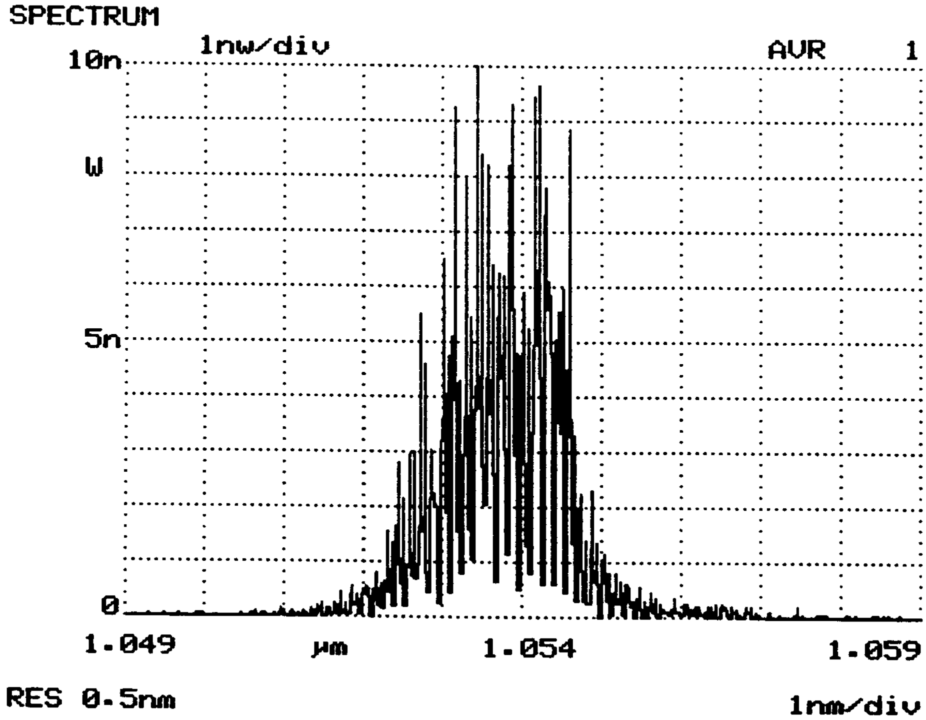
Pulse power and duration dependence on pump power



Pulse power and duration variation with repetition rate

Q-SWITCHED LASERS

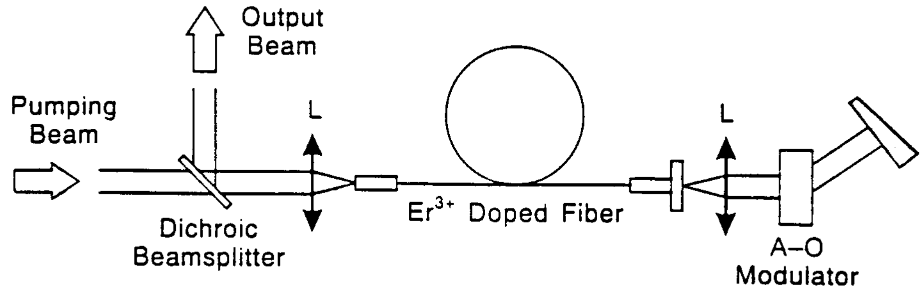
Q-switched Neodymium-doped fibre laser



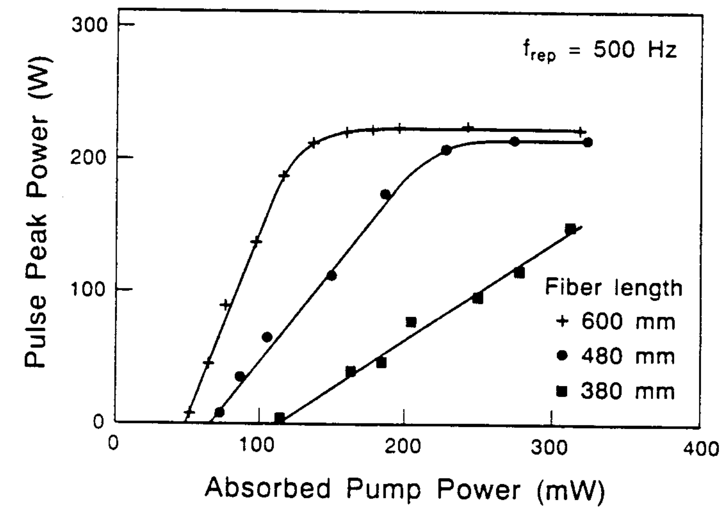
Q-switched Nd-doped fibre laser output spectrum

Q-SWITCHED LASERS

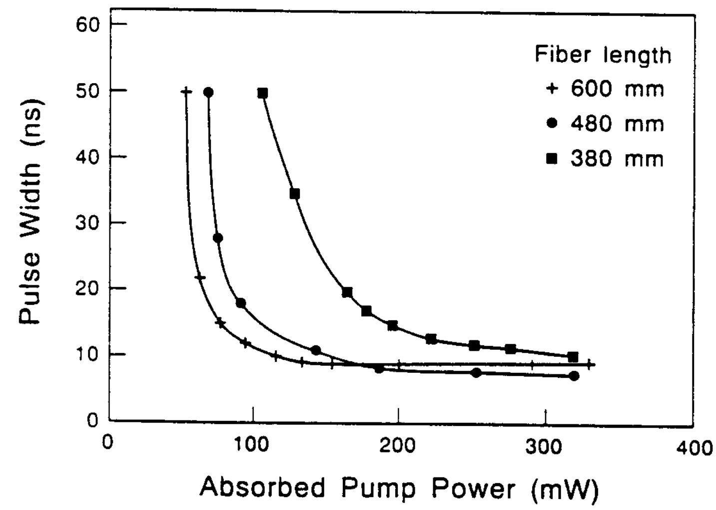
Q-switched erbium-doped fibre laser (Myslinski et al, IEEE Jounal of Quantum Electronics, 28(1), 1992.



Experimental configuration. 1600ppm erbium fibre. Pump 514nm.



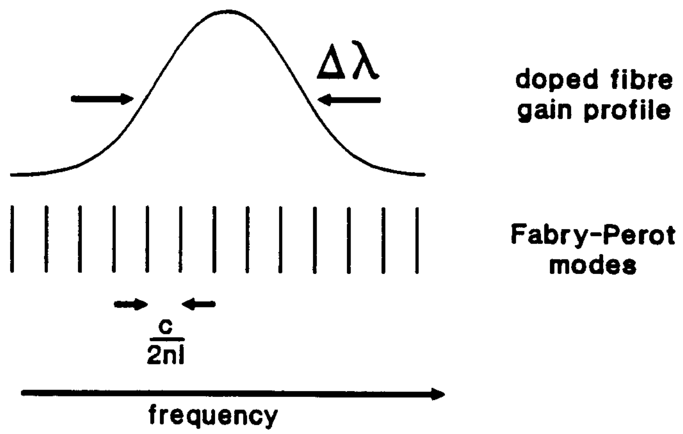
(a)



(b)

Experimental pulse power (a) and duration (b) dependence on pump power

MODE-LOCKED LASERS



Fabry-Perot mode spectrum

Randomly phased modes → noise

Phased modes → short pulses. Pulse duration $\delta t \sim 1/\Delta\lambda$ (~1ps)

Methods to lock phases:

Active

AM - Modulate cavity loss at cavity round trip frequency (or multiple)

FM - modulate cavity phase at cavity round trip frequency (or multiple)

Passive

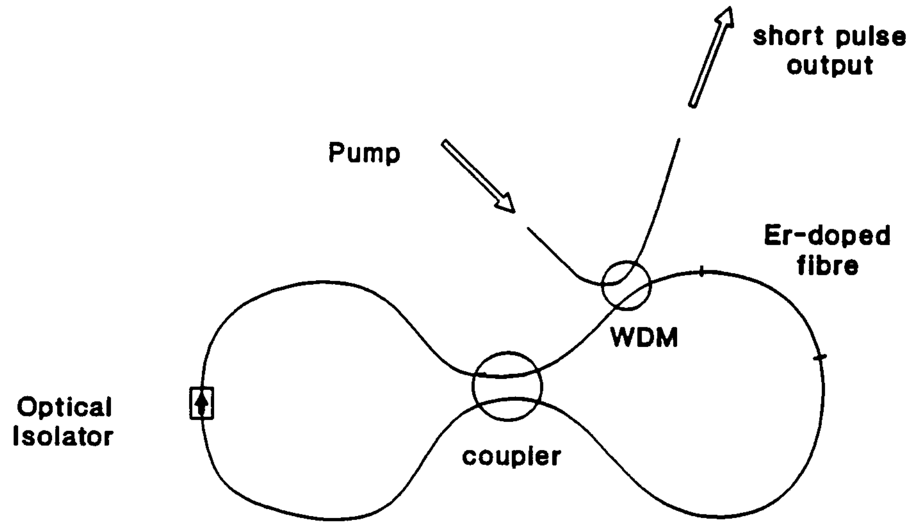
Introduce non-linear loss component (saturable absorber) into cavity

Passive mode-locking generally gives shorter pulses than active mode-locking for fibre lasers.

