3017

Bismuth Oxide Fibers for Nonlinear Applications

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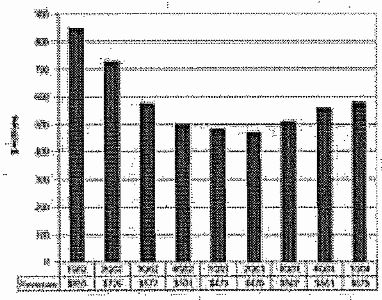
Outline

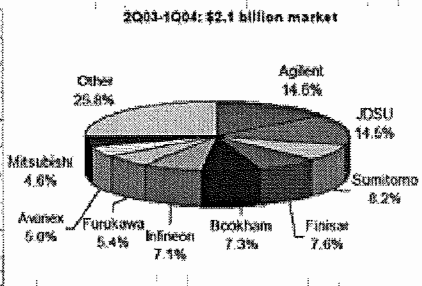
- OC Market
- Introduction – Basics for nonlinear fibers
- Glass materials – Why bismuth-oxide
- SI-Nonlinear fibers
- Holey fibers
- Loss: Figure of merit
- Potential applications

OC Market

In gradual recovery

- Gradual recovery since 3Q03 driven by LAN and Access sectors



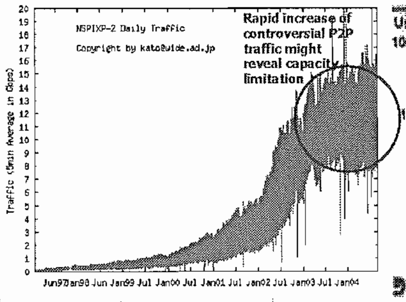


Source: RHK

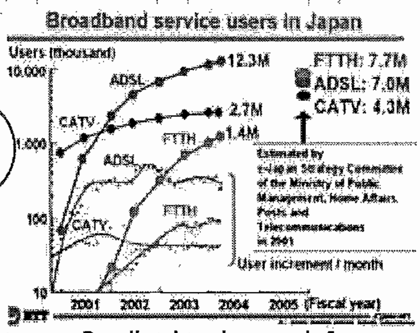
OC Market

Constant traffic growth, the wide spread of BB access

- Traffic is steadily increasing
- Broadband subscribers are increasing (unequally in global geometry)



Traffic trend at NSPIXP (Network Service Provider Internet eXchange Point)
http://nspixp.wide.ad.jp/2/



Broadband service users in Japan

Source: NTT Maeda, ECOC2004

METI: http://www.johotsusintokei.soumu.go.jp/field/

OC Market

Technologies - 10G almost matured, 40G the next

- 40G is going to have the first actual deployment

  Test sites (40G IP transmission): AT&T, Sprint , MCI

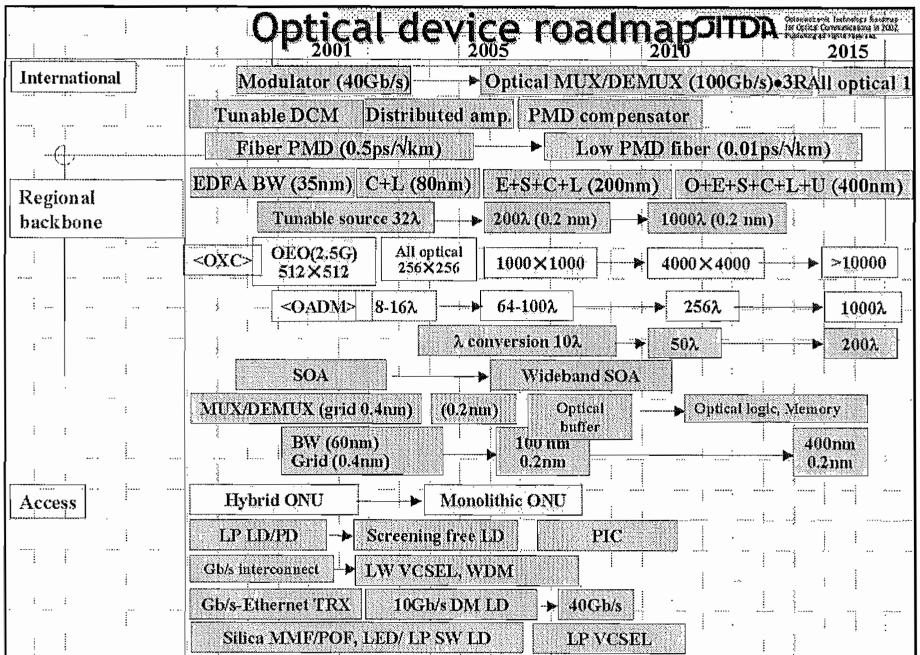
  System venders: Cisco, Lucent, Mintera, StrataLight etc.

