Nonlinear Effects in Optical Fibers

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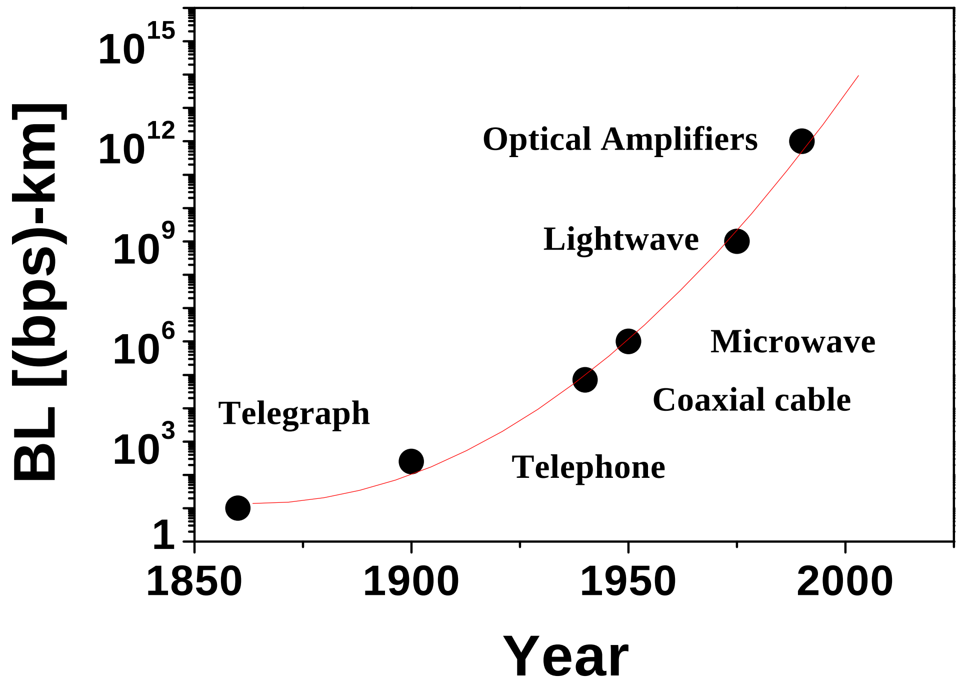
1. Introduction
2. Nonlinear Effects
3. XPM,SPM
   - Nonlinear Polarization Rotation
   - Optical Switch
   - Measurements of Nonlinear Coefficient
   - Coupling Length
4. FWM
   - Photon Pair Generation in SMF
   - Distributed measurements of CD
   - Distributed measurements of NC
5. Conclusion

Technological Evolution

- 1830 Telegraph
- 1900 Telephone
- 1940 Coaxial Cable
- 1950 Microwave
- 1970 Lightwave
- 1990 Optical Ampl.



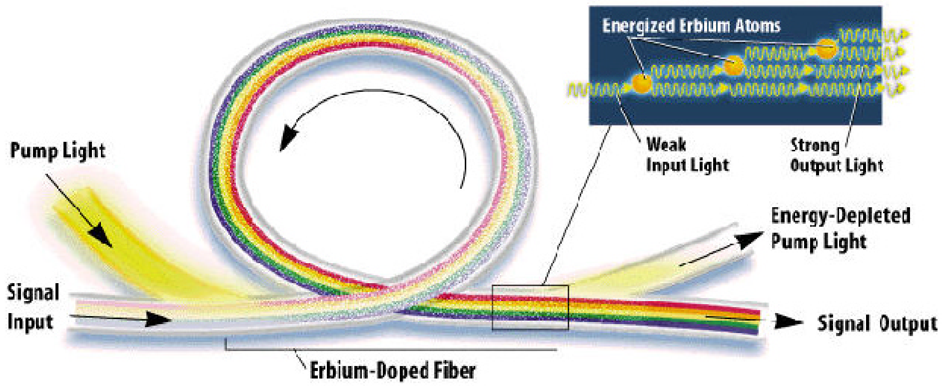
Breakthroughs

1. 1958 Bell Labs (Townes, Schawlow)
2. 1970 Corning (Keck, Schultz, Maurer)
3. 1986 Univ. Sauthampton – AT&T (Payne,Sesurvire)

- Laser
- Fiber Losses

  2000 dB/km -> 0.2 dB/km

- EDFA

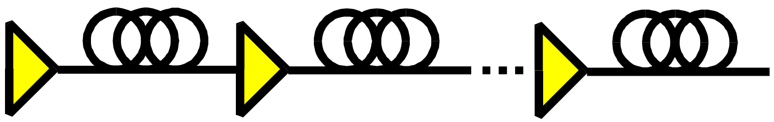


4

- 1988 BT AT&T (TAT-8 laid) **electric**

50 km

- 1995 TAT-12



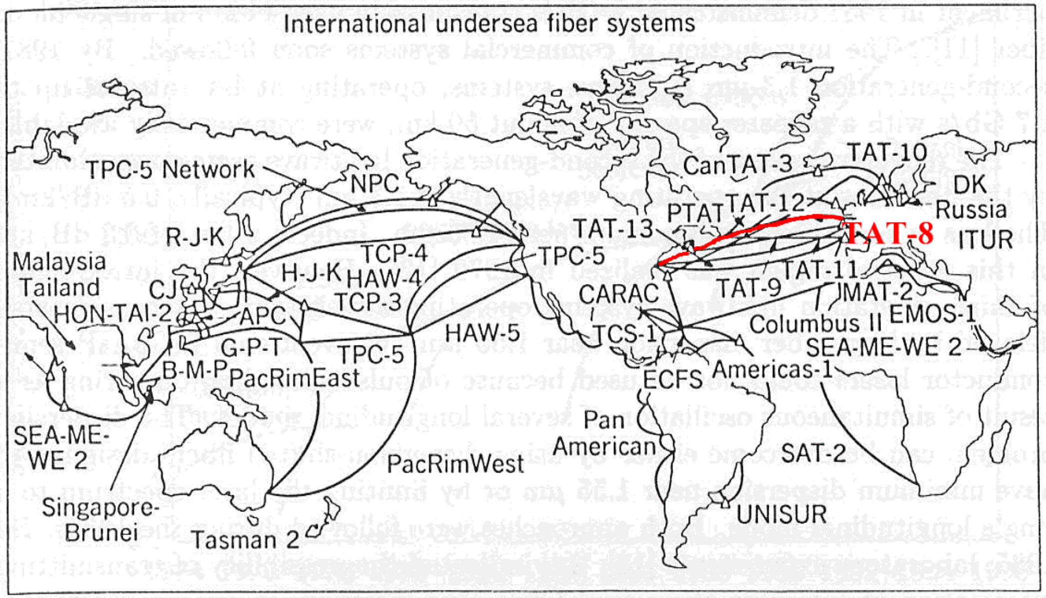


Figure 1.3 International undersea network of fiber-optic communication systems as installed by the end of 1996. (After Ref. [19]. ©1995 AT&T. Reprinted with permission.)

- 6500 km, 155 EDFA
  - $1 B
- 70 millions km installed
  - @2001
- 20000 km/day

Why optical fibers?

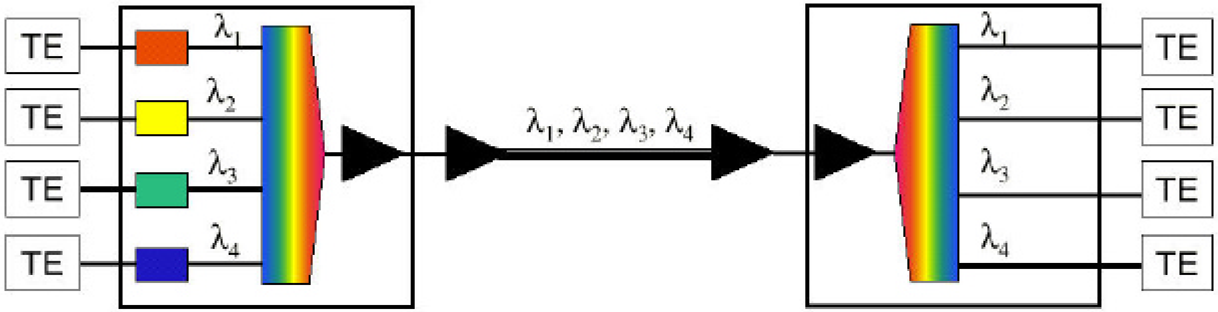
1. **Low Attenuation**
2. **No electromagnetic interference**
3. **Low weight**
4. **Security**
5. **High Bandwidth**

• coaxial cable	(2 Gbps/km)
• broadband coaxial cable	(300 MHz/km)
• optical fiber	(50 THz)

Resolving Capacity Crisis

5 Data Multiplexing

- Time Division Multiplexing
- Wavelength Division Multiplexing



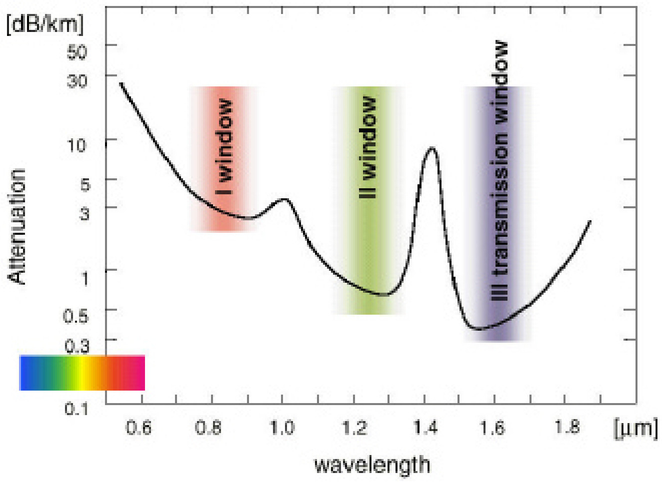
puts many lower bit-rate channels in the same fiber
by modulating them at different wavelengths.