MODE-LOCKED LASERS

Examples of mode-locked fibre laser configurations

Figure-8 laser

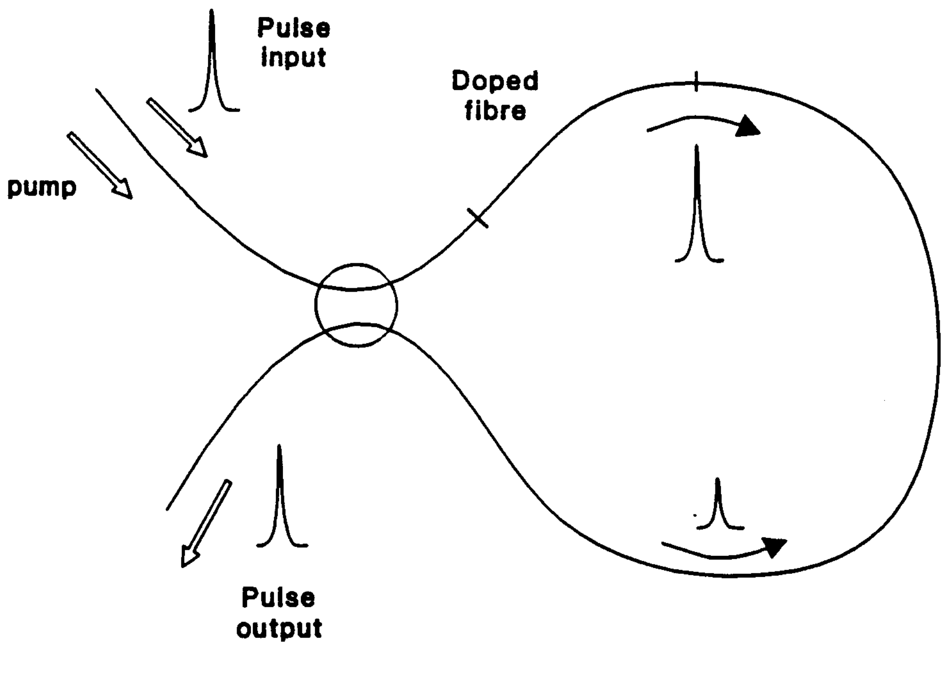


CW lasing → high loss

Short pulse operation (high peak power) → low loss

Shortest pulses ≈300fs

Non-linear amplifying loop mirror (NALM)



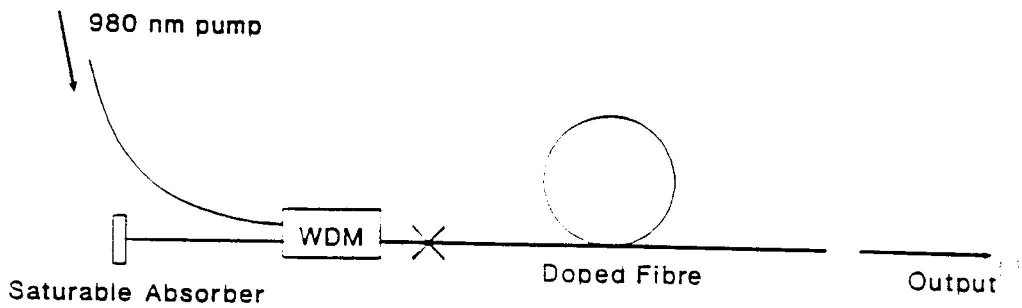
MODE-LOCKED LASERS

Semiconductor saturable absorber mode-locked fibre laser

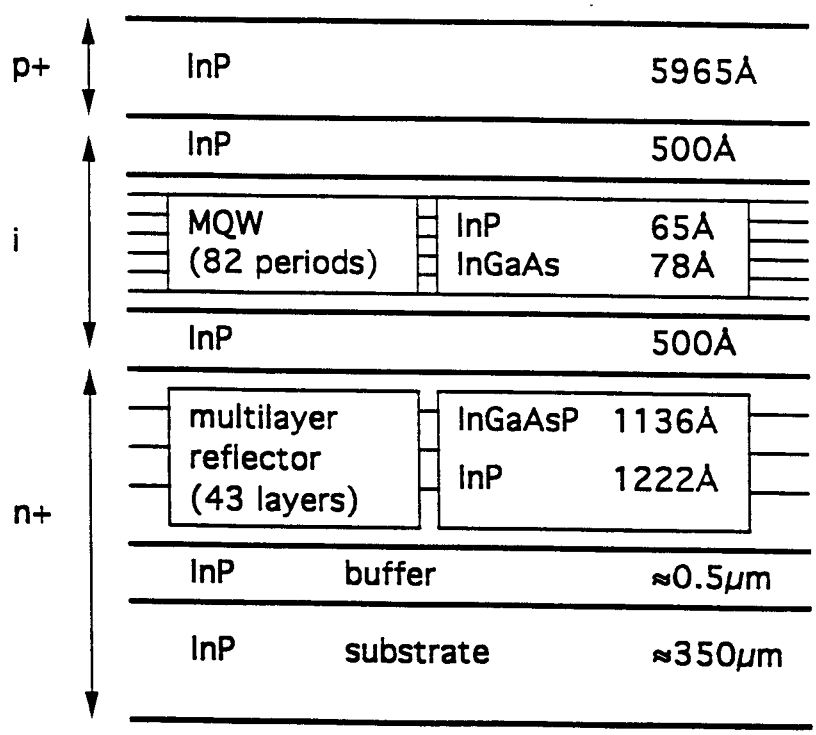
Loh et al, IEEE Photonics Tech. Lett, 5(1), Jan 1993

Principle: Saturation of absorption in a semiconductor material is used to provide a non-linear loss mechanism which favours short pulse and hence mode-locked operation. Fast carrier dynamics give rise to ultra-short pulses.