Market Segments	2001	2002	2003	2004
Test & Measurement	70%	74%	21%	27%
Communication	20%	9%	27%	38%
Univ. & Labs	10%	17%	52%	35%

The transition of major segments in 40G market

Source: HHI, ECOC2004

Optical device roadmap



Source: OITDA(2002)

Opportunities

Nonlinear devices for the next generation systems

- Gradual market recovery driven by LAN and Access
- Constant traffic increase and BB subscribers increase
- 10G off the shelf and 40G systems looming
- Pushing developments for elemental, device, system technologies towards the next generation systems

The reality of all-optical communication is an only, but difficult-to-answer, question of time - opportunities for nonlinear devices

Introduction

Basics for nonlinear devices

High nonlinearity fiber promises compact devices that can operate at low powers

$$\gamma \propto \frac{n_2}{A_{eff}}$$

large n_2 *and/or* small A_{eff}

Material

n_2(silica) $=2\times10^{-20}$ m^2/W
n_2(Bi-oxide) $=3.2\times10^{-19}$ m^2/W
$n_2(As_{40}S_{60}) = 2\times10^{-18}$ m^2/W

Fiber design

Large NA *and* Small core
Tight mode confinement
HFs allow extremely small A_{eff}
Large Δn SI fibres decrease A_{eff} as well

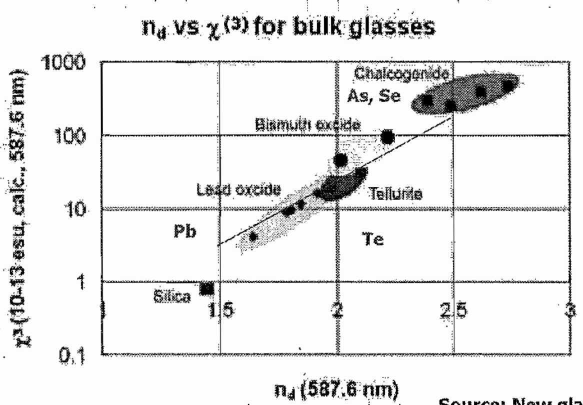
<u>Examples:</u>

$\gamma \approx 1$ $W^{-1}km^{-1}$ SMF28 fiber
$\gamma \approx 20.4$ $W^{-1}km^{-1}$ Silica HNDSF [Onishi et al. Opt Fiber Tech 4]
$\gamma \approx 70$ $W^{-1}km^{-1}$ Small-core Silica HF [Yusoff et al. IEEE PTL 15]
$\gamma \approx 1100$ $W^{-1}km^{-1}$ Bi_2O_3 holey fiber [Ebendroff-Heidepriem et al. Opt. Express]

Why Bismuth-oxide glasses ?

- ◈High nonlinear refractive index (~15 × higher than silica)
- ◈No toxic elements such as Pb, Te, As, Se
- ◈Oxide glass → easy handling
- ◈Good mechanical & thermal stability
- ◈Low-loss proven in SI fibers (0.7 dB/m)
- ◈Can be fusion-spliced to silica fibers
- ◈Fast response among 3rd order NLO materials
- ◈☹Normal material dispersion at 1.55 μm
  - Can be overcome with appropriate fiber design

