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Silver / Polystyrene Coated Hollow Glass Waveguides for the Transmission of Visible and Infrared Radiation

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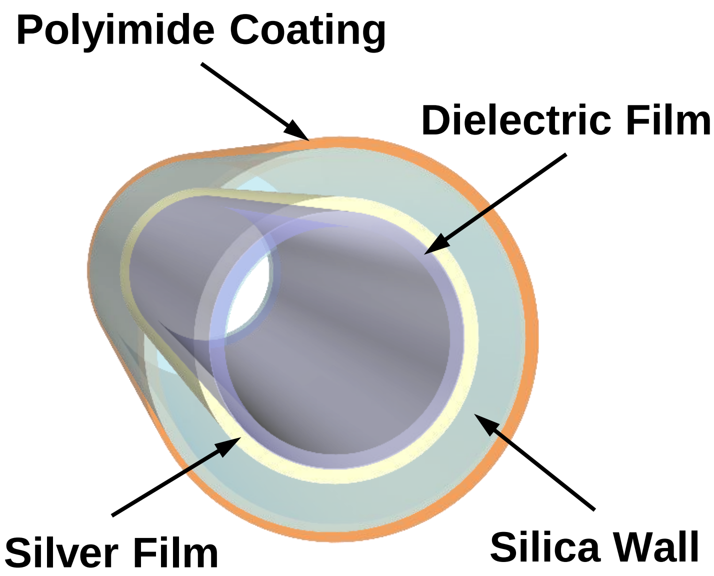
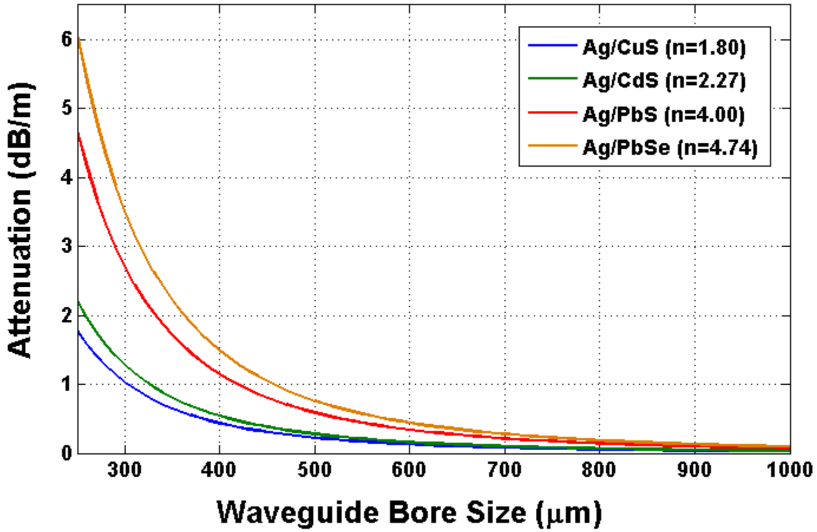
- Used in the low loss broadband transmission from λ = 1 – 16 μm
- Light propagation due to enhanced inner wall surface reflection



- Structure of HGWs
  - SiO_2 capillary tubing substrate
  - Ag film ~200 nm thick
  - Dielectric(s) such as AgI, CdS, PbS
  - Multilayer structures of interest

