INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040-224572 TELEFAX 040-224575 TELEX 460449 APH I

H4.SMR/544 - 10

Winter College on Ultrafast Phenomena

18 February - 8 March 1991

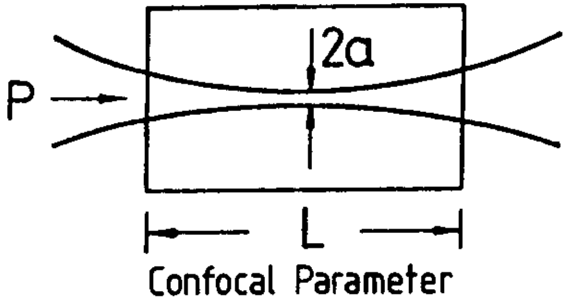
Application of Short Pulses to Non Linear Optics in Fibres

J.R. Taylor
Imperial College of Science & Technology
London, U.K.

MAIN BUILDING STRADA COSTIERA, 11 TEL. 22401 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449

APPLICATION OF SHORT PULSES TO NON LINEAR OPTICS IN FIBRES

IMAGINE A PUMP BEAM OF POWER **P** FOCUSSED TO A BEAM WAIST OF **2a** OVER A DISTANCE **L**



$L = 2\pi a^2 / \lambda$

THEREFORE $IL = (P/\pi a^2)\,(2\pi a^2/\lambda)$

$= 2P/\lambda$

IMAGINE THE SAME POWER FOCUSSED INTO A **FIBRE OF CORE DIAMETER 2a**

The confinement length is determined by

(1) The actual fibre length

(2) By a walk off length where dispersive effects contribute

(3) The absorption length

If we assume (3) $\mathbf{L = 1/\alpha}$

where α is the absorption coefficient
HENCE

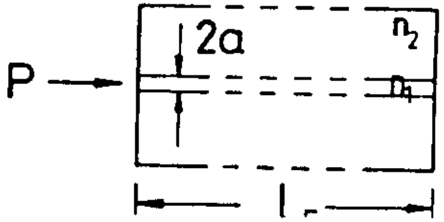
$$IL = (P/\pi a^2)(1/\alpha)$$

THEREFORE THE ENHANCEMENT IS

$$(P/\pi a^2)(1/\alpha)\,/(2P/\lambda)$$

Typically **a** has dimensions comparable to the wavelength and α has a value of around 1dB/km (ie after 10km, 90% is absorbed)

$$\text{ENHANCEMENT} = 1/a\alpha$$
$$= 10\text{km} / 1\mu\text{m}$$
$$= 10^{10}$$



ONE IMPORTANT NON-LINEAR EFFFECT IN OPTICAL FIBRES FOR THE

GENERATION OF NEW FREQUENCIES
GENERATION OF SHORT PULSES

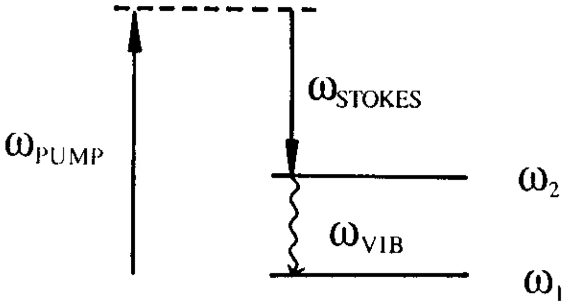
STIMULATED RAMAN EFFECT

FIRST OBSERVED

Stolen et al App.Phys.Lett. 20, 62 (1972)

RAMAN SCATTERING OCCURS WITH LOW EFFICIENCY BUT IS ALWAYS PRESENT

INELASTIC PROCESS

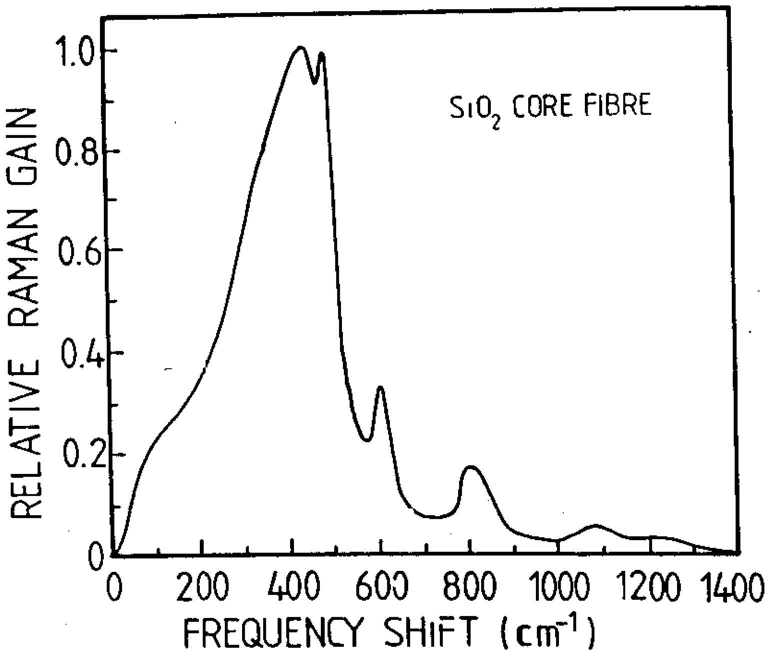


$$\omega_{PUMP} = \omega_{STOKES} + \omega_{VIB}$$

INCIDENT PUMP PHOTON INTERACTS WITH AN INTERNAL VIBRATION OF THE GLASSY MATERIAL OF THE FIBRE

IN GLASS (AMORPHOUS MATERIAL), LACK OF LONG RANGE ORDER RELAXES MOMENTUM CONSERVATION RULES, SO THAT ALL PHONONS INTERACT WITH THE INCIDENT LIGHT giving a

BROAD BAND SPECTRUM



For **INTENSE PUMP FIELDS, STIMULATED RAMAN SCATTERING** can take place

Woodbury Proc IRE 50, 2347 (1962)

RAMAN THRESHOLD

G.P. Agrawal "Non linear Fiber Optics"
Academic Press (1989)

Defined as the input power at which the Stokes and Pump powers are equal at the output

$$P_0 = 16\ A_{eff} / g\ L_{eff}$$

Assuming polarization is preserved
If unpolarized, g is effectively reduced by a factor of 2

EXAMPLE

Assume

$\alpha = 0.2$ dB/km
$g = 1\ X10^{-13}$ m/W
$A_{eff} = 50\ \mu m^2$
$L_{eff} = 20$ km

$$\mathbf{P_0 = 600mW}$$

The RAMAN GAIN is **INHOMOGENEOUSLY BROADENED**, as VARIOUS PHONON FREQUENCIES are associated with different sites

IN THE SMALL SIGNAL LIMIT, LASER OPERATION AT ONE FREQUENCY WILL NOT SIGNIFICANTLY AFFECT OPERATION AT ANOTHER

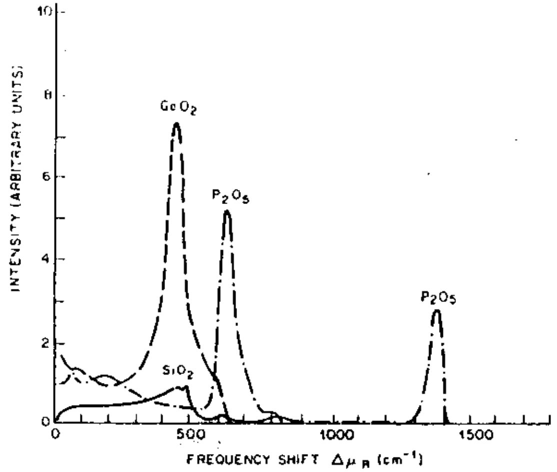
HOWEVER, IF **GAIN SATURATION** OCCURS,
SRS REDUCES THE PUMP
OPERATION AT ONE FREQUENCY AFFECTS ANOTHER

HENCE RAMAN GAIN BEGINS TO BEHAVE AS IF IT WERE **HOMOGENEOUS**

CHOICE OF FIBRE

(1) LOW LOSS

(2) DOPANT



(3) SMALL CORE

Single mode preferable
Constraints on the core size

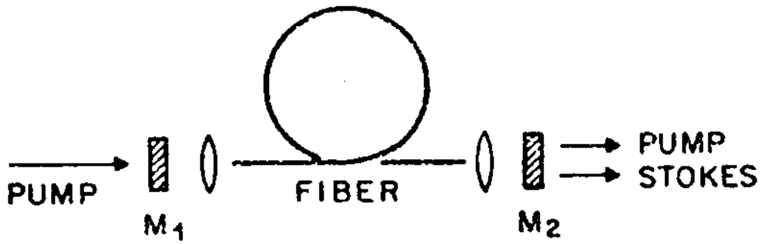
$$V = (n_1{}^2 - n_0{}^2)^{1/2}\, 2\pi a/\lambda$$

