Insight into the Design, Attenuation and Bend Loss of Optical Fibers

Presented by:

OSA Fiber Optics Technology and Applications Technical Group

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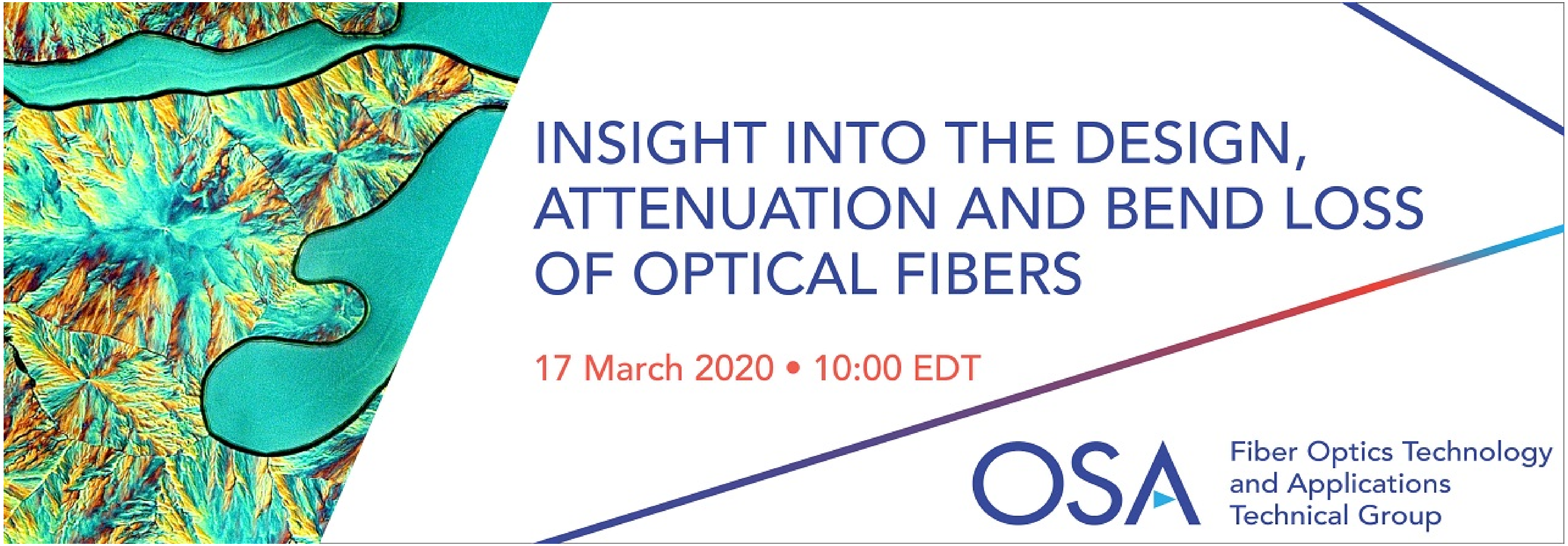

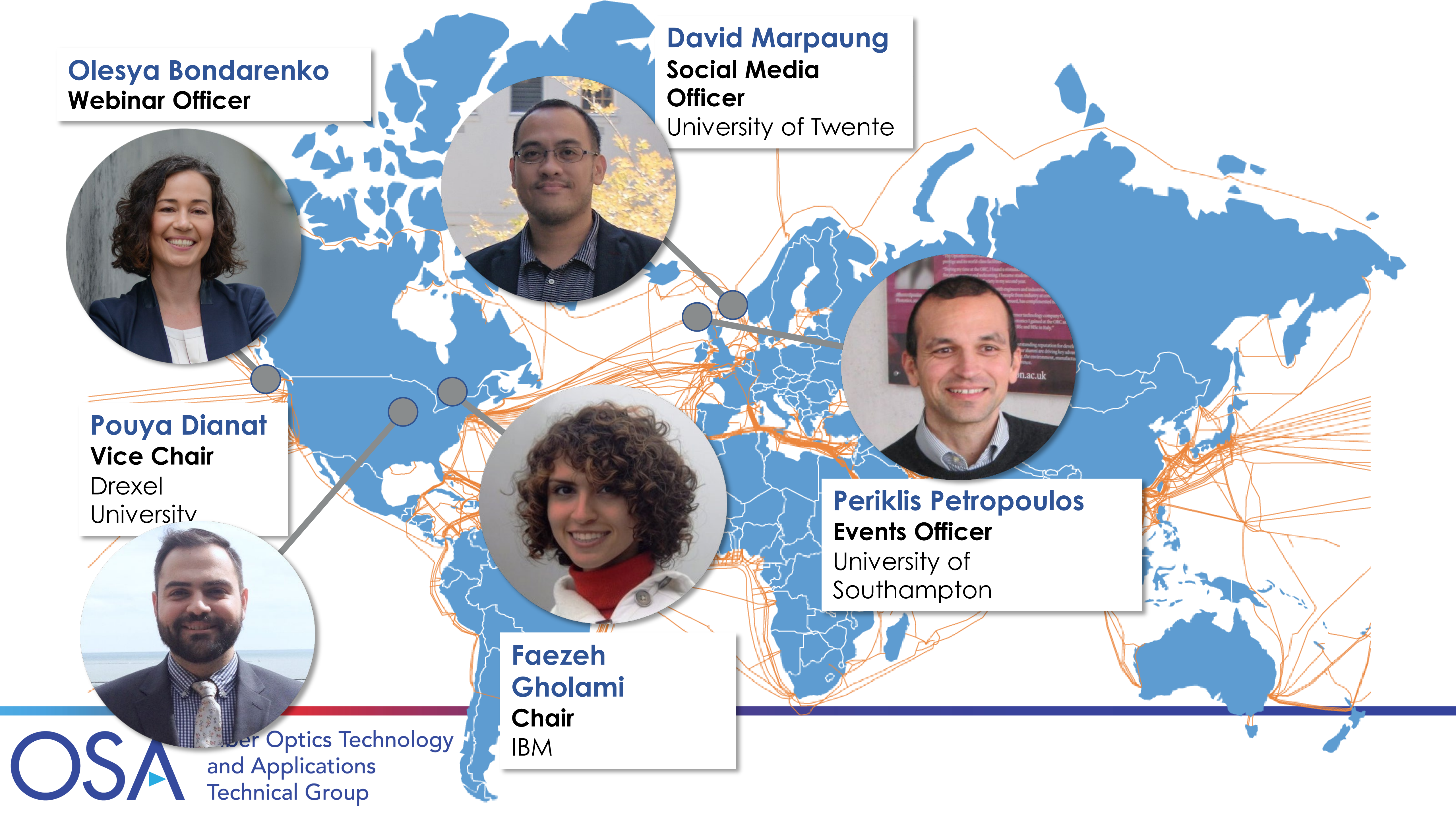
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Our Technical Group at a Glance

Our Focus

- Latest research and industry trends in passive and active fiber optics

Our Mission

- Connect you with piers and leaders in the sub-field
- Create opportunities to expand your network
- Help you stay up do date through webinars, social media, publications, technical events, business events, outreach

Where To Find Us

- Facebook: www.facebook.com/groups/OSAfiberopticstechnology
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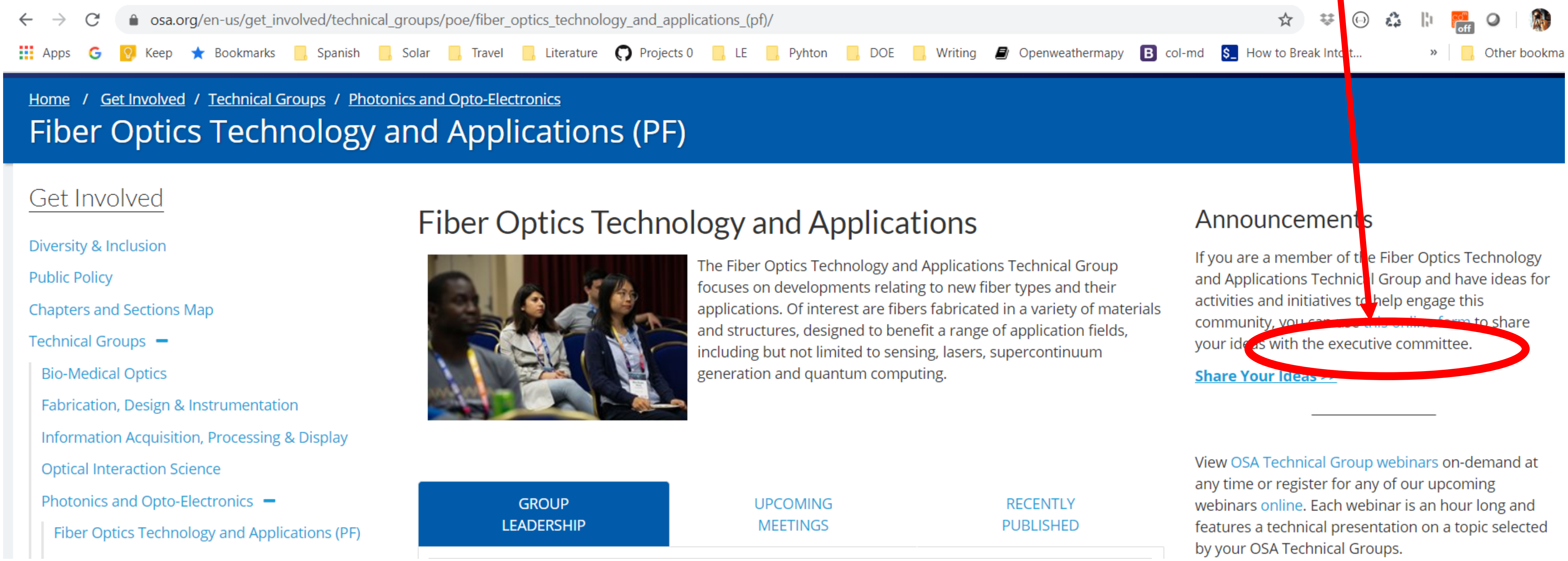
Contact us and get involved!

Share your ideas!



Insight into the Design, Attenuation and Bend Loss of Optical Fibers

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Short Bio:

Since joining Corning in 1999, Scott has led the development of low-attenuation fibers, bend-insensitive single-mode and multimode fibers and specialty fibers.