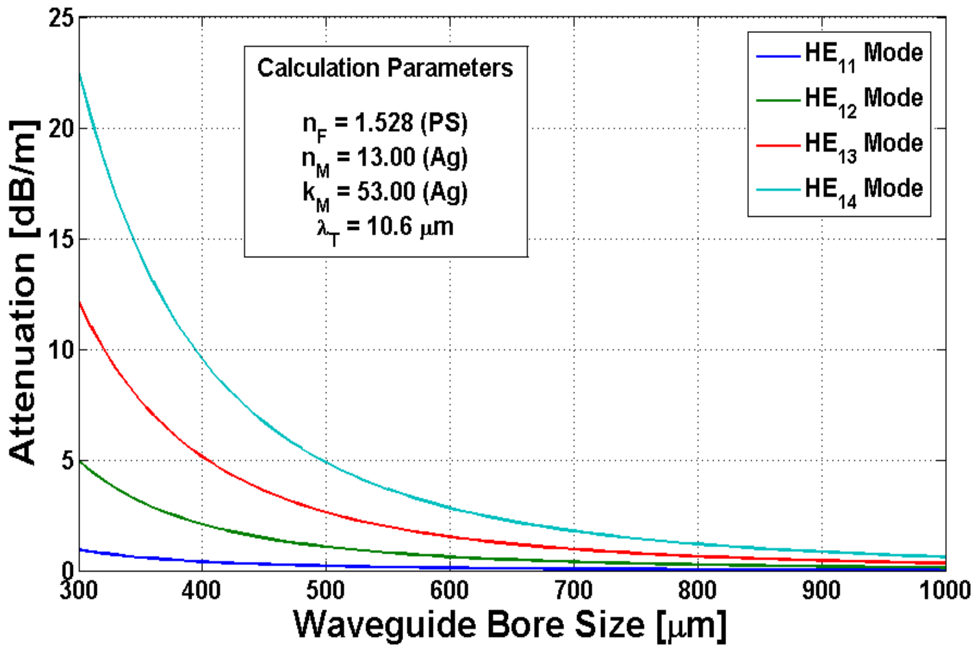


- Theoretical loss dependence *
  - ∝ $1/a^3$ (a is bore radius)
  - ∝ $1/R$ (R is bending radius)

* Harrington, J. A., Infrared Fiber Optics and Their Applications

Attenuation Considerations in HGWs

- Practical losses in HGWs:
  - Propagating modes
  - Dielectric thin film materials
  - Thickness of deposited films
  - Quality and roughness of films
  - Number of films deposited
  - ↑ Throughout ∝ ↓ mode quality



Wave Optics Attenuation Equation

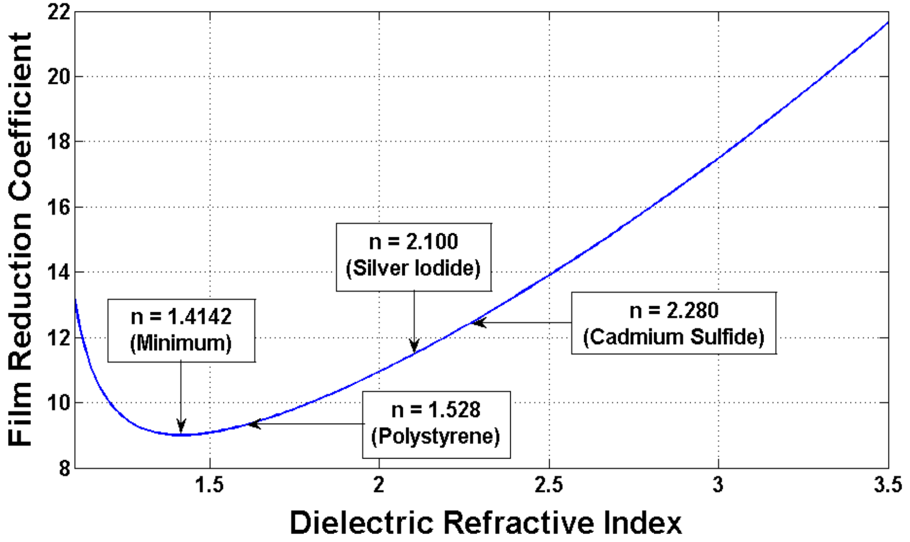
$$\alpha = \left(\frac{u_{nm}}{2\pi}\right)^2 \frac{\lambda^2}{a^3}\left(\frac{n_m}{n_m + k_m}\right) F_{film}$$

u_{nm} = mode parameter
λ = wavelength
a = HGW inner radius size
n_m = metal refractive index
k_m = metal absorption coefficient
F_{film} = film loss reduction term

- F_{film} term dependence on:
  - **Thin film structure**
  - Propagating mode(s)
- TE_{01} mode is lowest loss mode in metal / dielectric coated HWs
- HE_{11} mode is lowest loss mode in metal / dielectric coated HWs