Laser configuration

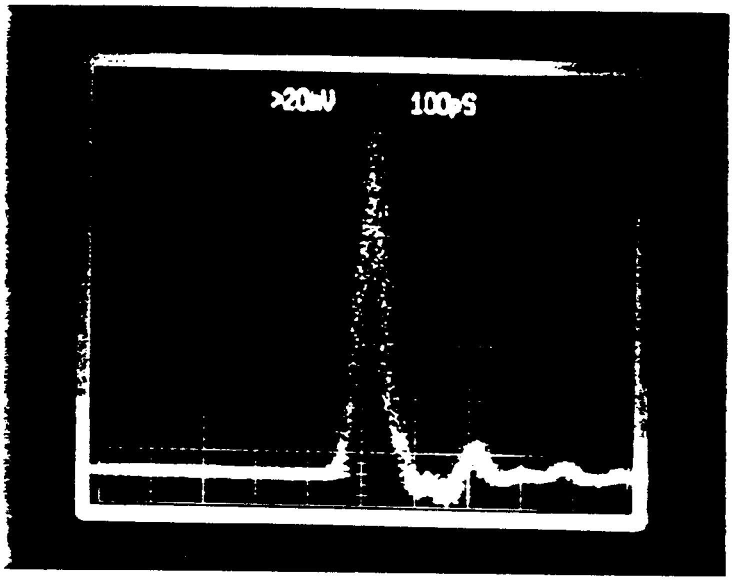


Saturable absorber construction

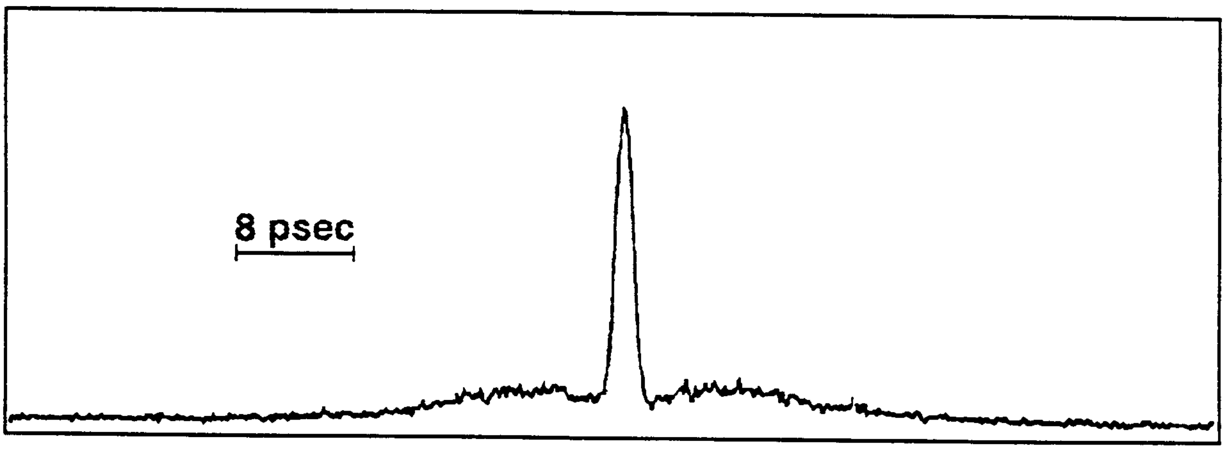


MODE-LOCKED LASERS

Semiconductor saturable absorber mode-locked fibre laser



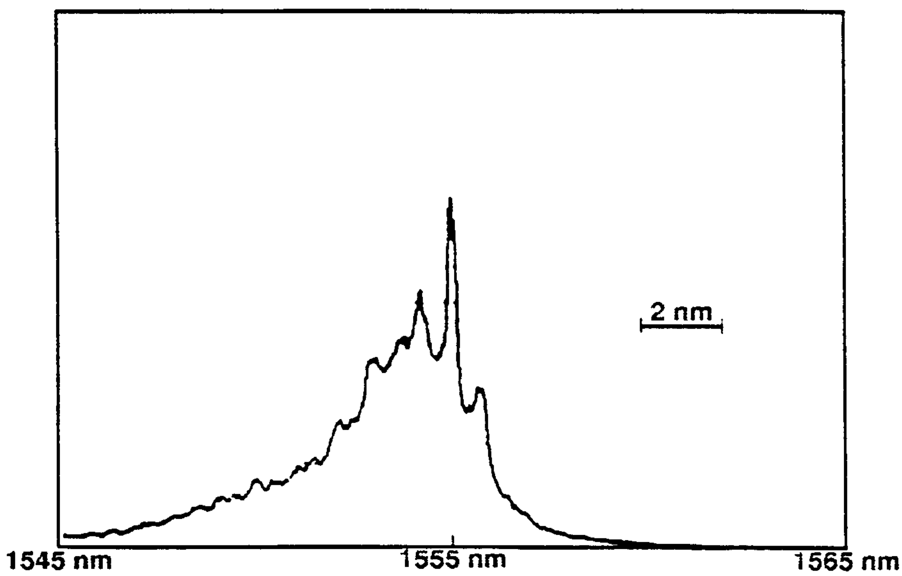
Pulse characteristic measured with fast InGaAs detector (bandwidth limited). After pulsing due to detector ringing.



Autocorellation trace showing pulse duration ≈ 1ps with slight pedestal.

MODE-LOCKED FIBRE LASERS

Semiconductor saturable absorber mode-locked fibre laser



Optical spectrum of mode locked laser. Residual etalon modulation apparent.

SINGLE FREQUENCY LASERS

Combination of wide gain bandwidth, spatial hole burning & long fibre cavities generally gives rise to multi-longitudinal-mode operation.

To achieve single mode or single frequency operation, two main approaches have been used:

1. Operate laser in travelling-wave mode (no spatial hole burning)

   Advantages:

   - Can incorporate tuning elements
   - Can use high efficiency, low concentration fibres
   - Very narrow ultimate linewidth (Shawlow Townes limit <1 Hz)

   Disadvantages:

   - Susceptible to mode hopping

2. Reduce cavity length and include frequency selective feedback elements (gratings) to maximize longitudinal mode loss discrimination.

   Advantages:

   - "Rugged" single mode operation without mode-hopping
   - Simple construction with fibre gratings

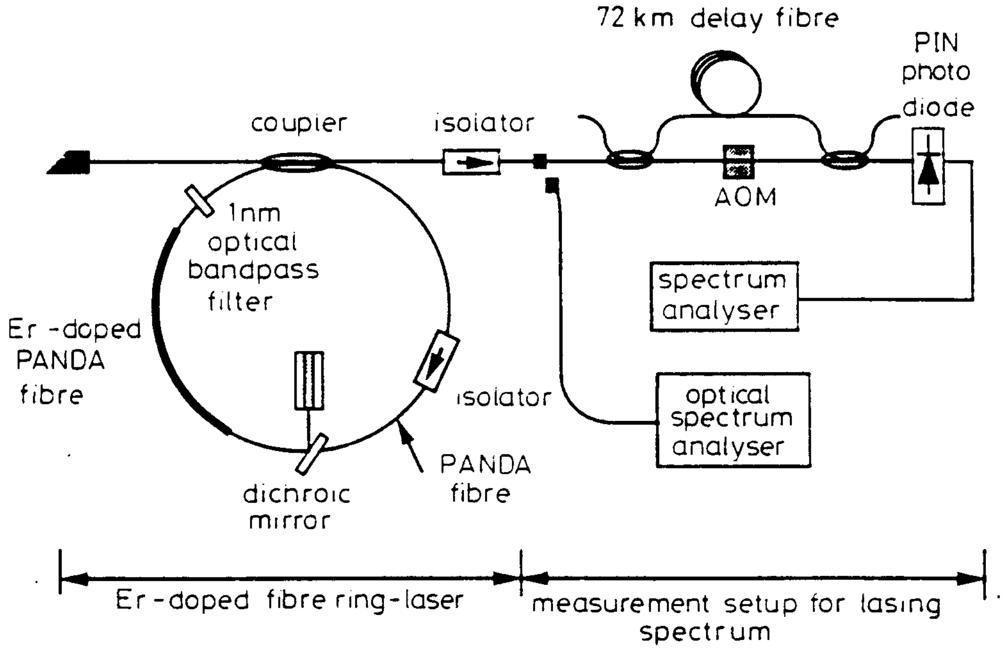
   Disadvantages:

   - Limited tuning potential
   - High concentration fibres required (reduced efficiency)

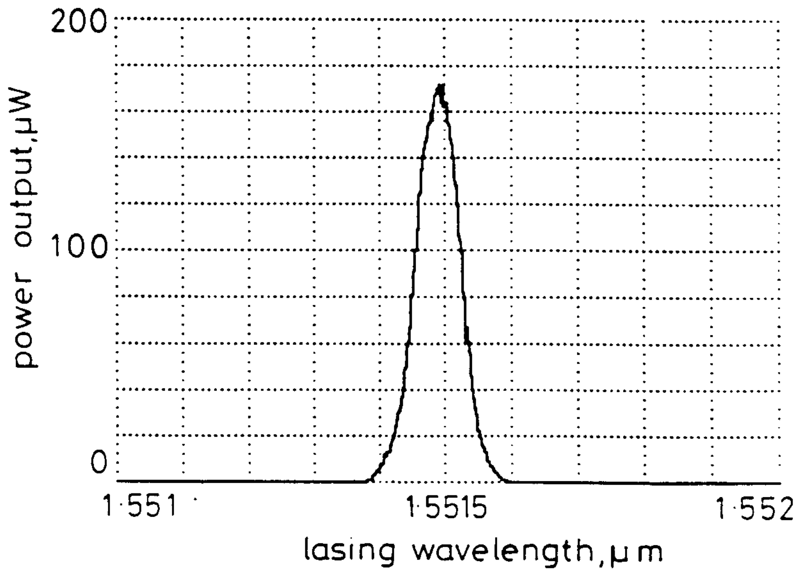
SINGLE FREQUENCY LASERS

Travelling-wave fibre laser

Iwatsuki et al. Electronics Letters, 26(4), Nov. 1990.



