Propagation Loss Optimization in Metal/Dielectric coated Hollow Flexible Terahertz Waveguides

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Introduction

- Security screening
- Remote sensing
- Bio-Medical Imaging

Theory

\[ \alpha_{\text{tot}} = \alpha_{\text{propagation}} + \alpha_{\text{bending}} \]

\[ \alpha(TM_{pq}) = 10 \times \frac{1}{r} \left( \frac{n}{n^2 + k^2} \right) \quad \text{and} \quad \alpha(TE_{pq}) = 10 \times \frac{u^4}{(u^2 - p^2)} \frac{n}{n^2 + k^2} \left( \frac{1}{k_0^2 r^3} + \frac{p^2}{u^4 r} \right) \]

Theoretical Loss as a function of Wavelength for lower order TE & TM modes
Selection of Metal

Skin Depth:

\[ \delta = \sqrt{\frac{2\rho}{\pi f \mu_0}} \]

- \( \rho \) - Resistivity (\( \Omega \)m)
- \( f \) - Frequency = 1.4THz
- \( \mu_0 \) - 4\( \pi \)x10\(^{-7}\) (Henries/meter)

\( \delta_{\text{Ag}} = 0.05\mu\text{m} \) with \( \rho = 1.59 \times 10^{-8} \text{\( \Omega \)m} \); \( \delta_{\text{Au}} = 0.07\mu\text{m} \) with \( \rho = 2.44 \times 10^{-8} \text{\( \Omega \)m} \)

\[ F_{\text{Metal}} = \frac{n}{n^2 + k^2} \propto \frac{1}{\text{Reflectivity}} \]

When \( \lambda = 215\mu\text{m} \)

- \( F_{\text{Ag}} = 0.684 \)
- \( F_{\text{Au}} = 0.878 \)
- \( F_{\text{Al}} = 0.994 \)
- \( F_{\text{Cu}} = 1.159 \)
- \( F_{\text{W}} = 1.965 \)
- \( F_{\text{Pb}} = 2.945 \)

**Mode Coupling**

\[
\eta = \frac{\beta}{(n_0 k_0)^2 r^3} \left( \frac{\omega_0}{r} \right)^2 \exp \left[ -\frac{u_{1q}^2}{2} \left( \frac{\omega_0}{r} \right)^2 \right]
\]

\[
\times \left\{ \frac{1}{1 - \left( \frac{1}{u_{1q}^2} \right) J_1^2 (u_{1q})} \right\} \quad \text{TE}_{1q} \text{ mode}
\]

\[
\frac{1}{J_0^2 (u_{1q})} \quad \text{TM}_{1q} \text{ mode}
\]

Phase Constant \( \beta = \sqrt{(n_0 k_0)^2 - \frac{u_{1q}^2}{r}} \)

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Theoretical coupling coefficients of lower order TE and TM modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Coupling Coefficient at ( \omega_0/r = 0.77 )</th>
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<tbody>
<tr>
<td>TE11</td>
<td>90.3</td>
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<tr>
<td>TE12</td>
<td>0.11</td>
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<tr>
<td>TM11</td>
<td>4.6</td>
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<tr>
<td>TM12</td>
<td>0.02</td>
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</tbody>
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According to Beer-Lambert’s Law,

$$\alpha = \frac{10}{2L} \log \left( \frac{P_{in}}{P_{out}} \right)$$

Modal Characteristics

Input and Output beam profiles of the propagated beam through a 3.2mm Silver coated waveguide
Propagation Loss

Theoretical and Experimental attenuation coefficients as a function of inner bore diameter of silver and gold coated waveguides
Basic Design

Schematic cross section of metal and dielectric coated Hollow-core THz waveguide
Metal & Dielectric Coated Waveguides

\[ \alpha(\text{HE}_{pq}) = 10 \times \frac{u_{pq}^2}{(n_0 k_0)^2 r^3 n^2 + k^2} F_{\text{diel}}; \quad F_{\text{diel}} = \frac{1}{2} \left( \frac{n_d^2}{\sqrt{n_d^2 - 1}} \right)^2 \]

\[ t_{\text{diel}} = \frac{\lambda}{2\pi \sqrt{n_d^2 - 1}} \tan^{-1} \left( \frac{n_d}{\sqrt{4 n_d^2 - 1}} \right) \]

Attenuation coefficient of as a function of bore diameter for lower order HE modes, for TE\textsubscript{11} and HE\textsubscript{11} modes of Silver coated waveguide
Hybrid Mode Coupling

\[ \eta_m = \frac{\int_0^r \exp \left(-\frac{r'}{\omega_0^2}\right) J_0 \left( \frac{r'}{r} \right) r' \, dr'}{\int_0^\infty \exp \left(-\frac{2r'^2}{\omega_0^2}\right) r' \, dr' \int_0^r J_0^2 \left( \frac{r'}{r} \right) r' \, dr'} \quad \text{for } \text{HE}_{1m} \text{ modes} \]

Theoretical coupling coefficients of lower order HE\textsubscript{1m} modes

<table>
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<tr>
<th>Mode</th>
<th>Coupling Coefficient at ( \omega_0/r = 0.64 )</th>
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<td>HE11</td>
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<td>HE12</td>
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<td>HE13</td>
<td>0.14</td>
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<td>HE14</td>
<td>0.09</td>
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</tbody>
</table>

\(^4\text{K. Nubling and James A. Harrington's “Launch conditions and mode coupling in hollow glass waveguides”}

Fabrication

Base Material: Polycarbonate  Metal: Silver, Gold  Dielectric Material: Polystyrene

Fabrication: Liquid Flow Coating Process

Fabrication: dynamic liquid phase coating process
Experimental Setup

Experimental setup for the measurement of Attenuation Coefficient for Metal/Dielectric coated Terahertz waveguides
Modal Characteristics

According to Beer-Lambert’s Law,

\[
\alpha = \frac{10}{2L} \log \left( \frac{P_{in}}{P_{out}} \right)
\]

Input and output beam profiles of the propagated beam through a 3.2mm silver/polystyrene coated waveguide
Propagation Loss

Theoretical and Experimental attenuation coefficients as a function of inner bore diameter of silver and silver/polystyrene coated waveguides
Summary

- Attenuation Characteristics of flexible Terahertz waveguides were studied at 215μm wavelength.

- Propagation loss of less than 1.77dB/m was achieved in metal coated waveguides by coupling the lowest loss TE_{11} mode.

- Transmission loss was reduced by coupling HE_{11} mode into the waveguide.

- Minimal propagation loss of 0.96dB/m was achieved in metal coated waveguides by the addition of dielectric layer.
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