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Helical motion in resistive structures

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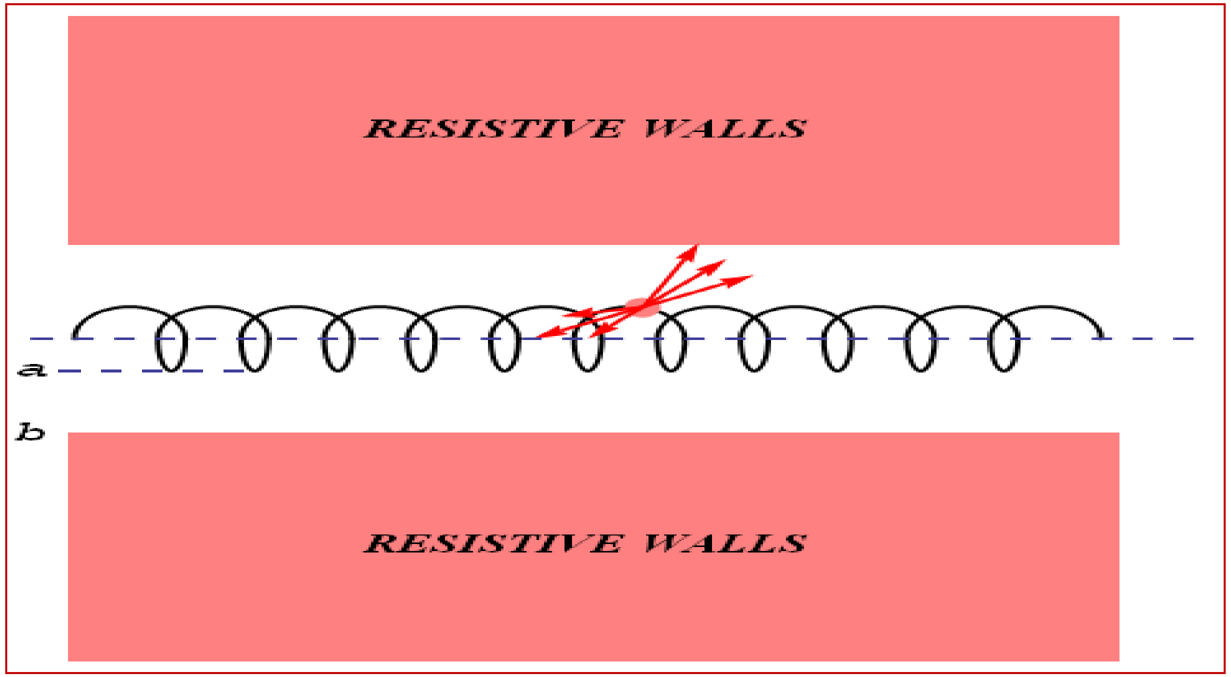
GEOMETRY OF THE PROBLEM



The radiation field of a particle moving on a helical trajectory in a cylindrical waveguide with resistive walls is calculated.
The deformation of the energy spectrum and damping of radiation as a result of the finite conductivity of the walls is investigated.

The radiation of a point particle moving along a helical trajectory in a waveguide with walls of finite conductivity is considered. The practical significance of this problem lies in the study of the possibility of combining a helical undulator with a cylindrical waveguide. In this case, the continuous spectrum of undulator radiation is transformed into a discrete one, which makes it possible to single out one mode as a source of monochromatic radiation.

IDEAL WAWEGUIDE

With an appropriate selection of parameters, it is possible to create conditions for the dominance of one mode, i.e., the mode containing most of the emitted energy. In this case, we are talking about the possibility of creating a powerful monochromatic radiation source.

Contribution of each mode to the radiation energy spectrum
in waveguide−undulator structures

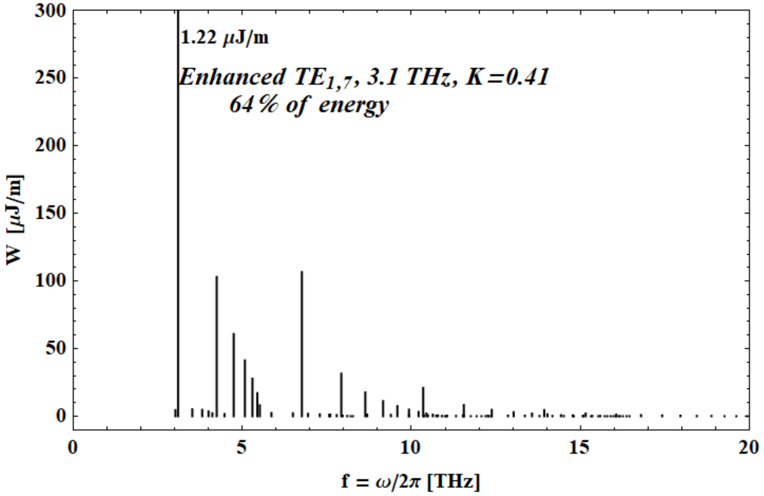
M.I. Ivanyan et al, Laser Phys. 30 (2020) 115002 (8pp)

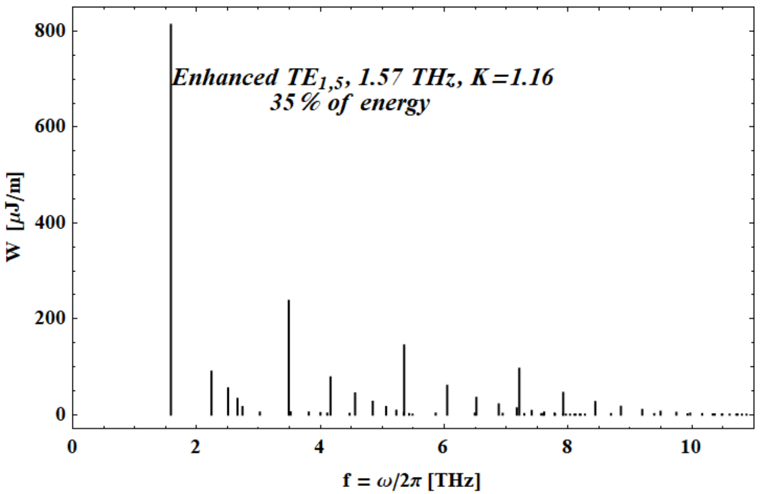
$$W_{mn}^{TM} = \frac{q^2\omega_{nm}^2}{2\pi\varepsilon_0 c^2}\frac{J_n^2(\alpha_{nm}\,a/b)}{\alpha_{nm}^2 J_n'^2(\alpha_{nm})} \qquad W_{nm}^{TE} = \frac{q^2\omega_{nm}^2}{2\pi\varepsilon_0 c^2}\frac{\beta_\perp^2 a^2}{b^2}\frac{J_n'^2(\alpha'_{nm}\,a/b)}{f^2(\alpha'_{nm})J_n^2(\alpha'_{nm})}\frac{\alpha_{nm}'^2}{\alpha_{nm}'^2 - n^2}$$