Experimental set-up of travelling-wave fibre ring laser.



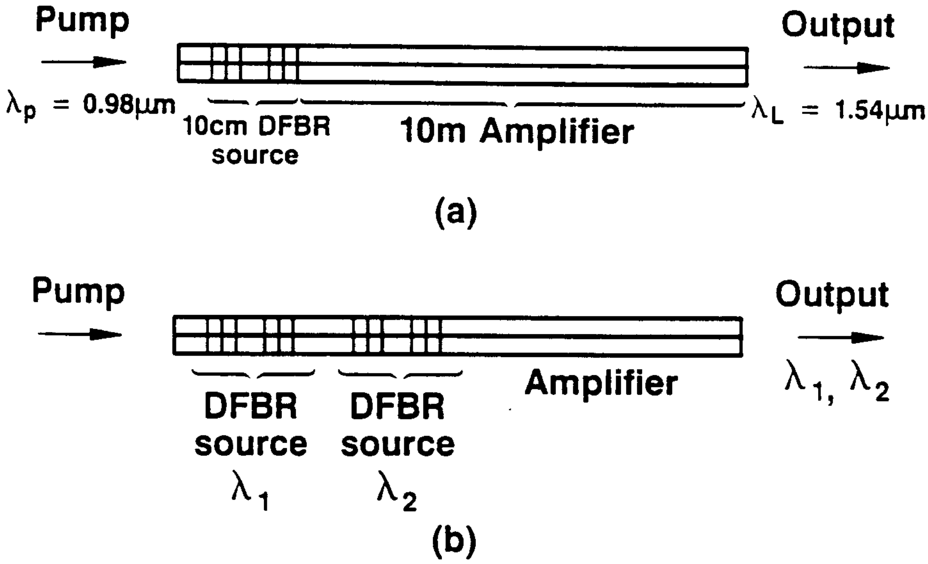
Optical spectrum of fibre laser.

Max output 1mW for 70mW pump power at 1480nm. Self heterodyne line width measurement ≈ 1.4kHz (narrowest line fibre laser).

SINGLE FREQUENCY LASERS

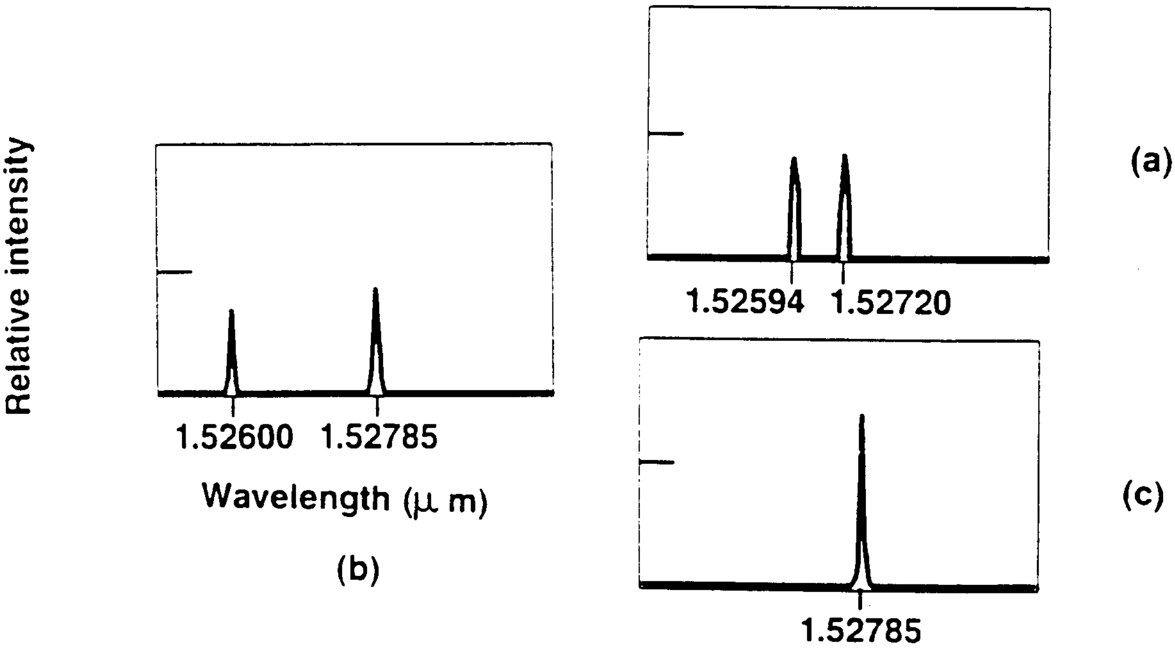
Fibre grating fibre laser

Ball & Morey, Proc OFC '92, paper WA3, p.97, San Jose, Feb 1992.



Experimental grating-fibre-laser/amplifier configuration.

(a) single laser, (b) two lasers

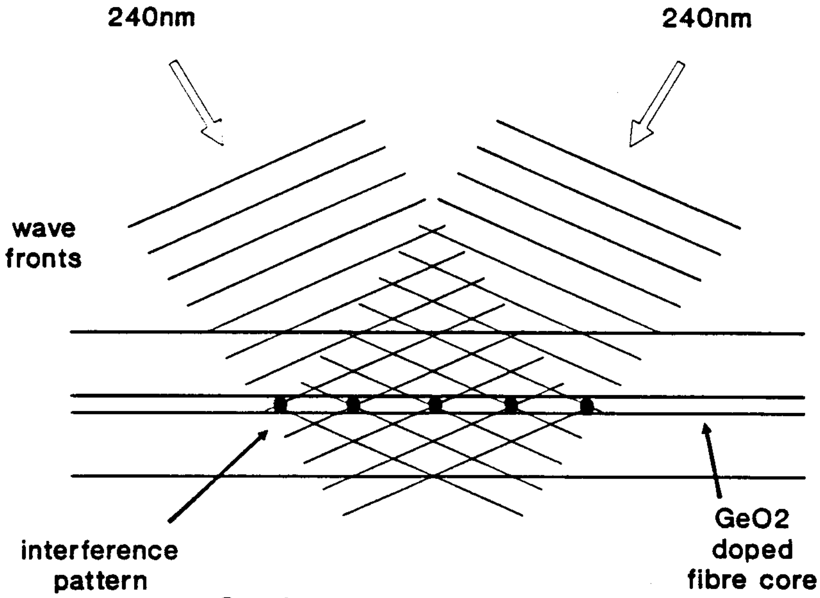


Output spectra of two lasers (a) & (b) showing wavelength tuning

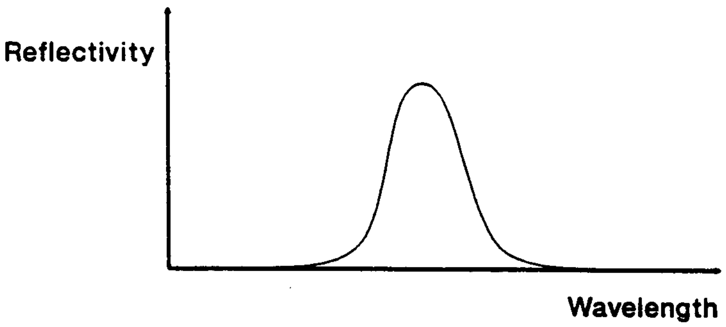
by stretching. Single laser operation (c)

FIBRE GRATING FABRICATION

- Refractive index perturbations formed in GeO_2 doped fibre cores by exposure to U.V. radiation around 240nm.
- Sources of suitable U.V. radiation include KrF Excimer lasers, frequency doubled Argon Ion lasers.
- Interference of UV beams in a fibre core produces longitudinal index-perturbation gratings with wavelength selective reflection characteristics.