Increase total bit rate

$$BL = (B_1 + B_2 + \ldots\ldots + B_N)L$$

Channel N	Bit Rate B (Gbps)	Capacity NB (Gbps)	Distance L (km)	NBL Product (Tbps · km)
10	10	100	50	5

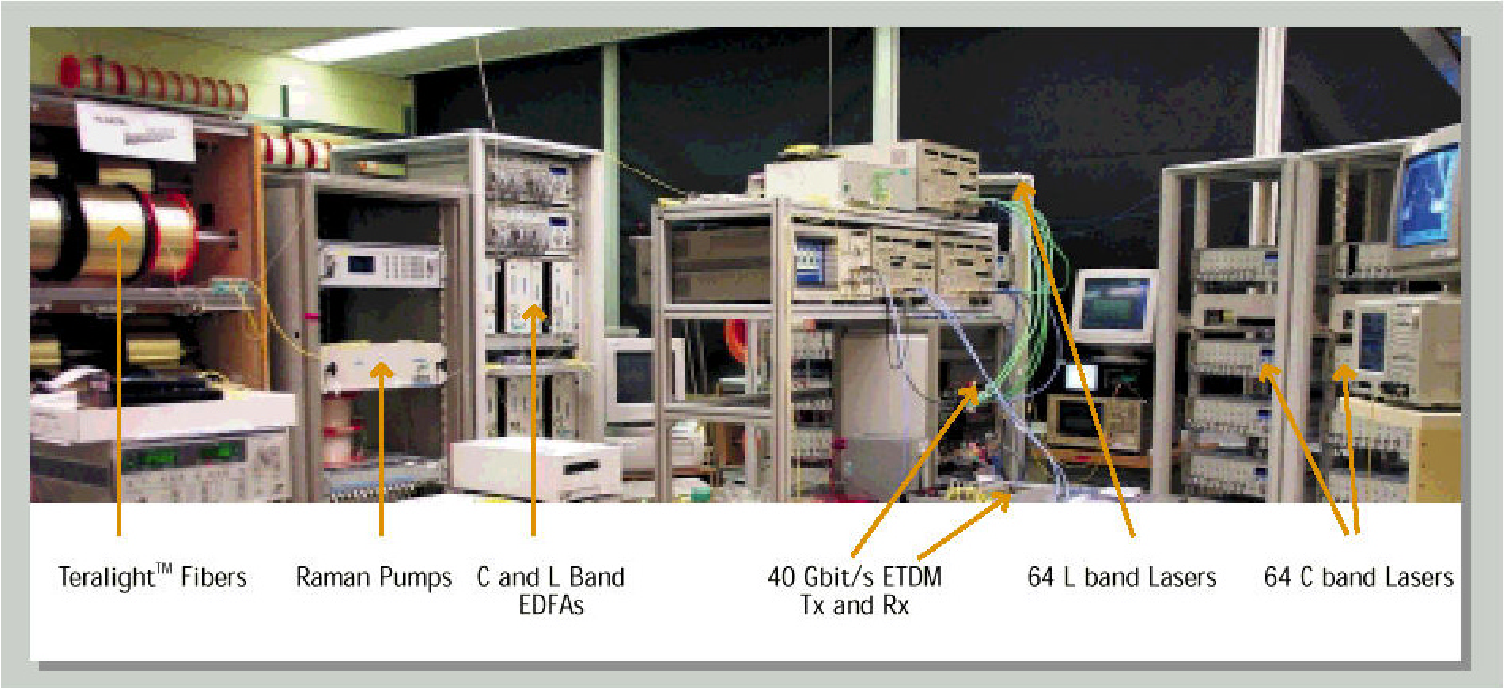
Channel bandwidth



Ultimate limit

minimum channel spacing

Multi Terabit transmission



256 Channels
C-L Band
Spacing 50 GHz
Polarization Diversity Scheme

10 Tbps

- 200 ml telephone calls
- 0.5 ml ADSL links

Bottleneck for Optical Fibers

- **Dispersion**
  - Chromatic Dispersion
  - Polarization Mode Dispersion

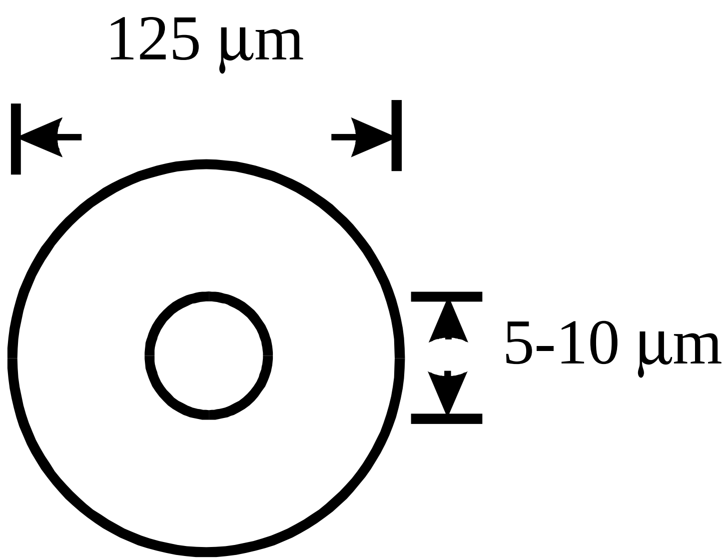
- **Optical Nonlinearities**

despite enormous bandwidth nonlinear effects may limit fibers capacity to carry information

present at relative low powers

- **small spot size**
- **low losses**

$$\longrightarrow \frac{P}{A_{eff}} L$$



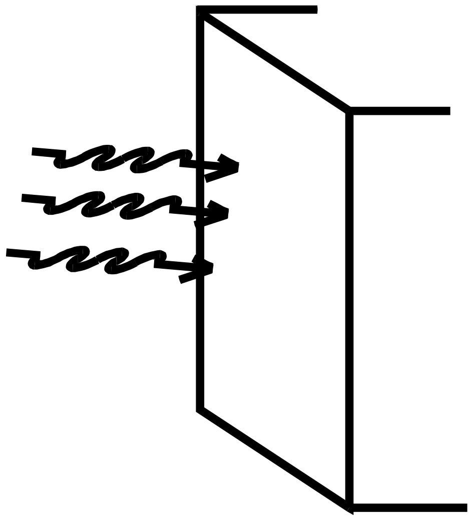
How Much Power ?

- receiver sensitivity

BER $10^{-9} – 10^{-12}$

ideal detector

20 photons



- in terms of power

-40 dBm @ 40 Gbps, 1.55 µm, RZ

real detector 20 dBm above

+24 dBm !!!