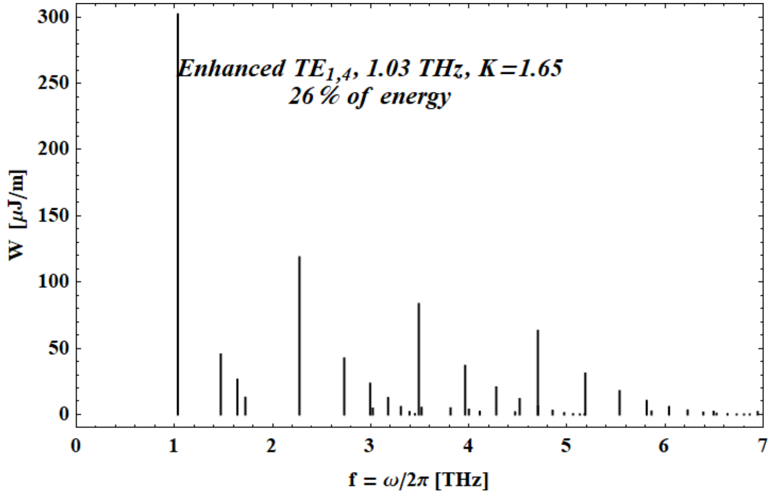
$$\boldsymbol{\omega_{nm} = n\omega_0 + V\gamma_z^2 a^{-1}\left[n\beta_z\beta_\perp + \sqrt{n^2\beta_\perp^2 - \gamma_z^{-2}x_{nm}^2 a^2/b^2}\right]}$$

Singularity at $f(\alpha'_{nm}) = 0$

Cases of dominance of one of the modes at different values of K







REAL RESISTIVE WAVEGUIDE

Basic harmonics

$$\vec{e} = \begin{cases} \vec{e}_H = \left\{(\alpha r)^{-1} n, H_n^{(1)}(\alpha r), jH_n^{(1)'}(\alpha r), 0\right\} exp(j\psi_n) \\ \vec{e}_J = \left\{(\alpha r)^{-1} n, J_n(\alpha r), jJ'_n(\alpha r), 0\right\} exp(j\psi_n), \end{cases}$$

$$\alpha = \begin{cases} \alpha_1 = \sqrt{\omega^2 \varepsilon_1 \mu_1 - k^2} & \textit{in metal} \\ \alpha_0 = \sqrt{\omega^2 / c^2 - k^2} & \textit{in vacuum} \end{cases}$$

$$\psi_n = k(z - vt) + n(\varphi - \omega_0 t)$$

$$k = (\omega - n\omega_0)/V$$

Field presentation

$$\vec{E} = \vec{E}^{TM} + \vec{E}^{TE} \qquad \vec{H} = \vec{H}^{TM} + \vec{H}^{TE}$$

$$\vec{E}^{TM} = A^{TM} rot\vec{e} \qquad \vec{H}^{TM} = B^{TM}\vec{e}$$

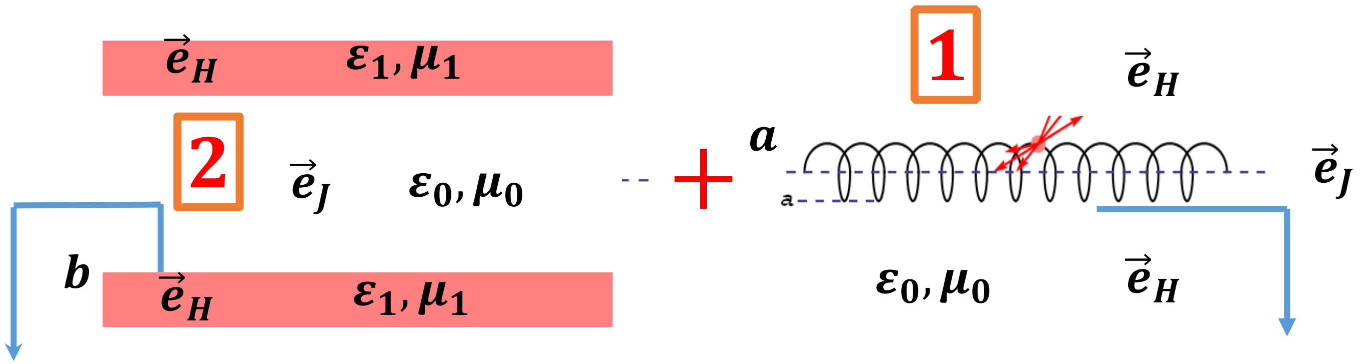
$$\vec{E}^{TE} = A^{TE}\vec{e} \qquad \vec{H}^{TE} = B^{TE} rot\vec{e}$$

Complete Solution

Common Solution + ***Particular Solution***

Solution of homogeneous Maxwell equations with undefinite amplitudes

Solution in free space **for given charges and currents**



Matching the tangential components of full field on the inner wall at ***r = b***

$$\vec{E}_{H,t} = \vec{E}_{J,t}$$

$$\vec{H}_{H,t} = \vec{H}_{J,t}$$

Matching fields using boundary conditions on a surface ***r = a***, Introduction of the coefficient χ_n.