Comparative refractive indices and $\chi^{(3)}$ of glasses



- $n_2 = 3.95 \times 10^{-6} \chi^{(3)} / n^2$ (m²/W)
- $\chi^{(3)} = [(n^2-1)/4\pi]^4 \times 10^{-10}$ (esu) (analogy with Miller's rule)

shortly,

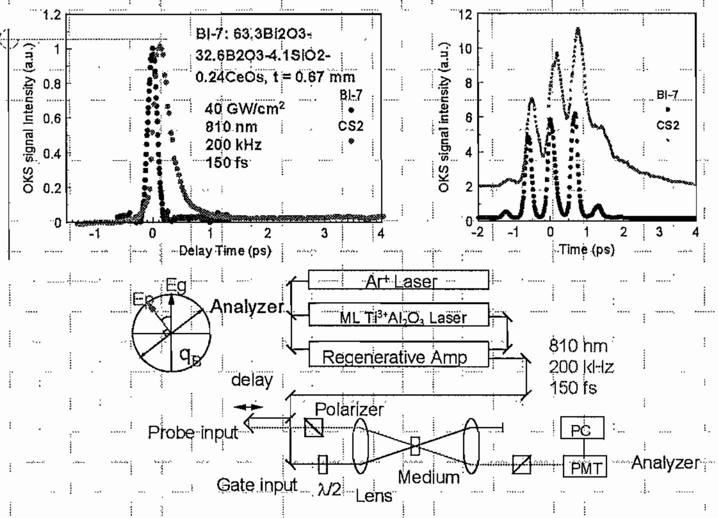
- $\chi^{(3)} \propto n^8$
- $n_2 \propto n^6$

Source: New glass handbook, Maruzen, Asahi

Bismuth oxide has large $\chi^{(3)}$ and is still stable and harmless.

Ultra-fast response

Switching time << 150 fs



Optical Kerr Shutter(OKS) experiment (1999)

R&D strategy

- Step Index fibers - easy handling, small A_{eff}
  - Asahi In-house technology
    - Core/clad glass design – high n_2, large Δn
    - Fiber fabrication
    - Splicing
- Holey fibers – dispersion control, small A_{eff}
  - Project at ORC (Soton)
    - Modeling of mode profile and dispersion
    - Fiber fabrication – extrusion
    - Splicing
    - Device development
- Sample characterization ⇒ Nonlinear applications
  - Rcast
  - ORC (Soton)
  - Others

R&D strategy

◈ Pros / Cons for SI fibers and Holey fibers

	Pros	Cons
SI fibers	◈Simple structure - relatively less heating duration/ processes ◈Matured modeling/ design technique	◈Difficult to control dispersion - large normal dispersion ◈Generally difficult to find a matched glass pair
Holey fibers by extrusion	◈Dispersion controllable for all the wavelength ◈High index contrast - small A_{eff} (A_{eff} depends on the design)	◈Wavelength-scale complex structure, Eg: relatively more heating duration/ processes, risks of glass degradation & structure deformation ◈Splicing technique not established

Step index nonlinear fibers (SI-NLFs)

ASAHI GLASS COMPANY

T. Nagashima, T. Hasegawa, N. Sugimoto
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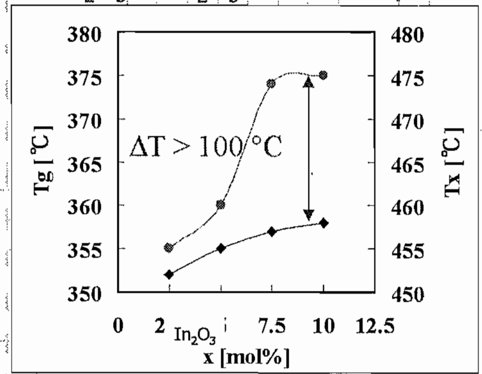
High refractive index glass for large n_2

- ◈The reconciliation of high n and the control of crystallization
- ◈Addition of In_2O_3 to Bi_2O_3-based composition



Both n > 2.2 and ΔT > 100 °C realized

Glass pair for High Δn and small A_{eff}

- ◈Target: Step index structure
  - Single mode
  - $\Delta n = 0.09(2.22-2.13)$ and $A_{eff} = 3.3\ \mu m^2$
- ◈Matched compositions for core and clad glasses
  - Thermal expansion
  - Viscosity
- ◈Orthodox melt, cast and RIT process