With increasing V, the fraction of power in the core is greatest

For single mode $V < 2.405$

Hence for wide spectral coverage fibre must be correctly selected

THRESHOLD IN A CW RAMAN OSCILLATOR



AT THRESHOLD

ROUND TRIP GAIN = LOSS

$$2gP_O(O)L/A=(\textit{loss}\ \ dB/10).\ln(10)$$

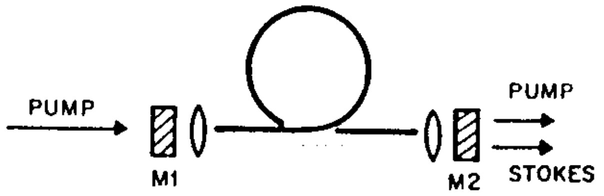
The factor of 2 , due to the addition of forward and backward gain

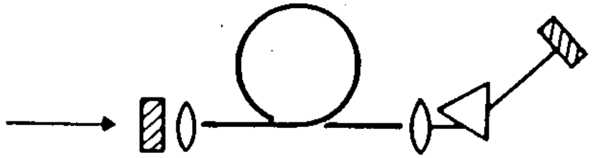
EXAMPLE

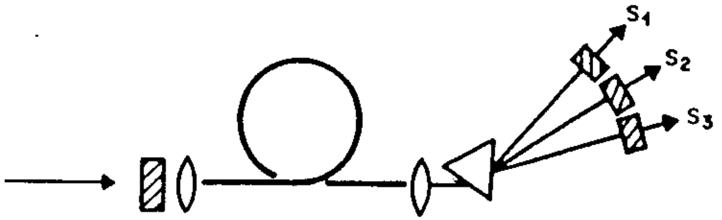
100m polarization preserving fibre
Pumped at 514nm
LOSS 20 dB/km ($\alpha = 4.6x10^{-5}$ cm^{-1})
L_{eff} 80.1 m
GAIN g $1.9X10^{-11}$ cm/W
V = 2.5 at 514 nm A_{eff} = 1.1A
Feedback loss approx 6dB

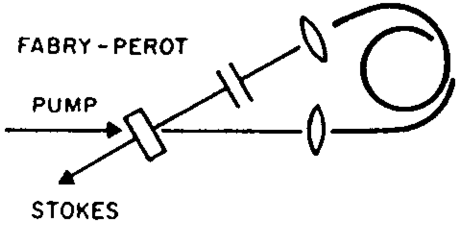
$$P_{TH} = 245\ mW$$

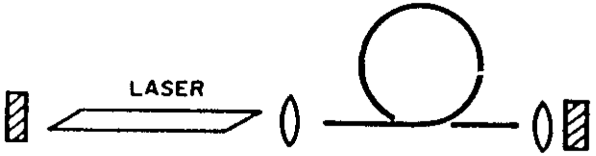
FIBRE LASER GEOMETRIES



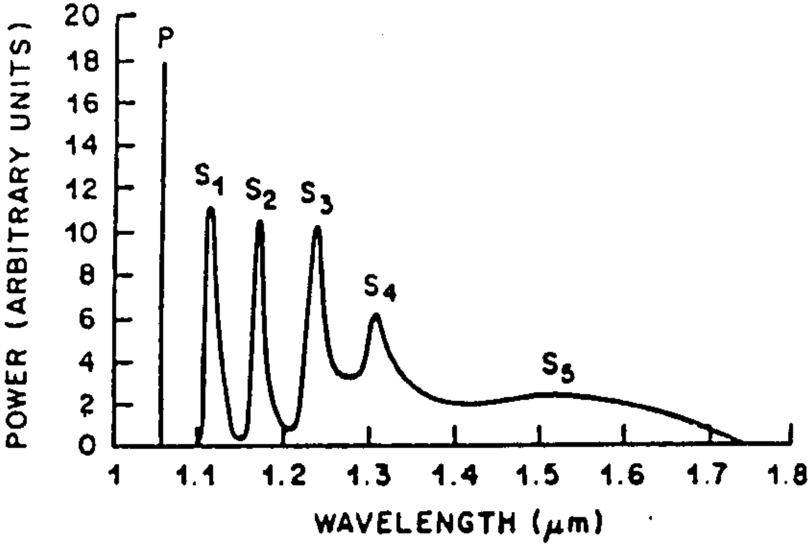








TYPICAL STIMULATED RAMAN SPECTRUM



LARGE SPECTRAL COVERAGE
MODEST POWER REQUIREMENT
EXCELLENT SOURCE FOR PULSES

PROBLEM DISPERSION!

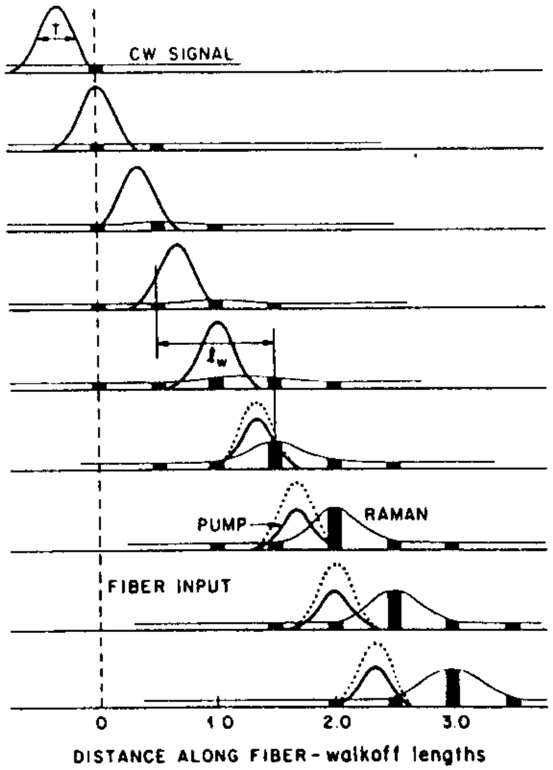
FOR SHORT PULSES< WALK OFF BETWEEN THE PUMP AND THE STOKES SIGNAL RESTRICTS THE EFFECTIVE FIBRE LENGTH

Previously, (CW) LIMIT was ABSORPTION

$$L_{eff} = (1-e^{-\alpha L}) /\alpha$$

Walk-off
Stolen & Johnson IEEE J Q E <u>QE22</u>, 2154 (1986)

WALK OFF LENGTH - Distance at which Stokes signal passes through one pumpwidth



THE WALK OFF LENGTH

$$L_W = [V_S V_P/(V_S - V_P)]T$$

The maximum Raman conversion occurs in approximately 1.5 -2 walk off lengths (depends on pump power)

THE TIME DELAY OF THE STOKES AND PUMP PULSE(Δt) AFTER A FIBRE LENGTH ΔL IS

$$\Delta t = (\Delta L/c)\ D(\lambda)\ (\Delta\upsilon/\upsilon)$$

$\Delta\upsilon$	Frequency separation (440 cm^{-1})
υ	Mean frequency
$D(\lambda)$	Dispersion in dimensionless units $Dc\lambda$

EXAMPLE

1.06 μm pump, Raman 1.12 μm, $\Delta t = 100$ ps

$D = 35$ ps/nm/km $D(\lambda) = 0.014$

$$\mathbf{\Delta L = 56.2\ nm}$$

THE CRITICAL POWER

$$P = 32A/gL$$

$G = 0.92 \times 10^{-11}$ cm/W at 1.06 μm
$L = 110$ m
$A = 38 \times 10^{-12}\ m^2$

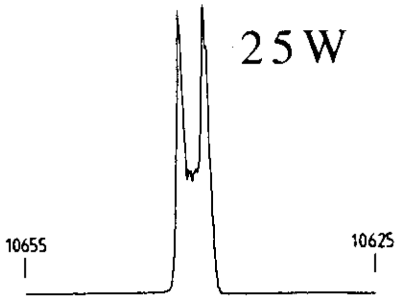
$$P = 120\ W$$

For input 100 psec pulses at a 100 MHz repetition rate this corresponds to an average power of