Grating writing technique



Schematic grating reflection characteristic

Narrowest linewidth achieved < 10GHz FWHM. Highest reflectivity > 99%.

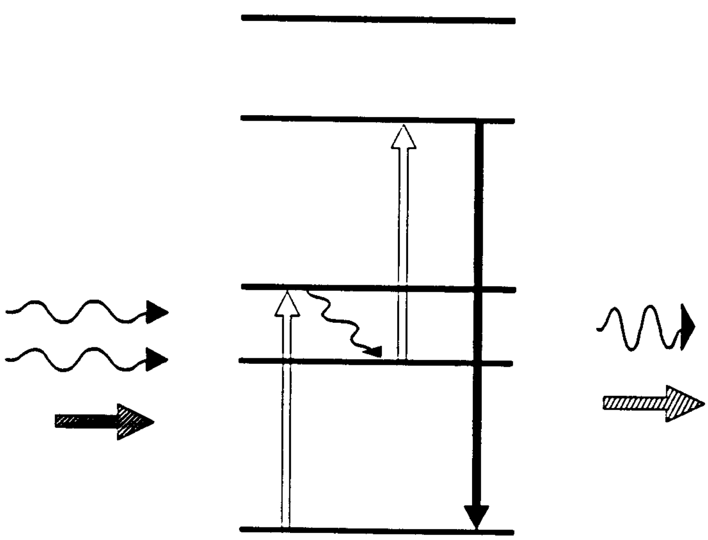
UPCONVERSION LASERS

- Multi-stage pumping achieved by absorption of more than one pump photon in a dopant ion. Gives rise to **upconversion** in frequency between pump light and laser emission

- Single or multiple wavelength pumping

- Fibre based on low phonon energy host glasses (eg Fluorides) usually required to ensure long lifetimes of multiple levels

- Emission in the visible spectrum

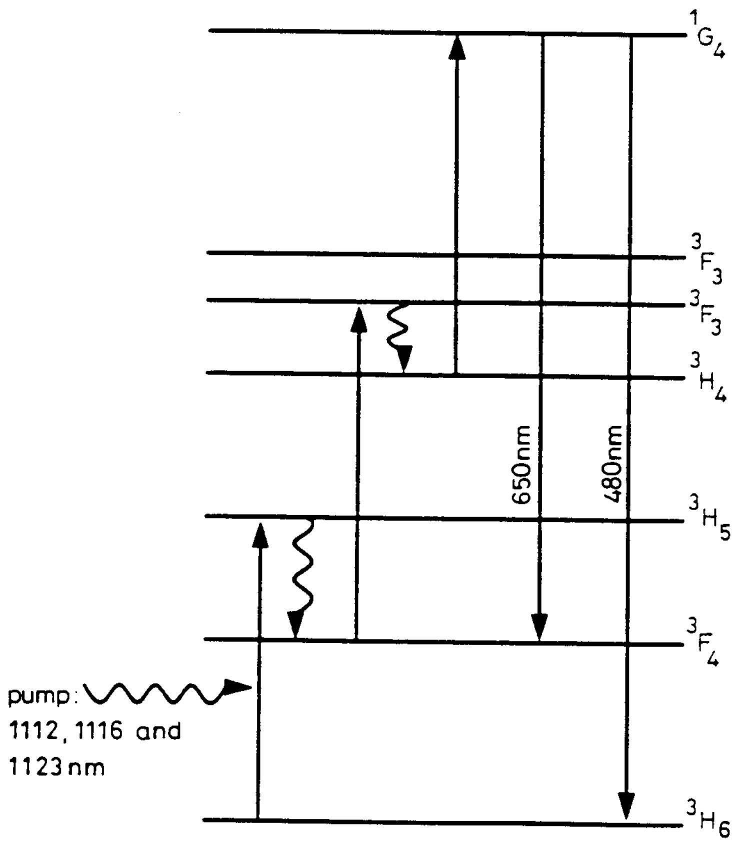


Upconversion schematic

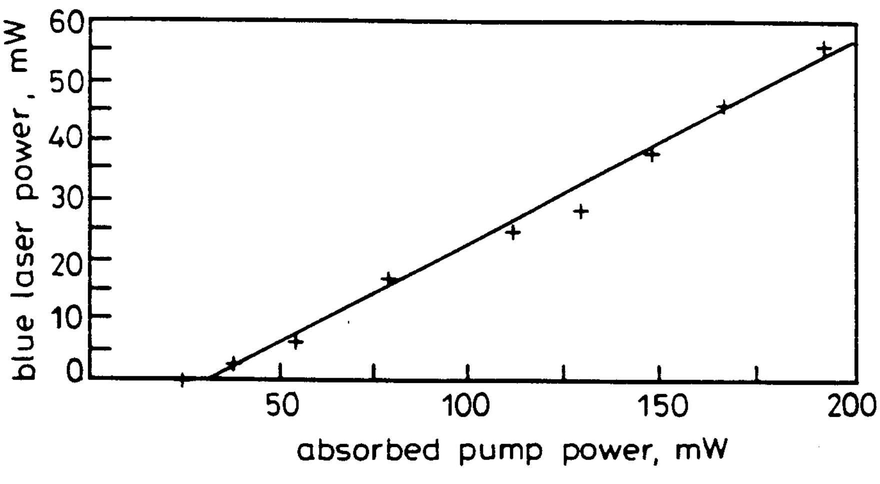
UPCONVERSION LASERS

Blue upconversion Tm^{3+}-doped ZBLAN fibre laser

Grubb et al., Electronics Letters, 28(13), p.1243, June 1992



Tm^{3+} energy level diagram showing upconversion pumping scheme



Laser characteristic for 1.12μm pumped Tm^{3+} upconversion fibre laser

FIBRE SUPERFLUORESCENT SOURCES

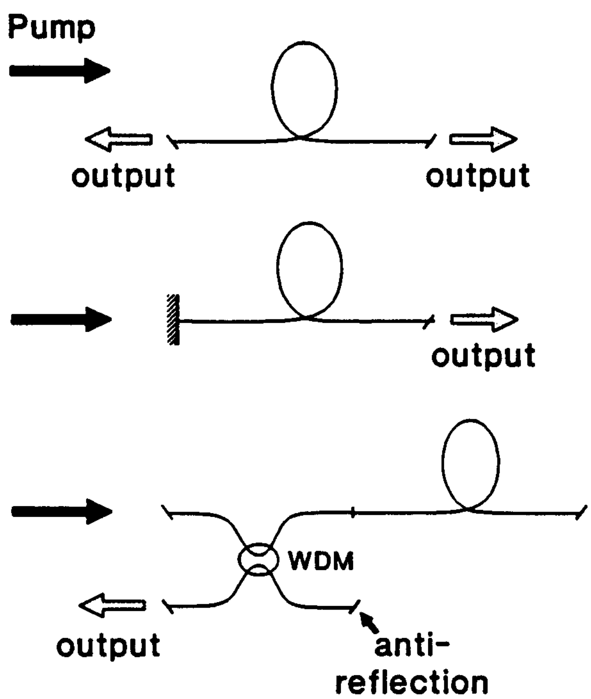
Principle:

- Very high gain amplifier >30 dB
- Substantial amplification of spontaneous emission in a single pass of the amplifier - Amplified Spontaneous Emission (ASE)
- ASE undergoes single-pass or double-pass of amplifier. No round-trip feedback

Other terms (same meaning):

Superfluorescence, Superradiance, Superluminescence

Configurations:

