Pole elektromagnetyczne zmienne w czasie

Równania Maxwella

Postać ogólna

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

$$\nabla \times \boldsymbol{E} = \frac{-\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\boldsymbol{D} = \epsilon \boldsymbol{E}, \boldsymbol{J} = \sigma \boldsymbol{E}, \boldsymbol{B} = \mu \boldsymbol{H}$$

Wyprowadzenie równania falowego

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} = \sigma \boldsymbol{E} + \epsilon \frac{\partial \boldsymbol{E}}{\partial t}$$

$$\nabla \times \nabla \times \boldsymbol{H} = \sigma \nabla \times \boldsymbol{E} + \epsilon \frac{\partial \nabla \times \boldsymbol{E}}{\partial t}$$

$$\nabla \times \boldsymbol{E} = \frac{-\partial \boldsymbol{B}}{\partial t} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

$$\nabla \times \nabla \times \boldsymbol{H} = -\sigma \mu \frac{\partial \boldsymbol{H}}{\partial t} - \epsilon \mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2}$$

$$\nabla \times \nabla \times \boldsymbol{H} = \nabla \nabla \cdot \boldsymbol{H} - \nabla^2 \boldsymbol{H},$$
$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla^2 \boldsymbol{H} = \sigma \mu \frac{\partial \boldsymbol{H}}{\partial t} + \epsilon \mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2}$$

$$\nabla^2 \boldsymbol{E} = \sigma \mu \frac{\partial \boldsymbol{E}}{\partial t} + \epsilon \mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2} \qquad (gdy\ \rho = 0)$$

Przypadki specjalne

$$\nabla^2 \boldsymbol{H} = \sigma \mu \frac{\partial \boldsymbol{H}}{\partial t} + \epsilon \mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2} \qquad \nabla^2 \boldsymbol{E} = \sigma \mu \frac{\partial \boldsymbol{E}}{\partial t} + \epsilon \mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2} \qquad (gdy\ \rho = 0)$$

Przewodniki:

$$\nabla^2 \boldsymbol{H} = \sigma \mu \frac{\partial \boldsymbol{H}}{\partial t}$$

$$\nabla^2 \boldsymbol{E} = \sigma \mu \frac{\partial \boldsymbol{E}}{\partial t}$$

Dielektryki:

$$\nabla^2 \boldsymbol{H} = \epsilon \mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2}$$

$$\nabla^2 \boldsymbol{E} = \epsilon \mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2}$$

Równania Maxwella dla pól harmonicznych

$$\boldsymbol{E}(\boldsymbol{r},t)=\boldsymbol{E}(\boldsymbol{r})\sin(\omega t+\psi)=Im(E(\boldsymbol{r})e^{j(\omega t+\psi)})=Im(\underline{\boldsymbol{E}}(\boldsymbol{r})e^{j\omega t})$$

$$\boldsymbol{D}(\boldsymbol{r},t)=\ldots=Im(\underline{\boldsymbol{D}}(\boldsymbol{r})e^{j\omega t})$$

$$\boldsymbol{H}(\boldsymbol{r},t)=\ldots=Im(\underline{\boldsymbol{H}}(\boldsymbol{r})e^{j\omega t})$$

$$\nabla\times\underline{\boldsymbol{H}}=(\sigma+j\omega\epsilon)\underline{\boldsymbol{E}} \qquad \nabla\times\underline{\boldsymbol{E}}=-j\omega\mu\underline{\boldsymbol{H}}$$

$$\nabla\times\underline{\boldsymbol{H}}=j\omega\underline{\epsilon}\,\underline{\boldsymbol{E}} \qquad \underline{\epsilon}=\epsilon-j\frac{\sigma}{\omega}$$

$$\underline{J_{\sigma}}=\sigma\underline{E},$$

$$\underline{J_{\epsilon}}=j\omega\underline{D}=j\omega\epsilon\underline{E} \qquad \frac{\underline{J_{\sigma}}}{\underline{J_{\epsilon}}}=\frac{\sigma}{\omega\epsilon}=\tan(\delta)$$

Równanie Helmholtza

$$\nabla^2 \boldsymbol{H} = \sigma\mu \frac{\partial \boldsymbol{H}}{\partial t^2} + \epsilon\mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2}$$

$$\nabla^2 \boldsymbol{H} = j\omega\sigma\mu \underline{\boldsymbol{H}} - \omega^2 \epsilon\mu \underline{\boldsymbol{H}}$$

$$\nabla^2 \boldsymbol{H} = \underline{\Gamma^2}\, \underline{\boldsymbol{H}} \qquad \underline{\Gamma^2} = j\omega\sigma\mu - \omega^2 \epsilon\mu = -\omega^2 \underline{\epsilon}\mu$$