Nonlinear Effects

1

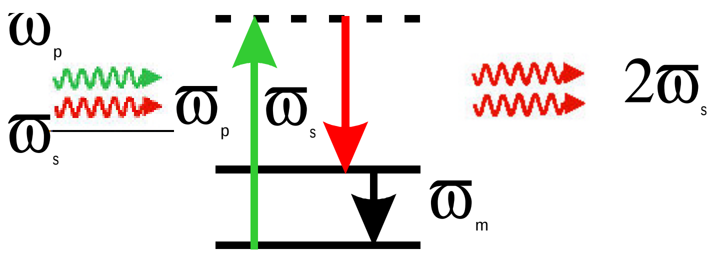
- **Stimulated Raman Scattering**

  effect strong when channels widely separated

- **Stimulated Brillouin Scattering**

  backscattered, low threshold

$$\hbar\nu_P + \hbar\nu_S = 2\hbar\nu_S + \hbar\nu_M$$



2

- **$\chi^{(3)}$ Nonlinear optics**
  - Self Phase Modulation
  - Cross Phase Modulation
  - Four Wave Mixing

$\chi^{(3)}$ Nonlinear optics

Propagating Wave $E(t) = A(t)e^{-ikz}$ $k = v\sqrt{me}$

$$\mathbf{P} = e_0\left(c^{(1)}\mathbf{E} + c^{(2)}\mathbf{E}^2 + c^{(3)}\mathbf{E}^3 + \ldots\right)$$

Lorentz Approx

SiO_2 inversion symmetry

$c^{(1)} = n^2 - 1$

$$n(v, I) = n_0(v) + n_2\frac{P}{A_{eff}}$$

KERR EFFECT

10^{-20} m^2/W

Intensity dependence of the refractive index n reflects in different phenomena

SPM

SELF INDUCED phase shift experienced by an optical field during its propagation in optical fibers

XPM

nonlinear phase shift of an optical field induced by a COPROPAGATING field at a different wavelength or polarization

FWM

ENERGY EXCHANGE among different waves

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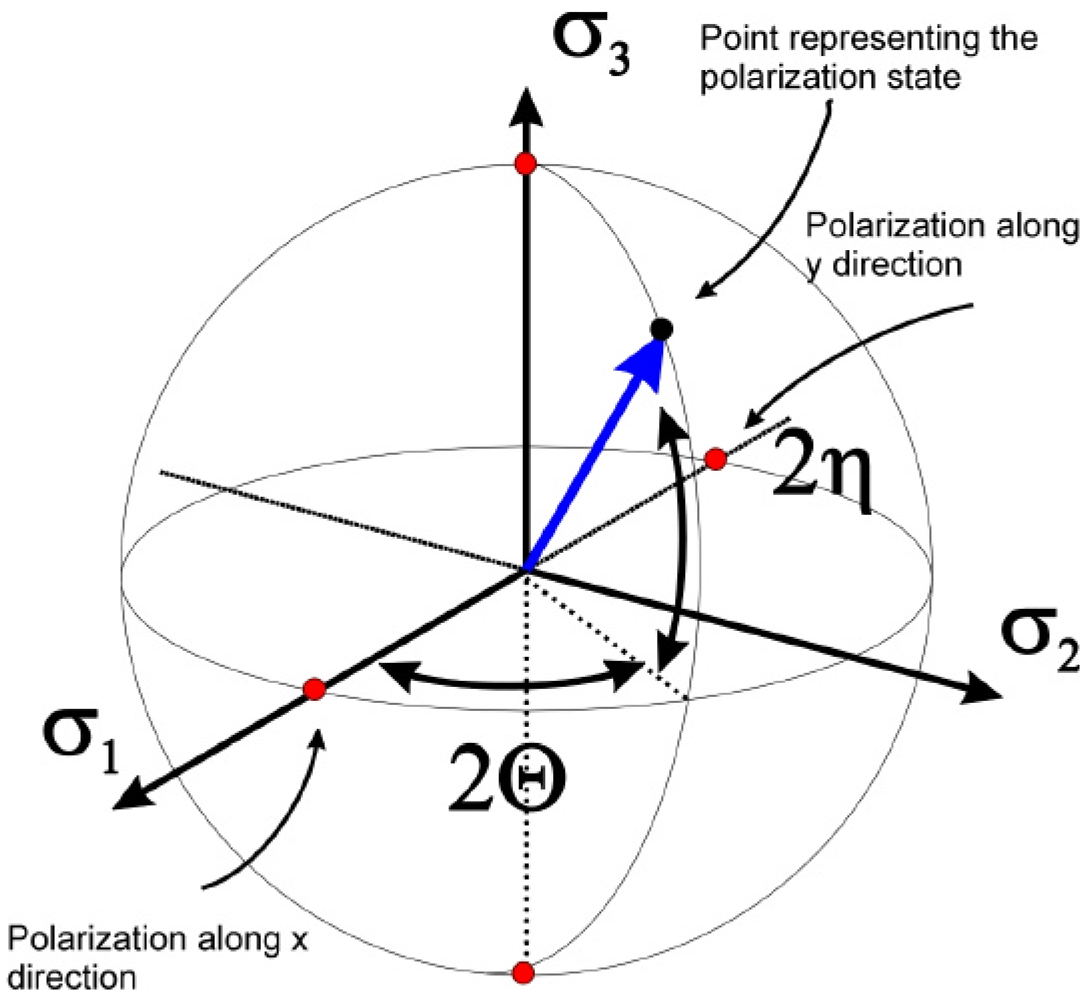
Poincare sphere

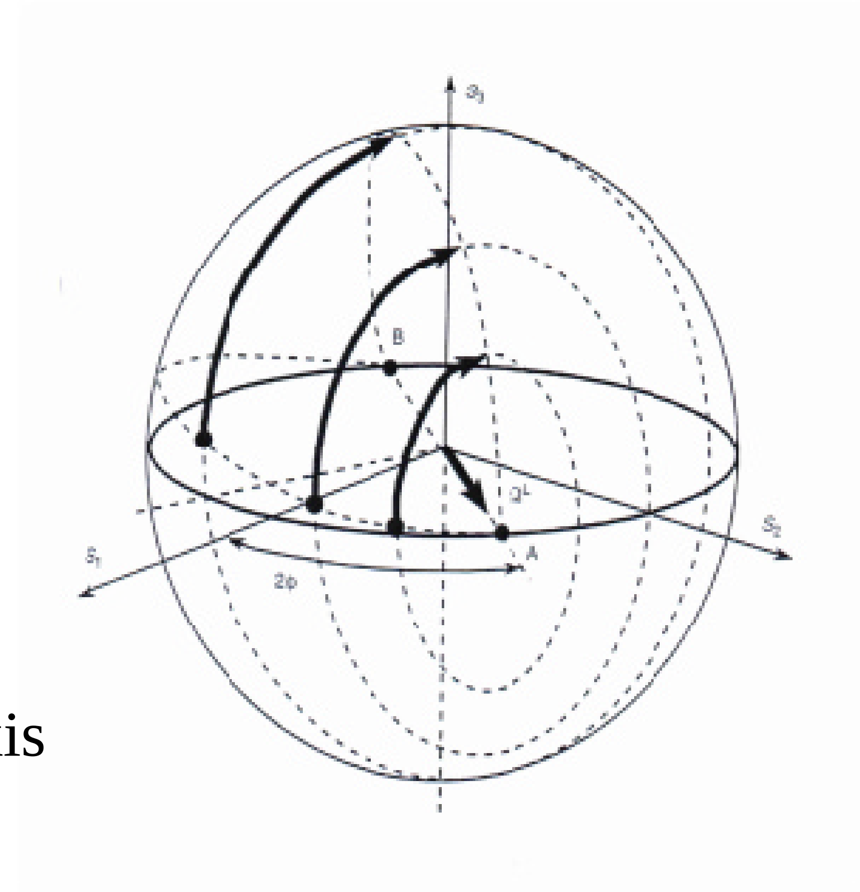


Nonlinear Polarization Rotation

How does evolve the SOP of the light during its propagation along a fiber?

