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

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Background on Hollow Glass Waveguides

- Used in the low loss broadband transmission from $\lambda = 1 - 16 \, \mu m$
- Light propagation due to enhanced inner wall surface reflection

**Structure of HGWs**
- $\text{SiO}_2$ capillary tubing substrate
- $\text{Ag}$ film $\sim 200$ nm thick
- Dielectric(s) such as AgI, CdS, PbS
- Multilayer structures of interest

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

* Harrington, J. A., Infrared Fiber Optics and Their Applications
• Practical losses in HGWs:
  – Propagating modes
  – Dielectric thin film materials
  – Thickness of deposited films
  – Quality and roughness of films
  – Number of films deposited
  – \( \uparrow \text{Throughout} \propto \downarrow \text{mode quality} \)

• Wave Optics Attenuation Equation

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

- \( u_{nm} \) = mode parameter
- \( \lambda \) = wavelength
- \( a \) = HGW inner radius size
- \( n_m \) = metal refractive index
- \( k_m \) = metal absorption coefficient
- \( F_{\text{film}} \) = film loss reduction term

• \( F_{\text{film}} \) term dependence on:
  – Thin film structure
  – Propagating mode(s)

• \( \text{TE}_{01} \) mode is lowest loss mode in metal / dielectric coated HWs

• \( \text{HE}_{11} \) 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
    - $\text{TE}_{01} \rightarrow \text{HE}_{11}$
    - Lower bending losses

Single Dielectric Film Loss Reduction

$$F_{\text{film}} = \begin{cases} 
\left( 1 + \frac{n_d^2}{\sqrt{n_d^2 - 1}} \right) \\
\frac{n_d^2}{\sqrt{n_d^2 - 1}} \left( 1 + \frac{n_d^2}{\sqrt{n_d^2 - 1}} \right) \\
\frac{1}{2} \left( 1 + \frac{n_d^2}{\sqrt{n_d^2 - 1}} \right)
\end{cases}$$

$\text{TE}_{0m}$ $\text{TM}_{0m}$ $\text{HE}_{1m}$

$n_d = \text{dielectric refractive index}$
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
• **Research objectives:**
  – Optimize Ag deposition procedure to ↓ $\alpha$
  – Fabrication of low-loss HGWs at visible $\lambda$ of longer lengths
  – Deposition of PS thin films in Ag coated HGWs for:
    • Low-loss transmission at visible $\lambda$ (500 – 700 nm)
    • Low-loss transmission at NIR $\lambda$ (800 – 1500 nm)
    • Low-loss transmission at THz $\lambda$ (> 100 $\mu$m)

• **Experimental Approach**
  – Dimensionality constant at ID = 1000 $\mu$m
  – 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 $\alpha$ at shorter $\lambda$
  - 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
• 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

• PS film quality and thickness control
  – Variation of pump pulling rate
  – Variation of PS solution concentration
  – Variation of organic solvent used
• Effect of sensitization procedure:
  – Reduction of Ag deposition time from 20 – 30 min $\rightarrow$ 2 – 3 min ($\sim 10\times$)
  – Optimal sensitization parameters:
    • $[\text{SnCl}_2] = 1.55 \text{ mM @ pH } \approx 4.3$
    • 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
    – Occasional ‘striping’ defects
    – Non-uniform film quality
    – Localized defects due to flow
    – Length varying coating rate
    – Generally for VFR < 20 mL/min
    – Few or none ‘striping’ defects
    – Uniform film quality
    – Reduction of defect occurrence
    – Uniform coating rate
    – Generally for VFR > 40 mL/min
• **Effect of Ag deposition time:**
  – Minimize Ag deposition time while attaining adequate Ag film thickness
  – **Optimal Ag deposition parameters:**
    - $[\text{Ag}^{2+}] = 7.18 \text{ mM} \at \text{pH} \approx 9.5$
    - $[\text{C}_6\text{H}_{12}] = 1.55 \text{ mM}$
    - Optimal Ag deposition time of 180 – 195 sec at VFR $\approx 45 \text{ mL/min}$

• **Attenuation measurements at VIS & NIR wavelengths**
  – Loss measurements taken at $\lambda = 535 \text{ nm}, 612 \text{ nm}, \text{ and } 1064 \text{ nm}$
  – Able to fabricate samples at $L > 5.0 \text{ m}$ with measured $\alpha \approx 0.25 \text{ dB/m} @ \lambda = 535 \text{ nm}$

* Laser graphics courtesy of Brian T. Laustsen*
- Polystyrene is transparent at VIS & NIR wavelengths

- VIS spectral analysis
  - Uniform PS films at 0.5 & 1 wt % PS
  - PS adequate dielectric for $\lambda = > 500 \text{ Nm}$
  - Film thicknesses: 0.1 – 0.2 $\mu \text{m}$
  - Attenuation measurements to follow
  - Thinner PS films necessary

- NIR spectral analysis
  - Uniform PS films at 3 & 4 wt % PS
  - PS adequate dielectric for $\lambda = 1 – 3 \mu \text{m}$
  - Film thicknesses: 0.2 – 0.6 $\mu \text{m}$
  - Attenuation measurements to follow
  - Possibility for simultaneous $\lambda T$
• Polystyrene thin films can be extended for THz \( \lambda \) transmission

• PS thin films of adequate thicknesses for THz transmission deposited
  – Film thicknesses from > 1 \( \mu m \)

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

- \( m \) = interference peak order
- \( k_m \) = 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
• 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 $\lambda = 535$ 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 $\lambda$
  – Fabrication of Ag/PS HGWs capable of low-loss THz $\lambda$ delivery
Thank you for your attention!