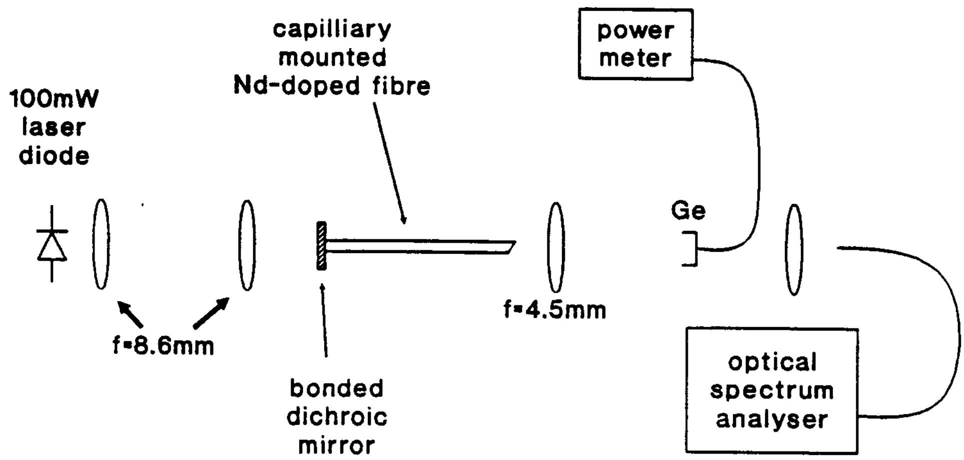


3-level

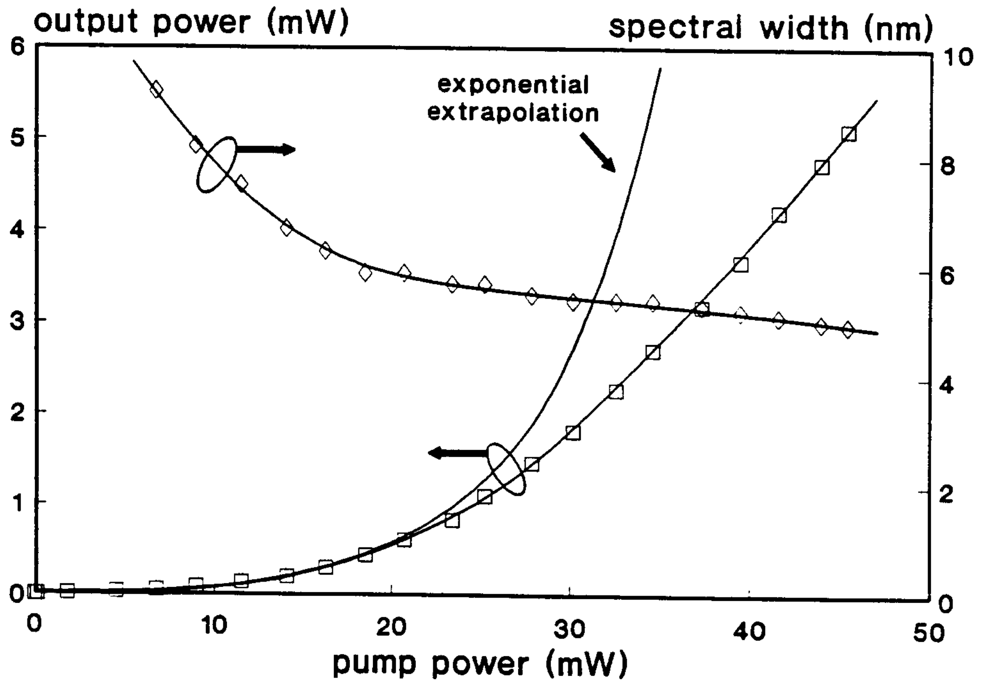
FIBRE SUPERFLUORESCENT SOURCES

Morkel et al, IEEE Photonic Tech Lett., 4(7), p.706, 1992

Superfluorescent source characteristics



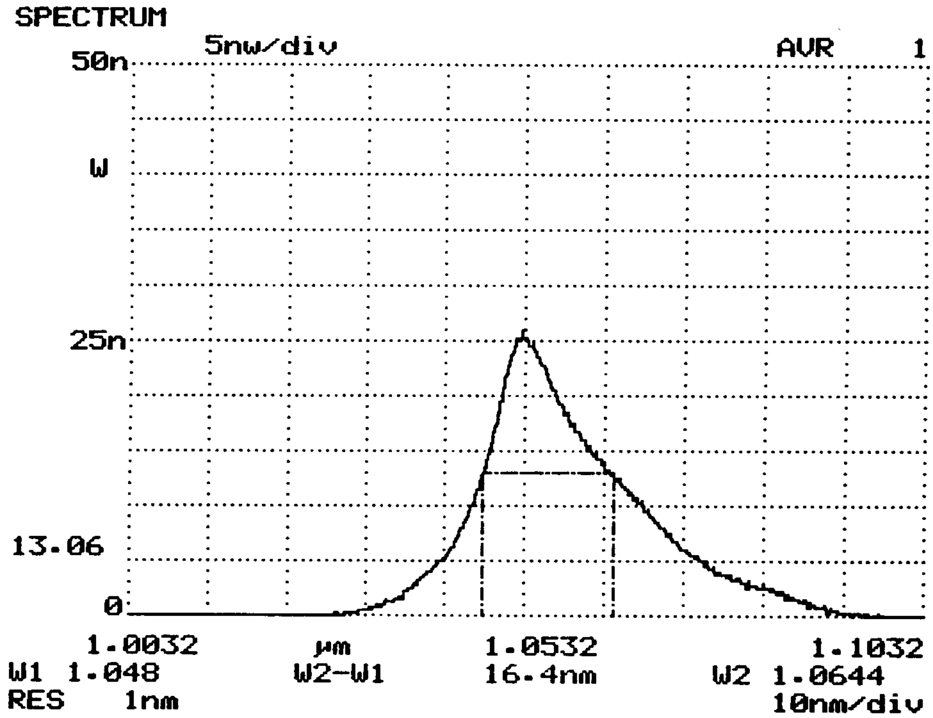
Nd-doped fibre superfluorescent source configuration



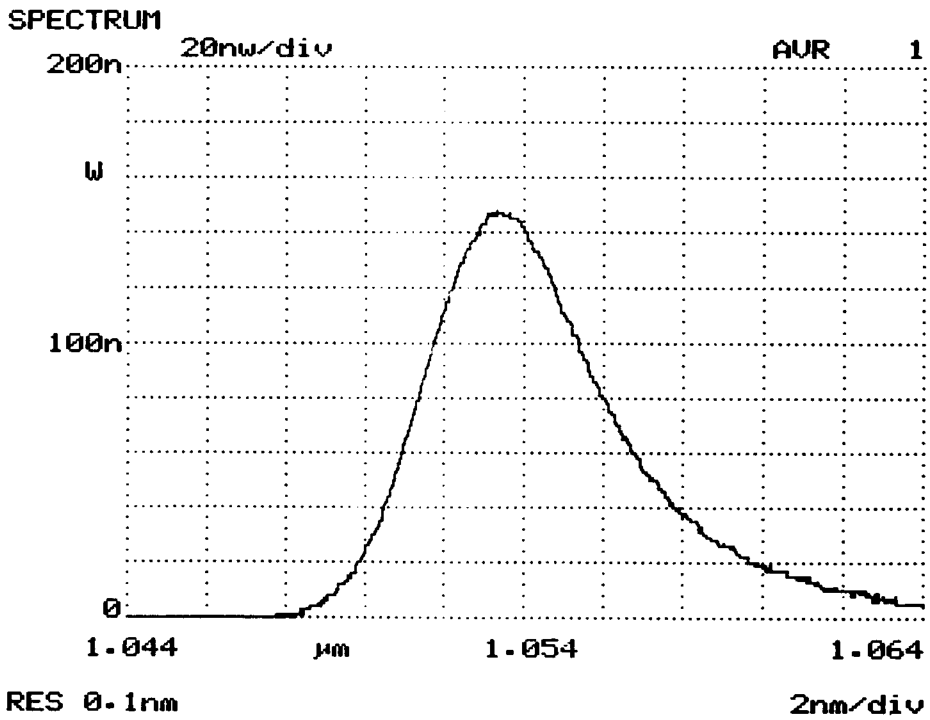
Nd-doped fibre superfluorescent source output characteristic

FIBRE SUPERFLUORESCENT SOURCES

Nd-doped fibre superfluorescent source spectral characteristics



Fibre emission spectrum (fluorescent)



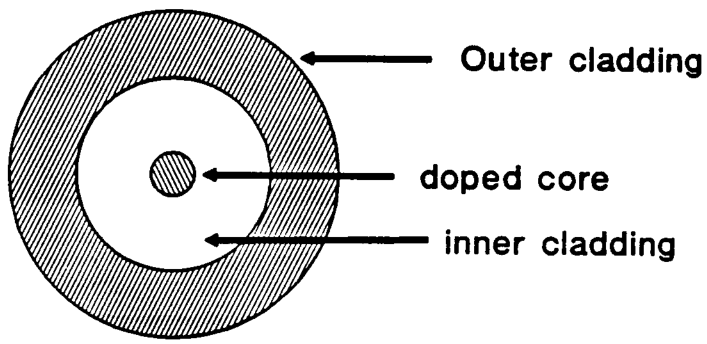
Fibre superfluorescent spectrum (5mW output power)

DOUBLE CLAD FIBRE LASERS

"Cladding pumping" with multi-stripe laser diodes

- Quasi longitudinal pumping.