Insight into the Design, Attenuation and Bend Loss of Optical Fibers

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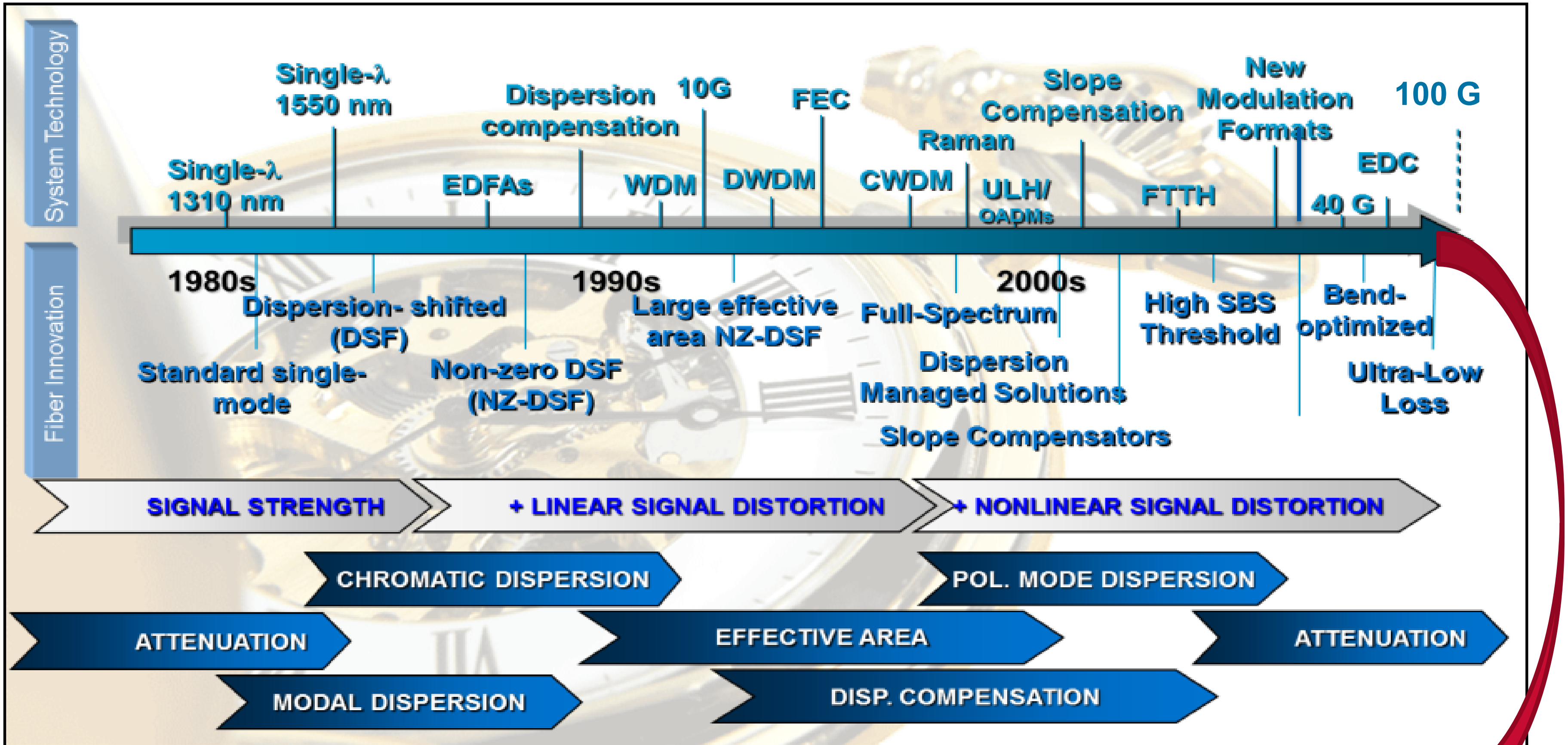
Outline

- Drivers for fiber innovation
- Overview of optical fiber manufacturing process
- Refractive index profile and the Sellmeier equation
- Solutions of the scalar wave equation
- Optical fiber attenuation
- Macrobending and microbending
- Key take-aways

Drivers for 50 Years of Fiber Innovation: System Evolution and New Application Spaces



Fiber design challenges in the 2020's:

- Advanced Modulation Formats
- Spatial Division Multiplexing
- 400 G → 800 G
- Silicon Photonics
- Fiber-Chip Coupling
- Dense Connectivity

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Primary Steps for Manufacturing Optical Fiber

- High purity (synthetic) glass is made from liquid chemicals

1. Form “soot” preform in a high temperature reaction:

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

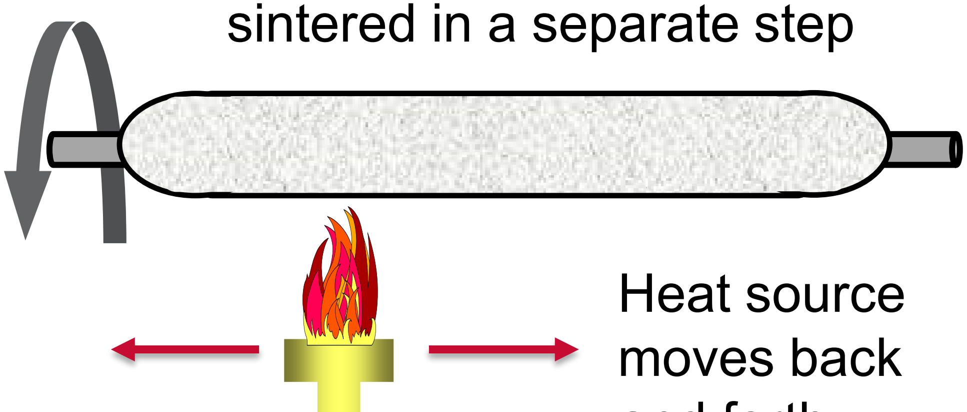
$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

2. Consolidate/sinter soot into glass
3. Draw glass preform into small diameter fiber and apply coatings
4. Proof-test, measure and package the finished product

Optical Preform Manufacturing Processes

OVD: Outside Vapor Deposition

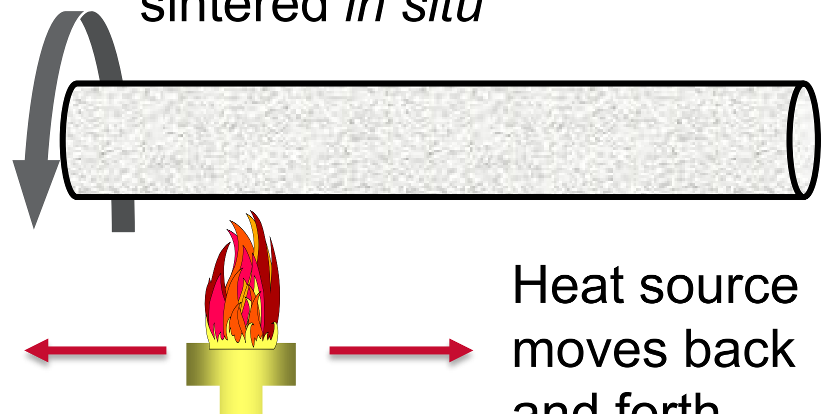
Soot is deposited on a rotating target rod and sintered in a separate step



Heat source moves back and forth

IVD: Inside Vapor Deposition

Soot is deposited on inside of rotating glass tube and sintered *in situ*

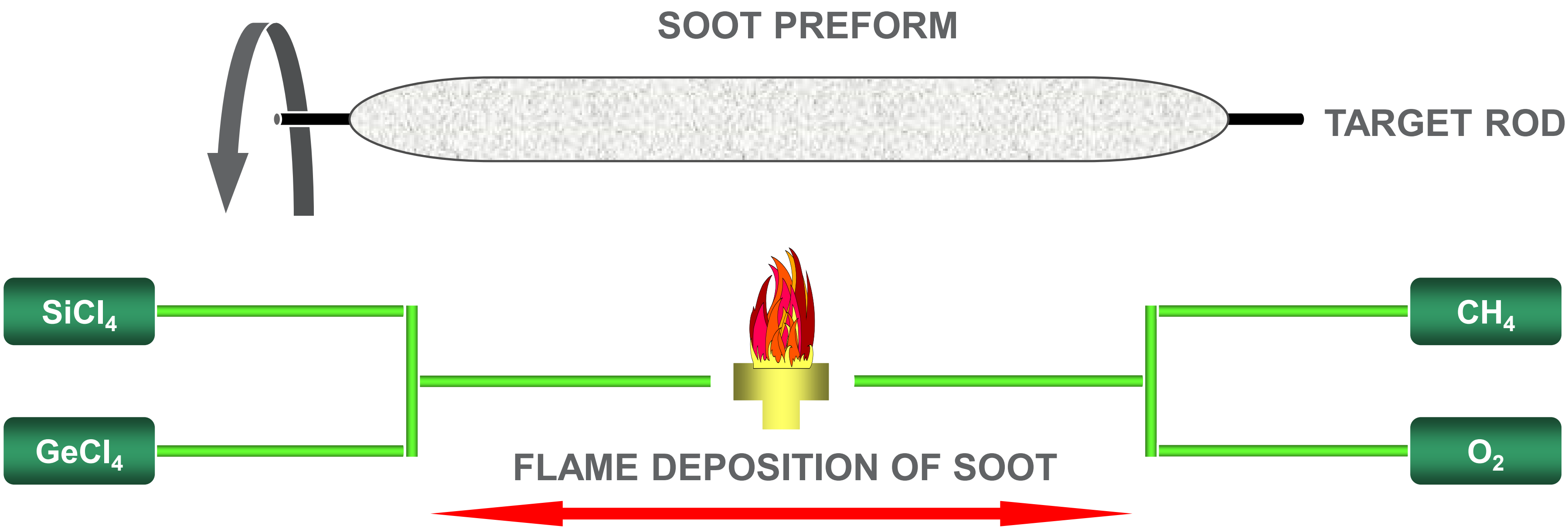


Heat source moves back and forth

- VAD is a variation with the preform mounted vertically
- POVD = Plasma Outside Vapor Deposition

- MCVD: Modified Chemical Vapor Deposition
- PCVD: Magnetron forms plasma inside tube