SI-NLF achievements

◆1st version – EDF composition

Glass codes for fibers	Refractive indices	n_2 (W^2/m)	A_{eff} (μm^2)	γ ($W^{-1}km^{-1}$)	D_2 (ps/nm/km)
A1310 / A1320	2.03 / 2.02	3.2E-19	20	64	- 126

Kikuchi et al. E Lett 38

◆2nd version – Ultra-high n composition

Glass codes for fibers	Refractive indices	n_2 (W^2/m)	A_{eff} (μm^2)	γ ($W^{-1}km^{-1}$)	D_2 (ps/nm/km)
HNLB160 / B027	2.22 / 2.13	1.1E-18	3.3	1360	- 250

Sugimoto et al. OFC04 PDP26

Comparison of nonlinearity γ

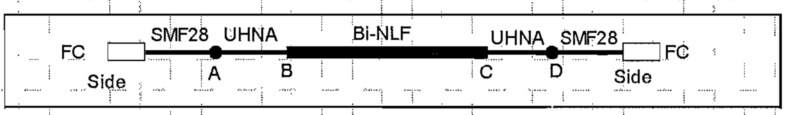
◆Record high γ by step index structure fibre

Fiber	γ ($W^{-1}km^{-1}$)	Papers
Bi-SI-NLF(n=2.22)	1360	Sugimoto et al. OFC04 PDP26
Bi-SI-NLF(n=2.03)	64	Kikuchi et al. E Lett 38
Bi-holey(n=2.03) to be published	1100	Ebendroff-Heidepriem et al. Opt Express
Bi-holey(n=2.02)	460	Ebendroff-Heidepriem et al. OFC04 ThA4
SF57-holey	640	Petropoulos et al. Opt Express 11
Silica-holey	70	Yuzoff et al. IEEE PTL 15
Silica-DSF	20.4	Onishi et al. Opt Fiber Tech 4
Silica-standard	≈ 1	

Comparison of nonlinearity γ

Splicing with conventional fibers

- Conventional fusion splicer and intermediate fiber to be used to alleviate big mode field mismatch



- The loss is ≈ 2 to 4 dB/end now, the improvement is under way

Holey fibers by extrusion

P. Petropoulos, H. Ebendorff-Heidepriem, S. Asimakis, R.C. Moore, K. Frampton, V. Finazzi, F. Koizumi*, T. M. Monro, and D. J. Richardson, UK

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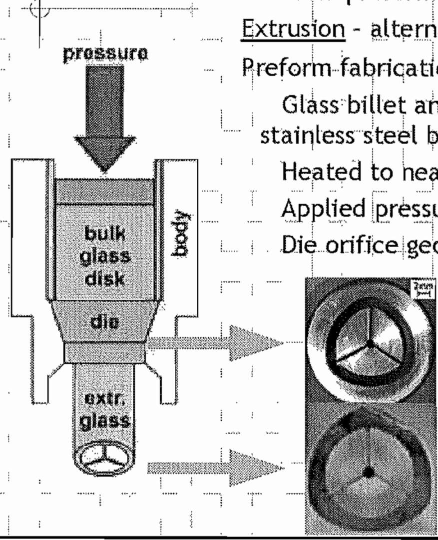
*Asahi Glass Company, Japan

THE ROYAL SOCIETY

Extrusion

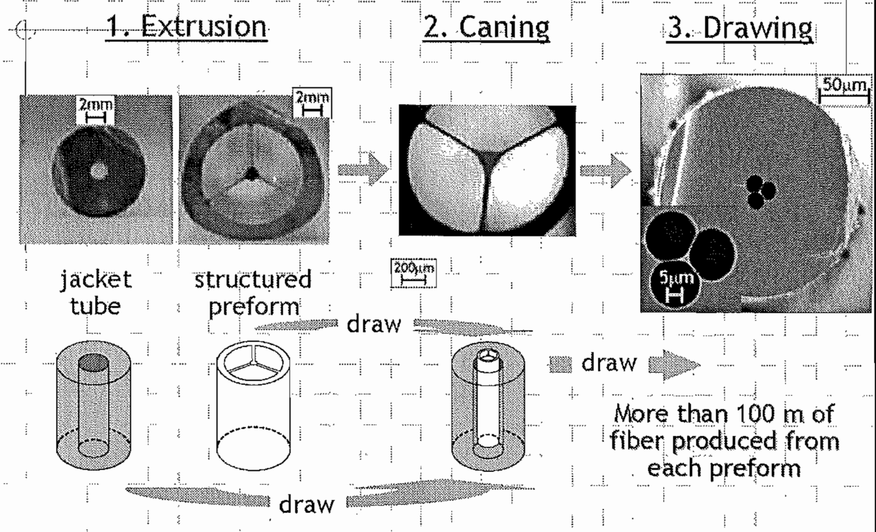
- Silica HF preforms typically made by stacking
- Extrusion - alternative technique for soft glasses
- Preform fabrication procedure:
  - Glass billet and stainless steel die are placed in stainless steel body
  - Heated to near the glass softening temperature
  - Applied pressure forces the glass through the die
  - Die orifice geometry determines preform geometry