- Linear
- Non-Linear

Linear Birefringence



Rotation along the birefringent axis

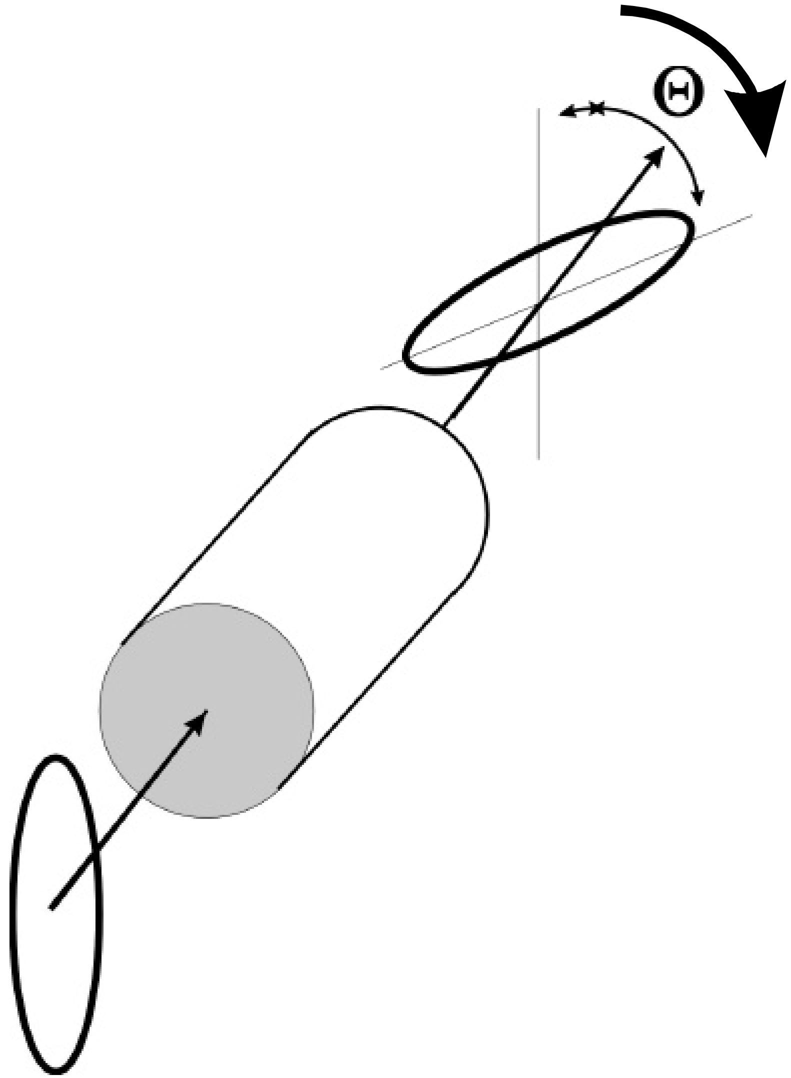
• Non-Linear

Isotropic medium

• elliptical SOP required
• ellipticity is mantained

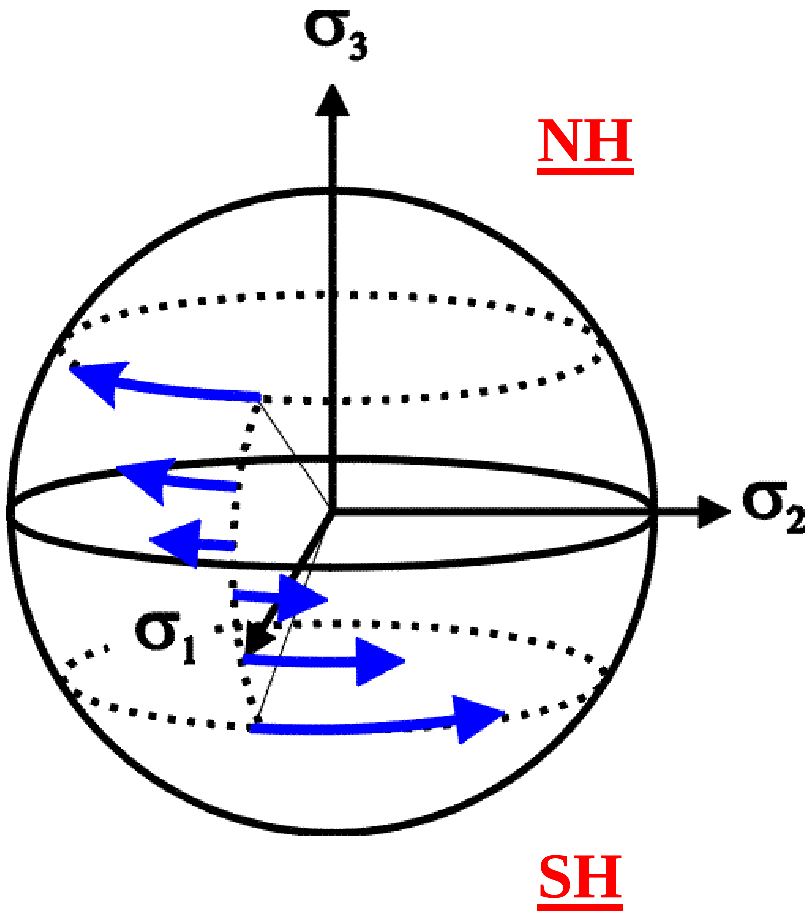
$$\Theta \propto P, L$$

POLARIZATION ELLIPSE SELF-ROTATION



On the Poincare sphere:

Arc parallel to the equator



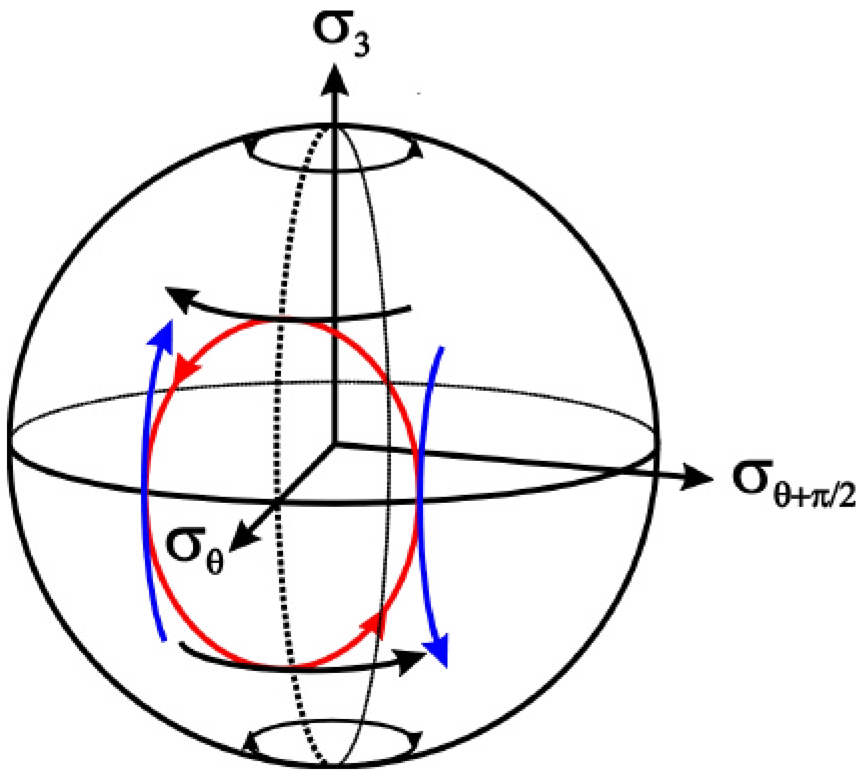
What's happening when linear birefringence is present?

$$\partial_z y = -i(vBs_J + va < s_3 > s_3)y \qquad a = -\frac{n_2 P}{3cA_{eff}}$$

B >> α

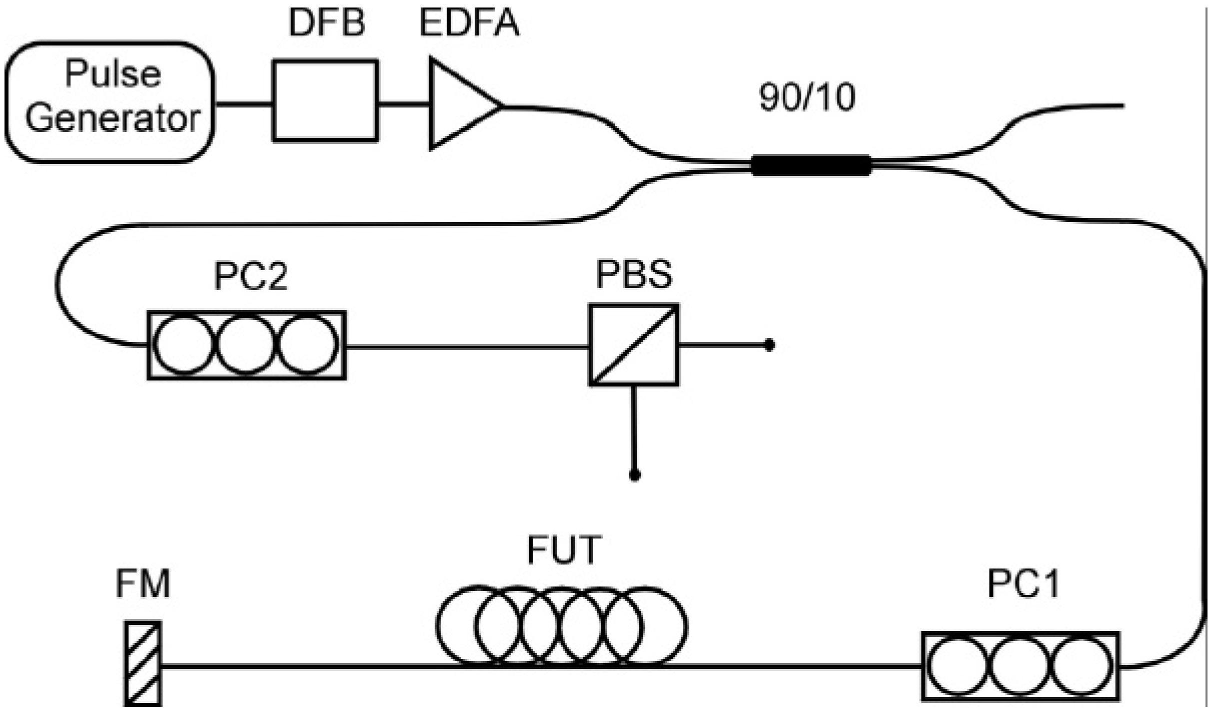
$$\mathbf{m}(z) = \hat{\mathrm{R}}_{[\theta]}(\beta) \cdot \mathbf{m}(0)$$

