THz-Streaking with Dielectric-Lined Waveguides

Francois Lemery
Klaus Floettmann
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Motivation

- Beam-driven acceleration in dielectric-lined waveguides (DLW) is a possible route toward efficient high-energy particle acceleration.
- The DLW has a notorious beam breakup (BBU) problem; where the beam breaks apart from the dipole mode excitation.

Beam breakup (BBU)
(C. Li et. al PhysRevSTAB.17.091302)
Schematic TDS setup

un-streaked beam size

streaked beam size
Resolution:

assume ideal optics with 90 degree phase advance between TDS and screen

\[
R = \frac{\sigma'_{sc, \text{un-streaked}}}{\sigma'_{sc, \text{streaked}}} = \frac{\sigma'_{TDS, \text{uncor.}}}{\sigma'_{TDS, \text{introduced}}} = \frac{\varepsilon}{\sigma_y} \frac{cp_z}{ekV} = \frac{\varepsilon n m_0 c^2}{\sigma_y ekV}
\]

\[
V = \int E_y(t, z) + c \beta_z B_x(t, z) dz
\]

\[
k = \frac{2\pi}{\lambda}
\]

a high resolution power \(1/R\) requires:
- large integrated voltage \(V\)
- short wavelength, large \(k\)
- large beam size in the structure \(\sigma_y\)
Wavelength scaling of a TDS structure:

S-Band (3 GHz) \hspace{1cm} \text{THz (300 GHz)}

wavelength: \( \lambda = 10 \text{ cm} \quad \lambda = 1 \text{ mm} \)
aperture radius: \( a \approx 0.1 \lambda = 1 \text{ cm} \quad a \approx 0.1 \lambda = 100 \mu \text{m} \)
beam size: \( \sigma_y \approx (0.01-0.001) \lambda = 0.1-1 \text{ mm} \quad \sigma_y \approx (0.01-0.001) \lambda = 1-10 \mu \text{m} \)

\[ k \sigma_y = \text{const}. \]

no profit if spot size is scaled with wavelength!
Mode description of transverse deflecting structures:

\[ V = \int E_x(t, z) - c \beta B_y(t, z) \, dz = 0 \ldots 2 \int E_x(t, z) \, dz \]

Panofsky-Wenzel theorem:

\[ V \neq 0 \text{ only if } E_z(x) \neq 0 \]

but not only that:

- transverse deflecting fields have always 6 components
- the mode description can be done in terms of so-called hybrid modes \( HE+HM \)
- the \( HEM_{11} \) mode exists in iris loaded waveguides (small-pitch approximation) and in dielectric lined waveguides (fundamental mode)
- theory for all cases worked out in the 1960s and 70s, at that time for S-Band frequencies, e.g.

V. A. Vagin, V. I. Kotov,

*Investigation of Hybrid Waves in a Circular Waveguide Partially Filled with Dielectric*,

Dispersion Curve:

Dielectric lined waveguide: \(a = 0.3\) mm, \(b = 0.398\) mm, \(\varepsilon_r = 4.41\) (Quartz) and dispersion curve. The 300 GHz structure is matched for \(v_p = 0.995c\) (5 MeV). The red line corresponds to the speed of light.
CST Results:

a) contour plot y-z in log scale
b) $E_z$ vs. $x, y$ at $z = 1$ cm in log scale
c) $E_z$ vs. $y$ at $z = 1$ cm
CST Results:

Panofsky-Wenzel theorem (or $\text{rot} \vec{E} = \frac{\partial}{\partial t} \vec{B}$):

$$\frac{\partial}{\partial y} E_z \propto E_y + cB_x$$

a linear longitudinal field corresponds to a constant transverse force.
Confirmed with ASTRA simulation
$\sigma_y = 125 \mu m$, $R = 250 \mu m$
Comparison – REGAE case:

<table>
<thead>
<tr>
<th>Type</th>
<th>S-band 20 cm</th>
<th>THz 3 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>5 kW</td>
<td>1.2 W</td>
</tr>
<tr>
<td>$V$</td>
<td>170 KV</td>
<td>9.2 kV</td>
</tr>
<tr>
<td>max. $\sigma_y$</td>
<td>0.4 mm</td>
<td>125 µm</td>
</tr>
<tr>
<td>$\sigma_{y,kV}$</td>
<td>4.3 kV</td>
<td>7.2 kV</td>
</tr>
<tr>
<td>shunt imp.</td>
<td>36.7 MO/m</td>
<td>1.88 GO/m</td>
</tr>
</tbody>
</table>
Tunability

- We should expect high frequency devices to be sensitive.
- Can look to tune with frequency.
- Can also consider temperature tuning with some low-absorption plastics where heat expansion coef. $10^4$. Some literature exists on treating HDPE for vacuum compatibility.