Stainless steel die

Structured glass preform

Fiber fabrication

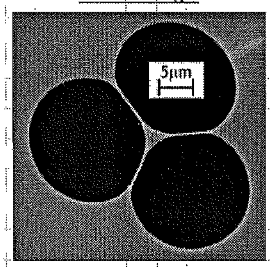


Fiber structure

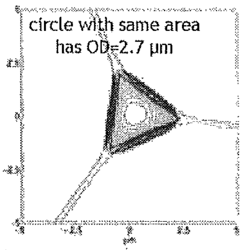
- Core diameter 1.5-2.7 μm
- Core diameter adjusted via appropriate choice of the fiber OD (130-215 μm)

core: 2.7 μm
strut length: ~5 μm
strut thickness: ~250 nm
calc. A_{eff} = 3.1 μm^2

SEM image

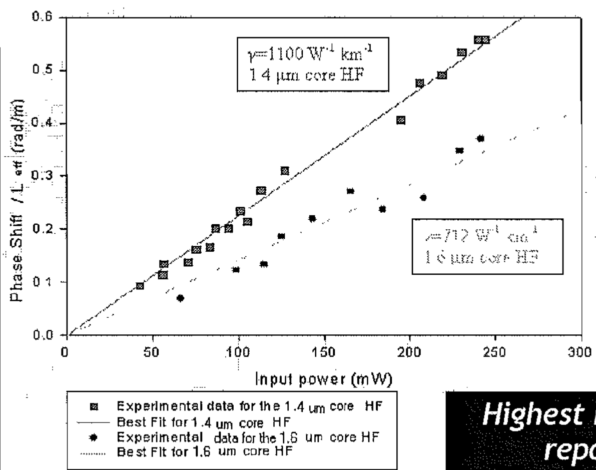


calc. mode profile



Fiber Nonlinearity

Nonlinear phase versus input power

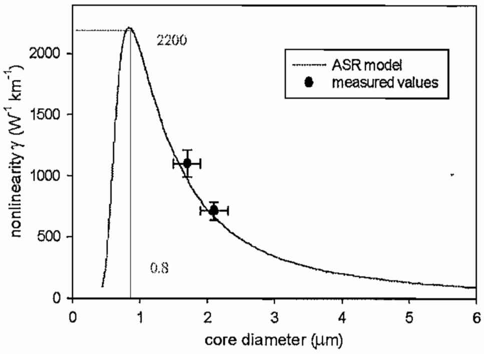


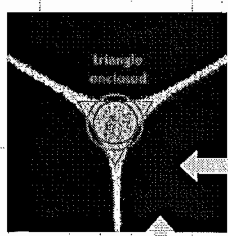
The nonlinearity increases as the core size is decreased

Highest nonlinearity reported in microstructured fiber

Comparison with predictions

THE ASR MODEL





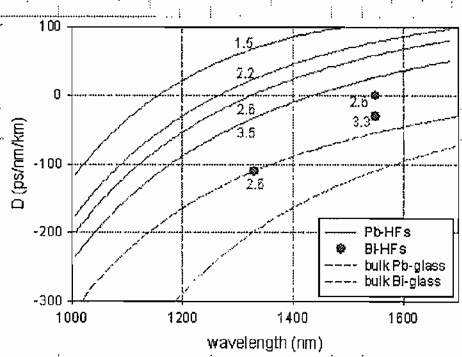
The triangle core diameter is used for comparison to the ASR Model