$$(\vec{H}_H - \vec{H}_J) \times \vec{e}_r = \chi_n \vec{J}$$

$$\varepsilon_0(\vec{E}_H - \vec{E}_J) \cdot \vec{e}_r = \chi_n q$$

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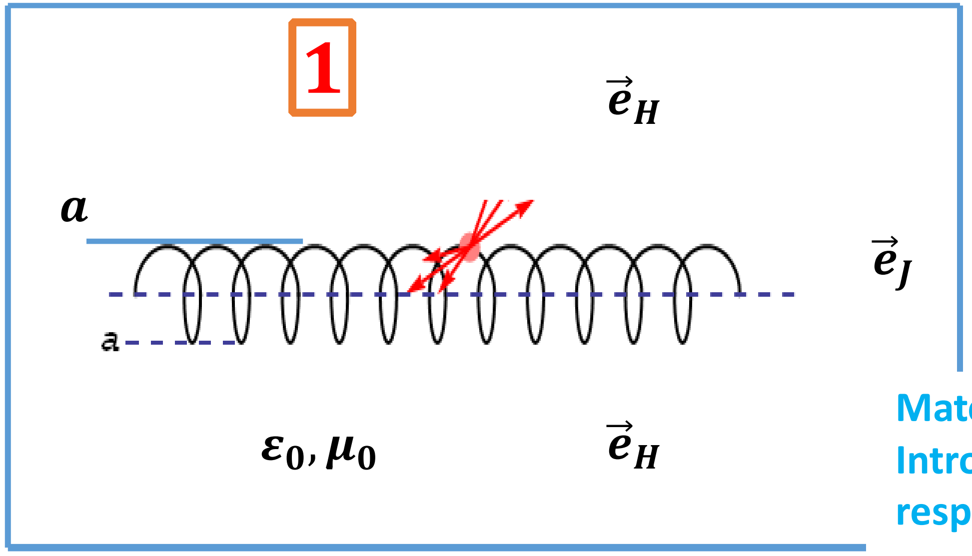
Determination of the coefficient χ_n is performed by comparison with the existing solution for an ideal waveguide

1. *Particular Solution.* *Solution in free space for given charges and currents*



Charge and current dencities

$$\rho(r,\varphi,z,t) = q\frac{\delta(r-a)}{\sqrt{ra}}\delta(\varphi-\omega_0 t)\delta(z-Vt)$$

$$\vec{j}(r,\varphi,z,t) = (\omega_b a\vec{e}_\varphi + V\vec{e}_z)\rho(r,\varphi,z,t)$$

Matching fields using boundary conditions on a surface ***r = a***.
Introduction of the coefficient χ_n, currents $\vec{j}^{TM}, \vec{j}^{TE}$ and charges ρ^{TM}, ρ^{TE},
responsible for the generation of **TM** and **TE** modes

TM modes

1) $E_{H,z}^{TM} - E_{J,z}^{TM} = 0$
2) $-E_{H,\varphi}^{TM} + E_{J,\varphi}^{TM} = 0$
3) $-H_{H,\varphi}^{TM} + H_{J,\varphi}^{TM} = q\chi_n j_{n,z}^{TM}$
4) $\varepsilon_0\left(E_{H,r}^{TM} - E_{J,r}^{TM}\right) = q\chi_n\rho_n^{TM}$
5) $H_{H,r}^{TM} - H_{J,r}^{TM} = 0$

TE modes

1) $-E_{H,\varphi}^{TE} + E_{J,\varphi}^{TE} = 0$
2) $H_{H,z}^{TE} - H_{J,z}^{TE} = q\chi_n j_{n,\varphi}^{TE}$
3) $-H_{H,\varphi}^{TE} + H_{J,\varphi}^{TE} = q\chi_n j_{n,z}^{TE}$
4) $\varepsilon_0\left(E_{H,r}^{TE} - E_{J,r}^{TE}\right) = q\chi_n\rho_n^{TE}$
5) $H_{H,r}^{TE} - H_{J,r}^{TE} = 0$

$$\rho_n^{TM} + \rho_n^{TE} = 1$$

$$j_z^{TM} + j_z^{TE} = V$$

Determined from the compatibility conditions of the equations included in the systems.

$$j_\varphi^{TE} = \omega_0 a \qquad \rho_n^{TE} = n\omega_0\omega/c^2\alpha_0^2$$

$$j_z^{TE} = kn\omega_0/\alpha_0^2 \qquad j_z^{TM} = \mathrm{V} - j_z^{TE}$$

1. *Particular Solution.* *Solution in free space for given charges and currents*

Amplitudes and fields

$$A_{n,J}^{0,TM} = -jq\frac{\pi}{2}\frac{a\chi_n}{\alpha_0 c^2\varepsilon_0}(V\omega - c^2k)H_n^{(1)}(\alpha_0 a)$$

$$A_{n,H}^{0,TM} = -jq\frac{\pi}{2}\frac{a\chi_n}{\alpha_0 c^2\varepsilon_0}(V\omega - c^2k)J_n(\alpha_0 a)$$

$$B_{n,J}^{0,TM} = -j\varepsilon_0\omega A_{n,J}^{0,TM},\ B_{n,H}^{0,TM} = -j\varepsilon_0\omega A_{n,H}^{0,TM}$$

$$A_{n,J}^{0,TE} = jq\frac{\pi}{2}\frac{a^2\chi_n\omega\omega_0}{c^2\varepsilon_0}H_n^{(1)}(\alpha_0 a),$$

$$A_{n,H}^{0,TE} = jq\frac{\pi}{2}\frac{a^2\chi_n\omega\omega_0}{c^2\varepsilon_0}J_n'(\alpha_0 a)$$

$$B_{n,J}^{0,TE} = -j\,A_{n,J}^{0,TE}/\omega\mu_0, B_{n,H}^{0,TE} = -j\,A_{n,H}^{0,TE}/\omega\mu_0$$

$$\vec{E}_n^{0,TM} = \begin{Bmatrix}\vec{E}_{H,n}^{0,TM}\\ \vec{E}_{J,n}^{0,TM}\end{Bmatrix} = \begin{cases}A_{H,n}^{0,TM}\,rot\,\vec{e}_H, & r > a\\ A_{J,n}^{0,TM}\,rot\,\vec{e}_J, & r < a\end{cases},$$