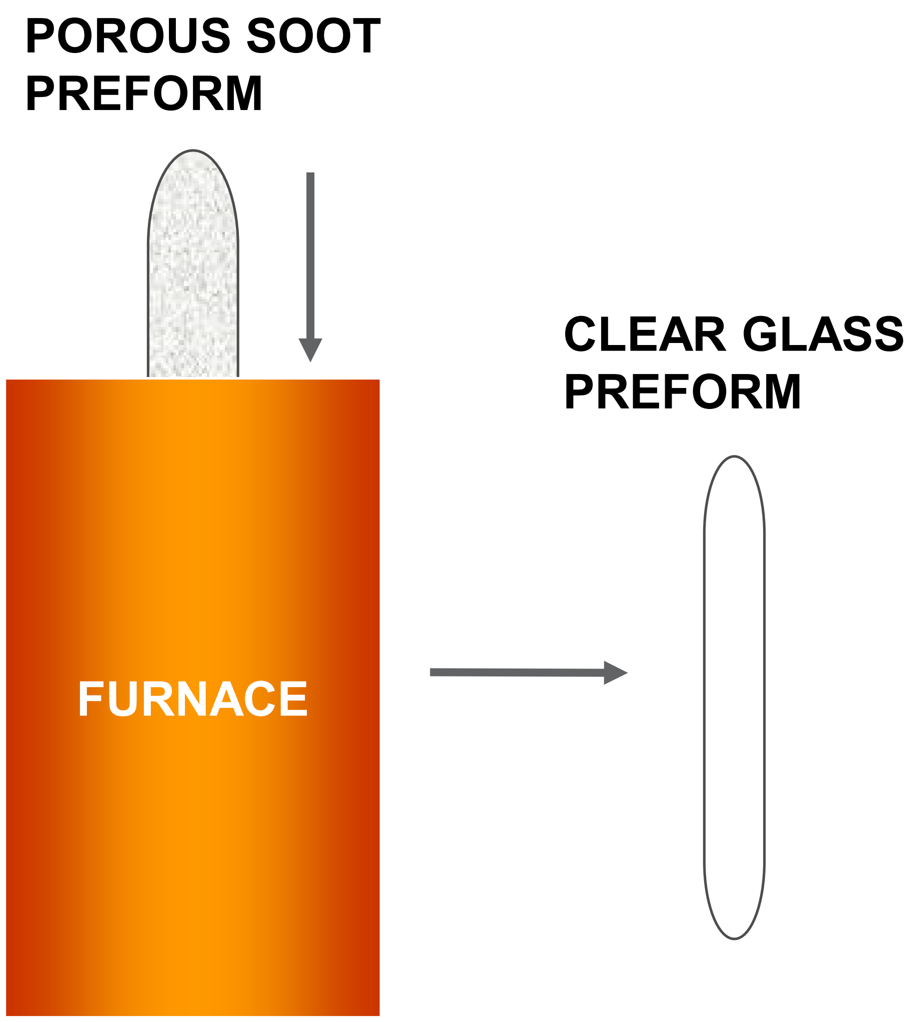
OVD Laydown Process



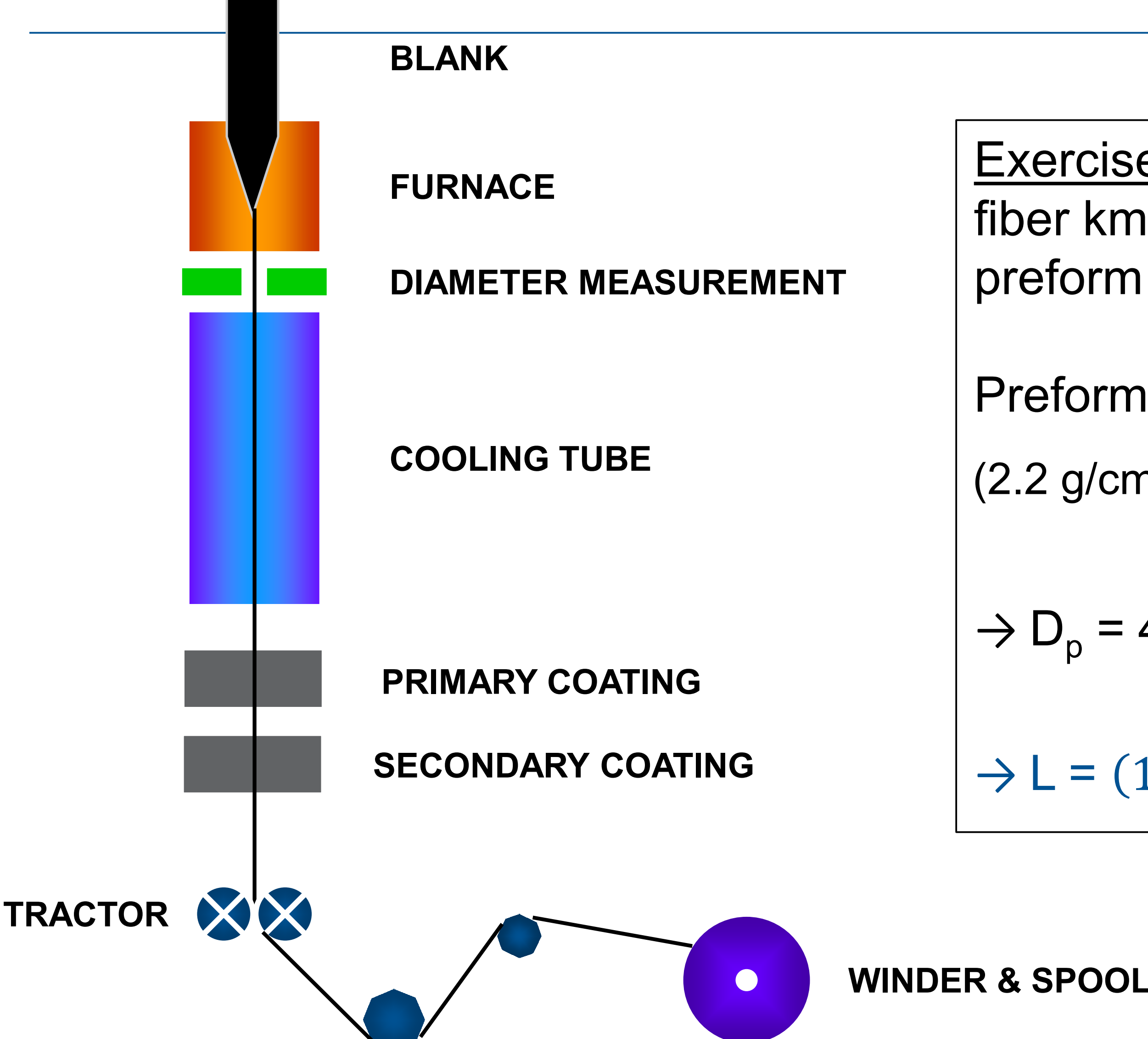
- Evaporated liquid metal halides are oxidized in a flame and deposited radially under computer control onto a rotating target rod
- Byproducts include H_2O and HCl
- Each time the burners traverse over the target, a new layer of soot is deposited
- The process builds the refractive index profile (RIP)

OVD Preform Consolidation

- Start with a “wet” soot preform with low density (typically < 0.5 g/cm^3)
- Preform is dried and consolidated in a furnace
- Process yields a dry glass preform with a density of ~2.2 g/cm^3
- Dopants such as Fluorine can be incorporated to change the refractive index



Simplified Fiber Draw Schematic



Exercise: What is maximum fiber km obtainable from a 1 m preform with a mass of 3000 g:

Preform diameter = D_P

$(2.2\ \text{g/cm}^3)\left(\frac{\pi}{4} D_P^2\right)(100\ \text{cm}) = 3000\ \text{g}$

$\rightarrow D_p = 4.17\ \text{cm} = 41.7\ \text{mm}$

$\rightarrow L = (1\ m)\left(\frac{41.7}{0.125}\right)^2 = 111\ \text{km}$

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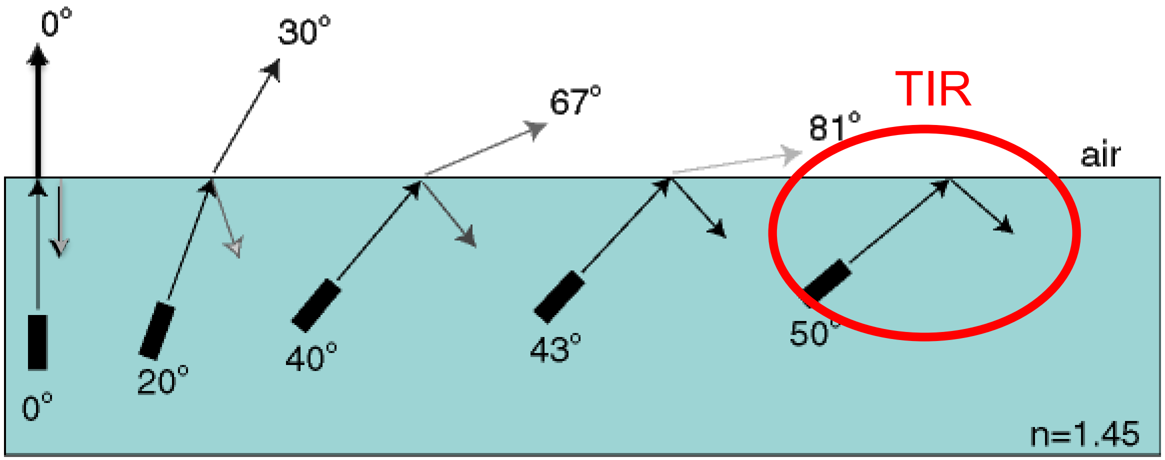
Optical waveguides exploit the phenomenon of total internal reflection (TIR)



θ_r	0°	20°	40°	43°	50°
R_s	4%	5%	25%	57%	100%
R_p	4%	2%	4%	30%	100%

For small angles most of the light is transmitted

For angles near 43° most of the light is reflected

For angles >43° **all** of the light is reflected → **TIR**

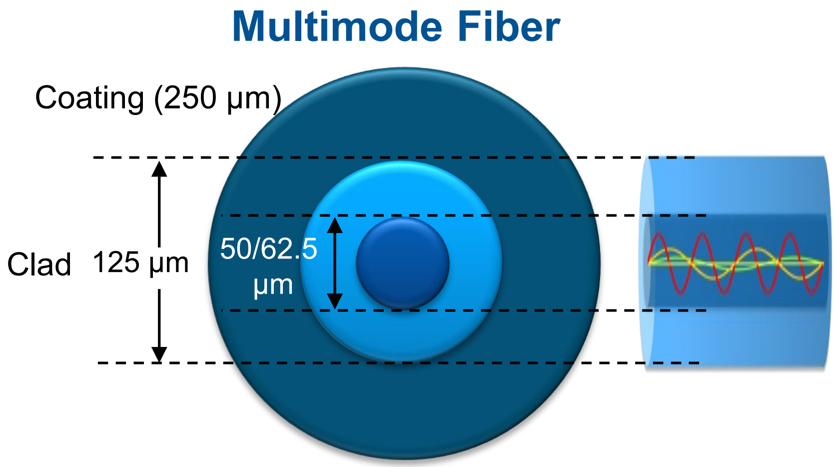
Critical angle for silica(n_1)/air(n_2) interface:

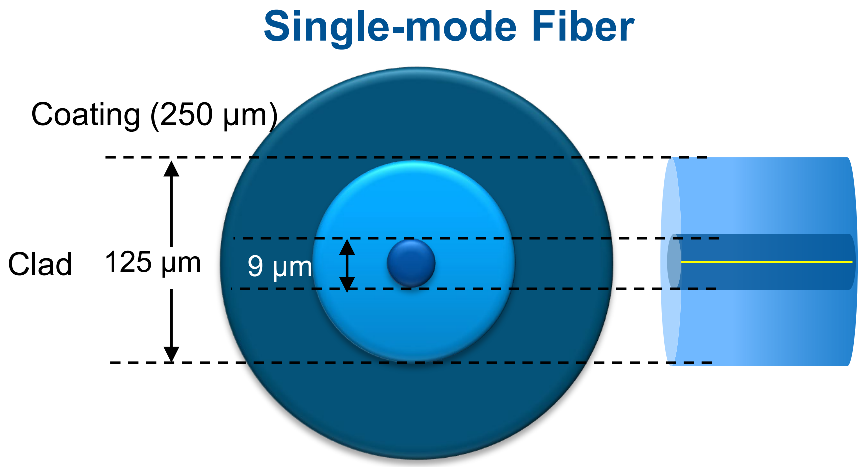
- $\sin(\theta_c) = n_2/n_1$
- $\theta_c = 43.6°$

SM Fiber: $\theta_c = 85°$

- TIR is a consequence of reflection/refraction when going from a high index material to a low index material
- In an optical fiber, small difference in refractive indices between the core and the cladding determine the strength of waveguide