$D_{triangle}=1.2861\times D_{internal}$

ASR: Air Suspended Rod

Internal core diameter(µm)	Triangle core diameter(µm)	Predicted γ (ASR model) (W^{-1} km^{-1})	Measured γ (W^{-1} km^{-1})
1.6	2.1	680	714
1.4	1.8	1020	1100
0.62	0.8	2200	*Fundamental Limit*

Dispersion

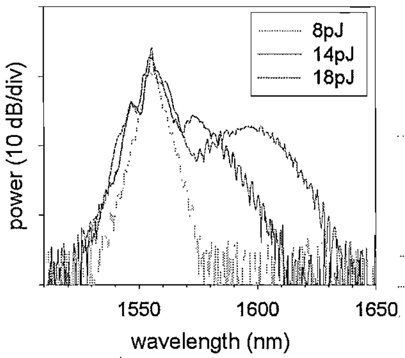


- Modelling with orthogonal method and measurement plots

dispersion of bulk glass and HFs with different core diameters (numbers in µm in the graph)

Extreme guidance allows to overcome large normal material dispersion

Self-Phase Modulation

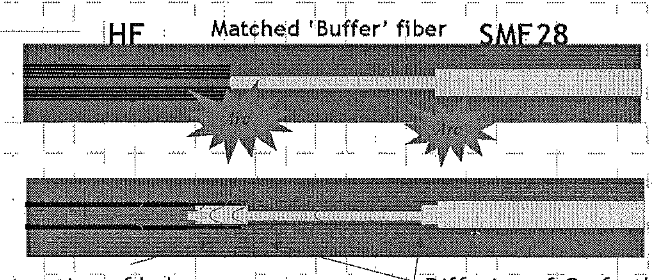


Raman soliton spectra at the output of 53cm of the 1.8 μm core HF with g=1100 W^{-1} km^{-1}

- Pulse source:
  - Actively mode-locked Er-fiber ring laser free space coupled
  - λ = 1556 nm
  - ~2.0 ps solitons at 9.95 GHz
- Fiber length = 0.53 m

Shape of broadened spectrum confirms anomalous fiber dispersion

Splicing with conventional fibers



Contraction of holes allows tapered mode expansion

Diffusion of Ge further facilitates mode matching

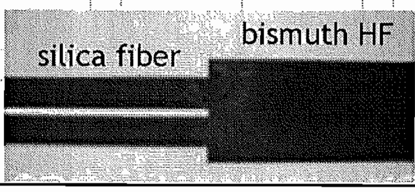
- Tapered splices provide excellent mode matching, Eg: SMF28 (9μm core) to 2μm core HF = 0.6dB with <-40dB back reflection

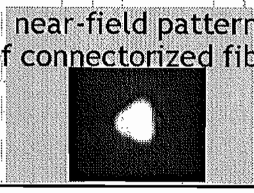
Splicing to a silica patch-cord

- Using mechanical cleaver and conventional fusion splicer
- Two intermediate buffer stages to reduce mode-mismatch
- Bismuth HF core diameter: 2.0 μm
- Splicing loss: mode mismatch: 3.8 dB

Fresnel reflection:	0.2 dB
excess loss:	1.8 dB
total:	5.8 dB

- Coupling losses reduced by 0.9 dB relative to butt coupling
- Free-space coupling: Multi-mode guidance
- Splicing: Robust single-mode guidance





Achievements to date for holey fibers

- Bismuth-oxide holey fibers with very high nonlinearity have been fabricated using the extrusion technique
- Lowest loss: 2.7 dB/m for a 1.6 μm core fiber
- A record-high effective nonlinearity of 1100 $W^{-1}km^{-1}$ was observed for a 1.4 μm core fiber
- Anomalous chromatic dispersion at 1.55 μm
- Splicing to standard fibers