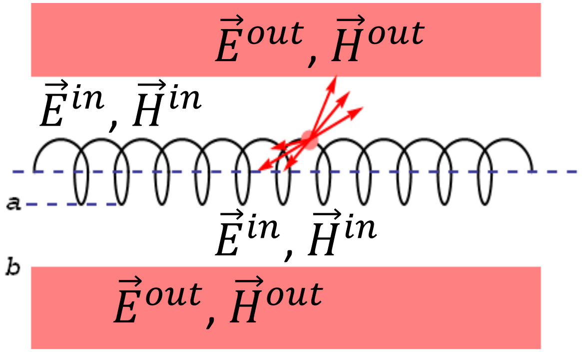
$$\vec{H}_n^{0,TM} = \begin{Bmatrix}\vec{H}_{H,n}^{0,TM}\\ \vec{H}_{J,n}^{0,TM}\end{Bmatrix} = \begin{cases}B_{H,n}^{0,TM}\vec{e}_H, & r > a\\ B_{J,n}^{0,TM}\vec{e}_I, & r < a\end{cases}$$

$$\vec{E}_n^{0,TE} = \begin{Bmatrix}\vec{E}_{H,n}^{0,TE}\\ \vec{E}_{J,n}^{0,TE}\end{Bmatrix} = \begin{cases}A_{H,n}^{0,TE}\vec{e}_H, & r > a\\ A_{J,n}^{0,TE}\vec{e}_J, & r < a\end{cases},$$

$$\vec{H}_n^{0,TE} = \begin{Bmatrix}\vec{H}_{H,n}^{0,TE}\\ \vec{H}_{J,n}^{0,TE}\end{Bmatrix} = \begin{cases}B_{H,n}^{0,TE}\,rot\,\vec{e}_H, & r > a\\ B_{J,n}^{0,TE}\,rot\,\vec{e}_J, & r < a\end{cases}$$

Complete Solution

2. Matching the tangential components of full field on the inner wall at *r = b*



$$\vec{E}^{in} = \vec{E}^{1,TM} + \vec{E}^{1,TE} + \vec{E}^{0,TM} + \vec{E}^{0,TE}$$
$$\vec{H}^{in} = \vec{H}^{1,TM} + \vec{H}^{1,TE} + \vec{H}^{0,TM} + \vec{H}^{0,TE}$$

$$\vec{E}^{out} = \vec{E}^{2,TM} + \vec{E}^{2,TE}, \quad \vec{H}^{out} = \vec{H}^{2,TM} + \vec{H}^{2,TE}$$

$$\vec{E}^{1,TM} = A_n^{1,TM} rot\, \vec{e}_J, \quad \vec{H}^{1,TM} = B_n^{1,TM} \vec{e}_J,$$
$$B_n^{1,TM} = -jA_n^{1,TM} \varepsilon_0 \omega,$$

$$\vec{E}^{2,TM} = A_n^{2,TM} rot\, \vec{e}_H, \quad \vec{H}^{2,TM} = B_n^{2,TM} \vec{e}_H,$$
$$B_n^{2,TM} = -jA_n^{2,TM} \varepsilon_1 \omega,$$

$$\vec{E}^{1,TE} = A_n^{1,TE}\, \vec{e}_J, \quad \vec{H}^{1,TE} = B_n^{1,TE} rot\, \vec{e}_J,$$
$$B_n^{1,TE} = -j\, A_n^{1,TE} / \mu_0 \omega.$$

$$\vec{E}^{2,TE} = A_n^{2,TE}\, \vec{e}_H, \quad \vec{H}^{2,TE} = B_n^{2,TE} rot\, \vec{e}_H,$$
$$B_n^{2,TE} = -j\, A_n^{2,TE} / \mu_1 \omega.$$

$$\begin{cases} \vec{E}_t^{in} = \vec{E}_t^{out} \\ \vec{H}_t^{in} = \vec{H}_t^{out} \end{cases} \quad at\ \boldsymbol{r} = \boldsymbol{b}$$

Complete Solution

Amplitudes

$$\widehat{A} = \widehat{A}_1 + \widehat{A}_2$$

$$\widehat{A}_{1,2} = \left\{A^{1,TM}_{n_{1,2}}, A^{1,TE}_{n_{1,2}}, A^{2,TM}_{n_{1,2}}, A^{2,TE}_{n_{1,2}}\right\}$$

$$A^{1,TM}_{n_1} = jq\frac{\pi}{2}a\chi_n C_u \tilde{J}_n \frac{W_{\varepsilon\mu}}{\alpha_0 c^2 \varepsilon_0 D},$$

$$A^{1,TE}_{n_1} = qa\chi_n kn\mu_0 \frac{C_u \alpha_1^2 \alpha_{01} H_n^2 \tilde{J}_n \omega^2}{\alpha_0 c^2 D},$$

$$A^{2,TM}_{n_1} = -qa\chi_n b \frac{C_\omega \alpha_0^2 \alpha_1^2 \tilde{J}_n I_\mu \omega^2}{\alpha_0 c^2 D},$$

$$A^{2,TE}_{n_1} = qa\chi_n kn\mu_1 \frac{C_\omega \alpha_1 \alpha_{01}^2 H_n J_n \tilde{J}_n \omega^2}{c^2 D},$$

$$A^{1,TM}_{n_2} = -qa^2\alpha_1^2\alpha_{01}\chi_n \frac{\tilde{J}_n' H_n^2 kn\omega\omega_0}{c^2\varepsilon_0 D},$$

$$A^{1,TE}_{n_2} = -jq\frac{\pi}{2}\chi_n ka^2\omega\omega_0 \tilde{J}_n' \frac{W_{\mu\varepsilon}}{c^2\varepsilon_0 D}$$

$$A^{2,TM}_{n_2} = -qa^2\chi_n kn\omega\omega_0\alpha_0\alpha_1\alpha_{01}\frac{\tilde{J}_n' H_n J_n}{c^2\varepsilon_0 D},$$

$$A^{2,TE}_{n_2} = q\mu_1\chi_n ba^2\omega^3\omega_0\alpha_0^2\alpha_1^2\frac{\tilde{J}_n' I_\varepsilon}{c^2\varepsilon_0 D}$$