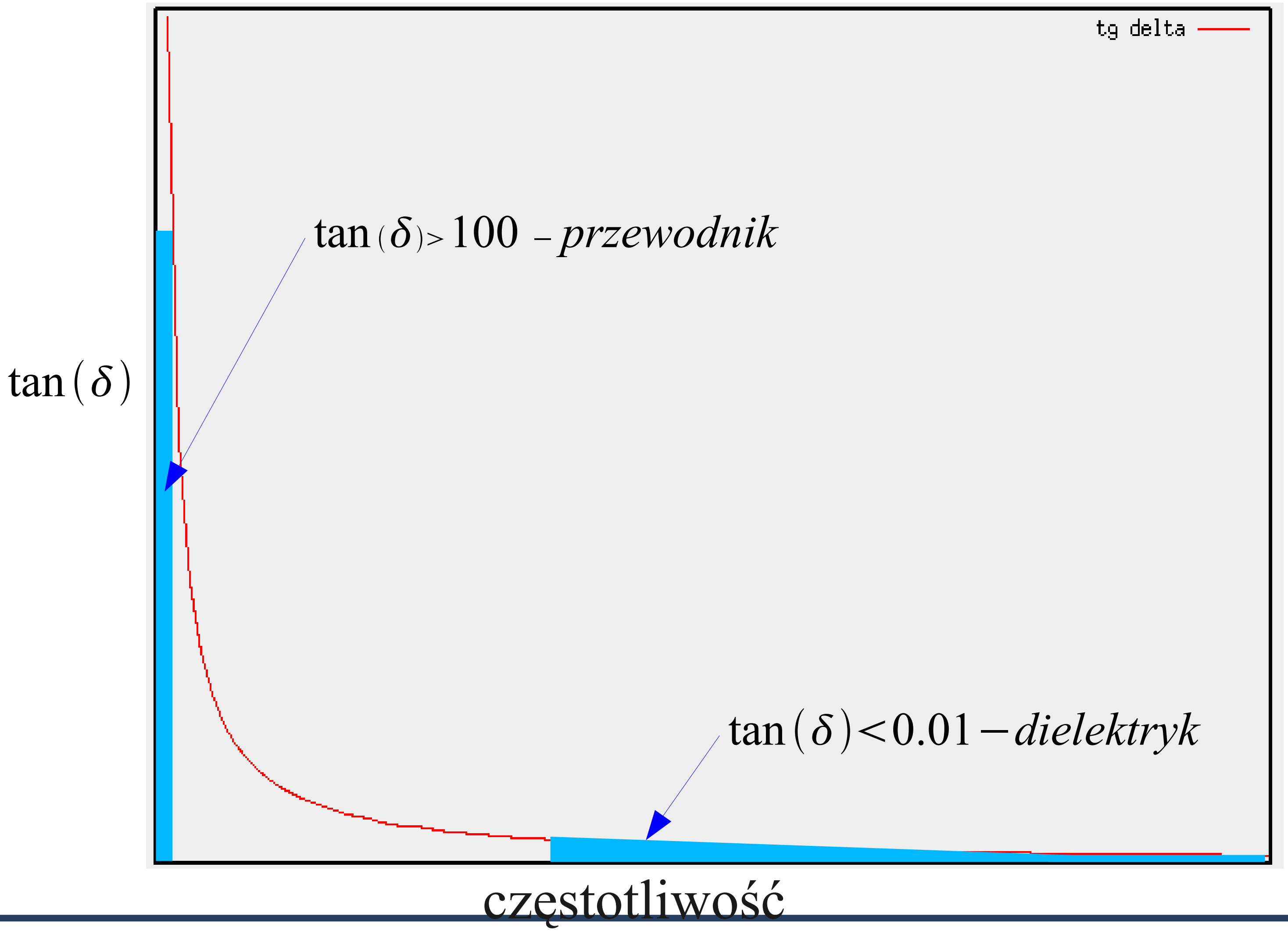
$$\underline{\epsilon} = \epsilon - j\frac{\sigma}{\omega}$$

$$\underline{\Gamma} = \sqrt{j\omega\sigma\mu - \omega^2 \epsilon\mu} = \alpha + j\beta$$