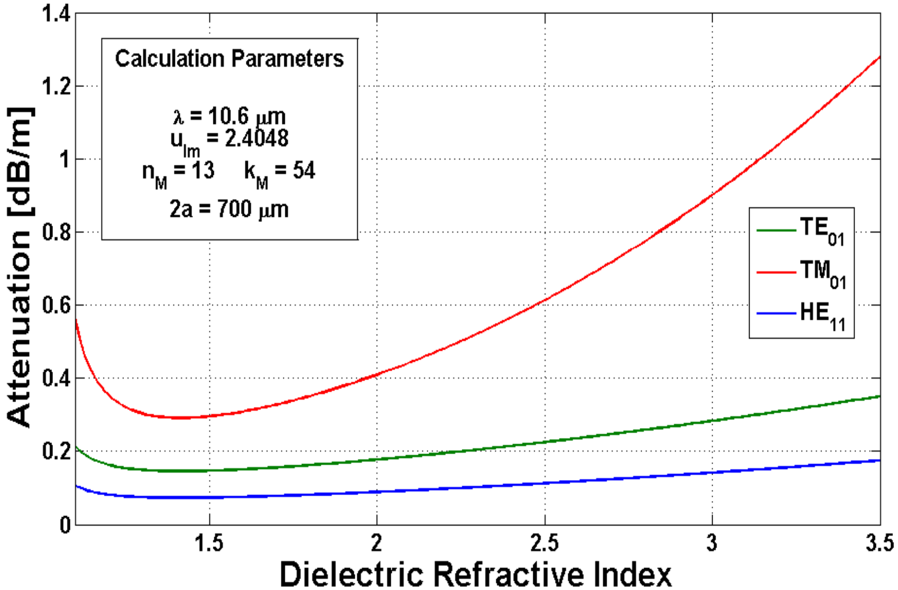
Single Layer Dielectric Thin Films

- Effect of dielectric layer on HGW
  - Constructive thin film interference
  - Reflection enhancement
  - Change in lowest loss mode
    - $TE_{01} \rightarrow HE_{11}$
  - Lower bending losses



Single Dielectric Film Loss Reduction

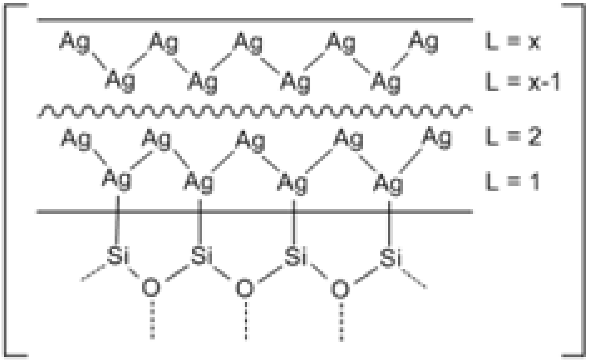
$$F_{film} = \begin{cases} \left(1 + \dfrac{n_d^2}{\sqrt{n_d^2 - 1}}\right) & TE_{0m} \\ \dfrac{n_d^2}{\sqrt{n_d^2 - 1}}\left(1 + \dfrac{n_d^2}{\sqrt{n_d^2 - 1}}\right) & TM_{0m} \\ \dfrac{1}{2}\left(1 + \dfrac{n_d^2}{\sqrt{n_d^2 - 1}}\right) & HE_{1m} \end{cases}$$