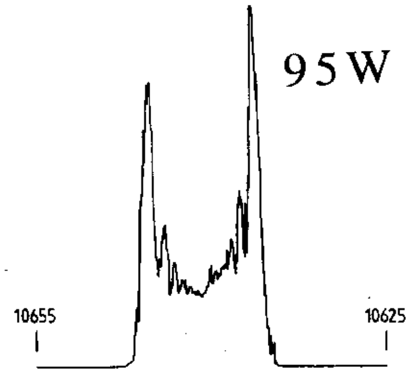
$$P_{av} = 1.2\ W$$

120 m Fibre

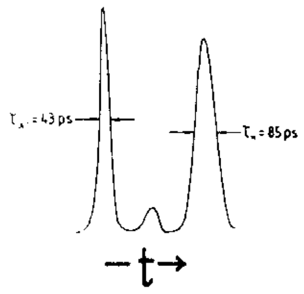
Predicted Raman threshold power 100W

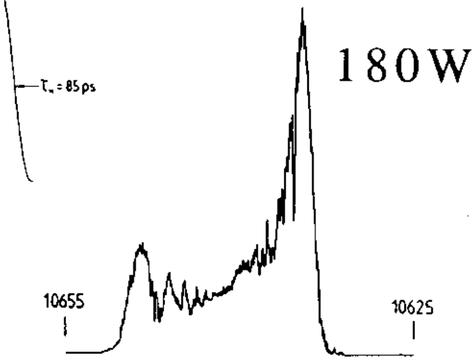


25W



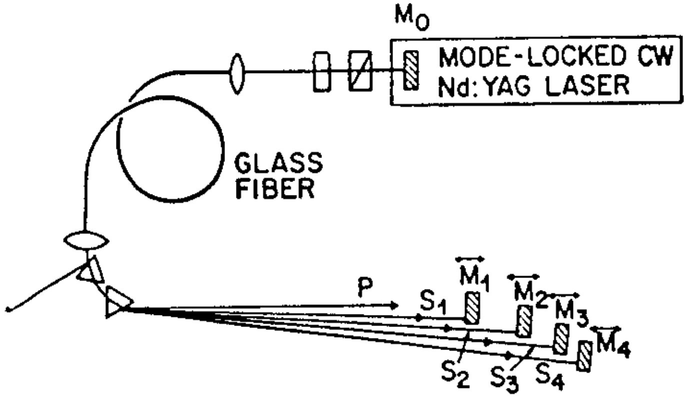
95W

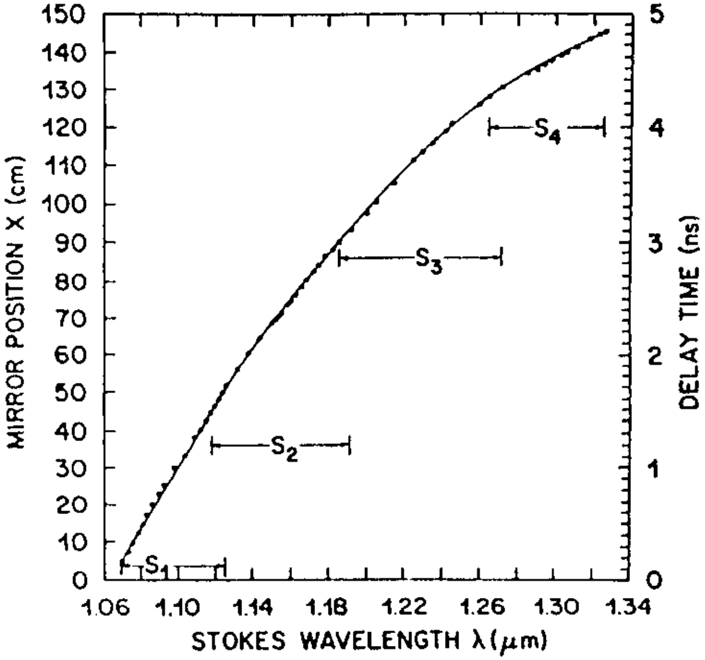




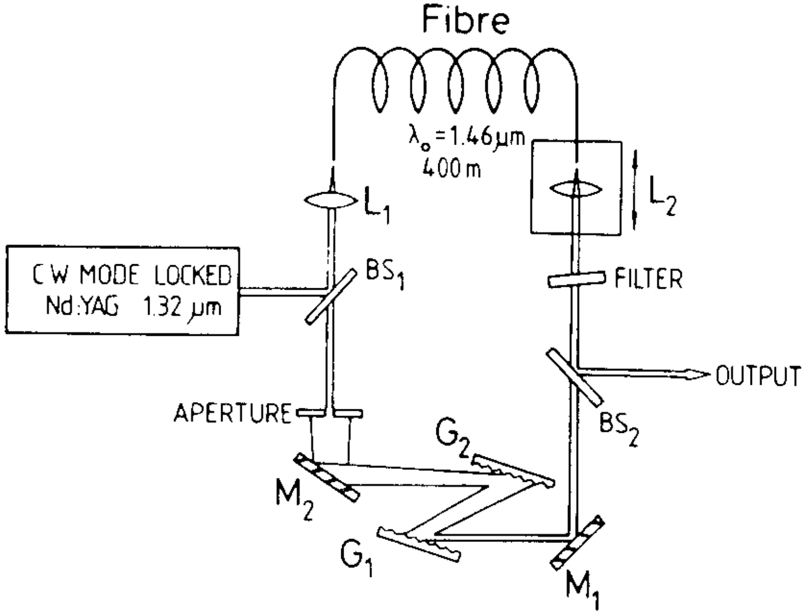
180W

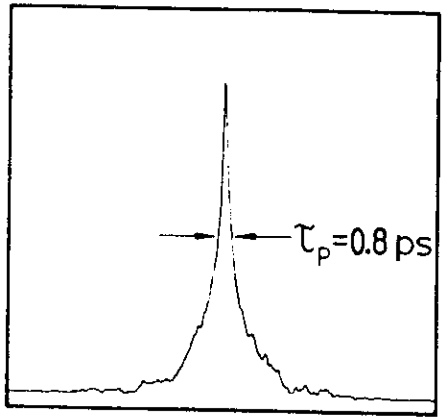
DISPERSION TUNING





DISPERSION CORRECTION



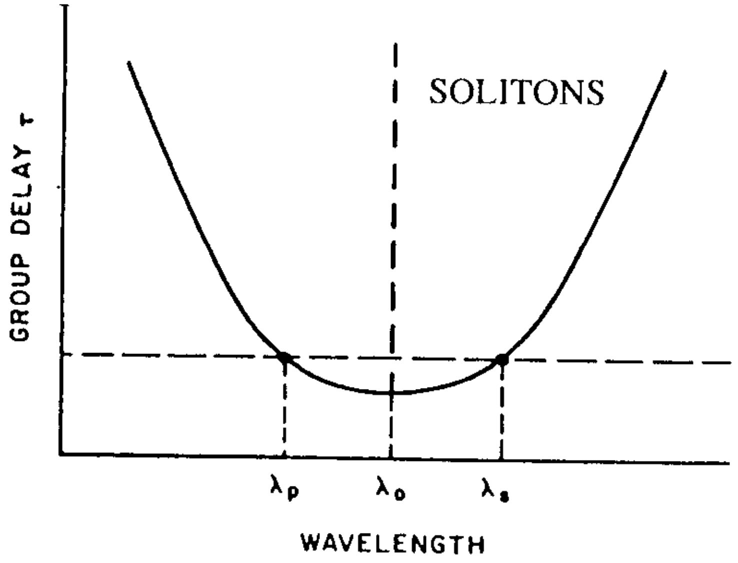


PUMP POWER 1W
OUTPUT POWER 20 mW av
250 W peak

WHY NOT USE SELF DISPERSION CORRECTION

ABOVE ABOUT 1.27 µm SILICA FIBRE IS ANOMALOUSLY DISPERSIVE

SOLITON SHAPING



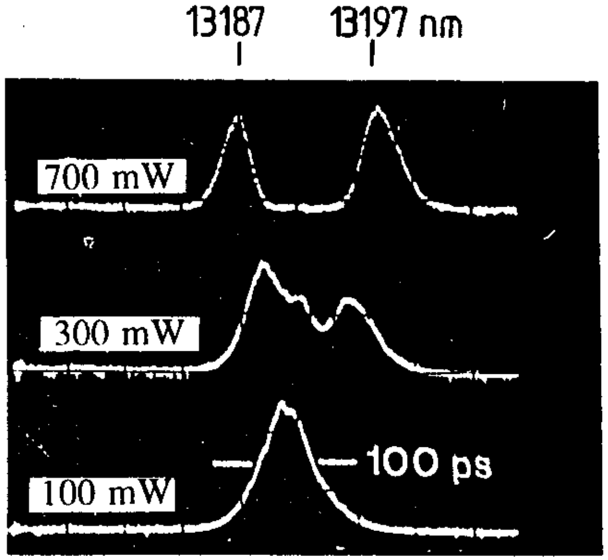
Ingredients :

Raman generation (efficient)
Non linearity (Kerr Effect)
Anomalous dispersion

SIMPLE EXPERIMENTAL SCHEME

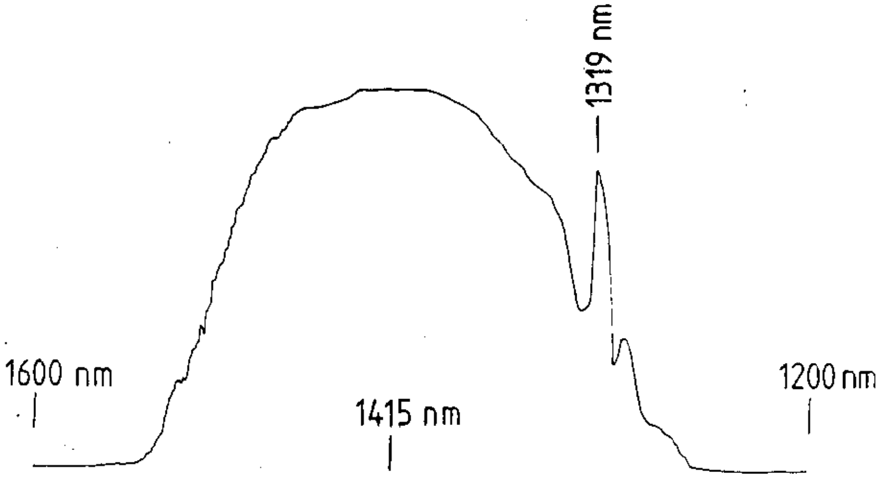
FOCUS LIGHT FROM A MODE LOCKED Nd:YAG LASER (1.32 µm) INTO A SINGLE MODE FIBRE

Standard single mode at 1.32 µm
Core diameter 7 µm
Minimum dispersion λ_0 1.31 – 1.32 µm
Loss < 1dB/km at 1.32 µm
Walk off for 300m = 61 psec
Input pulsewidth 100 psec