and let us consider the example from Fig. 8, where $k_z^0 = \frac{\omega}{c} = \frac{2\pi f}{c}$, then,

$$k_z = \frac{\omega}{v_g} + \frac{\omega_0}{c} (1 - \frac{c}{v_g}),$$

introducing a dimensionless scaling factor $\omega = \alpha \omega_0$, simplifying and reorganizing leads to

$$k_z = \frac{\omega_0}{c} (n(\alpha - 1) + 1).$$

The phase velocity is given by

$$v_p = \frac{\omega}{k_z} = \frac{\alpha c}{n(\alpha - 1) + 1},$$

finally, introducing the normalized phase velocity for simplicity $\beta_p = \frac{v_p}{c}$, we can solve for $\alpha$ in terms of $\beta_p$: after some algebra, the result is given by

$$\alpha = \frac{n - 1}{n - 1/\beta_p}.$$

As an example, a phase velocity change of 0.01c (e.g. from $v_p = c$ to $v_p = .99c$) can be achieved by a frequency change of $\alpha = 1.009$; i.e. a frequency shift from $f = 300$ GHz to $f = 302.7$ GHz. We note smaller $n$ generally has larger impact on $v_p$ for a given frequency shift.

Control over the THz-generation frequency would be a valuable asset to control the accelerating conditions inside the structure.
THz waveguides beyond THz streaking:

- Dielectric lined hollow cylindrical metallic waveguides exhibit the lowest loss of all investigated waveguides at THz frequencies (1dB/m)
- Loss reduction in this waveguide is attributed to an ideal profile of the dominant hybrid HE mode.
- This mode profile also results in relatively low dispersion and very high coupling efficiency.
Common THz waveguides and their estimated transmission loss and dispersion characteristics in the region of 1–2 THz.
Oleg Mitrofanov et. al
*Reducing Transmission Losses in Hollow THz Waveguides*
THz waveguides – thick layer (~100 µm):

EXPERIMENTAL DEMONSTRATION OF BALLISTIC BUNCHING WITH DIELECTRIC-LINED WAVEGUIDES AT PITZ

F. Lemery*, Dept. of Physics, University of Hamburg, 20355 Hamburg, Germany
P. Piot², Northern Illinois Center for Accelerator & Detector Development and Dept. of Physics, Northern Illinois University, DeKalb, IL 60115, USA
G. Amatuni†, P. Boonpornprasert, Y. Chen, J. Good, B. Grigoryan†, M. Krasilinikov, O. Lishilin, G. Loisch, S. Philipp, H. Qian, Y. Renier, F. Stephan,
Deutsches Elektronen-Synchrotron, 15738 Zeuthen, Germany
¹also at the Center for Free-Electron Laser Science (CFEL), DESY, 22607 Hamburg, Germany
²also at Accelerator Physics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
THz waveguides – thin layer (~10 µm):

Apparatus to deposit polymer thin films over Ag films. Inset: an optical micrograph of a 2.2 mm bore diameter Ag/PS waveguide showing the PS layer.

Oleg Mitrofanv et al. ibid.
Acknowledgements

Thomas Vinatier
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Franz Kaertner
Flexible THz waveguides:

(a) Photograph of the PS-lined cylindrical metallic waveguide. (b) Photograph of the input section (top) and schematic of the near-field waveguide mode imaging system (bottom).
Inset: detail of the PS-lined cylindrical metallic waveguide. (c) Schematic of the subwavelength aperture near-field probe configuration. Near-field electric field $E_x$ profiles (1.2 mm × 1.2 mm) at the output of the cylindrical metallic waveguide without (d) and with (e) the PS internal layer showing the TE11 and HE11 modes.

Oleg Mitrofanov et. al,
*Terahertz wave transmission in flexible polystyrene-lined hollow metallic waveguides for the 2.5-5 THz band*
Optics Express 21, 23748, (2013).
Schematic cross section of the near-field collection mode probe. L, thickness of the GaAs layer, sets the distance from the aperture to the dipole antenna.

Oleg Mitrofanov et. al,
*Study of single-cycle pulse propagation inside a terahertz near-field probe*
Space-time maps of the THz wave coupled to different combinations of waveguide modes. Maps of the electric field Ex(t) are shown in the left column and the corresponding maps of the field amplitude Ex(ω) at 2.3 THz are shown in the right column. The position of the input pinhole, the incident field polarization and the spatial scan lines are schematically shown on the right.

Oleg Mitrofanov, James Harrington, 
*Dielectric-lined cylindrical metallic THz waveguides: mode structure and dispersion* Optics Express 18, 1898, (2010).