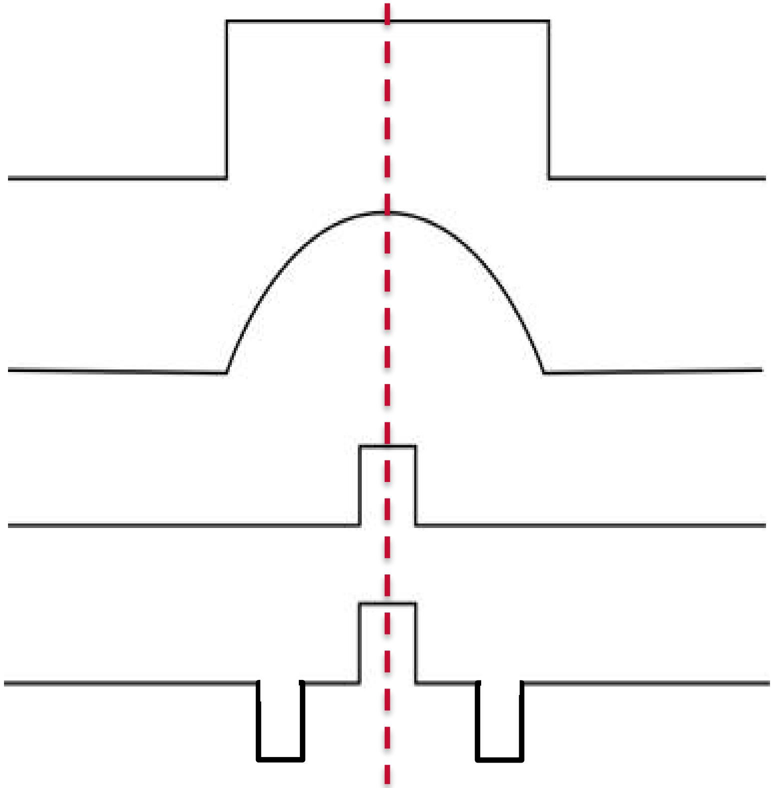
Multimode Fiber vs. Single-mode Optical Fiber





- MMF supports (or can support) many modes; single-mode fiber supports only one mode
- Laser sources couple into many modes in a MMF; these modes propagate along different paths in the core
- The number of modes is determined by the relative refractive index and the core diameter
- Small core of single-mode fiber ensures that only one mode (the “fundamental” or LP01 mode) propagates above the cut-off wavelength

Core + Cladding form the Refractive Index Profile



Multimode step-index

Multimode graded-index

Single-mode step-index

Bend-insensitive single-mode

- Optical properties of fiber are determined by the cylindrically symmetric refractive index profile
- More complex profiles can shift the dispersion, increase the effective area, improve bend performance, etc.

Refractive Index Profile Notation

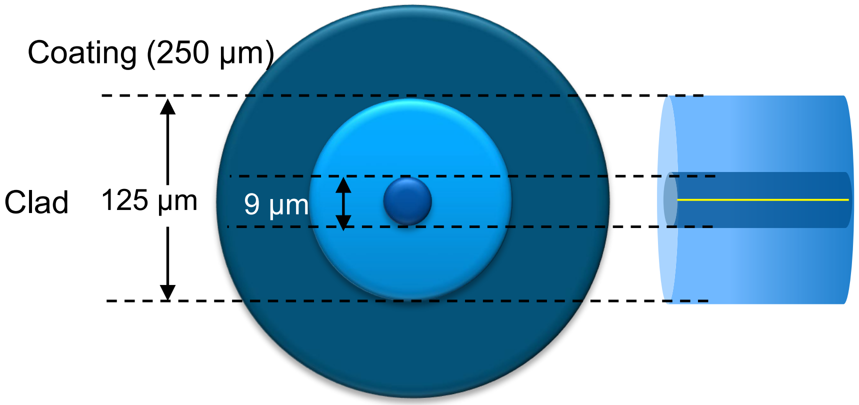
- Refractive index profile is a designed modification of the refractive index of an optical waveguide

$$\Delta(r) = \frac{n^2(r) - n_2^2}{2n^2(r)} \approx \frac{n(r) - n_2}{n(r)}$$

$$\Delta n(r) = n(r) - n_2$$

- $\Delta(r)$ is the relative refractive index, normalized by n(r)
- Example: step-index single-mode fiber with core radius r_c
  - n_1 ($r \leq r_c$) ≈ 1.4491 (core)
  - n_2 =1.444 (cladding)
  - $\Delta(r \leq r_c) \approx 0.0035 = 0.35\%$
  - $\Theta_c = 85°$

Single-mode Fiber



Sellmeier equation describes the material dispersion

- Effect of dipole resonances in the glass medium
- Three terms are typically used for pure silica:

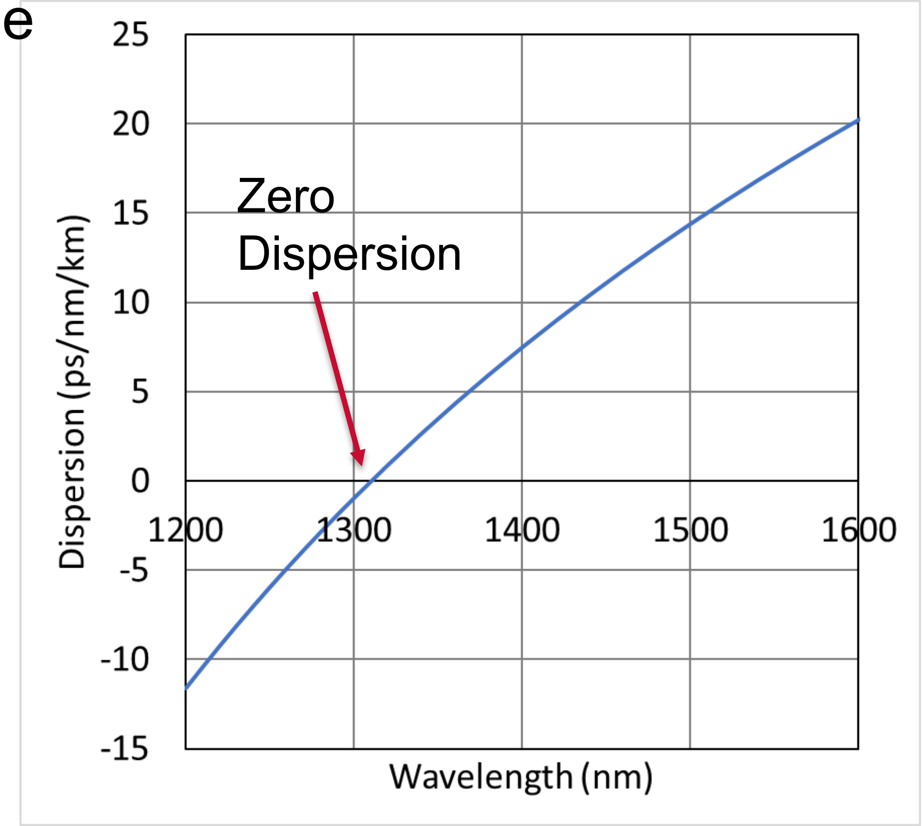
$$n^2 - 1 = \sum_{i=1}^{3} \frac{a_i}{1 - (\lambda_i/\lambda)^2}$$

n : refractive index

λ : wavelength

a_i : oscillator strengths

λ_i : oscillator wavelengths



SiO_2: λ_1 = 0.068 μm, λ_2 = 0.116 μm, λ_3 = 9.90 μm

S. Kobayashi *et al.*, IOOC '77, pp. 309-312

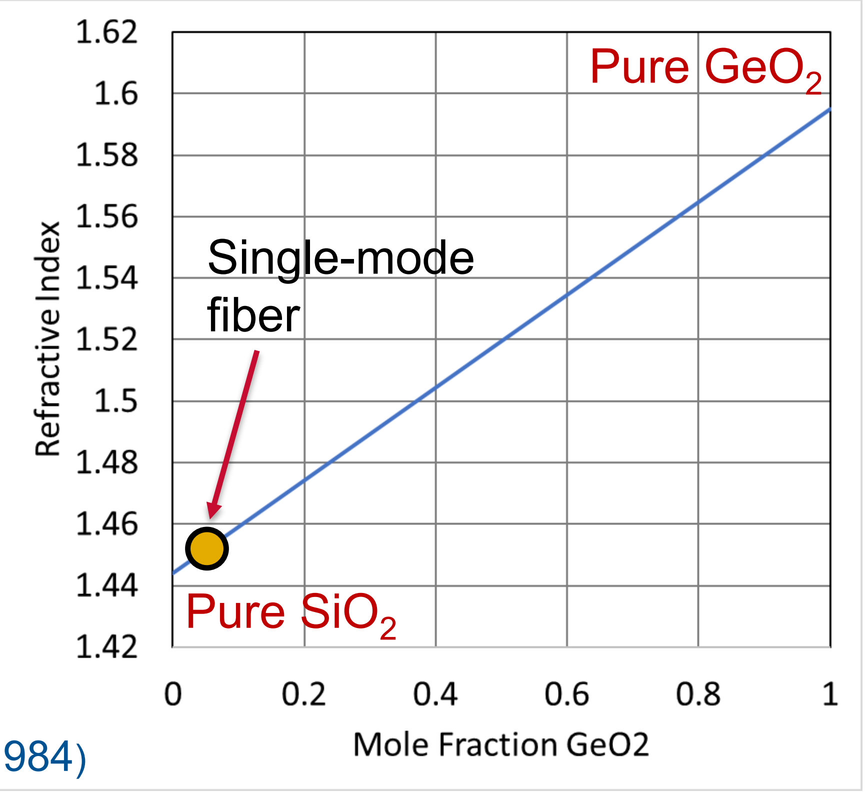
Dopants modify the Sellmeier coefficients

- "Updopants" (e.g. GeO_2, Al_2O_3, P_2O_5, TiO_2, Cl) increase the dispersion
- "Downdopants" (F and B) decrease the dispersion
- GeO_2 and F are most common
- Modified Sellmeier equation:

$$n^2 - 1 = \sum_{i=1}^{3} \frac{a_i(\chi^{Ge}, \chi^F)}{1 - [\lambda_i(\chi^{Ge}, \chi^F)/\lambda]^2}$$

$$a_i(\chi^{Ge}, \chi^F) = a_i^0 + \chi_i^{Ge}\ \delta a_i^{Ge} + \chi_i^F\ \delta a_i^F$$

$$\lambda_i(\chi^{Ge}, \chi^F) = \lambda_i^0 + \chi_i^{Ge}\ \delta \lambda_i^{Ge} + \chi_i^F\ \delta \lambda_i^F$$



J. Fleming, Appl. Opt. **23**, pp. 4486-4493 (Dec. 1984)

Maxwell's equations describe the propagation of electromagnetic energy in waveguides

- First order approximation assumes that the medium is linear, homogeneous, sourceless and isotropic:

$$\nabla^2 \boldsymbol{E} - \mu\epsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0 \qquad \nabla^2 \boldsymbol{H} - \mu\epsilon \frac{\partial^2 \boldsymbol{H}}{\partial t^2} = 0$$

ϵ is the permittivity, μ is the permeability

- For a harmonic wave propagating along z-axis:

$$\boldsymbol{E} = \boldsymbol{E}_0 exp[i(\omega t \pm \beta z + \phi)]$$

where $\beta = \omega / v_p$ is the propagation constant

v_p is the phase velocity

- The wave equation is then: $\nabla_t^2 \boldsymbol{E}_0 + (k^2 - \beta^2)\boldsymbol{E}_0 = 0$

where $k = 2\pi/\lambda$

Fiber designs are optimized solutions of the scalar wave equation (SWE) that solve a problem

- Derived from the wave equation for a waveguide with cylindrical symmetry

$$\frac{d^2\psi}{dr^2} + \frac{2m+1}{r}\frac{d\psi}{dr} + [k^2n^2(r,\lambda) - \beta^2]\psi = 0$$