200 m FIBRE LENGTH

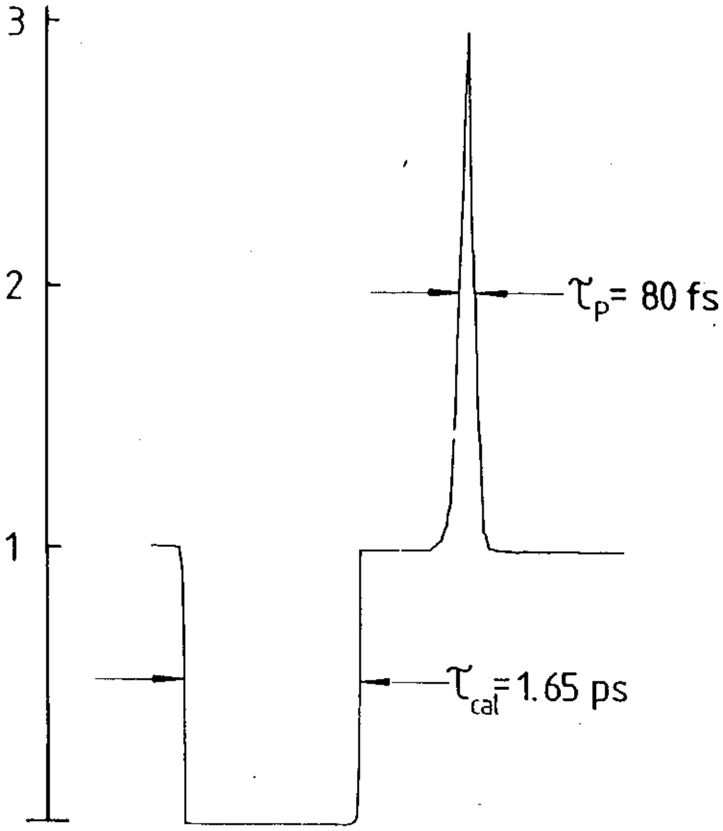
700 mW average power



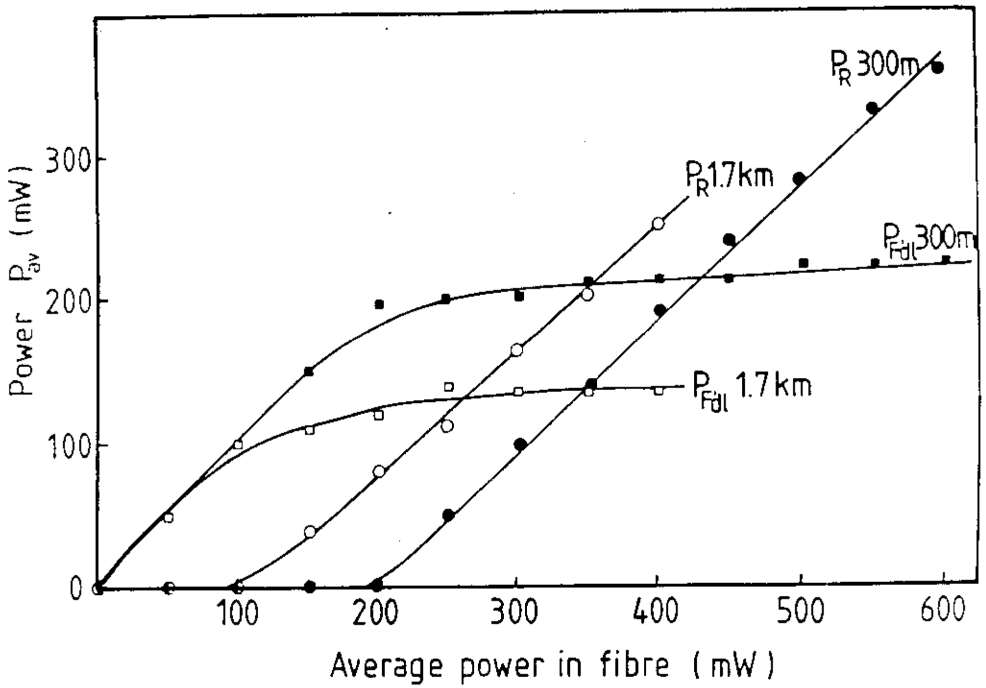
AUTOCORRELATION

140 m FIBRE LENGTH

800 mW average power



HIGH CONVERSION EFFICENCIES
PUMP TO RAMAN BAND

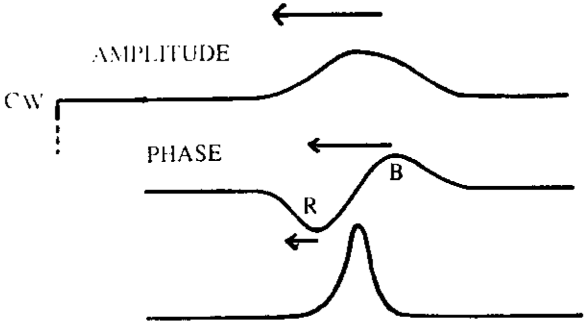


WHEN THE PUMP PULSE IS IN THE REGION OF ANOMALOUS DISPERSION THE EVOLUTION PROCESS CAN PROCEED VIA **MODULATIONAL INSTABILITY**

WHEN LONG INPUT PULSES ARE USED, THE TIME SCALE OF THE GENERATED PULSES IS << THE INPUT PULSE LENGTH

MODULATIONAL INSTABILITY

AMPLITUDE OR PHASE MODULATIONS (WHICH CAN ARISE FROM SPM) SHOW AN EXPONENTIAL GROWTH AS A RESULT OF THE INTERPLAY BETWEEN NON-LINEARITY AND ANOMALOUS DISPERSION

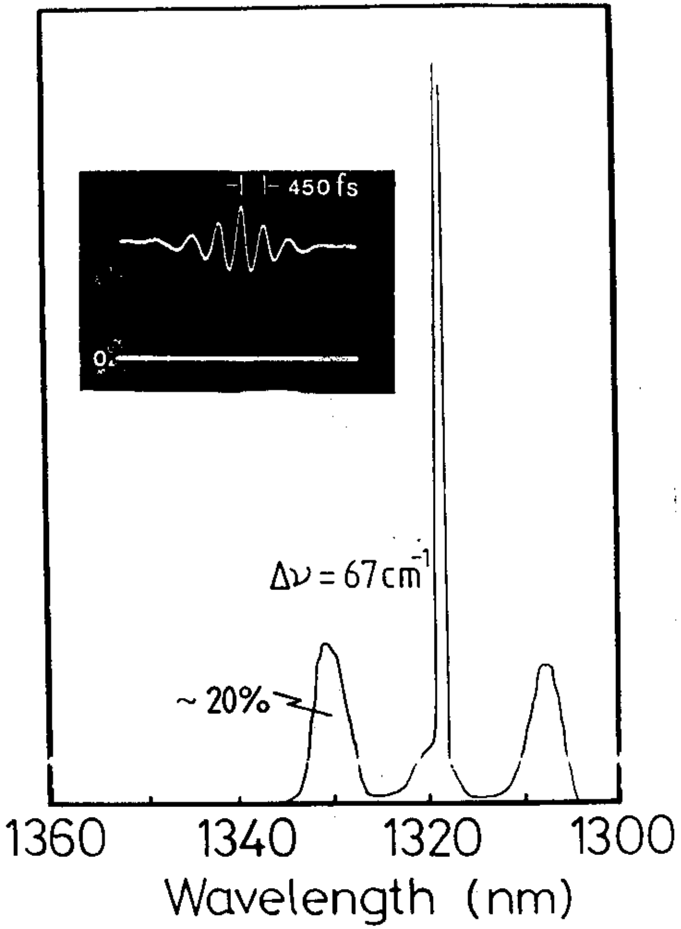


if $\Omega < \Omega_C = [(2\omega/c)(n_2E_0^2/k'')]^{1/2}$

Side bands develop at

$$\Delta\Omega = n\Omega_C / 2^{1/2} \quad n=1,2,$$

AVERAGE POWER = 60 mW 500m FIBRE



FORMATION MECHANISM

Modulational instability breaks up the central region of the pump into solitons

Solitons are amplified on transmission via SRS

Solitons compress due to amplification and experience intra pulse Raman scattering