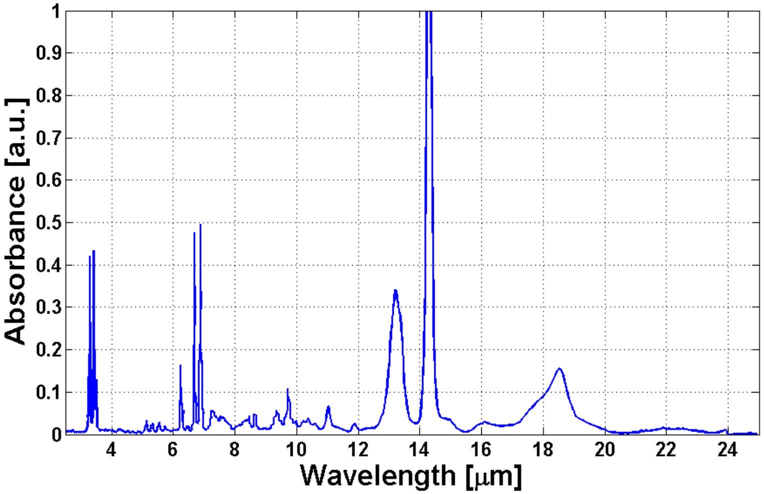
n_d = dielectric refractive index

Advantages of Ag & Ag / PS HGWs

- Advantages of Ag coated HGWs:
  - High laser damage threshold (CW & pulsed laser propagation)
  - No end reflection losses
  - Capable of broadband transmission (air core)
  - Reliability & durability in applications
  - Relatively low manufacturing costs



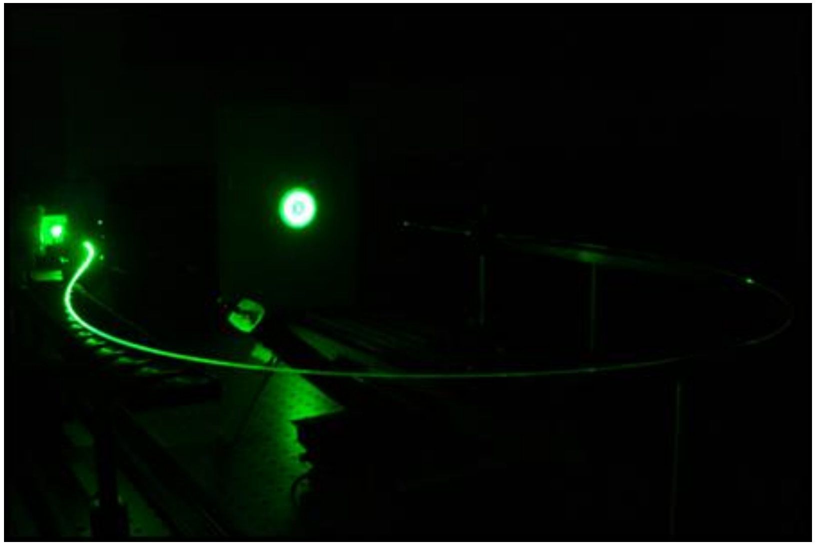
- Advantages of Ag / PS coated HGWs:
  - Close to optimal refractive index of n = 1.414
    - Very low-loss HGW dielectric film material
  - PS transparency from 500 nm to > 100 µm
    - Dielectric for VIS, IR, and THz λ
  - Chemically inert / high durability
  - Protective / optically functional coating
  - Inexpensive material / Non-hazardous
  - HE_{11} mode propagation



Experimental Approach

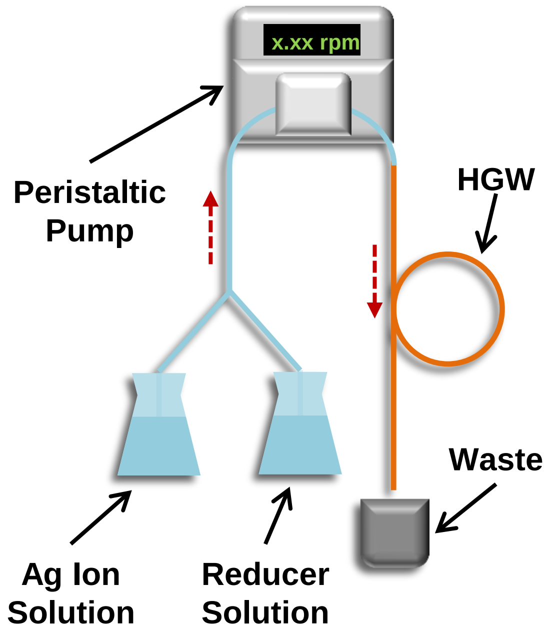
- Research objectives:
  - Optimize Ag deposition procedure to ↓ α
  - Fabrication of low-loss HGWs at visible λ of longer lengths
  - Deposition of PS thin films in Ag coated HGWs for:
    - Low-loss transmission at visible λ (500 – 700 nm)
    - Low-loss transmission at NIR λ (800 – 1500 nm)
    - Low-loss transmission at THz λ (> 100 μm)