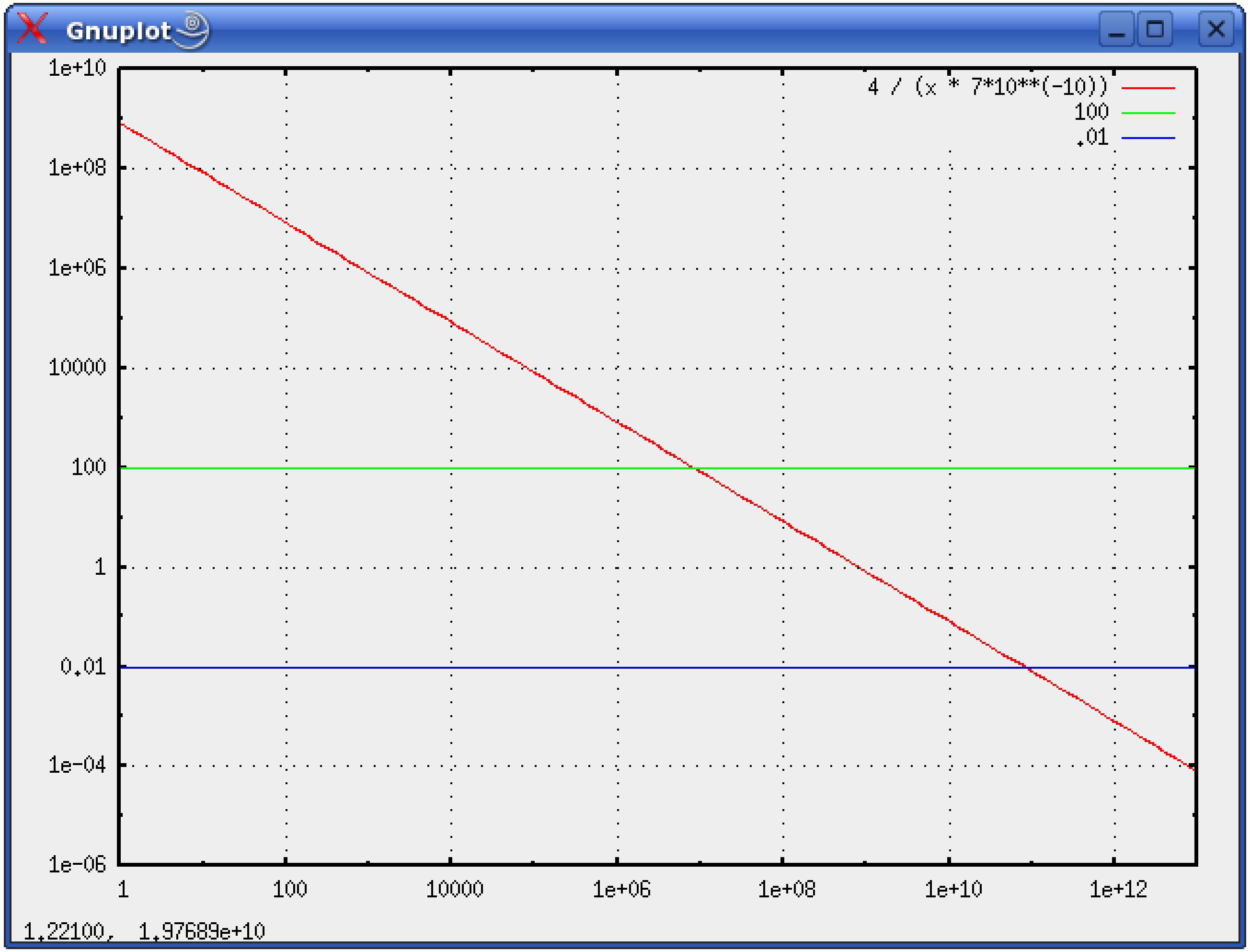
Klasyfikacja materiałów:

$\underline{J}_{\sigma}=\sigma\,\underline{E}\,,\quad \underline{J}_{\epsilon}=j\,\omega\,\underline{D}=j\,\omega\,\epsilon\,\underline{E}$

$$\frac{\underline{J}_{\sigma}}{\underline{J}_{\epsilon}}=\frac{\sigma}{\omega\,\epsilon}=\tan(\delta)$$