$\psi\,(r)$ = normalized electric field intensity

$n\,(r, \lambda)$ = local index of refraction

β = propagation constant

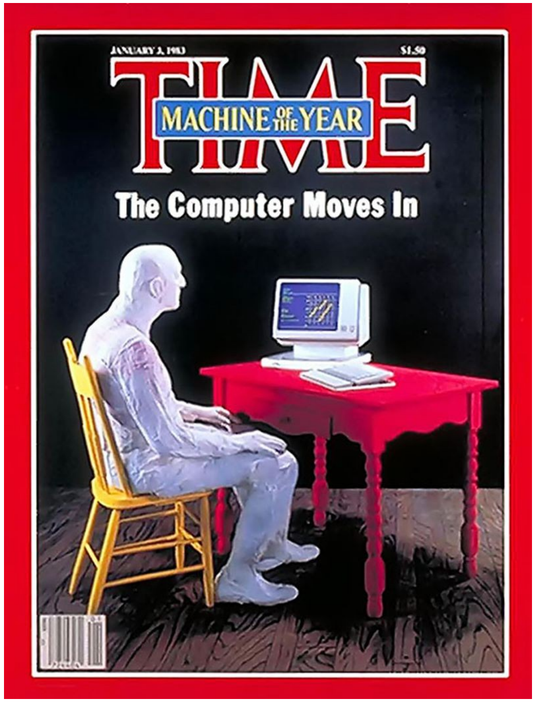
m = integer corresponding to eigen-solution

(*m*=0 for fundamental mode)

- Additional assumptions:
  - weakly absorbing
  - weakly guiding [$n_{core} \cong n_{clad}$, $\Delta(r) << 1$]
  - infinite cladding

Historical Approaches for Solving the SWE

- Can be solved analytically for a step-index profile (next slide)
- Analytical techniques can help understand phenomena such as bend loss, index perturbations and mode-coupling
- Numerical techniques (modeling) became possible with the advent of computers
  - W.L. Mammel and L.G. Cohen, “Numerical prediction of fiber transmission characteristics from arbitrary refractive-index profiles” (1982)
  - T. A. Lenahan, “Calculation of modes in an optical fiber using the finite-element method and EISPACK” (1983)



1982: TIME magazine named the PC its "Machine of the Year"

Exact Analytical Solution for a Step-Index Profile

$$\left.\begin{array}{ll} n_1(r) = n_1, & \Delta(r) = \Delta_1 \\ n_2(r) = n_2, & \Delta(r) = 0 \end{array}\right\{ \begin{array}{l} (0 \le r \le r_1) \\ (r > r_1) \end{array}$$

Normalized frequency (V-number)

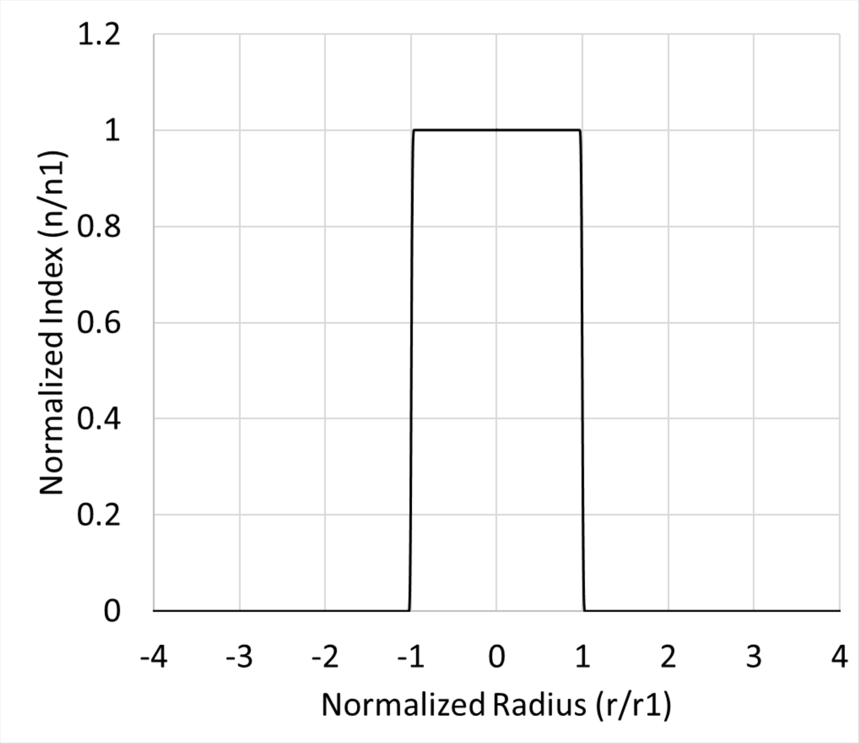
$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi a n_2}{\lambda}\sqrt{\frac{2\Delta}{1 - 2\Delta}}$$

Single mode condition:

$$0 \le V \le 2.405$$

Cutoff wavelength: $\lambda_c = \dfrac{V\lambda}{2.405}$

Core volume: $\dfrac{2\pi a^2 \Delta}{2} \propto V^2$



Solutions are Bessel functions in the core and modified Bessel functions in the cladding

$$E_{x,y} = E_0 \times \begin{Bmatrix} \dfrac{J_0(ur/r_1)}{J_0(u)} & 0 \le r \le r_1 \\ \dfrac{K_0(ur/r_1)}{K_0(u)} & r > r_1 \end{Bmatrix}$$

$$u = r_1\sqrt{n_1^2k^2 - \beta^2}$$

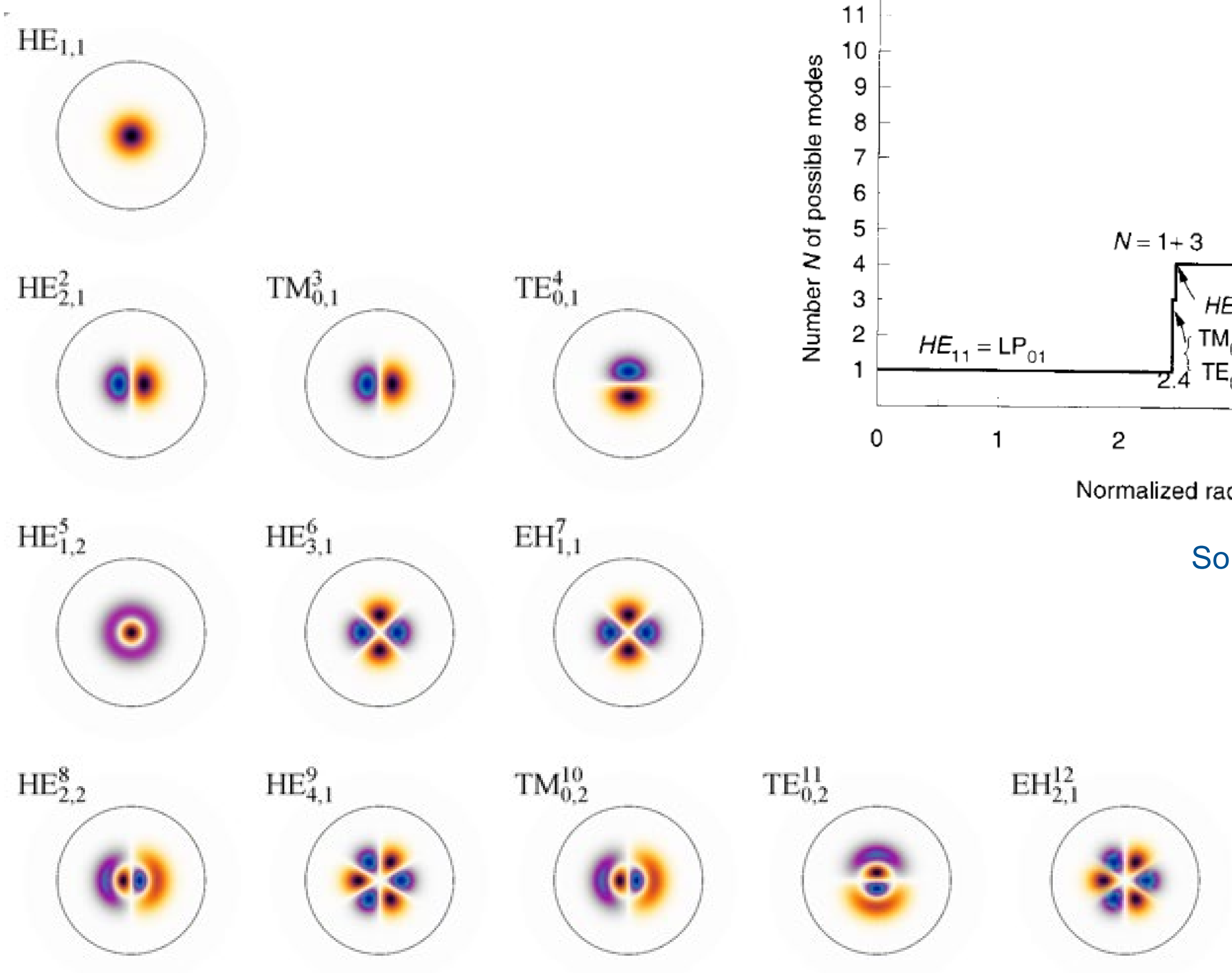
$$v = r_1\sqrt{\beta^2 - n_2^2k^2}$$

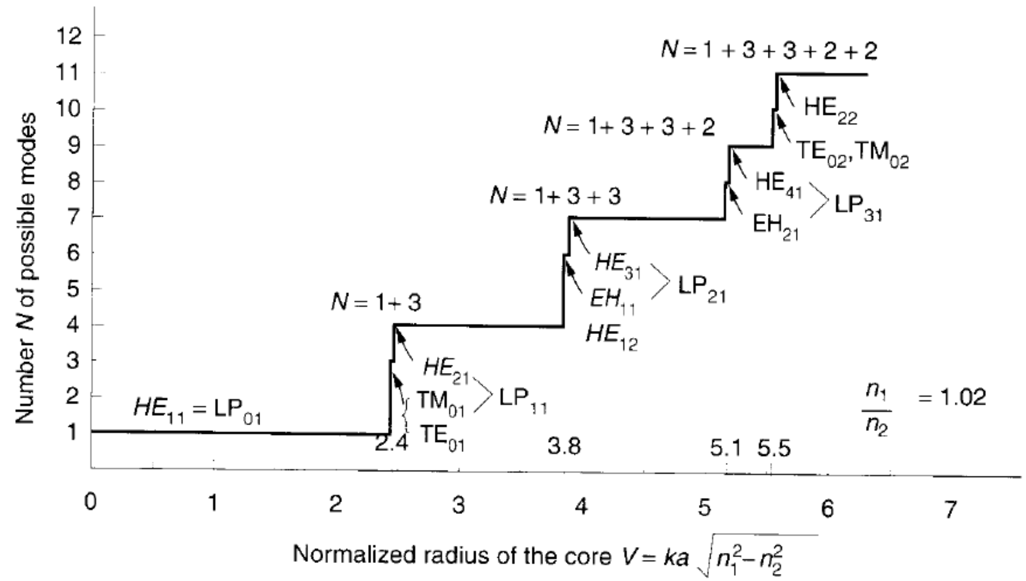
The solutions of the SWE are:

1. Meridional rays pass through the fiber axis and propagate with no ϕ dependence:
   - Transverse Electric ($TE_{0\mu}$)
   - Transverse Magnetic ($TM_{0\mu}$)
2. Skew hybrid rays follow helical paths:
   - $EH_{\nu\mu}$ (electric component is dominant)
   - $HE_{\nu\mu}$ (magnetic component is dominant)

- β = propagation constant
- Modified Bessel function describes exponential decay of field in the cladding
- Solutions in the core and cladding must be continuous

Weakly Guided Approximation: Linear Polarized (LP) modes are combinations of meridional and skew modes