$$\beta = \omega(B - \frac{\alpha}{2} m_\theta(0))$$

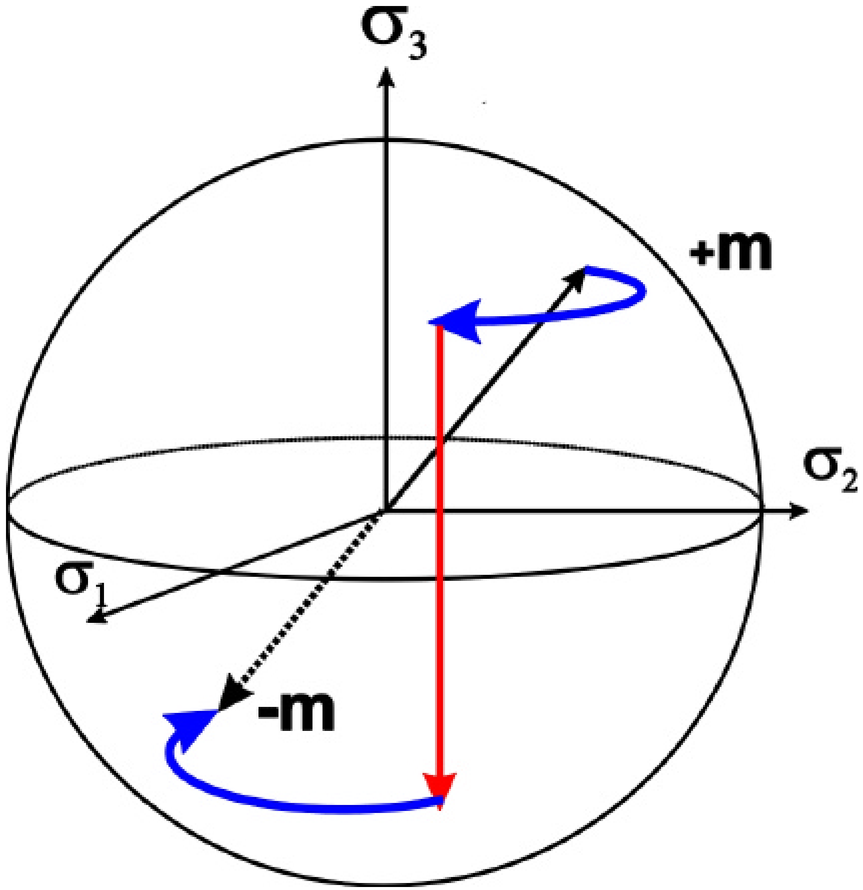


Effective birefringence

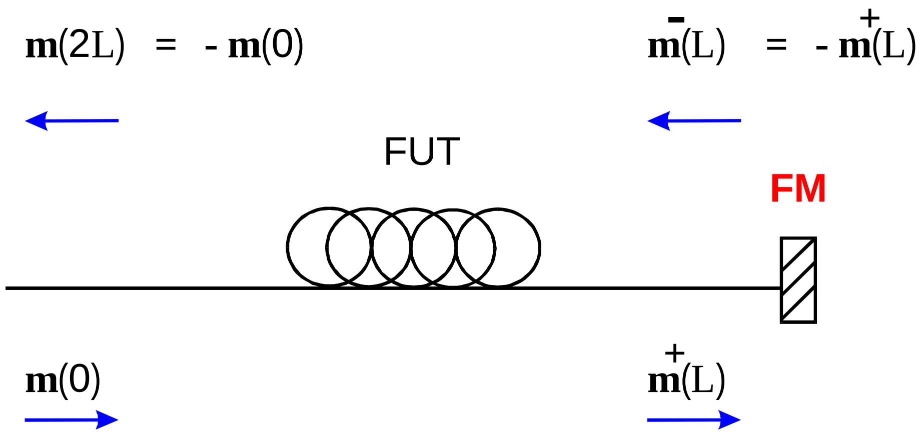
EXPERIMENTAL SETUP



Faraday Mirror



remove linear birefringence



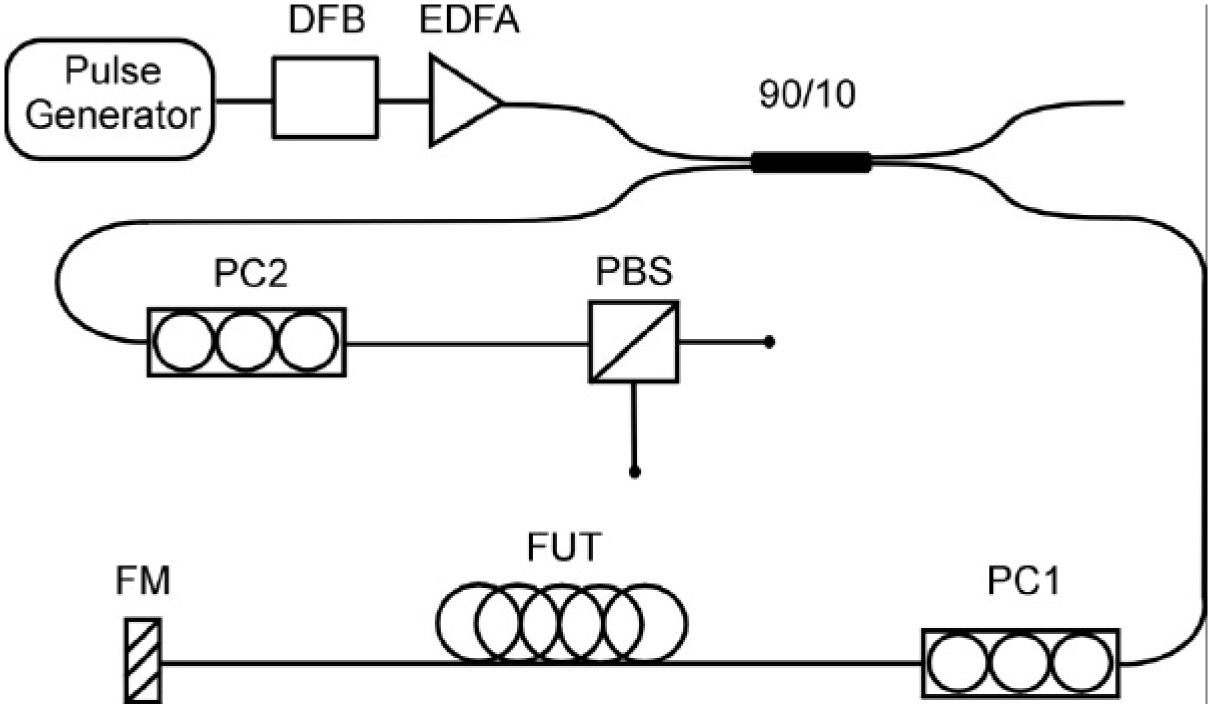
double pass pass of the FUT results in:

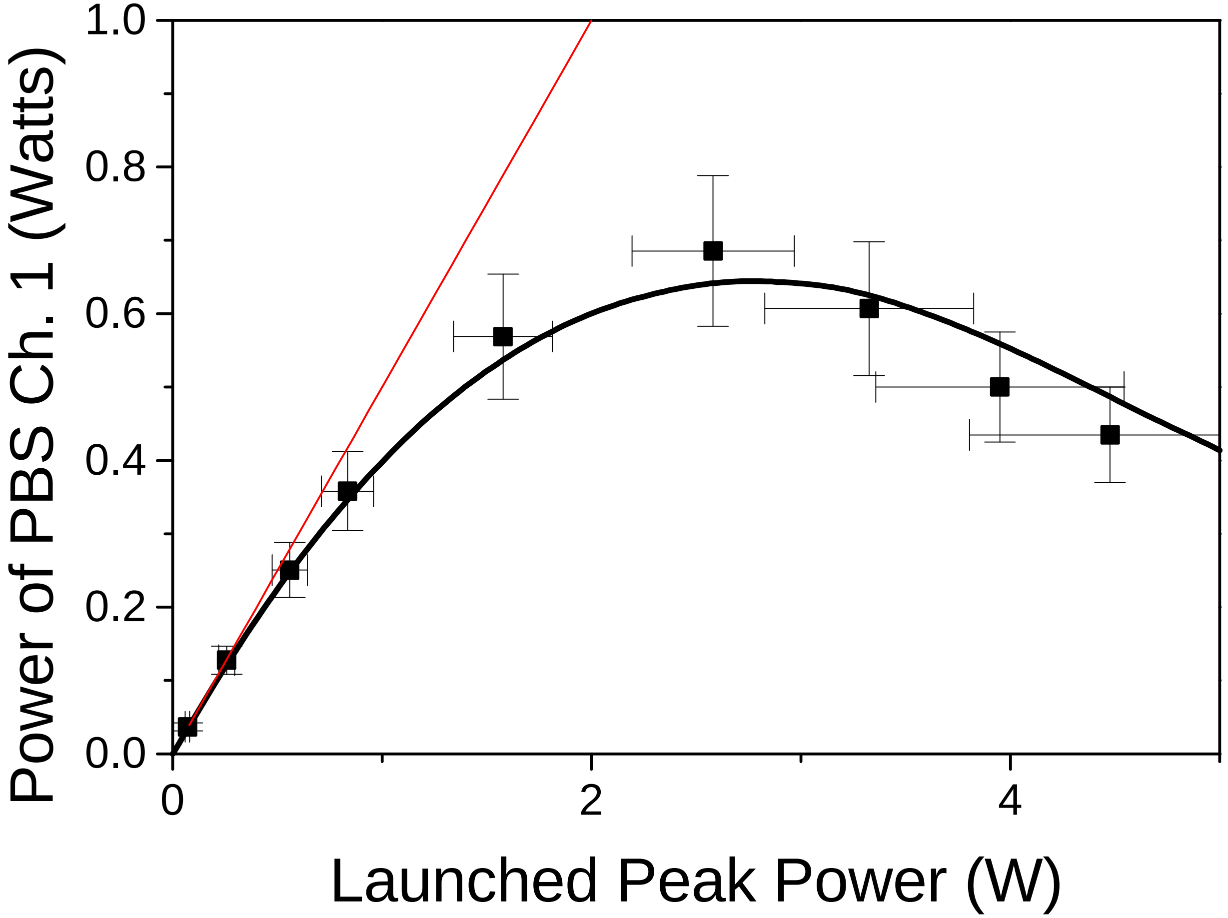
$$\beta = \omega(B - \frac{\alpha}{2} m_\theta(0))$$