- Experimental Approach
  - Dimensionality constant at ID = 1000 μm
  - Optimize Ag deposition procedure by:
    - Varying fabrication parameters
    - Reducing manufacturing defects
  - Deposition of PS dielectric thin films
    - Control of deposition parameters
    - Increase reliability & consistency
  - Characterization to include:
    - FTIR spectroscopy
    - Optical attenuation measurements



Fabrication Methodology of Ag Films

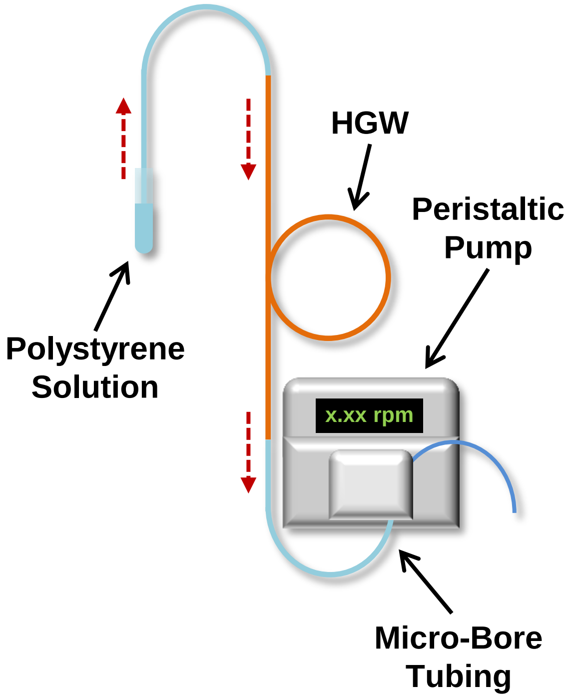
- Films deposited via dynamic liquid phase deposition process (DLPD)
- Factors with major influence on Ag film quality
  - Solution concentrations (particularly Ag ion & reducer solutions)
  - Temperature of solutions (influences film growth rate)
  - Fluid flow rate (optimal flow velocity at ≈ 75 cm/s)
  - Atmospheric lighting (UV exposure results in low quality films)



- Optimization of Ag deposition procedure
  - Improve film quality → lower α at shorter λ
  - Applications at visible & NIR wavelengths
  - Fabrication of longer HGW samples (> 5 m)
- Key experimental parameters
  - Solution concentrations
  - Sensitizing procedure time
  - **Silver deposition time**
  - Fluid flow rate

Fabrication Methodology of PS Films

- Films deposited via modified DLPD procedure
- The DLPD process for deposition of PS films:
  - PS deposition technique based on viscous drag rather than chemical reactions
    - Considerably harder to deposit uniform films along long HGW lengths
  - Vacuum pull technique used to pull polystyrene in organic solvent solution



1. Sn^{2+} Sensitization Step
2. Silver Film Deposition
3. Dielectric Thin Film
   Polystyrene (PS)

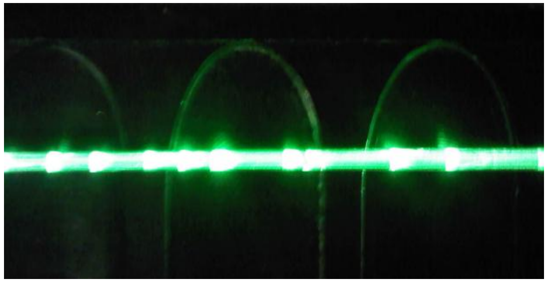
- PS film quality and thickness control
  - Variation of pump pulling rate
  - **Variation of PS solution concentration**
  - Variation of organic solvent used

Optimization of Ag Coated HGWs #1

- Effect of sensitization procedure:
  - Reduction of Ag deposition time from 20 – 30 min → 2 – 3 min (~ 10×)
  - Optimal sensitization parameters:
    - [$SnCl_2$] = 1.55 mM @ pH ≈ 4.3
    - Sensitization time of 5 min followed by 7.5 min drying time