Designations

$$\tilde{J}_n = J_n(\alpha_0 a), \widetilde{H}_n = H_n^{(1)}(\alpha_0 b), \qquad \alpha_{01} = \alpha_0^2 - \alpha_1^2$$

$$\left.\begin{matrix} I_\varepsilon \\ I_\mu \end{matrix}\right\} = -\alpha_1 J_n' H_n \begin{Bmatrix} \varepsilon_0 \\ \mu_0 \end{Bmatrix} + \alpha_0 J_n H_n' \begin{Bmatrix} \varepsilon_1 \\ \mu_1 \end{Bmatrix}$$

$$\left.\begin{matrix} Y_\varepsilon \\ Y_\mu \end{matrix}\right\} = -\alpha_1 \widetilde{H}_n' H_n \begin{Bmatrix} \varepsilon_0 \\ \mu_0 \end{Bmatrix} + \alpha_0 \widetilde{H}_n H_n' \begin{Bmatrix} \varepsilon_1 \\ \mu_1 \end{Bmatrix}$$

$$\left.\begin{matrix} W_{\varepsilon\mu} \\ W_{\mu\varepsilon} \end{matrix}\right\} = k^2 n^2 \alpha_{01}^2 H_n^2 J_n \widetilde{H}_n - b^2 \alpha_0^2 \alpha_1^2 \begin{Bmatrix} Y_\varepsilon I_\mu \\ Y_\mu I_\varepsilon \end{Bmatrix} \omega^2$$

$$D = k^2 n^2 \alpha_{01}^2 H_n^2 J_n^2 - b^2 \alpha_0^2 \alpha_1^2 I_\varepsilon I_\mu \omega^2$$

Dispersion equation

$$D(\omega) = 0$$

has discrete complex roots

$$, \qquad \omega = \omega_{nm}, \qquad k = \frac{\omega - n\omega_0}{V}$$

Transition to an ideal waveguide:

$$\varepsilon_1 \to \infty, \qquad \mu_1 = \mu_0$$

Amplitudes, obtained for common solution (full field matching at *r = b*):

$$A_n^{1,TM} = A_{n_1}^{1,TM} = jq\frac{\pi}{2}\frac{a\chi_n C_u H_n^{(1)}(\alpha_0 b) J_n(\alpha_0 a)}{\alpha_0 c^2 \varepsilon_0 J_n(\alpha_0 b)}$$

$$A_n^{1,TE} = A_{n_2}^{1,TE} = -jq\frac{\pi}{2}\omega\omega_0\frac{a^2\chi_n H_n^{(1)'}(\alpha_0 b) J_n'(\alpha_0 a)}{c^2 \varepsilon_0 J_n'(\alpha_0 b)}$$

Amplitudes, obtained for particular solution (free space field matching at *r = a*):

$$A_{n,J}^{0,TM} = -jq\frac{\pi}{2}\frac{a\chi_n}{\alpha_0 c^2 \varepsilon_0} C_u H_n^{(1)}(\alpha_0 a)$$

$$A_{n,H}^{0,TM} = -jq\frac{\pi}{2}\frac{a\chi_n}{\alpha_0 c^2 \varepsilon_0} C_u J_n(\alpha_0 a)$$

$$A_{n,J}^{0,TE} = jq\frac{\pi}{2}\frac{a^2\chi_n\omega\omega_0}{c^2\varepsilon_0} H_n^{(1)}(\alpha_0 a)$$

$$A_{n,H}^{0,TE} = jq\frac{\pi}{2}\frac{a^2\chi_n\omega\omega_0}{c^2\varepsilon_0} J_n'(\alpha_0 a)$$

$$C_u = V\omega - c^2 k$$

Full field, radiated in ideal waveguide

$$\vec{E}_n^0 = \vec{E}_n^{0,TM} + \vec{E}_n^{0,TE},\ \vec{H}_n^0 = \vec{H}_n^{0,TM} + \vec{H}_n^{0,TE}$$

$$\vec{E}^{,TM} = A_n^{1,TM} rot\ \vec{e}_J + \begin{cases} A_{H,n}^{0,TM} rot\ \vec{e}_H, & r > a \\ A_{J,n}^{0,TM} rot\ \vec{e}_J, & r < a \end{cases}$$

$$\vec{H}^{TM} = B_n^{1,TM} \vec{e}_J + \begin{cases} B_{H,n}^{0,TM} \vec{e}_H, & r > a \\ B_{J,n}^{0,TM} \vec{e}_I, & r < a \end{cases}$$

$$\vec{E}^{,TE} = A_n^{1,TE}\ \vec{e}_J + \begin{cases} A_{H,n}^{0,TE} \vec{e}_H, & r > a \\ A_{J,n}^{0,TE} \vec{e}_J, & r < a \end{cases}$$

$$\vec{H}^{,TE} = B_n^{1,TE} rot\ \vec{e}_J + \begin{cases} B_{H,n}^{0,TE} rot\ \vec{e}_H, & r > a \\ B_{J,n}^{0,TE} rot\ \vec{e}_J, & r < a \end{cases}$$

Expansion of the resulting solution in a series in terms of eigenfunctions of an ideal waveguide. Comparison with existing solution

TM modes. Poles at $\alpha_0^2 = j_{nm}^2$, additional pole at $\boldsymbol{\alpha_0^2}$ = 0 in obtained solution.

$J_n(bj_{nm}) = 0$

Existing solution

$$\tilde{E}_{nm,z}^{a,TM} = -j2q\frac{a\chi_n C_u}{b^2}\frac{J_n(aj_{nm})}{(\alpha_0^2 - j_{nm}^2)J_{n-1}^2(bj_{nm})}J_n(j_{nm}r)F$$

$$\tilde{E}nn_{,z}^{b,TM} = -j2q\frac{C_u}{b^2c^2\varepsilon_0}\frac{J_n(aj_{nm})}{(\alpha_0^2 - j_{nm}^2)J_{n-1}^2(bj_{nm})}J_n(rj_{nm})F$$

$$\tilde{E}_{nm,r}^{a,TM} = j2q\mu_0\frac{ka\chi_n C_u}{\alpha_0^2 b^2}\frac{j_{nm}J_n(aj_{nm})J_n'(j_{nm}r)}{(\alpha_0^2 - j_{nm}^2)J_{n-1}^2(bj_{nm})}F$$