x2

- **SUBTRACTION** of linear birefringence
- **ADDITION** of nonlinear birefringence

EXPERIMENTAL SETUP




1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
Power of PBS Ch. 1 (Watts)
Launched Peak Power (W)

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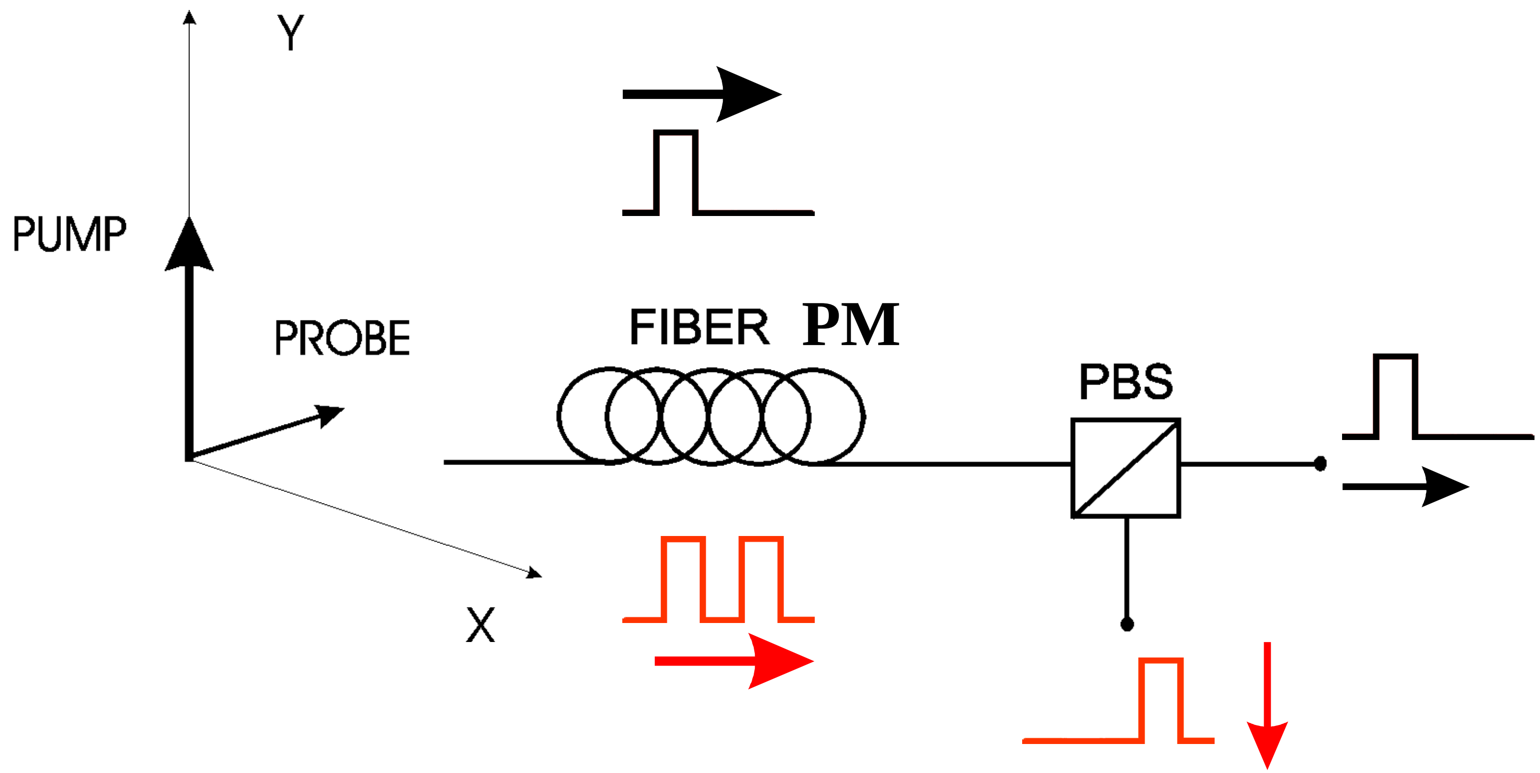
Optical Switch