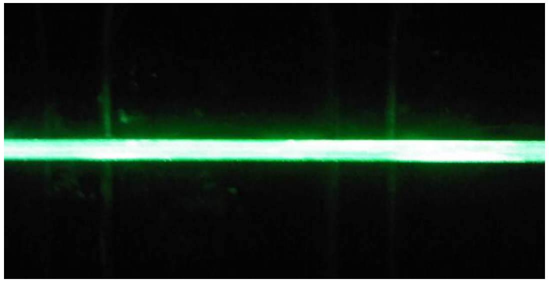
- Effect of deposition fluid flow rate:
  - High correlation between fluid flow rate (VFR) & film quality

Low Fluid Flow Rates



- Occasional 'striping' defects
- Non-uniform film quality
- Localized defects due to flow
- Length varying coating rate
- Generally for VFR < 20 mL/min

High Fluid Flow Rates



- Few or none 'striping' defects
- Uniform film quality
- Reduction of defect occurrence
- Uniform coating rate
- Generally for VFR > 40 mL/min

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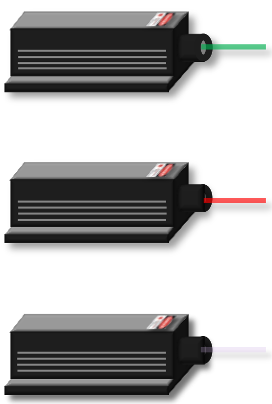
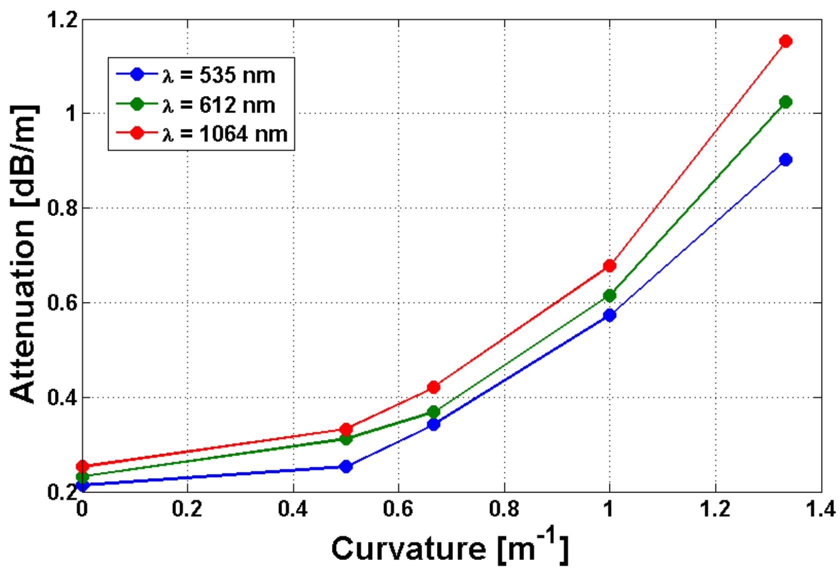
Optimization of Ag Coated HGWs #2

- Effect of Ag deposition time:
  - Minimize Ag deposition time while attaining adequate Ag film thickness
  - Optimal Ag deposition parameters:
    - $[Ag^{2+}]$ = 7.18 mM @ pH ≈ 9.5 $[C_6H_{12}]$ = 1.55 mM
    - Optimal Ag deposition time of 180 – 195 sec at VFR ≈ 45 mL/min

- Attenuation measurements at VIS & NIR wavelengths
  - Loss measurements taken at λ = 535 nm, 612 nm, and 1064 nm