General fibre cross section-section



Attractions:

- Allows higher power laser diodes to be used for high output power
- Simplified pump coupling (direct butting to LD)

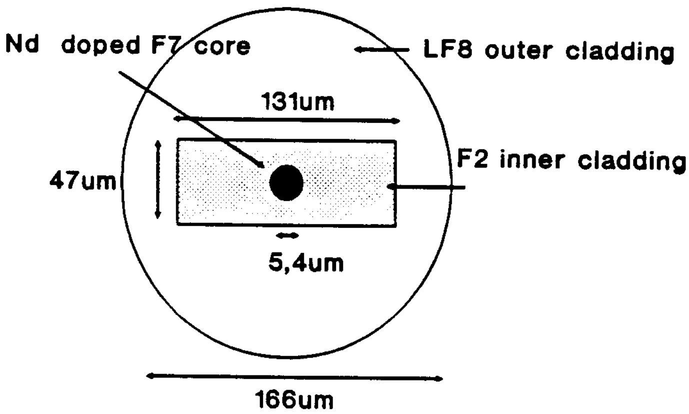
Problems:

- Difficult fibres to make
- Higher background loss fibres
- Fibres not completely compatible with standard telecoms fibres
- Limited application for 3-level systems

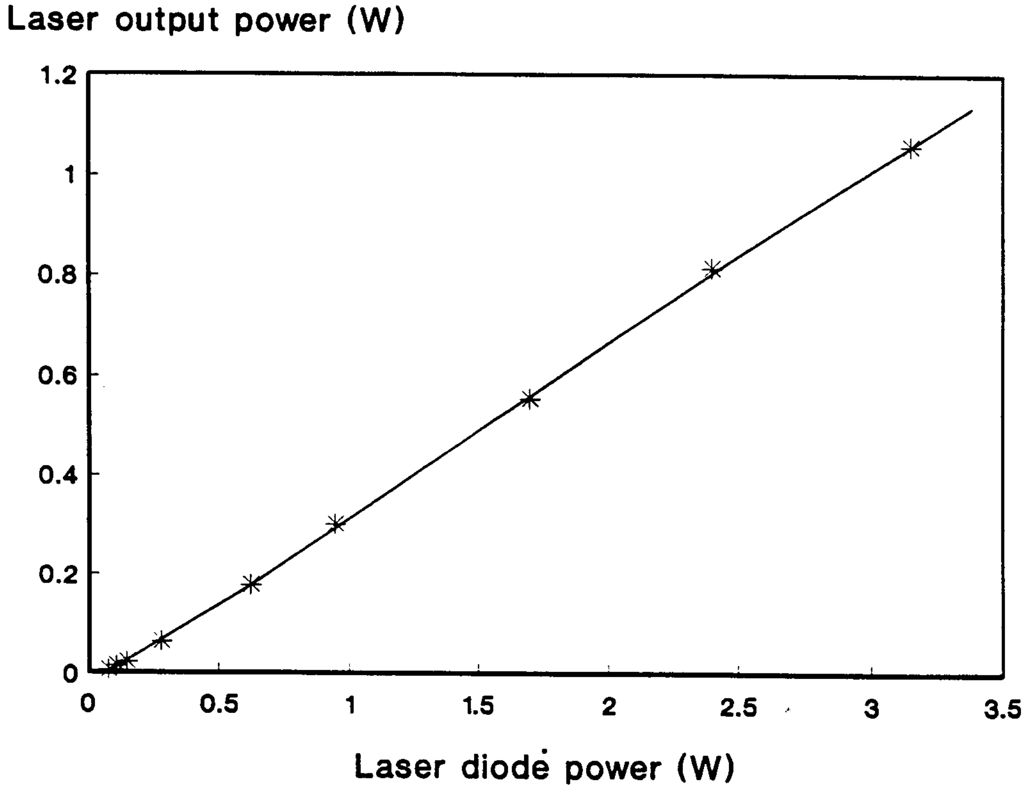
DOUBLE CLAD FIBRE LASERS

Neodymium-doped lead-silicate, multi-clad fibre laser

Minelly et al, paper CWE6, Proc. CLEO '92, Anaheim, Ca.



Fibre construction



Fibre laser output characteristic

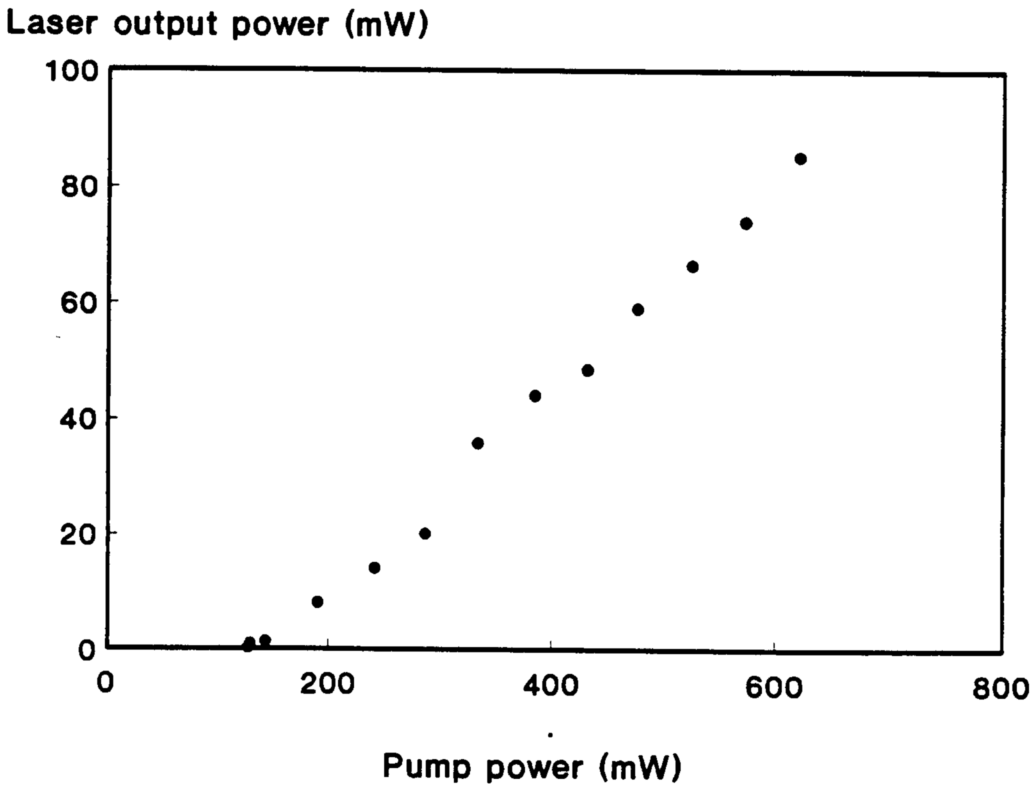
DOUBLE CLAD FIBRE LASERS

Erbium/Ytterbium double-clad-silica fibre laser

- Pump at 962 nm with multistripe laser diode

- Pump absorption in Yb with resonant energy transfer to Er. Lasing at 1.54μm due to gain in erbium.