λ_P

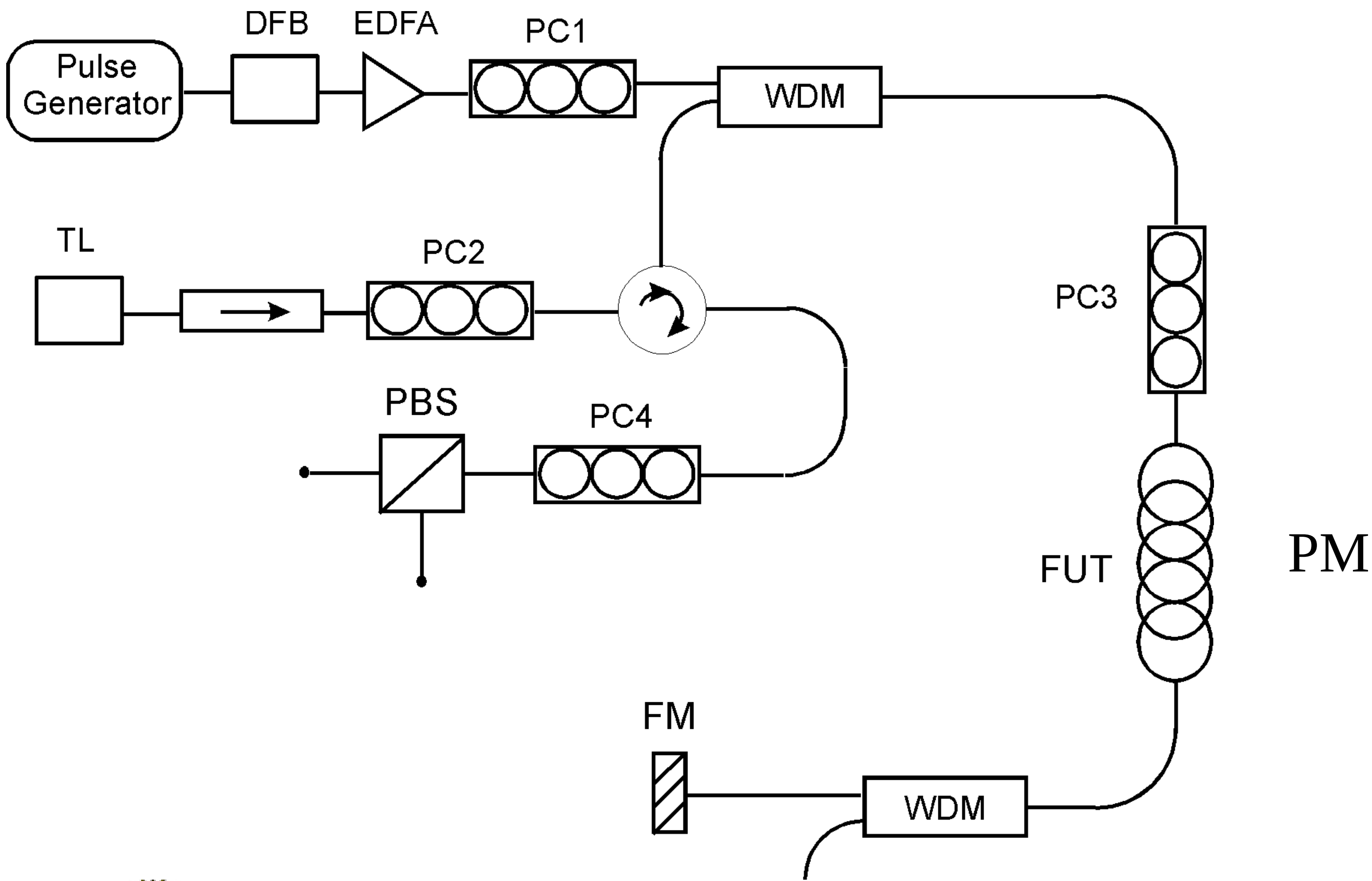
λ_S



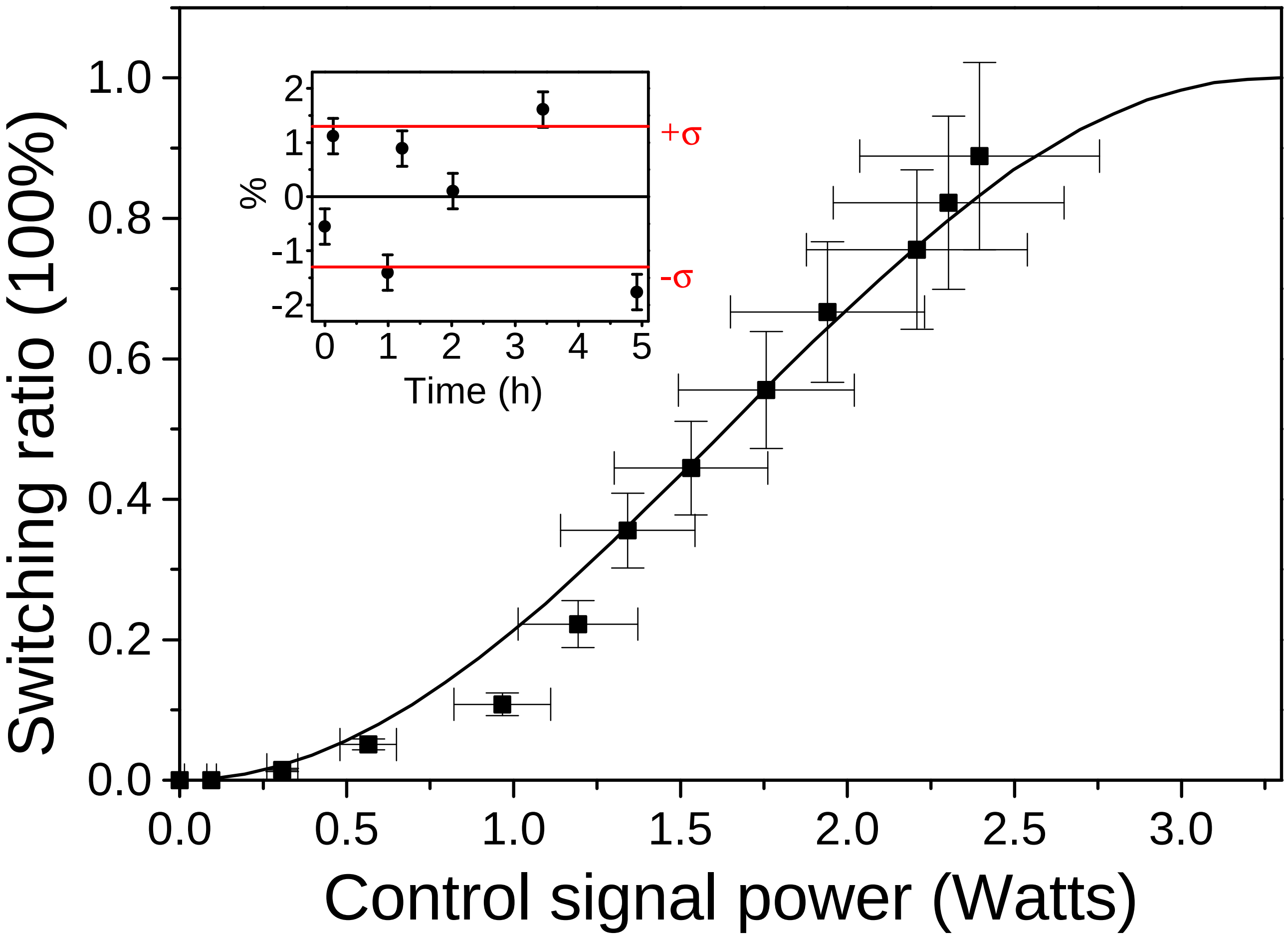
$I_P >> I_S$

PUMP INDUCED BIREFRINGENCE

EXPERIMENTAL SETUP



PM fiber



Switching ratio (100%)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Control signal power (Watts)
%
2
1
0
-1
-2
0 1 2 3 4 5
Time (h)
+σ
-σ

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Measurement of n_2/A_{eff}

1 **INTERFEROMETRIC**

- SPM
- XPM

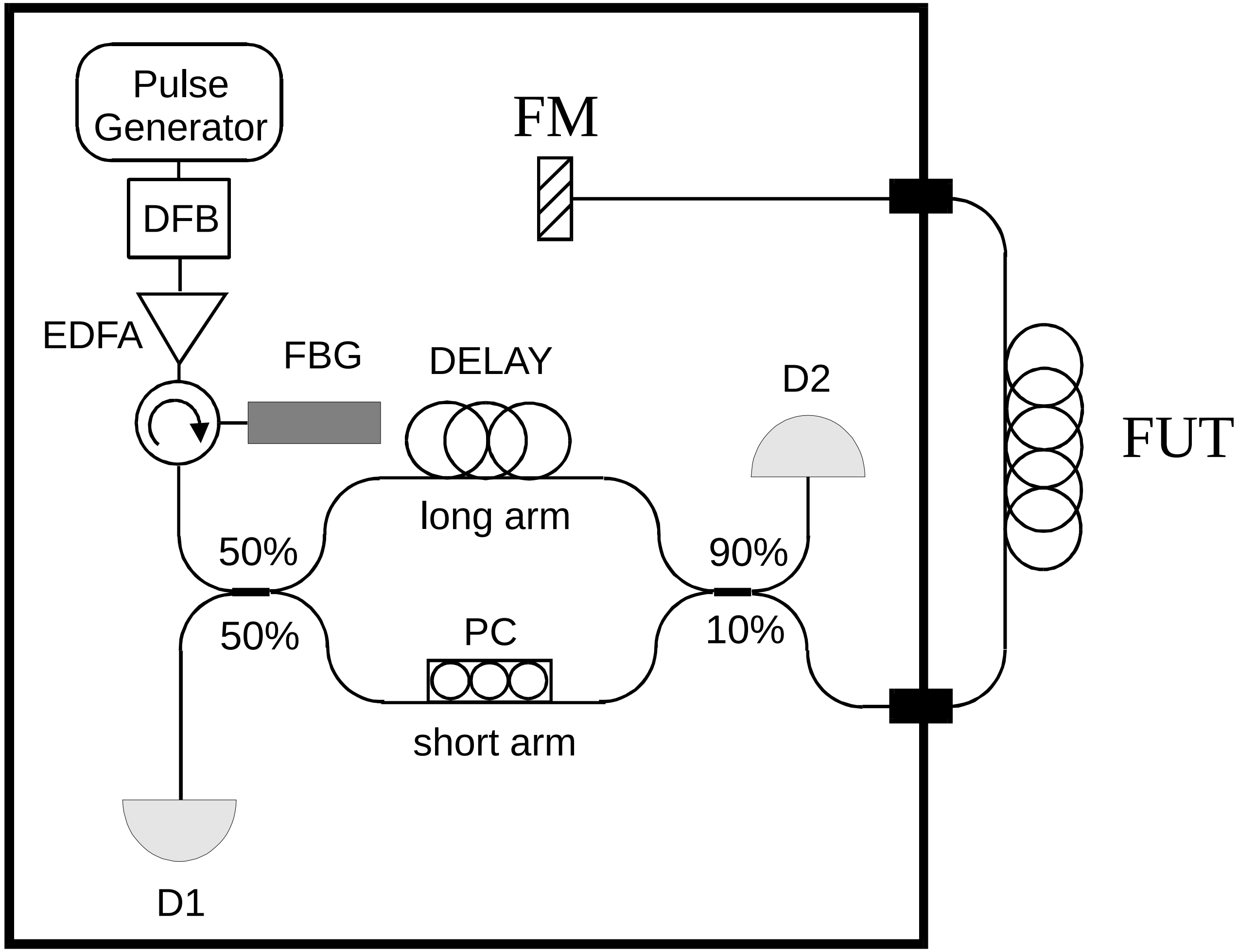
2 **NON-INTERFEROMETRIC**

- FWM
- MI
- CW

Self Aligned Interferometer

$$f(P) = f_l + f_{nl} = n_0 kL + kL_{eff} \frac{n_2}{A_{eff}} Pm$$

EXPERIMENTAL SETUP



$$P_{OUT}(P) \propto P\cos^2(\Delta f_{nl})$$

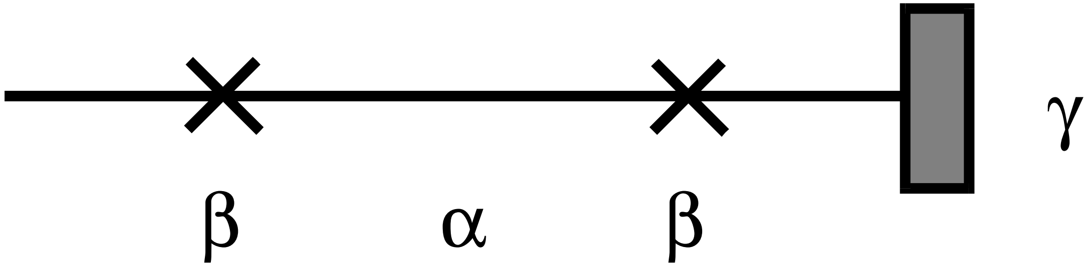
How to take into account losses?