New fibers for compact low power nonlinear devices

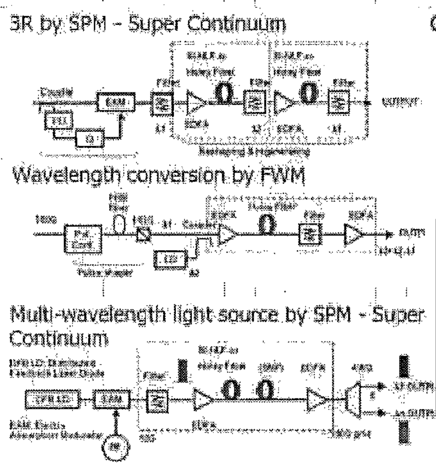
Loss: Figure of Merit

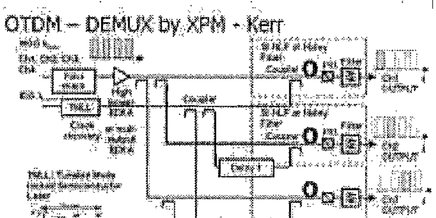
- Bare (unclad) fiber loss: 1.65 dB/m
- HF losses 2.7 - 3.4 dB/m, depending on the core size
  - Impact of imperfections and surface roughness increases for smaller core fibers
- Potential for lower loss using dehydrated glass. Bare fiber loss: 0.45 dB/m

All measurements at 1.55 μm

- One useful figure of merit: $\gamma \times L_{eff}$
- Low Power Devices: ideally require maximization of the fiber length, and thus loss has a significant impact
- Compact Devices: For short fiber lengths (< 1 m) the drastic increase in nonlinearity of these fibers outweighs the increased loss

Potential applications



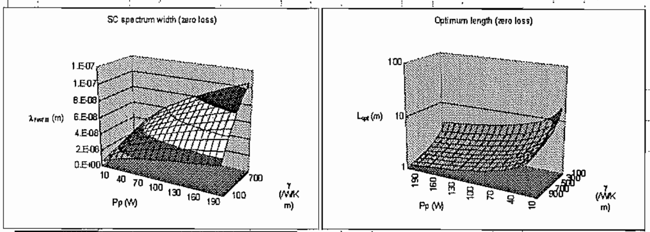


To be explored:

- Loss - practical nonlinearity and practical light power
- Compactness criteria
- Dispersion control
- Merits for System stability
- Polarization control - mandatory ?

Applications
Feasibility for SC generation

◈ Trial calculation for zero-loss case: Power and γ requirements for good quality spectrum broadening with T_0 =1.25 ps pulse source



$L_d = T_0^2/|\beta_2|$

$L_{nl} = 1/\gamma P$

$F_C \approx \sqrt{(L_d/L_{nl})} / 1.6$

$L_{opt} \approx \sqrt{(6 L_d L_{nl})}$

T_0 = 1.25 ps

(T_{FWHM} = 2.08 ps)

λ_{FWHM} = 1.7 nm

D_2 = -5 ps/nm/km

(β_2 = 6.37 × 10^{-27} s^2/m)

accommodate

160G RZ Gaussian

If γ is given	Optimum length	Spectrum width
Small β_2	☹ long	☺ large
large β_2	☺ short	☹ small

Calculation based on the approximation: Tomlinson et al. J. OSA 1984

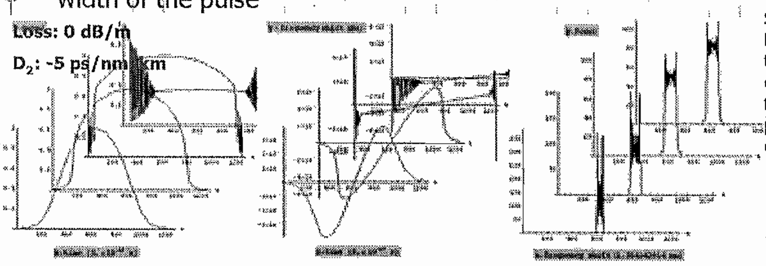
20 W peak power, γ = 1000 w^{-1} km^{-1} and ≈ 8.6 m for ≈ 75 nm SC light (D_2 = -5 ps/nm/km) for zero-loss case

Applications
Feasibility for SC generation

◈ Loss: The loss impairs both the chirp linearity and the spectral width of the pulse