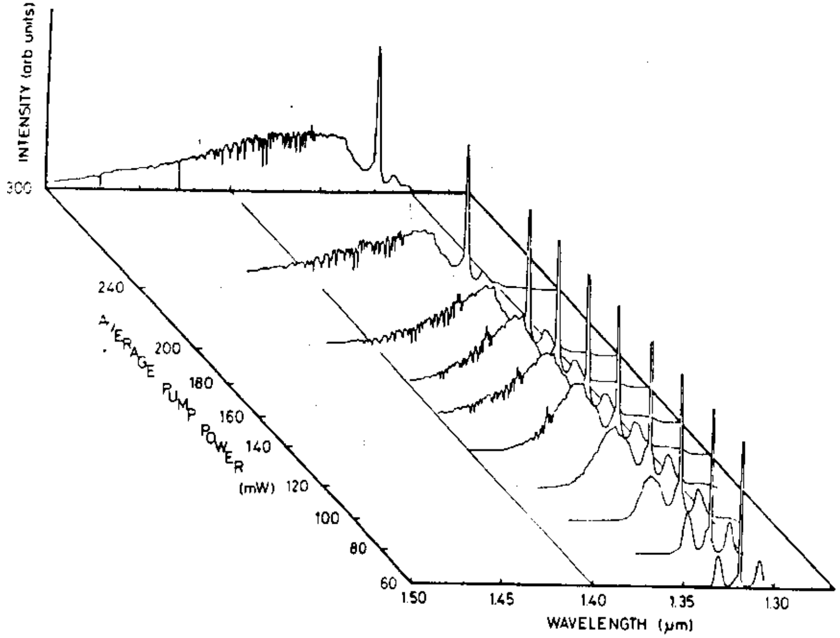
Solitons experience a frequency down shift

Solitons at the pump peak are formed first, since they experience the highest gain, then move to the rear of the pump pulse where they experience soliton collisions

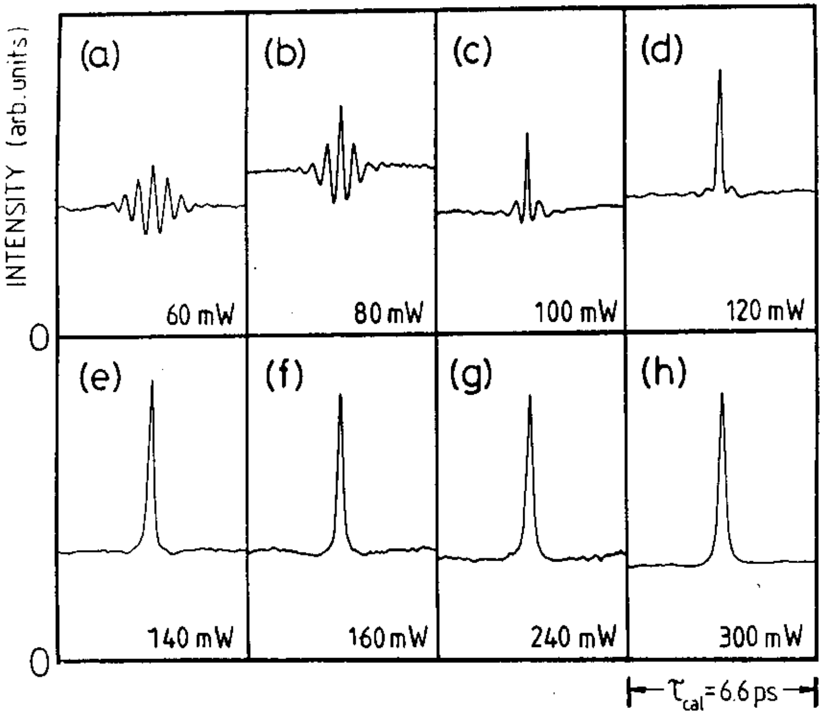
RESULTS IN A SPECTRALLY BROAD ENSEMBLE OF FEMTOSECOND DURATION SOLITONS

SPECTRAL EVOLUTION OF SOLITON RAMAN CONTINUUM

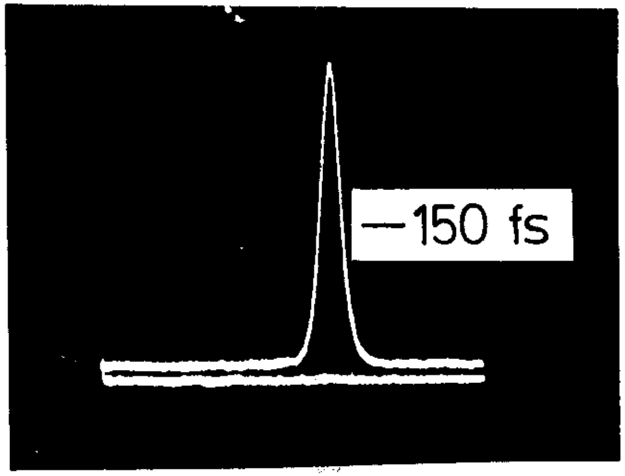
100 psec PUMP PULSE 500 m FIBRE



TEMPORAL EVOLUTION OF RAMAN SOLITONS



AUTOCORRELATION OF SOLITON RAMAN PULSE



OPERATION ON FIRST STOKES BAND

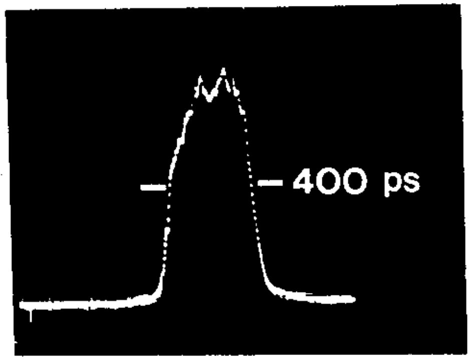
Can either be Raman or Modulational Instability fed

Selectable between 1.34 μm - 1.46 μm

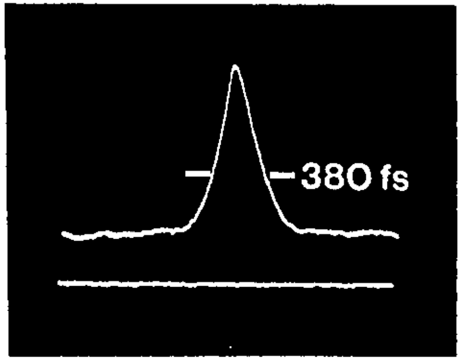
PULSE POWER 1 kW

Good transform limited pump pulses are not required to initiate the process

PUMP PULSE



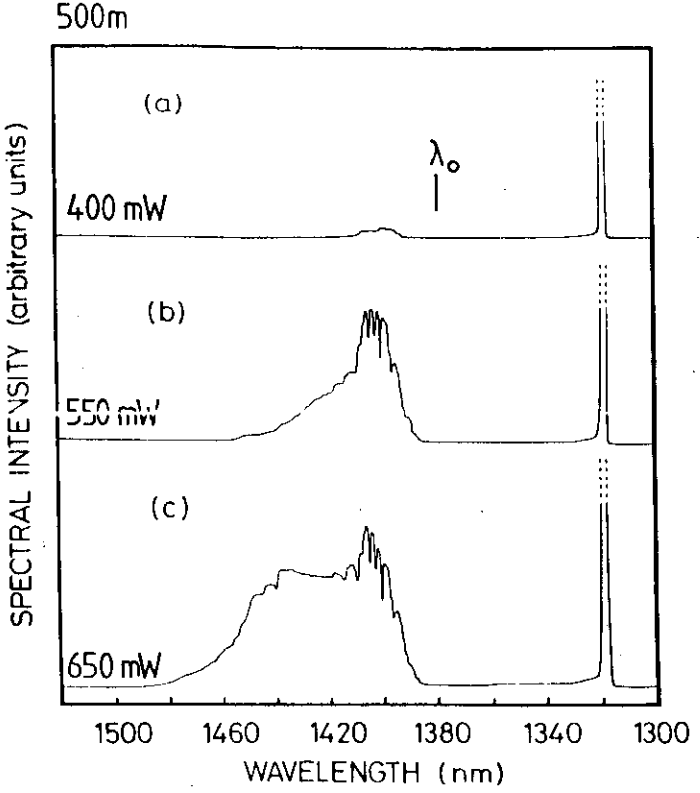
SOLITON RAMAN PULSE



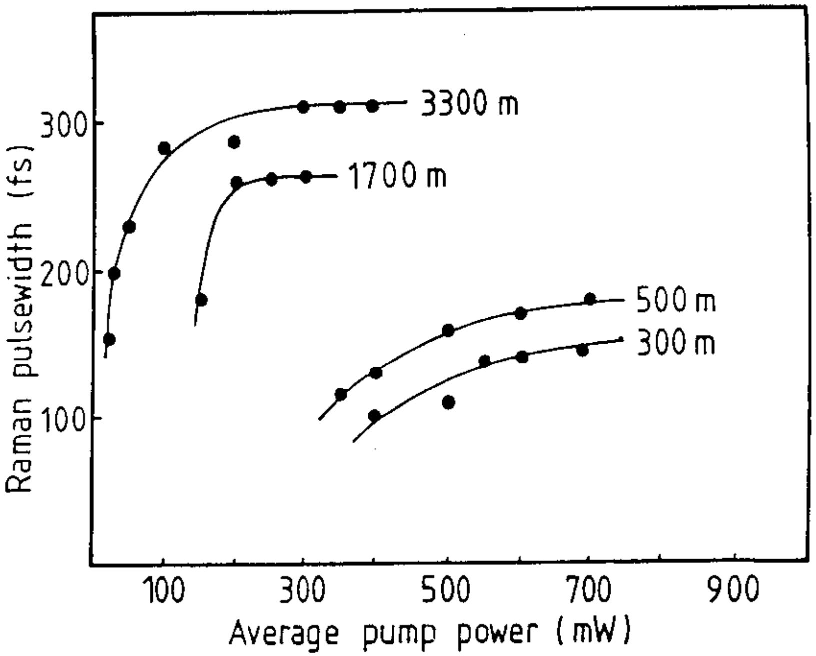
Although **modulational instability** can act as the **precursor** to **SOLITON RAMAN CONTINUUM** generation
Taylor et al Opt.Lett. 12, 1035 (1987)