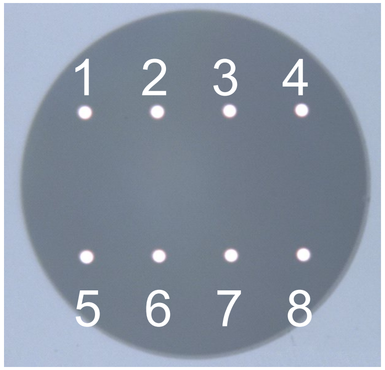
Source: *Elements of Photonics, Vol. 2* (Wiley)

Modern Approaches for Solving the SWE

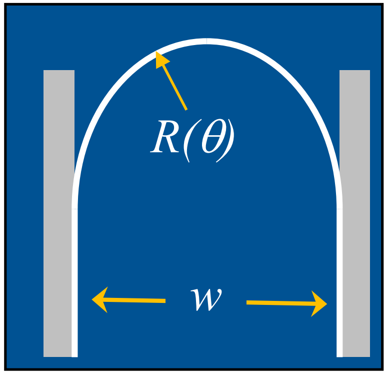
- Fast algorithms can be encoded and run on a PC

$$n(r) \longrightarrow \frac{d^2\psi}{dr^2} + \frac{2m+1}{r}\frac{d\psi}{dr} + [k^2n^2(r,\lambda) - \beta^2]\psi = 0 \longrightarrow \beta, \psi(r)$$

- Commercial packages for fiber and photonic modeling are available but many fiber designers use proprietary software
- Asymmetric perturbations and more complex waveguide structures require a full vectoral analysis using finite element methods



Multiple cores and macrobend both break the cylindrical symmetry



SWE Solutions for Arbitrary Refractive Index Profile

- Most refractive index profiles can easily be parameterized:
  - Core: Maximum Δ, radius, step- or graded-index shape
  - Updoped ring (segmented core): Maximum Δ, radius, width
  - Downdoped trench: Minimum Δ, radius, width
- Generate n(r) using a small enough step size (<< λ) that captures variations in the RIP and a reasonable truncation of the "infinite" cladding
- Boundary conditions: $\psi \rightarrow 0$ as $r \rightarrow \infty$

$$r = 0: \begin{cases} \psi=1,\ d\psi/dr=0\ (m=0) \\ \psi=0,\ d\psi/dr=1\ (m=0) \end{cases}$$

- The SWE can then be iteratively solved to self-consistently solve eigenvalue equation for $\psi(r)$ and β

Many fiber attributes can be calculated once ψ(r) and β (propagation constant) are determined

- Mode group delays (of a MMF): $$\tau_{lm} = \frac{1}{c}\frac{d\beta_{lm}}{dk}$$
- Dispersion is the wavelength dependence of τ_{lm}: $$D_{lm} = \frac{d\tau_{lm}}{d\lambda}$$
- Mode field diameter and the effective area:

$$MFD = 2\ \left(\frac{2\ \int_0^\infty \psi^2(r) r dr}{\int_0^\infty [d(\psi(r))/dr]^2 r dr}\right)^{1/2}$$

$$Aeff = \frac{2\pi\left(\int_0^\infty \psi^2(r)\ r dr\right)^2}{\int_0^\infty \psi^4(r)\ r dr}$$

- Gaussian intensity profile: $$Aeff = \pi\left(\frac{MFD}{2}\right)^2$$

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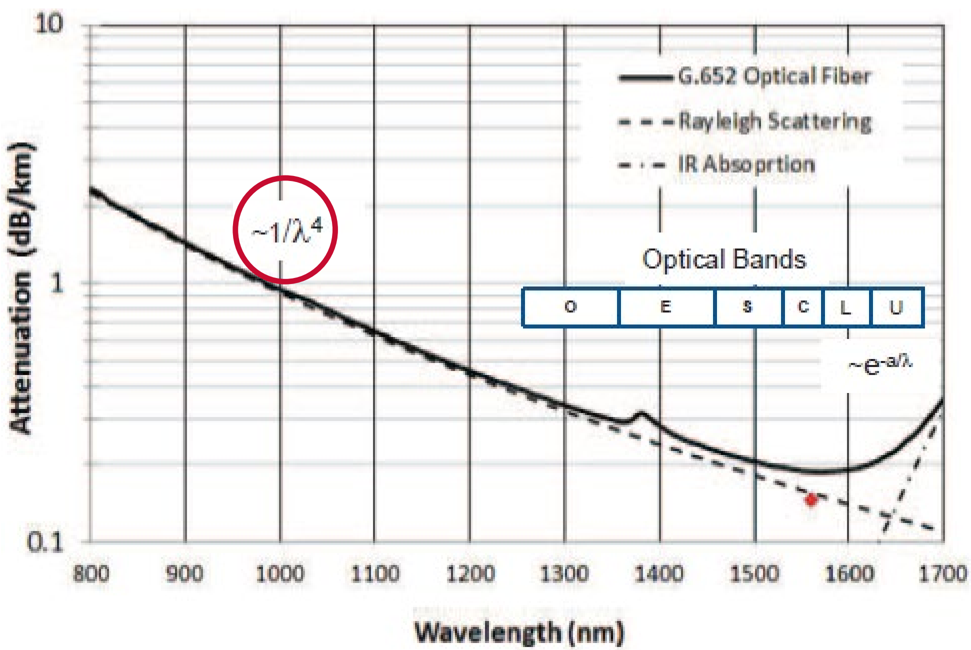
Fiber attenuation is converging to the theoretical limit



Year	Record Attenuation (dB/km)	Attenuation of G.652 at 1550 nm (dB/km)	Wavelngth if not 1550-1600 nm window
1970	20		632.8
1973	5		850
1976	0.47		1200
1979	0.20		
1986	0.154	0.26	
2001	0.152	0.2	
2002	0.1495	0.2	
2004		0.19	
2007		0.18	
2013	0.148	0.17	
2015	0.146		
2018	0.142		

- Majority of transmission applications today use O- and C- bands
- Reduction in Rayleigh scattering has provided the largest improvement in attenuation

S. Ten, "Ultra Low-loss Optical Fiber Technology", OFC 2016, Paper Th4E.5

Contributions to Optical Fiber Attenuation

- The total attenuation of an optical fiber is a sum of different attenuation components with unique spectral dependences

$$\alpha = \alpha_{RS} + \alpha_{OTHER} = \alpha_{RS} + (\alpha_{IR} + \alpha_{UV} + \alpha_{TM} + \alpha_{OH})$$

α_{TM} = transition metal impurities (largely eliminated)

- Rayleigh contributions includes density and concentration fluctuations: $\alpha_{RS} = \alpha_{\rho} + \alpha_{c}$
- Density fluctuations depend on the fictive temperature, T_f:

$$\alpha_{\rho} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_T k_B T_f$$

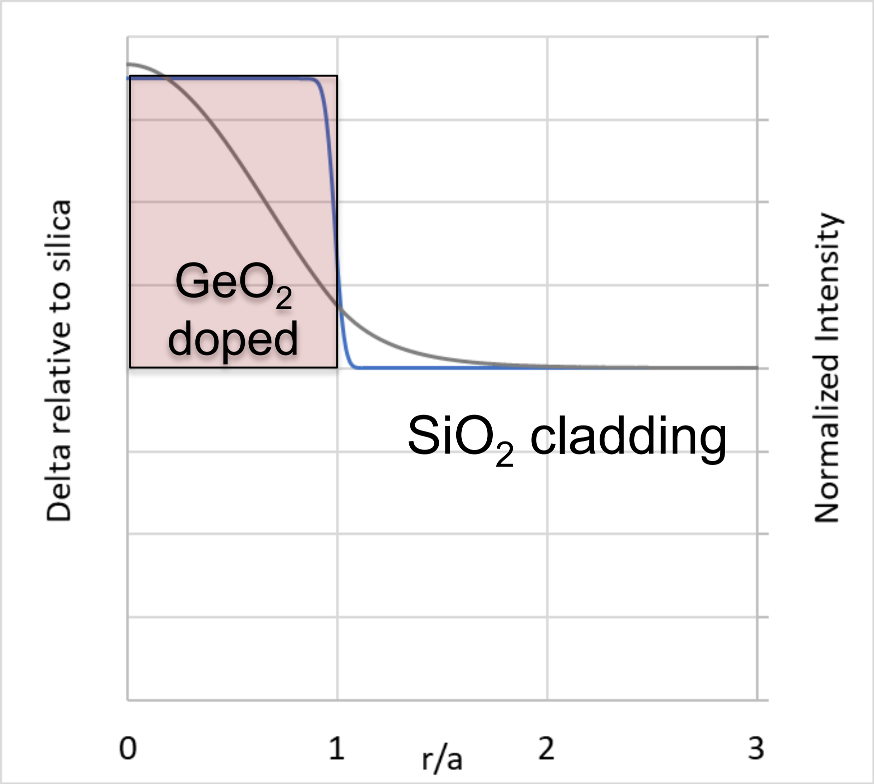
- Dopants such as Ge add concentration fluctuations:

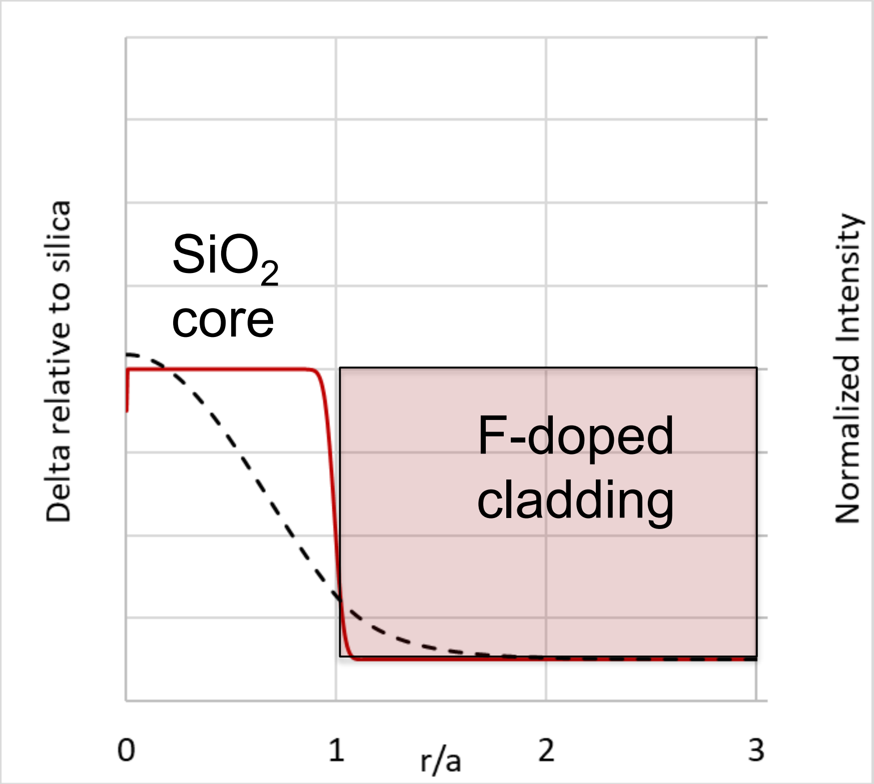
$$\alpha_c \sim \frac{1}{\lambda^4}\left(\frac{\partial n}{\partial C}\right)^2 \langle \Delta C^2 \rangle T_f$$

c.f. K. Tsujikawa, J. Lightwave Tech. 18, pp. 1528-1532 (2000)