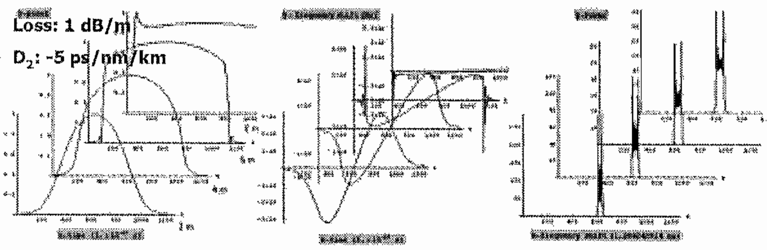
Loss: 0 dB/m

D_2: -5 ps/nm/km



Loss: 1 dB/m

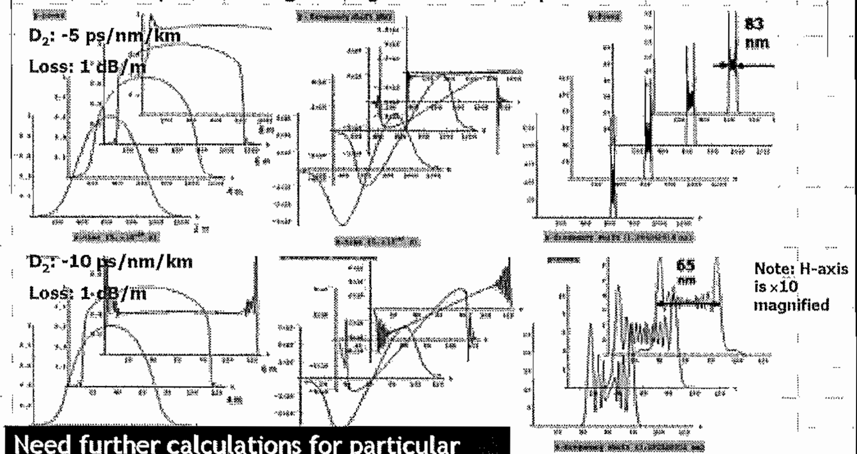
D_2: -5 ps/nm/km



Split step Fourier transform calculation for the the previous case

Applications
Feasibility for SC generation

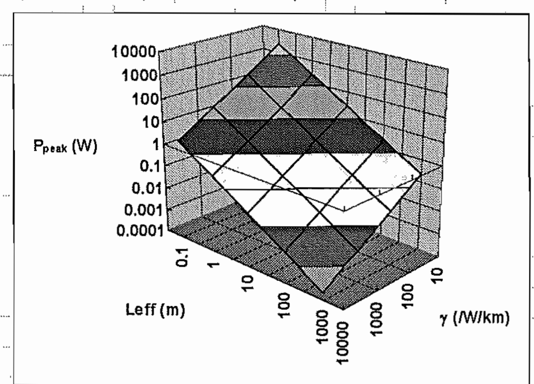
- Dispersion: Larger dispersion impairs the spectral width but allows shorter optimum length for good linear chirp



Need further calculations for particular cases along with experiments

Applications
Feasibility for Kerr switch

- Power, γ and L_{eff} requirements for π phase shift



$L_{eff} = [1-\exp(\alpha L)]/\alpha$

$\phi = 2\pi n_{2B} P L_{eff}/\lambda/A_{eff}$

$= 4/3 \times \gamma \times PL_{eff}$

$(n_{2B} = 2n_2(1-b)$, $b=1/3)$

W-class peak power for $\gamma \approx 1000$ ($W^{-1}km^{-1}$) and $L_{eff} \approx 1$ m for π phase shift - not crucial

Summary

◈OC Market is in gradual recovery - Opportunities for new devices in the future

◈Nonlinear fibers - Keys: large n_2 and small A_{eff} (additionally, loss and dispersion)

◈Bismuth-oxide: large n_2 and other good properties but large normal material dispersion to overcome

◈SI-Nonlinear fibers: simple and legacy structure, fusion splice with standard fiber, 1360 $w^{-1}km^{-1}$ achieved to date

◈Holey fibers: dispersion controllable , fusion splice with standard fiber, 1100 $w^{-1}km^{-1}$ achieved to date

◈Loss - Figure of merit: Considering the compactness of the devices, short fibers (< 1 m) with extraordinary nonlinearity will make sense

◈Potential applications: Further exploration needed for loss - power, dispersion, compactness and system stability