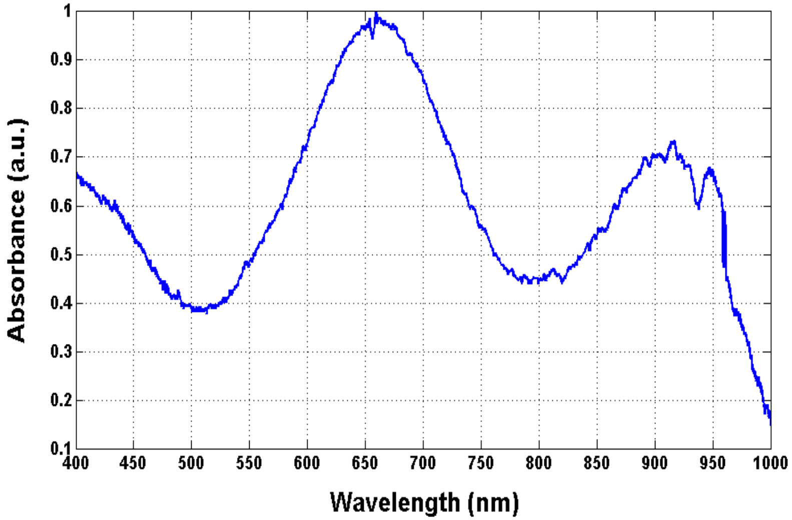


  - Able to fabricate samples at L > 5.0 m with measured α ~ 0.25 dB/m @ λ = 535 nm

* Laser graphics courtesy of Brian T. Laustsen

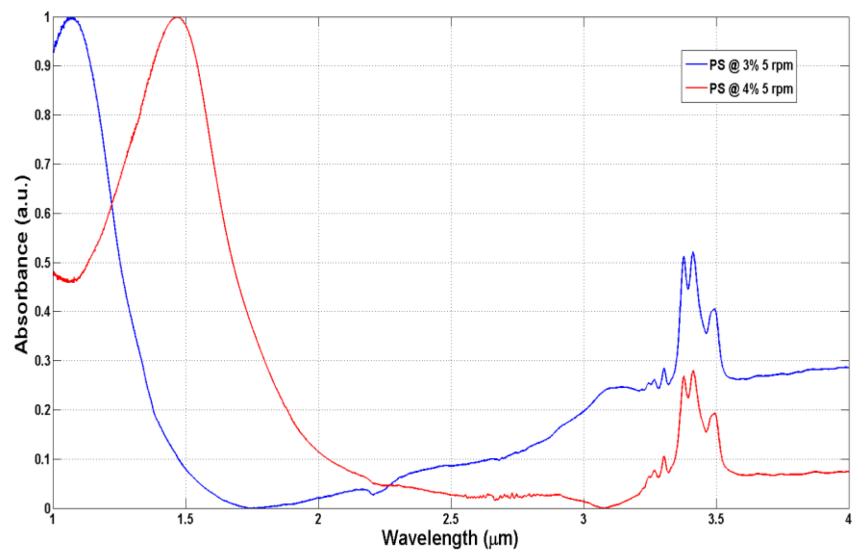
PS Coatings in HGWs for VIS & NIR

- Polystyrene is transparent at VIS & NIR wavelengths



- VIS spectral analysis
  - Uniform PS films at 0.5 & 1 wt % PS
  - PS adequate dielectric for λ = > 500 Nn
  - Film thicknesses: 0.1 – 0.2 μm
  - Attenuation measurements to follow
  - Thinner PS films necessary

- NIR spectral analysis
  - Uniform PS films at 3 & 4 wt % PS
  - PS adequate dielectric for λ = 1 – 3 μm
  - Film thicknesses: 0.2 – 0.6 μm
  - Attenuation measurements to follow
  - Possibility for simultaneous λ T