it is **NOT** a **PREREQUISITE**
However, it does **LOWER** the **THRESHOLD**

Spectral behaviour for pump wavelength in region of normal dispersion
Femtosecond soliton structures are formed



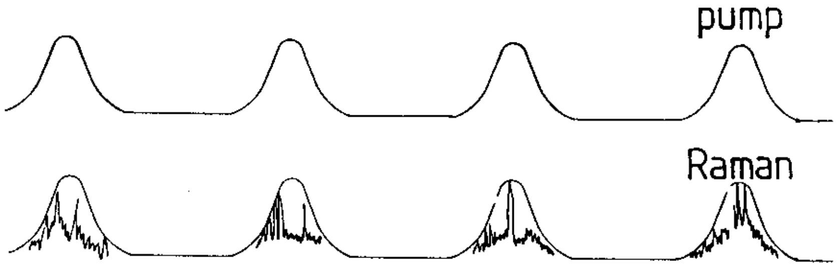
SOLITON RAMAN PULSE WIDTHS ARE PUMP POWER - FIBRE LENGTH DEPENDENT

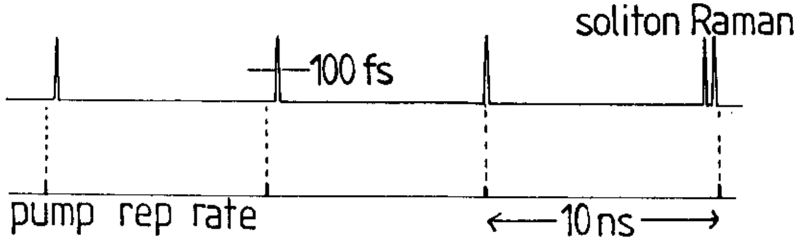


PROBLEM :
SINCE THE SOLITON RAMAN PULSES EVOLVE FROM NOISE, THERE IS NO REAL CONTROL OVER

SPECTRUM
NUMBER OF SOLITONS
JITTER

THE LATER INFERS THAT THEY ARE OF LIMITED USE IN TIME RESOLVED SPECTROSCOPY (PUMP- PROBE OK)



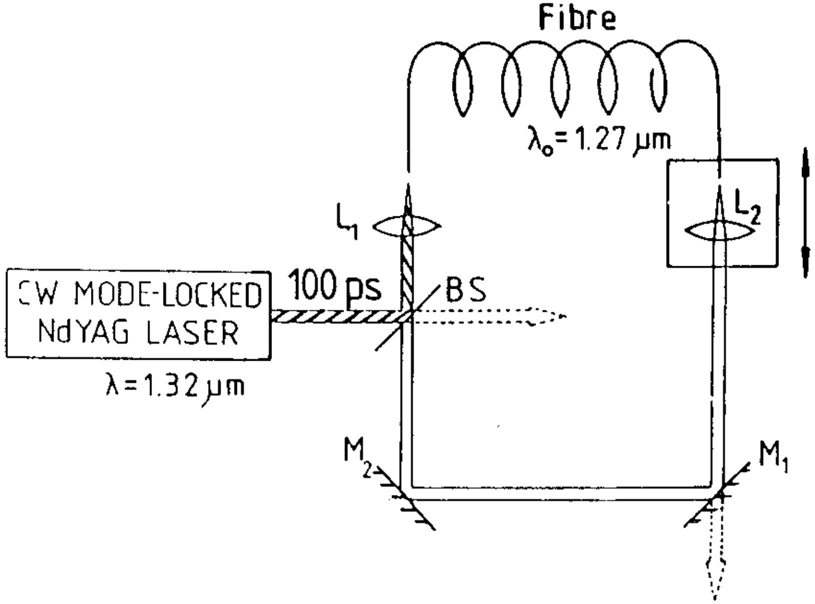


FIBRE RAMAN LASERS

Ippen	App.Phys.Lett.	16, 303 (1970)
Stolen et al	ibid	20, 62 (1972)
Hill et el	ibid	29, 181 (1976)

SOLITON-RAMAN FIBRE LASERS

Kafka et al	Opt. Lett.	12, 181 (1987)
Taylor et al	Elect Let.	23, 537 (1987)

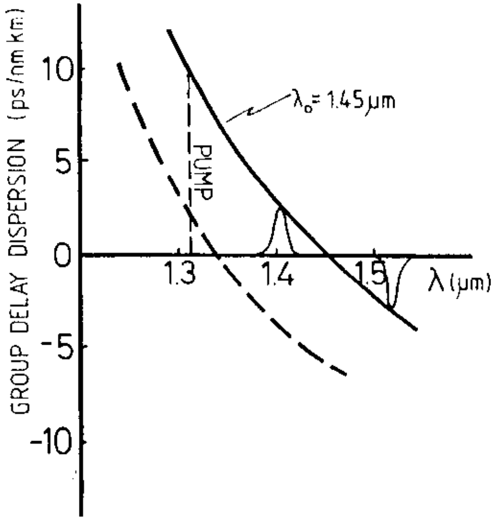


CASCADED OPERATION TENDS TO BE **PRECLUDED**.

THE **SOLITONS** WHICH FORM (in for example the **first Stokes band**) HAVE DURATIONS IN THE **100 fsec** REGIME

THE **INTERACTION LENGTH** (1st STOKES to 2nd STOKES) **IS SMALL**, HENCE **CONVERSION EFFICIENCY** EXTREMELY **LOW**

OPERATION ON HIGHER ORDER STOKES BANDS CAN BE ACHIEVED BY **USING DISPERSION SHIFTED** (λ_0LONGER)**FIBRE**



ALLOWS FEMTOSECOND SOLITON RAMAN GENERATION UP TO 1.8 μm

CHARACTERISTIC SOLITON POWER

$$\mathbf{P_1 = 0.0064.\ D.\ \lambda^3.\ d^2 / \tau^2}$$

where

D(ps/nm/km)	group delay dispersion
λ(µm)	wavelength
d(µm)	effective core diameter
τ(psec)	pulse duration

EXAMPLE

D = 5 ps/nm/km $\qquad$ λ = 1.32 µm

τ = 1 psec $\qquad$ d = 9 µm

SOLITON POWER = 5.96 W

A FIBRE GRATING COMPRESSED Nd:YAG OPERATING AT 1.32 µm CAN READILY GIVE PEAK POWERS OF 3kW (see lecture notes by Dr. A. M. JOHNSON)