Pure silica core shifts α_c contribution to the cladding

- Concentration fluctuations are unavoidable in glass
- A pure silica core shifts dopants to the cladding region where the optical field has much lower intensity





Role of residual stress in fiber attenuation

- Draw tension is due to the shear stress in the molten neckdown region
- Residual stress after cooling is:

$$\sigma_1 = \frac{A_2E_2}{A_1E_1 + A_2E_2}\frac{F}{A_1}\left(1 + \frac{\eta_2A_2}{\eta_1A_1}\right)^{-1}$$

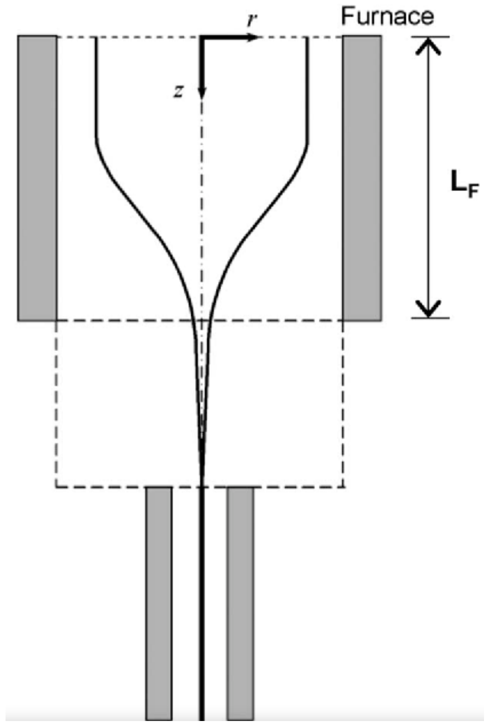
F = Draw tension

E = Young's modulus

A = Cross-sectional area

η = Viscosity

1/2 subscripts refer to core/clad



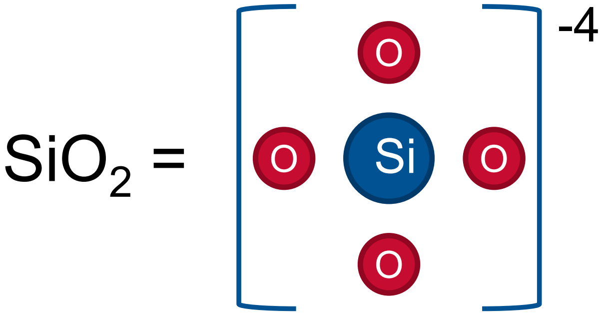
- SiO_2 core/F-doped cladding: $\eta_1 \gg \eta_2$
- Ge-doped core/SiO_2 cladding: $\eta_2 \gg \eta_1$
- Single-mode fiber: $A_2 >> A_1$

Hibino *et al*., Appl. Phys. Lett. **50** (1987)

Density Fluctuations and Fictive Temperature

- Fictive temperature T_F:
  - Related to the temperature at which the molten glass is quenched
  - Depends on the viscosity and time/temperature history
- Density fluctuations: thermal vibrations of molecules in the glass
  - partially frozen into the glass matrix when the drawn fiber is quenched
- Annealing can facilitate further structural relaxation and reduce T_F

- Basic building blocks of amorphous SiO_2 are 6-fold coordinated rings with random orientations
- Si and O prefer to form single bonds in silica but there are also double bonds



- 3-, 4- and 7-fold coordinated rings create local density fluctuations

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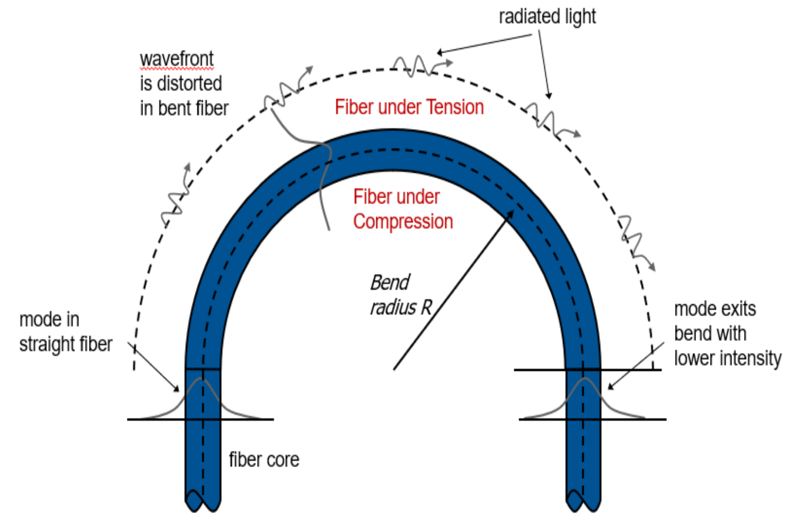
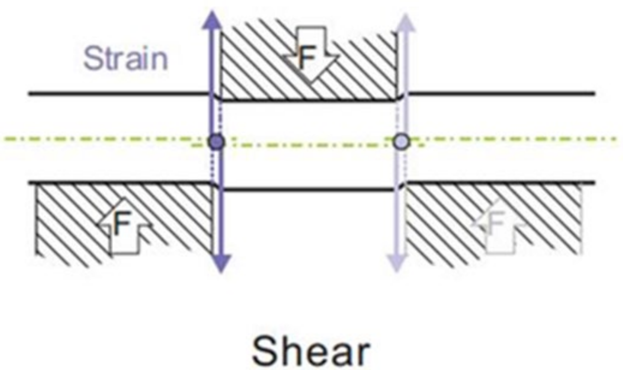
Bending Contributions to Optical Link Loss

Macrobend	Macrobend is a bend that is large compared to the fiber diameter which places the outside of the bent fiber under tension, reducing the relative refractive index of the core and allowing light to leak into the cladding.

Light radiates away from direction of bend:

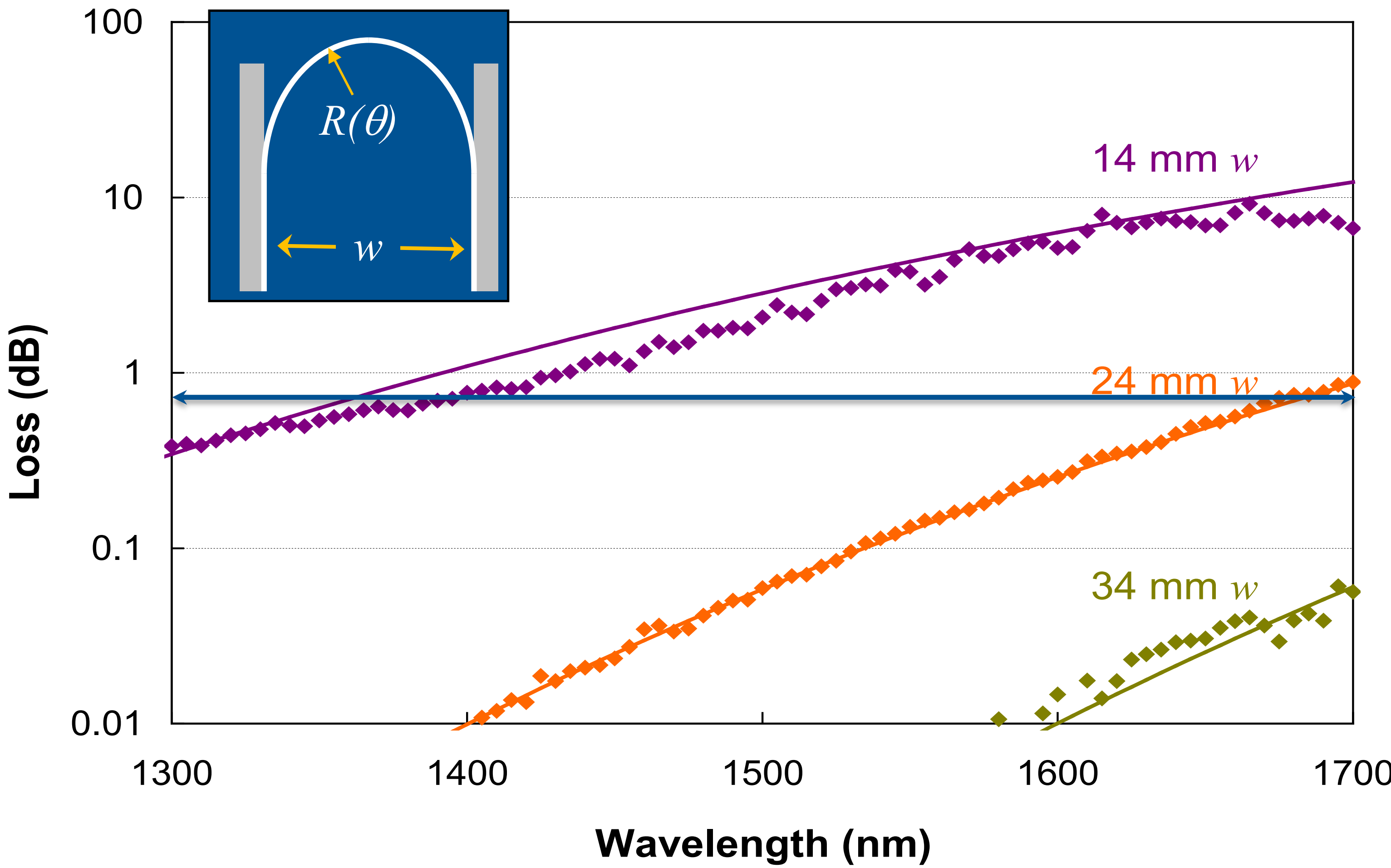


Microbend	Microbend is the loss in the signal intensity due to small distributed lateral (shear) forces on the fiber.