- Silica core and inner cladding. Polymer outer cladding

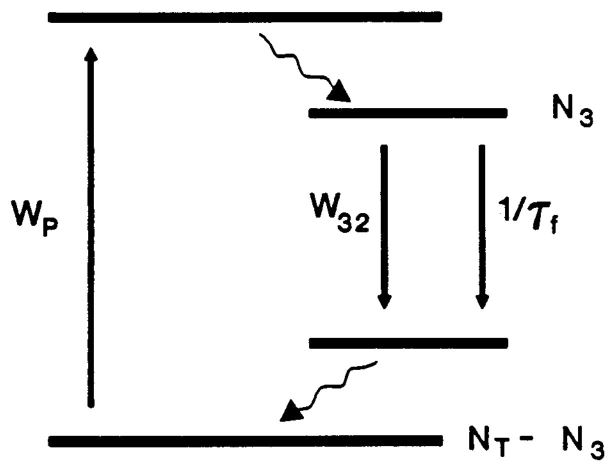


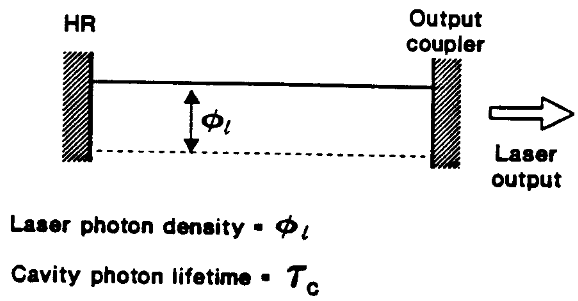
Er/Yb doped fibre laser characteristic

FIBRE LASER THEORY

Fibre laser output can be described by rate-equations for **population inversion** and laser **photon density**

4-level laser (e.g. Nd-doped)





For fast non-radiative decay rates (relative to fluorescent lifetime):

$$\frac{dN_3}{dt} = \frac{I_p \sigma_p}{h\nu_p}(N_T - N_3) - \frac{N_3}{\tau_f} - c\phi_l \sigma_{32} N_3$$

$$\frac{d\phi_l}{dt} = c\phi_l \sigma_{32} N_3 - \frac{\phi_l}{\tau_c} + S$$

laser output:

$$P_{out} = \phi_l h\nu_l c A$$

where:

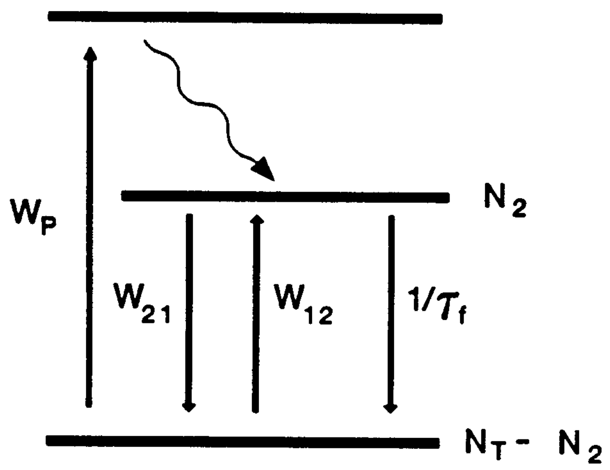
I_p, σ_p, $h\nu_p$ = pump intensity, absorption cross section & photon energy

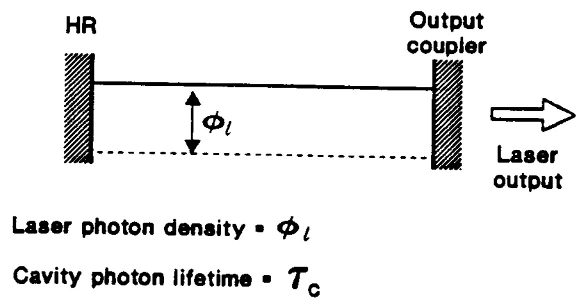
σ_{32} = emission cross section, τ_f = fluorescent lifetime, A = core area

S = spontaneous emission component, $h\nu_l$ = laser photon energy

FIBRE LASER THEORY

3-level laser (e.g. Er-doped)





$$\frac{dN_2}{dt} = W_p(N_T - N_2) - \frac{N_2}{\tau_f} - c\phi_l[N_2(\sigma_{21}+\sigma_{12}) - \sigma_{12}N_T]$$

$$\frac{d\phi_l}{dt} = c\phi_l[N_2(\sigma_{21}+\sigma_{12}) - \sigma_{12}N_T] - \frac{\phi_l}{\tau_c} + S$$

laser output:

$$P_{out} = \phi_l h\nu_l cA$$

where:

I_p, σ_p, $h\nu_p$ = pump intensity, absorption cross section & photon energy

σ_{21} = emission cross section, σ_{12} = absorption cross section

τ_f = fluorescent lifetime, A = core area, $h\nu_l$ = laser photon energy

S = spontaneous emission component

FIBRE LASER THEORY

Laser input/output characteristic

Solution of 3-level rate equations in equilibrium gives a general laser characteristic for low loss cavities (applicable for 3 & 4-level lasers):

$$P_l^{out} = \frac{T}{T+L} h\nu_l \frac{1}{1+\alpha} A \left(\frac{(1+\alpha)\eta P_p}{h\nu_p A} - \frac{(L+T)+2\alpha\sigma_{21}N_T l}{2\tau_f\sigma_{12}} \right)$$

where: $\alpha = \sigma_{12}/\sigma_{21}$ = 0 for 4-level system, 1 for 3-level

T = laser output mirror transmission

L = other optical losses in the cavity

A = fibre core area, l = fibre length

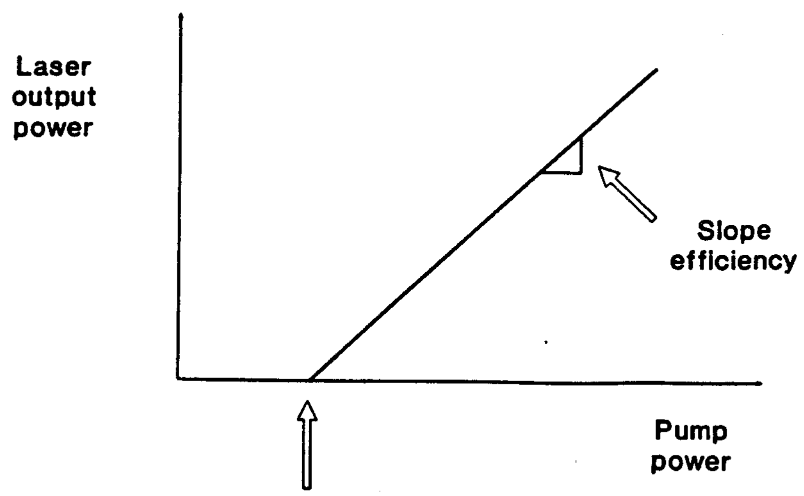
N_T = dopant concentration, η = pump quantum efficiency

Laser threshold power:

$$P_p^{th} = h\nu_p A \frac{((L+T) + 2\alpha\sigma_{21}N_T l)}{2(1+\alpha)\eta\tau_f\sigma_{21}}$$

laser slope efficiency:

$$S = \eta\frac{\nu_l}{\nu_p}\frac{T}{T+L}$$



FIBRE LASERS

Summary (1)

Research and development of fibre lasers has seen a resurgence in activity over the past 7 years due primarily to:

- Availability of high brightness laser-diode pump sources
- Development of high NA low-loss doped silica fibres.

Main features of doped fibres which make them attactive as gain media:

- Small active volume give high gain
  - Low threshold lasers
  - Efficient Q-switched lasers
  - Superfluorescent sources
  - Up-conversion lasers
  - Wide tuning range lasers
  - Simple cavity constructions

- Broad emission and absorption lineshapes
  - Low sensitivity to pump wavelength
  - Wide tuning ranges
  - Short pulse mode-locking
  - Low-coherence fluorescent and superfluorescent sources

FIBRE LASERS

Summary (2)

- Preform engineerring allows high power multistripe laser diode pumps to be used.

- Output characteristics well described by rate-equation theory

- Applications in:

  - optical sensors (gyros, temperature sensors)
  - Fibre diagnostics (OTDR)
  - Environmental sensing (eg. gas sensors)
  - Communications (single-frequency sources, soliton sources)
  - Spectroscopy (mode-locked sources)

  etc. etc.