THE POWER REQUIRED TO GENERATE A SOLITON OF ORDER **N** IS GIVEN BY

$$\mathbf{P_N = N^2\ P_1}$$

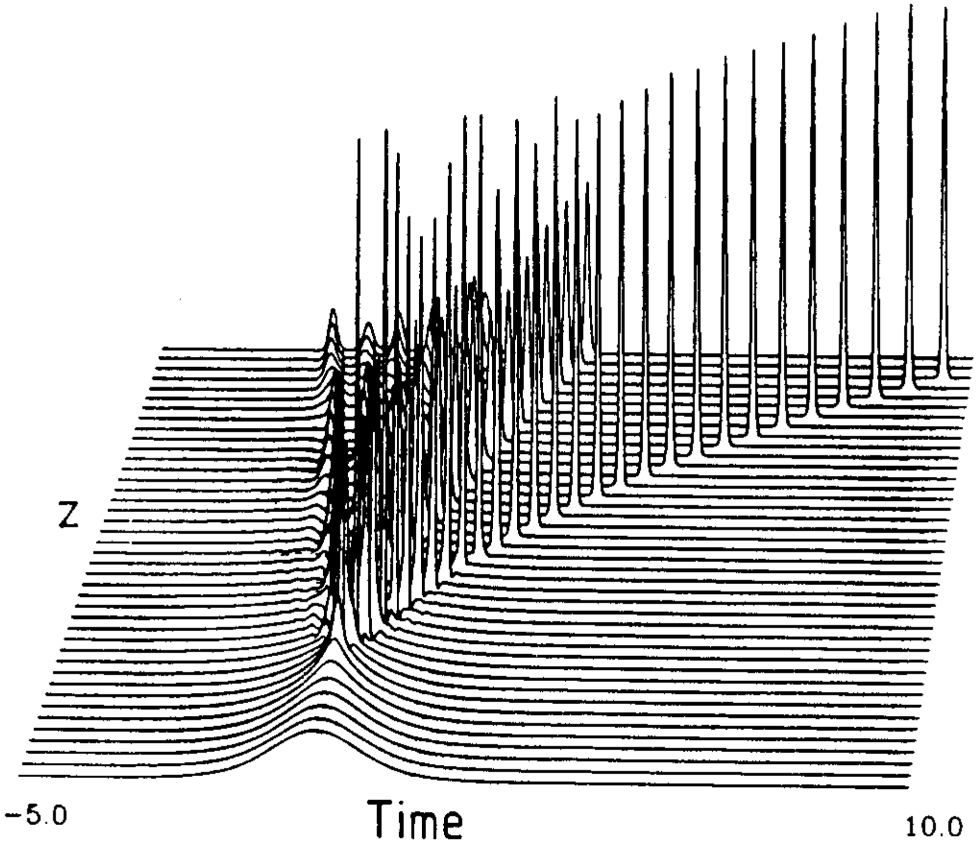
HIGH ORDER SOLITONS ARE UNSTABLE AND TEND TO BREAK UP INTO SOLITONS WITH REDUCED PULSE DURATIONS

TO A GOOD APPROXIMATION THE COMPRESSION FACTOR IS GIVEN BY

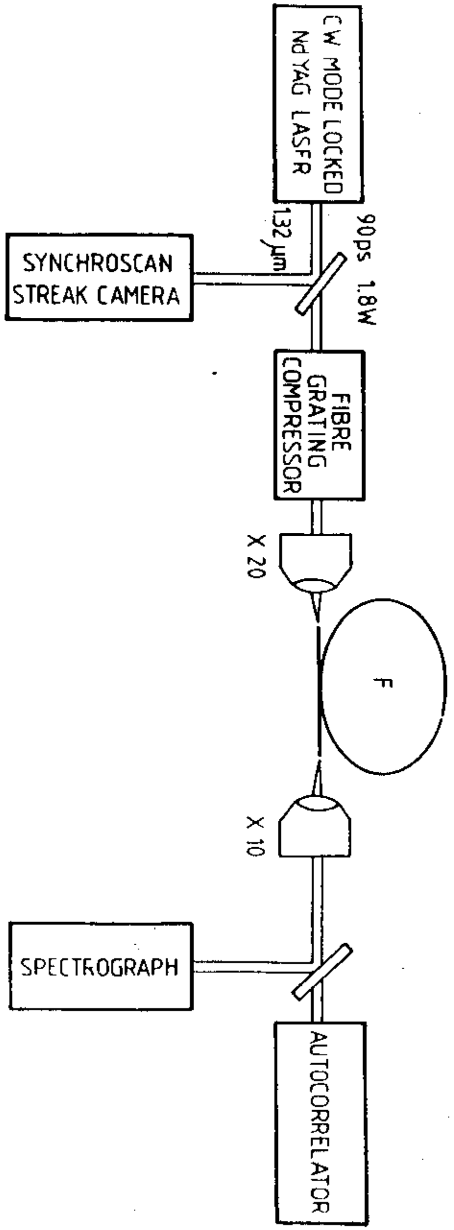
$$4.1\ N$$

A N=15 SOLITON SHOULD COMPRESS APPROXIMATELY BY A FACTOR OF 61

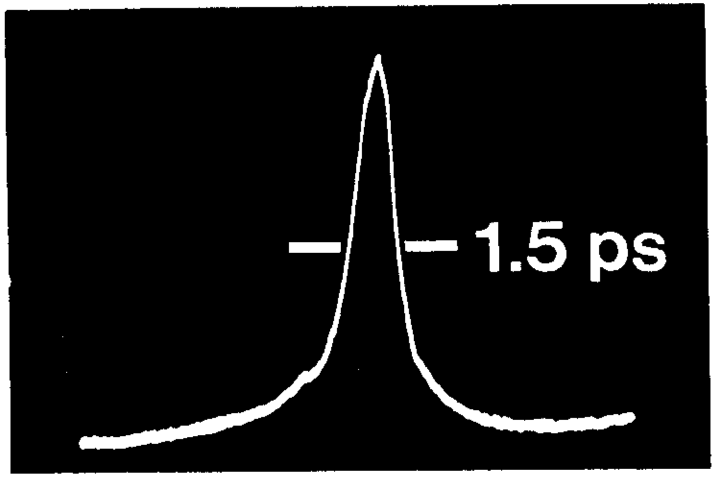
THEORETICAL PREDICTION OF THE BREAK UP OF A N= 15 SOLITON



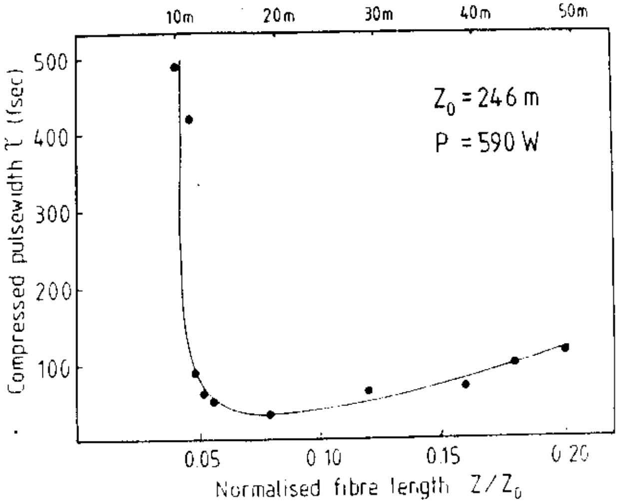
EXPERIMENTAL SCHEME



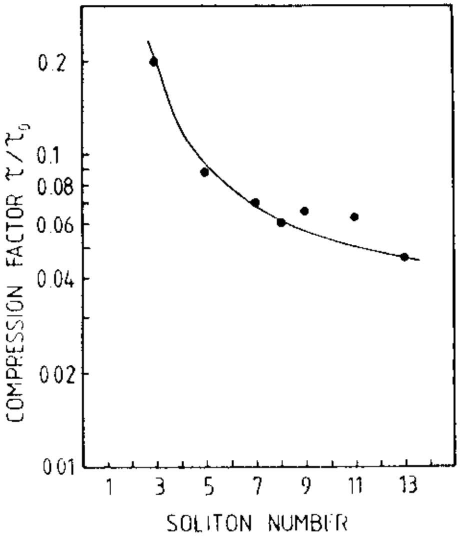
INPUT SOLITON PULSE OF ORDER N = 15



PULSE REACHES ITS MINIMUM DURATION AFTER AN OPTIMUM DISTANCE

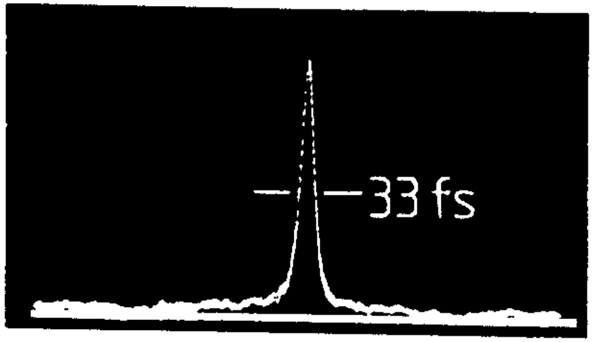


MEASURED PULSE COMPRESSION WITH INPUT POWER

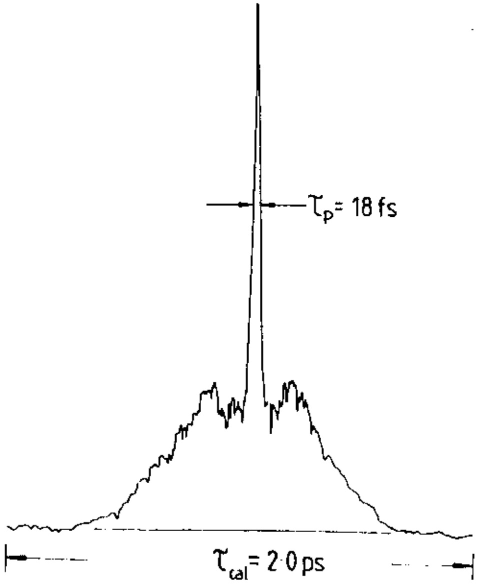


TYPICAL OUTPUT PULSEWIDTHS

N = 11 (Input = 1.5 psec)



N = 15 (Input = 1.1 psec)