Macrobend: Fiber bent at diameter >> 0.25 mm

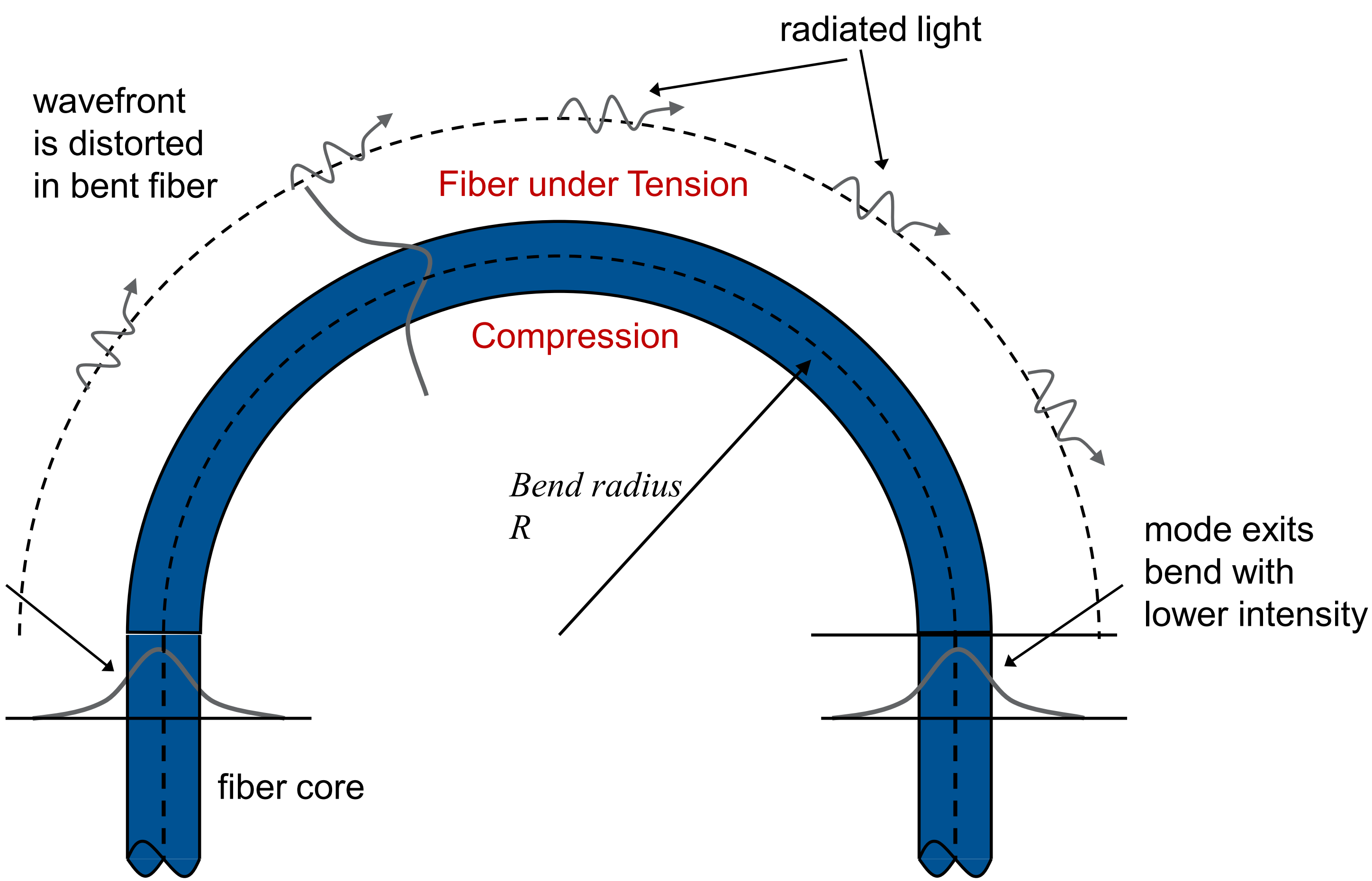
Example: Parallel Plate Bend Loss Measurement



G.657.A1: 0.75 dB max at 20 mmϕ, 1550 nm

Phenomenological Picture of Macrobending

Light radiates away from direction of bend:

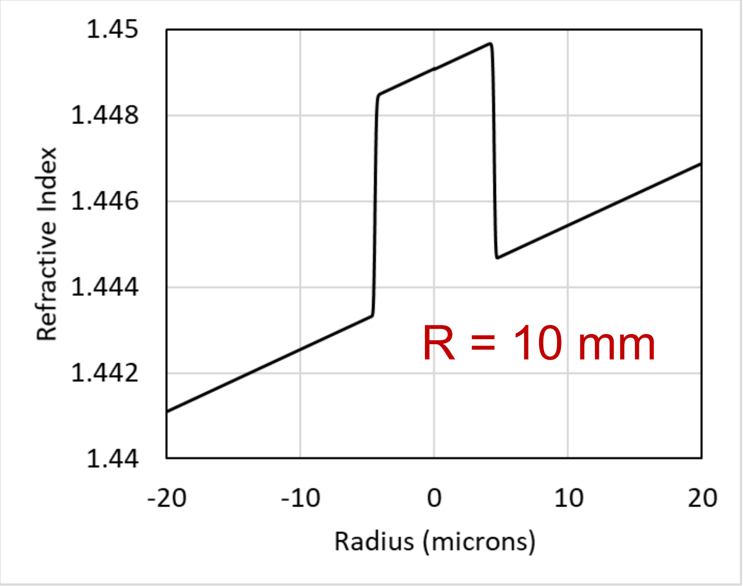


Scalar Wave Equation for a Bent Fiber

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r}\frac{\partial E}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E}{\partial \phi^2} + \left[k_0^2 n^2 \left(1 + \frac{2r}{R}\cos\phi\right) - \beta^2\right] E = 0$$

- Solution assumes bend condition is a perturbation with R/a >> 1
- Normal SWE is restored in straight fiber (bend radius R → ∞)
- The effective refractive index is now "tilted" by an amount inversely proportionally to the radius of curvature:

$$n_{eff}^2 = n^2 \left(1 + \frac{2r}{R}\cos\phi\right)$$



- ϕ = 0 at outside of bend
- $\phi = \pi$ at inside of bend

D. Marcuse. "Influence of curvature on the losses of doubly-clad fibers," Applied Opt. Vol. 21, 4208 (1982).

Meaning of the Tilted Effective Refractive Index

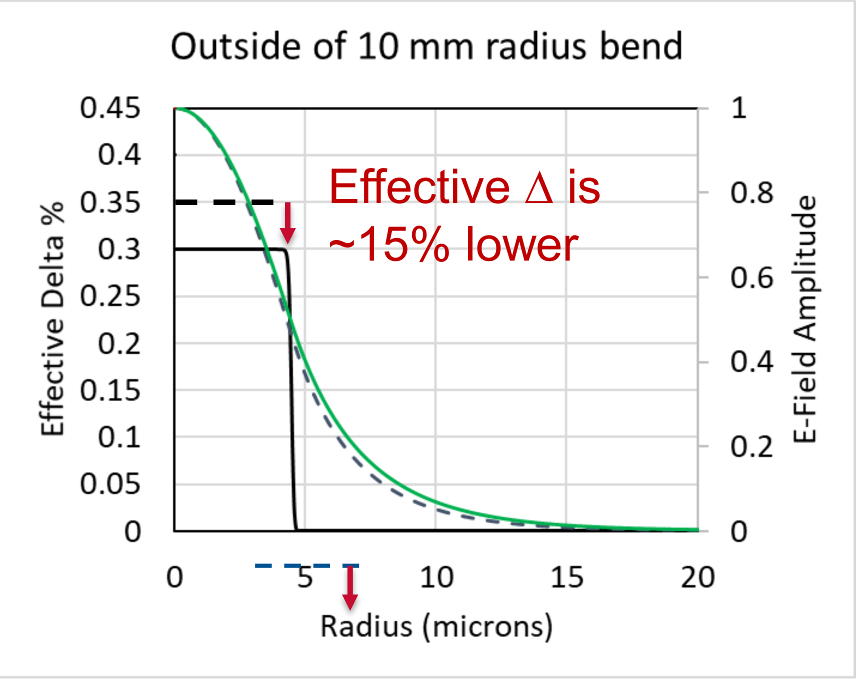
<u>Possible point of confusion</u>

- If the effective refractive index is higher at the outside of the bend, why does the energy radiate outward?

→ The effective cladding index is also higher at the outside of the bend

- Effective delta is lower
- Effective MFD is higher
- More power in cladding

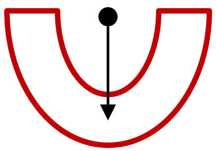
Weaker mode confinement

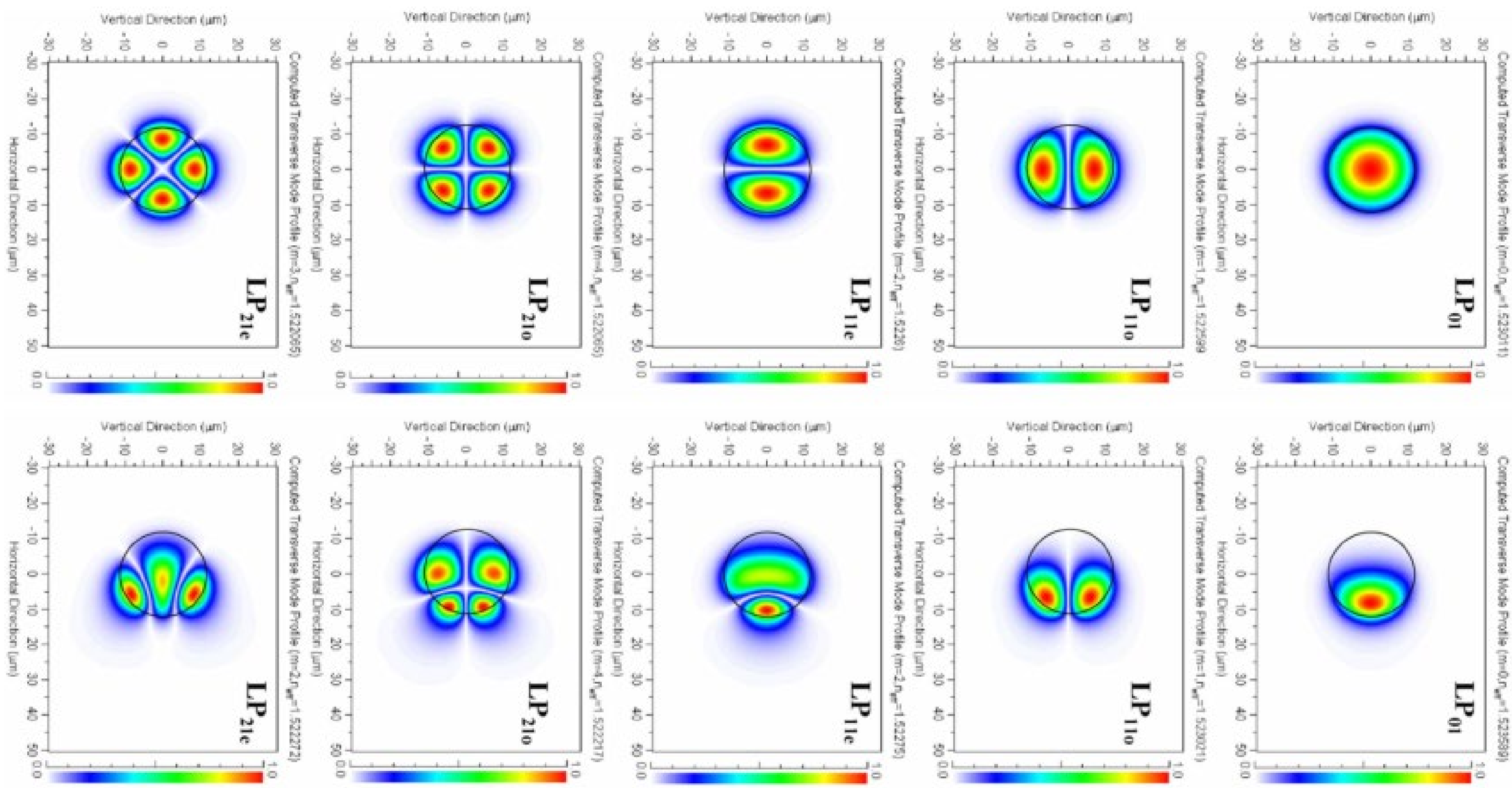


- Converse is true at inside of bend

Modeling: Simulated Optical Field Distortion in a Bent Fiber Using a Beam Propagation Model (BPM)

Bend axis





Ross T. Schermer and James H. Cole, "Improved Bend Loss Formula Verified for Optical Fiber by Simulation and Experiment" (2007)

Key Take-aways

- 2020 marks the 50th anniversary of the fabrication of the first low-loss optical fiber
- Fiber designs and manufacturing processes continue to evolve to address new transmission technologies and application spaces
- The fabrication of optical fibers with attenuation close to the theoretical limit has required synergy between fiber design, coating expertise and process development

Thank you for your kind attention!

CORNING