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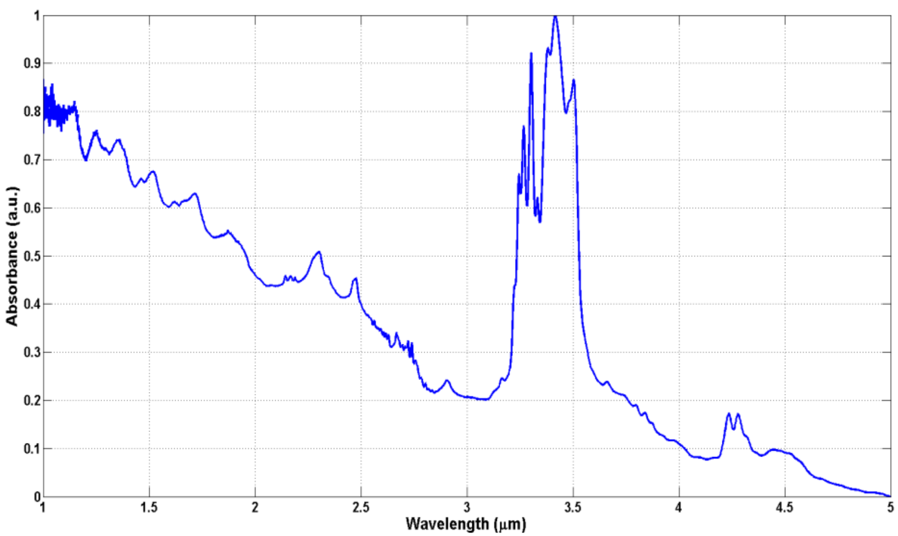
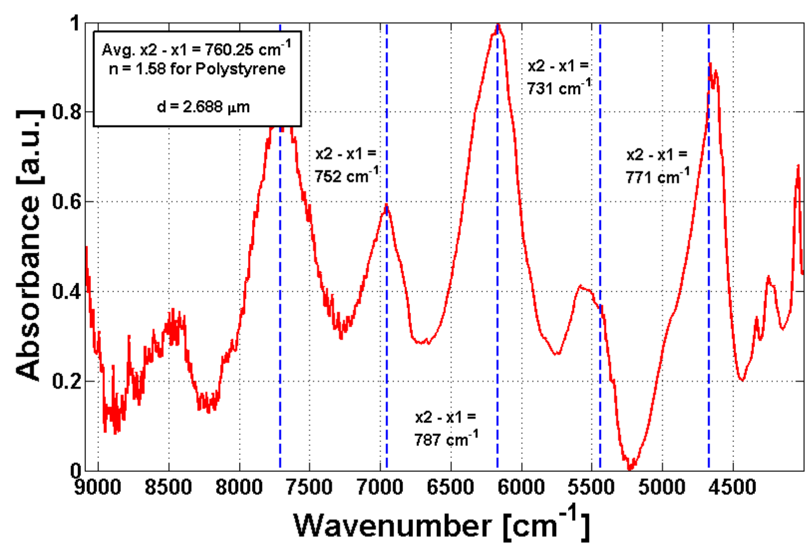
PS Coatings in HGWs for THz

- Polystyrene thin films can be extended for THz λ transmission
- PS thin films of adequate thicknesses for THz transmission deposited
  - Film thicknesses from > 1 μm



$$d = \frac{(k_m - k_{m-1})^{-1}}{4 \cdot \sqrt{n_F{}^2 - 1}}$$

m = interference peak order
k = interference peak wavenumber
n_F = dielectric refractive index

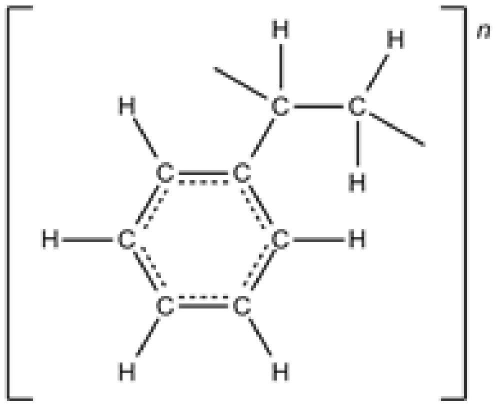


- PS deposition procedure for THz
  - High [PS] solutions (22 – 28 weight %)
  - Thicknesses found through extrapolation
  - Losses ~ 1.5 dB/m at 2.9 THz

Conclusion

- Substantial improvement of Ag coated HGWs
  - Improvement of Ag film quality through fabrication optimization
  - Considerable decrease in loss at VIS & NIR wavelengths
  - Fabrication of low-loss HGWs > 5 m in length
  - Necessary reproducibility achieved
  - High power (> 1 MW) laser delivery attained
    - Pulsed laser at λ = 535 nm

- PS coatings in HGWs:
  - Successful deposition of PS thin films via DLPD
  - Further film quality control necessary
  - Continue development of coating techniques
  - Promising measured losses at THz frequencies



- Future research:
  - Continue improvement of PS thin film deposition procedure
    - Acquire consistent solution concentration / film thickness dependency
  - Comparison of Ag/PS HGWs vs. Ag HGWs at VIS & NIR λ
  - Fabrication of Ag/PS HGWs capable of low-loss THz λ delivery

Thank you for your attention!

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