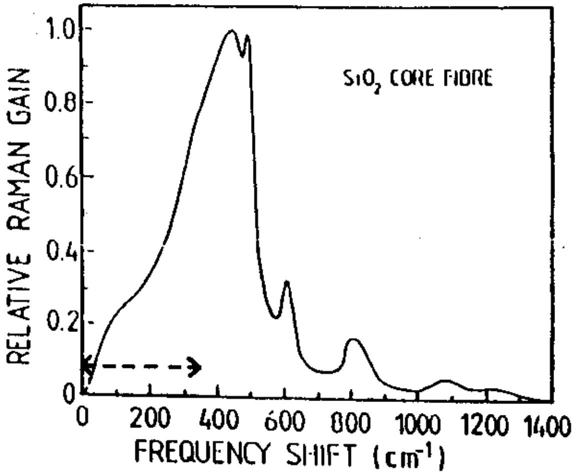
INTRA PULSE RAMAN CONVERSION

Stimulated Raman Conversion of Multisoliton Pulses
Dianov et al JETP Lett 42, 87 (1985)

Discovery of the **Soliton Self Frequency Shift**
Mollenauer et al Opt.Lett. 12, 659 (1986)

A SHORT PULSE HAS A BROAD BANDWIDTH

EXAMPLE
30 fsec at **1.32 μm** REQUIRES **60.9 nm**
349 cm^{-1}

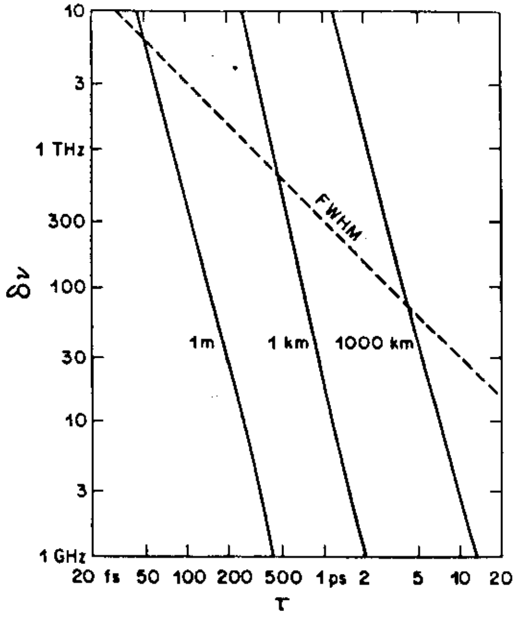


FOR SUCH WIDE BANDWIDTH PULSES THE **HIGH FREQUENCY COMPONENTS** CAN PROVIDE **RAMAN GAIN** FOR THE **LOW FREQUENCY COMPONENT**

LEADING TO A **CONTINUOUS SHIFT (INCREASE)** IN THE **CENTRAL WAVELENGTH** AS THE PULSE PROPAGATES DOWN THE FIBRE

THEORETICAL TREATMENT
GORDON Opt.Lett.11, 662 (1986)

FREQUENCY SHIFT $\Delta\upsilon \; \alpha \; \tau^{-4}$

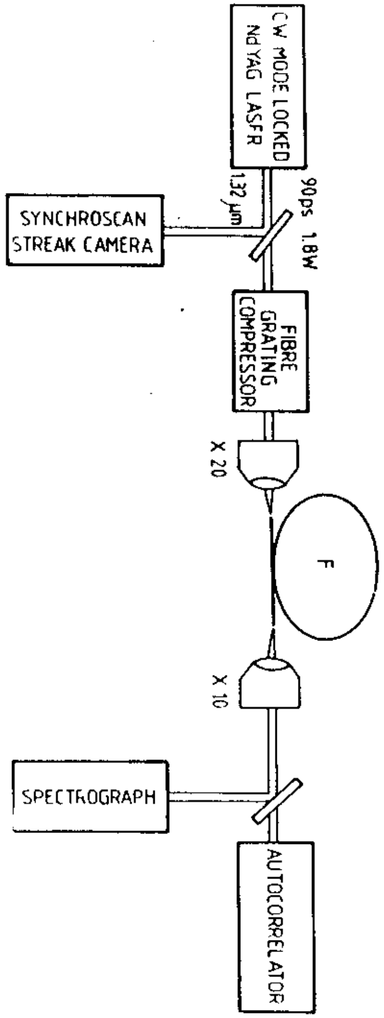


EXAMPLE
In 1 km of fibre a 500 fsec pulse will shift by approximately 10 THZ
i e

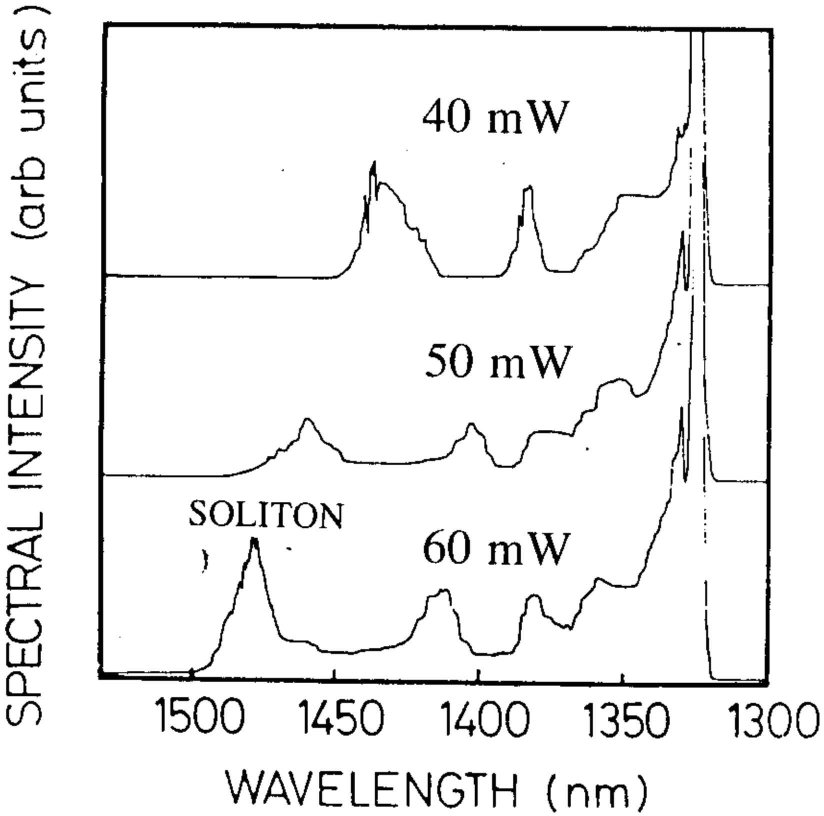
1.32 μm to 1.38 μm

CAN PROVIDE A USEFUL SOURCE OF TUNABLE ULTRASHORT PULSES

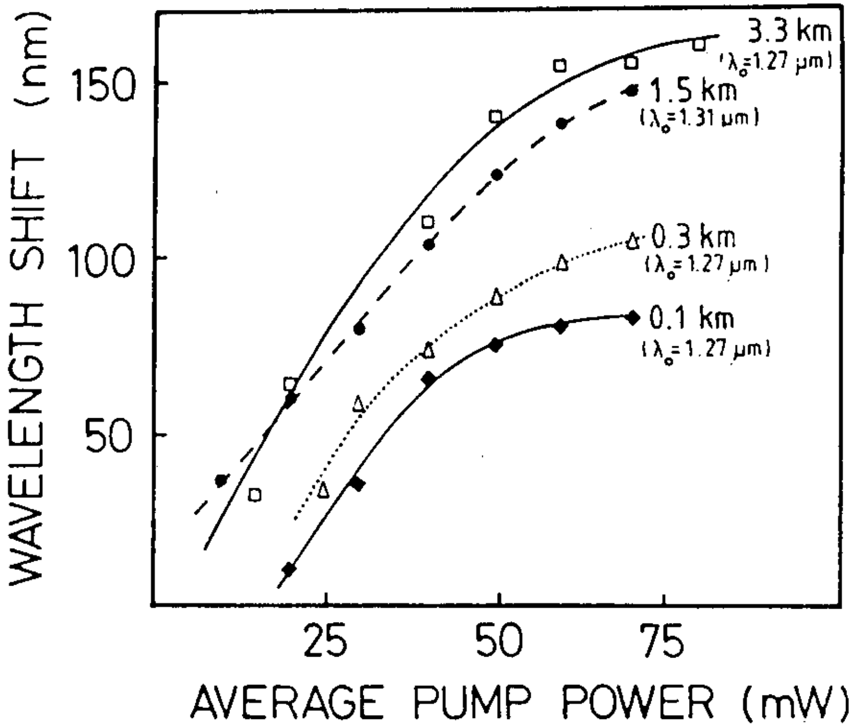
SIMPLE EXPERIMENTAL SCHEME



OUTPUT SPECTRAL VARIATION WITH PUMP POWER



VARIATION OF WAVELENGTH SHIFT WITH AVERAGE PUMP POWER FOR VARIOUS FIBRE LENGTHS



TYPICAL AUTOCORRELATION OF SPECTRALLY SELECTED SOLITON GENERATED USING SELF FREQUENCY SHIFTING TECHNIQUE