$$\tilde{E}_{nm,r}^{b,TM} = -2q\mu_0\frac{c^2(\alpha_0^2 - j_{nm}^2) - kC_u}{bj_{nm}(\alpha_0^2 - j_{nm}^2)J_{n-1}^2(bj_{nm})}J_n(aj_{nm})J_n'(rj_{nm})F$$

$$\tilde{E}_{n,m\varphi}^{a,TM} = j2q\mu_0\frac{kna\chi_n C_u}{\alpha_0^2 b^2 r}\frac{J_n(aj_{nm})J_n(j_{nm}r)}{(\alpha_0^2 - j_{nm}^2)J_{n-1}^2(bj_{nm})}F$$

$$\tilde{E}_{nm,\varphi}^{b,TM} = -2jqn\mu_0\frac{c^2(j_{nm}^2 - \alpha_0^2) - kC_u}{rb^2j_{nm}^2(j_{nm}^2 - \alpha_0^2)J_{n-1}^2(bj_{nm})}J_n(aj_{nm})J_n(rj_{nm})F$$

TE modes. poles at $\nu_{nm}^2 = \alpha_0^2$; no extra poles in obtained solution

$$E_{nm,r}^{a,TE} = E_{nm,r}^{b,TE} = \tilde{A}_{nm}\frac{jn}{kr}J_n(\nu_{nm}r),$$

$$E_{nm,\varphi}^{a,TE} = E_{nm,\varphi}^{b,TE} = \tilde{A}_{nm}J_n'(\nu_{nm}r),$$

$$H_{nm,z}^{a,TE} = H_{nm,z}^{b,TE} = \tilde{B}_{nm}J_n(\nu_{nm}r)$$

$$\tilde{A}_{nm} = \frac{j2q\mu_0 Q_n\nu_{nm}^2\omega\omega_b J_n'(a\nu_{nm})}{(n^2 - b^2\nu_{nm}^2)(\alpha_0^2 - \nu_{nm}^2)J_n^2(b\nu_{nm})},$$

$$Q_n = \begin{cases} a\chi_n & \text{— for obtained solution} \\ 1 & \text{— for existing solution} \end{cases}$$

$$\tilde{B}_{nm} = -\frac{2qa^2\nu_{nm}^3\omega_b Q_n}{(n^2 - b^2\nu_{nm}^2)(\alpha_0^2 - \nu_{nm}^2)}\frac{J_n'(a\nu_{nm})}{J_n^2(b\nu_{nm})}$$

$J_n'(b\nu_{nm}) = 0$

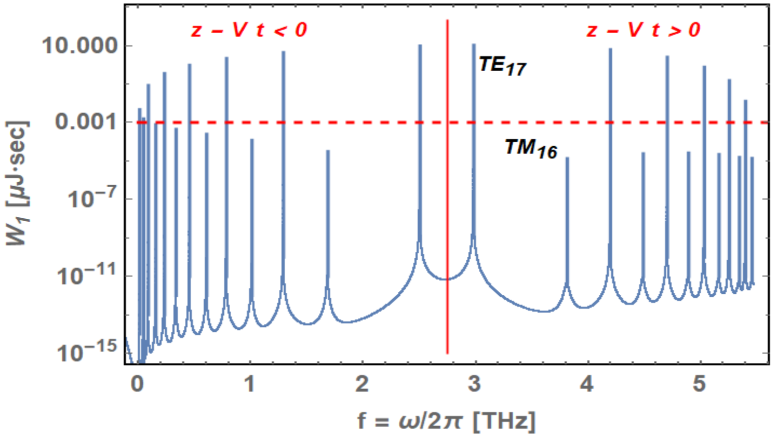
Chosen form of function χ_n:

$$\chi_n = a^{-1}\left\{1 - 4^n \Gamma^2(n) n \frac{J_n(\alpha_0 b) J_n'(\alpha_0 b)}{(\alpha_0 b)^{2n-1}}\right\},$$
$$\Gamma(n) = (n-1)!,$$

$\chi_n \to a^{-1}$ at $\alpha_0 \to j_{nm}\ (\nu_{nm})$

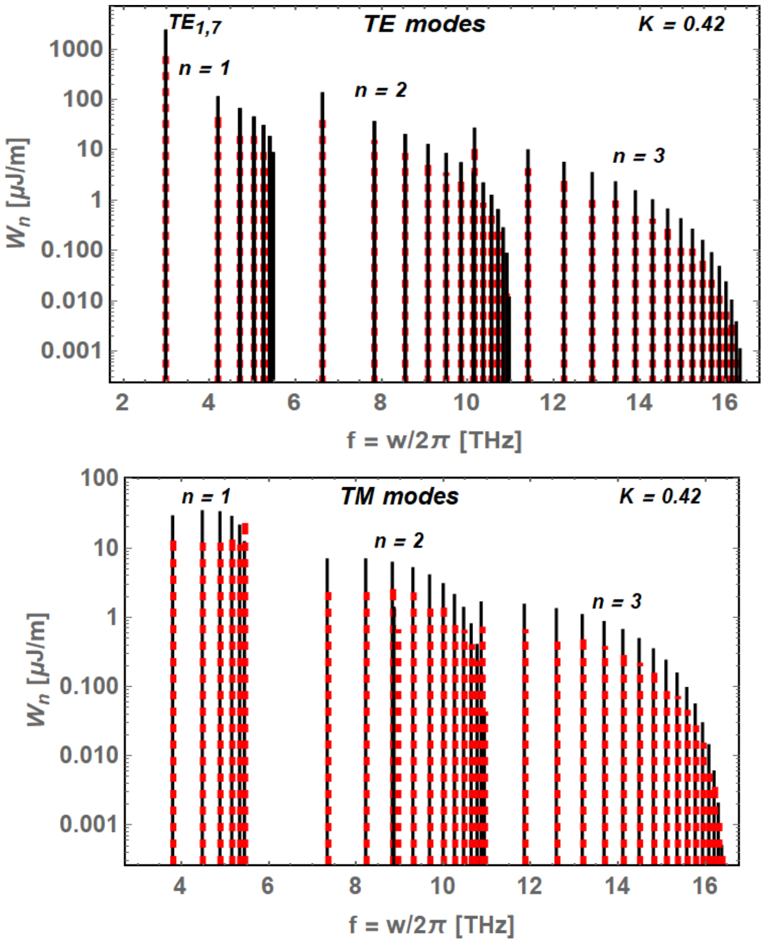
$\chi_n \to \alpha_0^2 a$ at $\alpha_0 \to 0$