$$\Delta f = kL^*_{eff}P\left(\frac{1}{2}-\frac{1}{10}\right)\frac{n_2}{A_{eff}}m$$

- **distributed losses**
- **point losses**

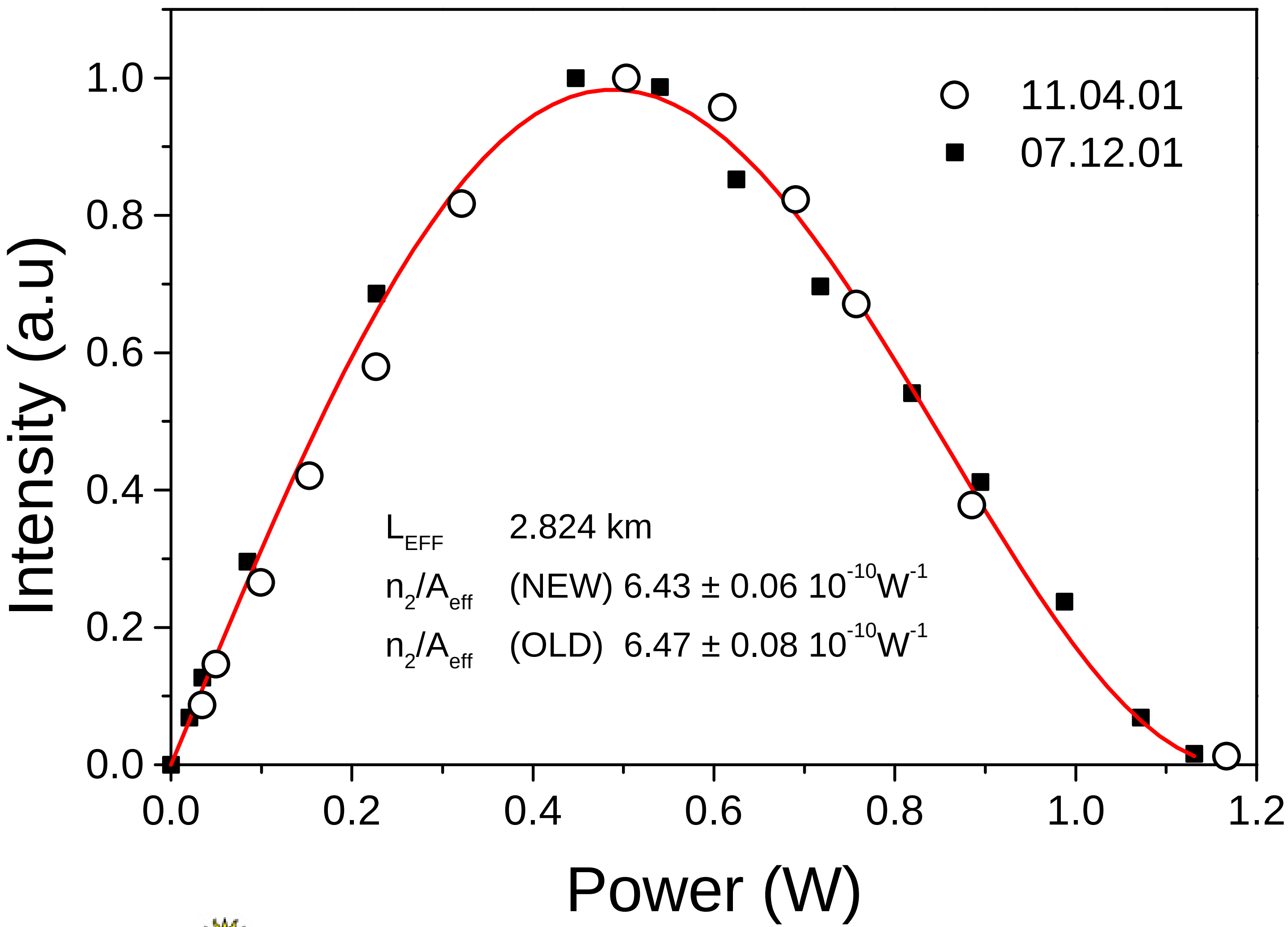
EFFECTIVE LENGTH

$$L_{eff} \equiv \frac{1-\exp(-aL)}{a}$$



$$L^*_{eff} \equiv (1+bag)bL_{eff}$$

REPRODUCIBILITY



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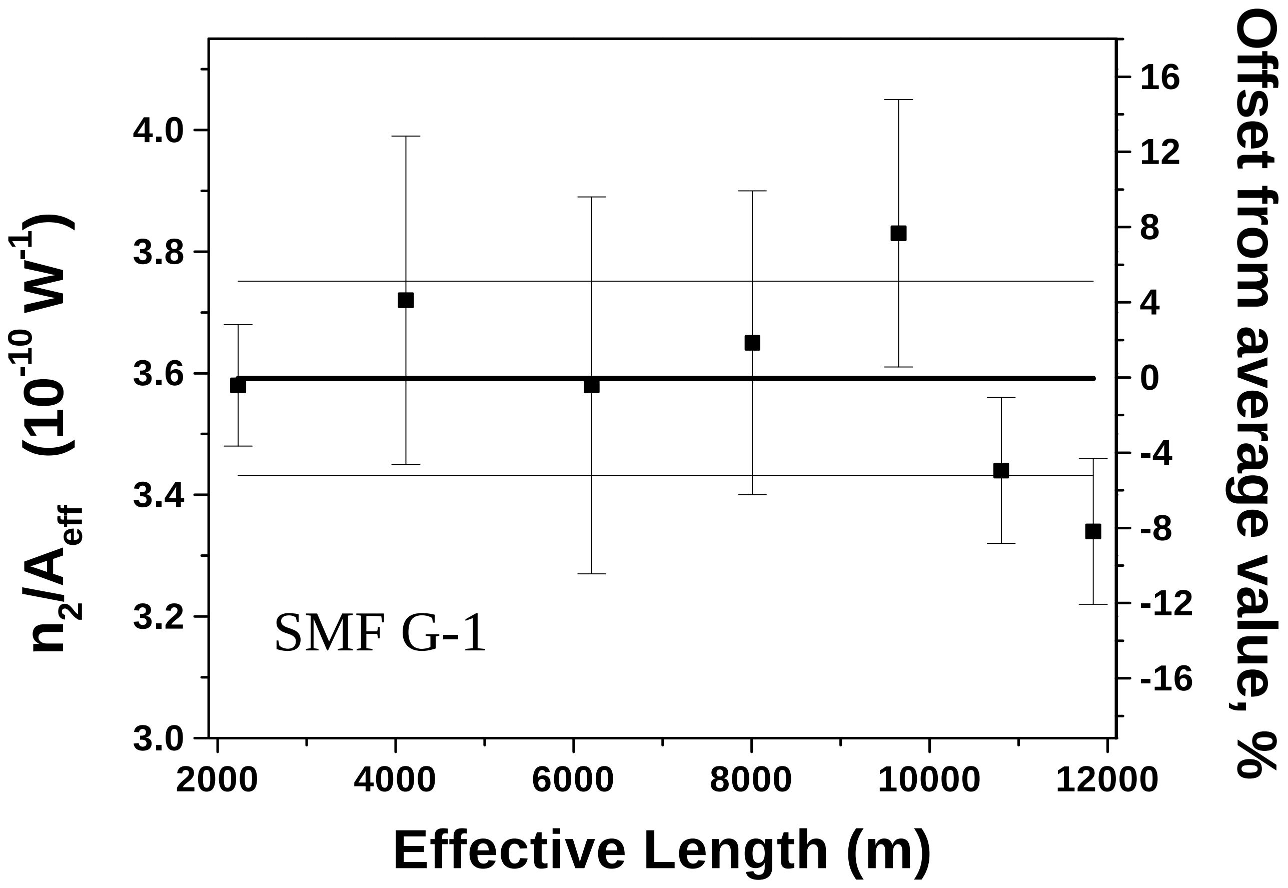
LENGTH INDEPENDENT



Conclusion

- fascinating
- detrimental properties
- exploitation of nonlinear effects (Kerr switch, NPR)
  (distributed measurements)
- characterize the amount of nonlinearities

Acknowledgements

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