Numerical examples

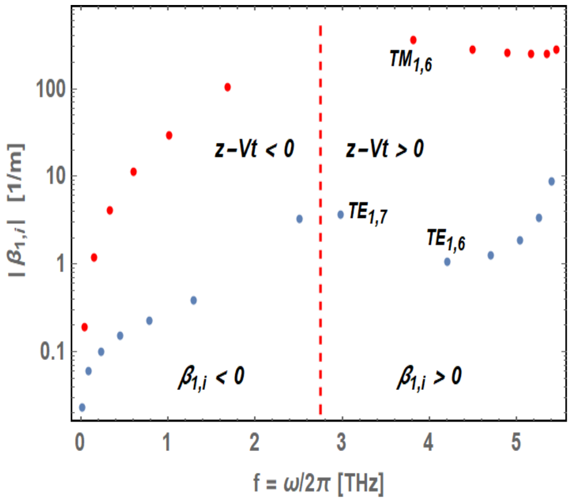


Spectral distribution of dipole mode ($n = 1$) radiation in a copper waveguide; forward (right) and back (left) radiation.

$$a = 1cm, l = 8cm,$$
$$K = 0.42, E = 15MeV,$$
$$n = 1$$

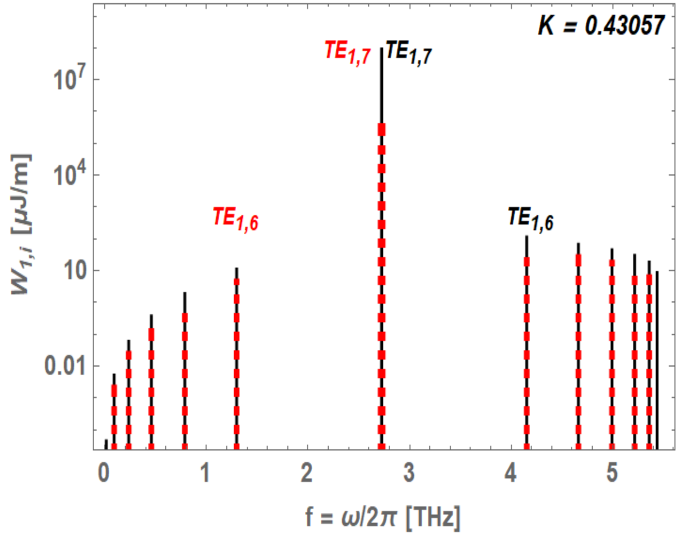


Spectral distribution (space-time domain, forward direction, $z - Vt \to 0$) of first three multipoles ($n = 1,2,3$) stored radiation energy for TE (top) and TM (bottom) modes in a copper (red, dased) and ideal (black, solid) waveguides.

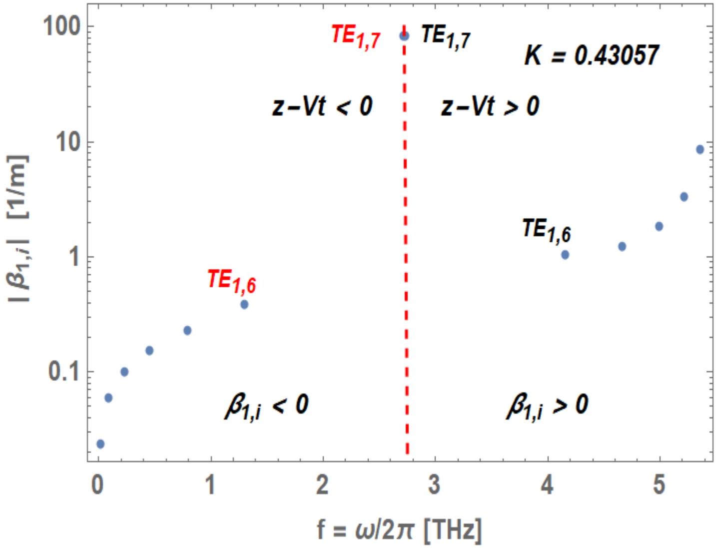


Damping factors of TE (blue) and TM (red) modes at resonant frequencies for $n = 1$.

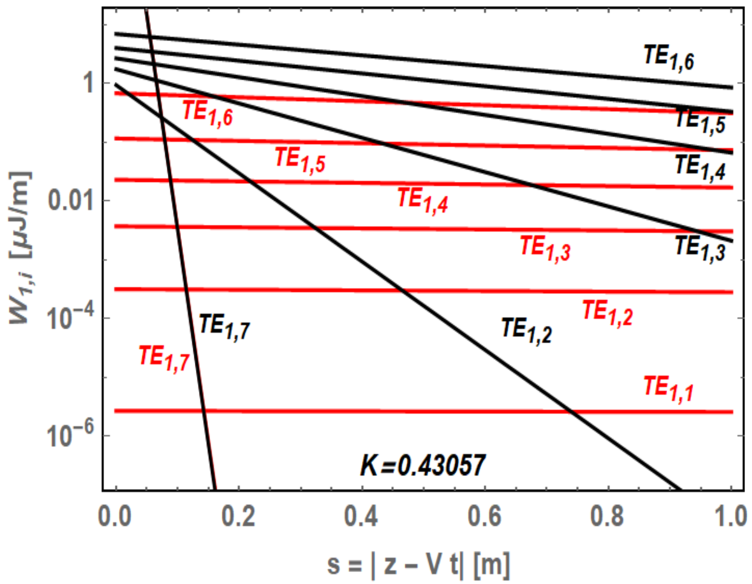
The case of proximity of the resonant and critical frequencies



Spectral distribution (space-time domain) of dipole mode $(n = 1)$ stored radiation energy for TE modes in a copper (red, dashed) and ideal (black, solid) waveguides.

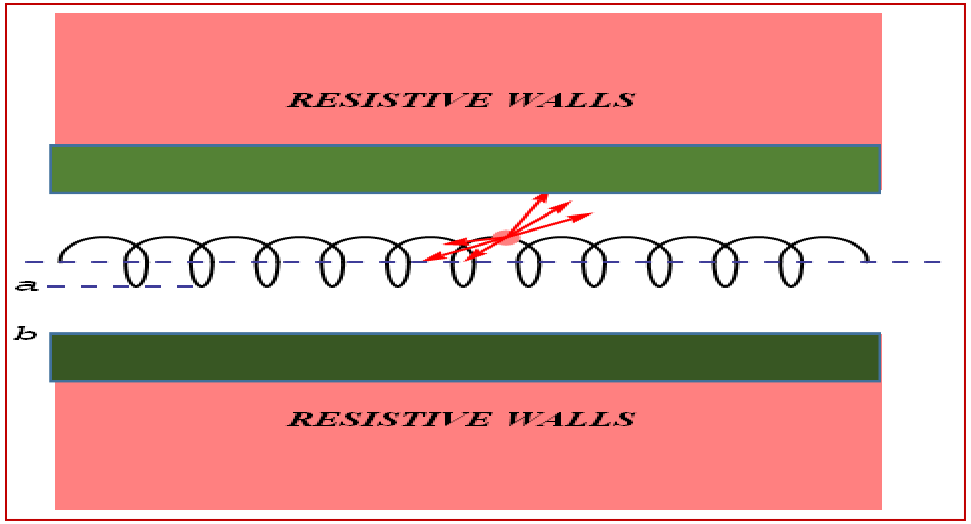


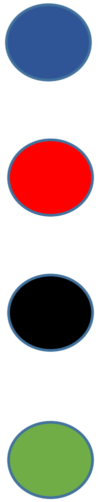
Damping factors of TE modes at resonant frequencies for $n = 1$.



The dependence of the accumulated energy density on the distance to the particle, TE modes, $n = 1$; radiation forward (black lines) and backward (red lines).

Dielectric loaded resistive waveguide. Damping factors



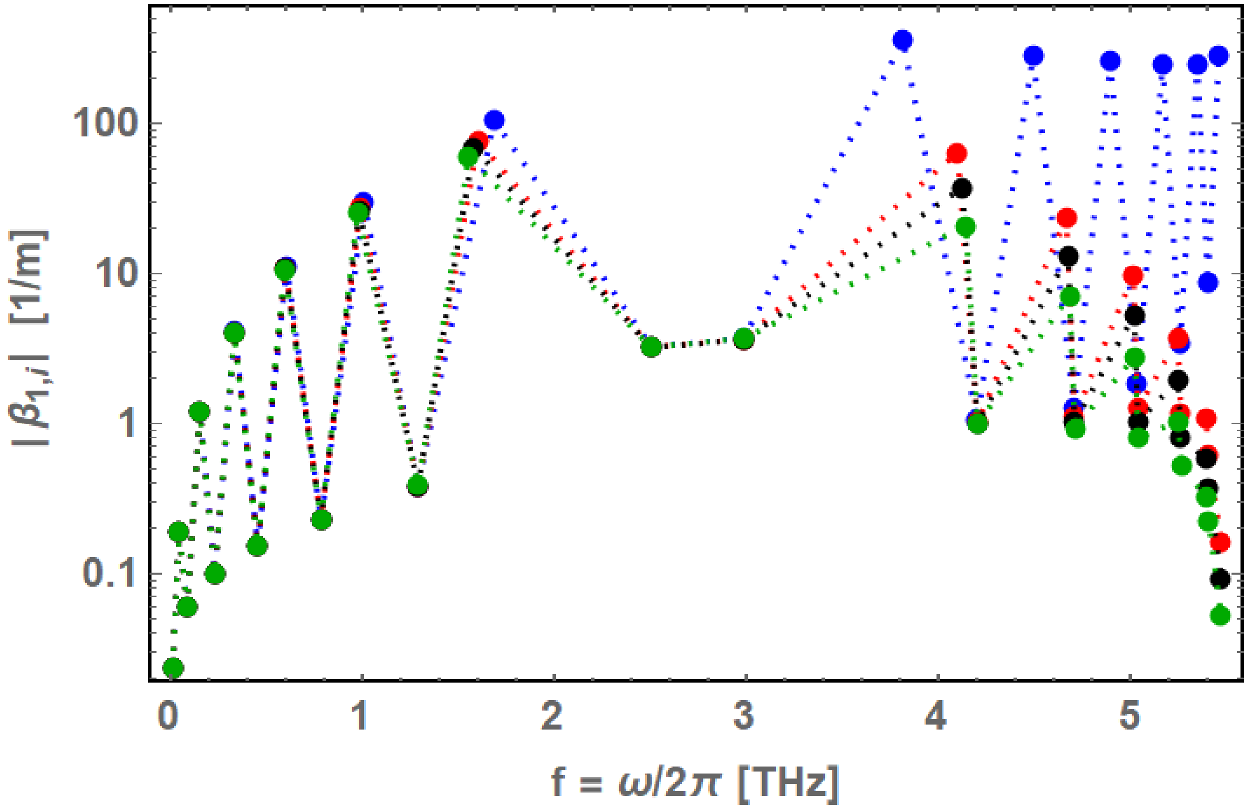


$\varepsilon = 1$

$\varepsilon = 2$

$\varepsilon = 3$

$\varepsilon = 10$



Dipole mode (n=1)

$$a = 1cm, d = 1\mu m, l = 8cm,$$
$$K = 0.42, E = 15MeV, n = 1$$

CONCLUSION

The obtained exact solution, in contrast to the case of an ideal waveguide, has no singularities at the critical (TE modes, space-time domain) and resonant (TE and TM modes, frequency domain) frequencies. Along with the greater prevalence of TE modes (due to higher attenuation of TM modes) than in an ideal waveguide, the maximum value of the amplitude of the dominant TE mode is limited due to the finite conductivity of the walls.

The solution presents a realistic picture of radiation and creates wide opportunities for research on optimizing the parameters of the structure, depending on its purpose.

The solution can be extended to two-layer and multilayer waveguides

THANK YOU!