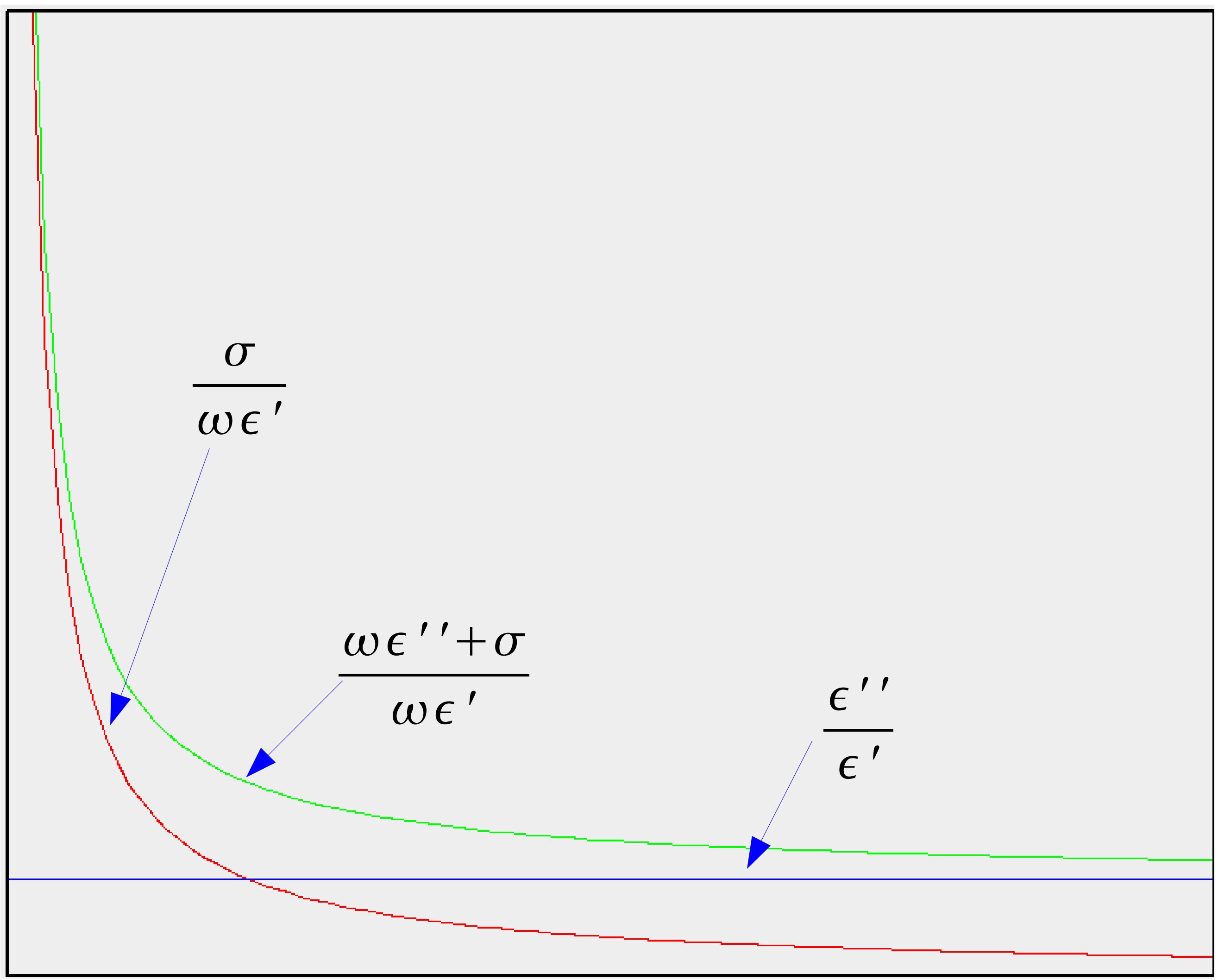


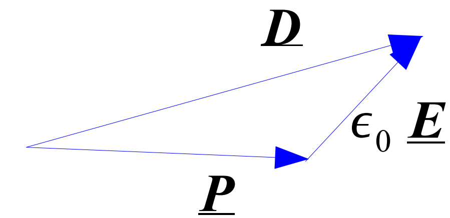
Klasyfikacja materiałów:



Woda morska: 4 S/m, 7e-10 F/m

Dyspersja częstotliwościowa:





$$\underline{\boldsymbol{D}} = \left(\epsilon' - j\,\epsilon''\right)\underline{\boldsymbol{E}}$$

$$\underline{\epsilon} = \epsilon' - j\left(\epsilon'' + \frac{\sigma}{\omega}\right)$$

$$\underline{\boldsymbol{J}_{\sigma}} = \left(\sigma + \omega\,\epsilon''\right)\underline{\boldsymbol{E}}$$

$$\tan(\delta) = \frac{\left(\sigma + \omega\,\epsilon''\right)}{\omega\,\epsilon'}$$

Przemiany energetyczne

$$W = W_E + W_H = \frac{1}{2}\int_V \left(\epsilon E^2 + \mu H^2\right) dV$$

$$P = \frac{\partial D}{\partial t}$$

Moc dodatnia – dostarczana,
Moc ujemna – strata i wypromieniowywanie

$$\boldsymbol{H}\, rot\, \boldsymbol{E} - \boldsymbol{E}\, rot\, \boldsymbol{H} = div\left(\boldsymbol{E} \times \boldsymbol{H}\right)$$

$$-\frac{\partial P}{\partial t} = \int_V \left(\epsilon \boldsymbol{E} \frac{\partial \boldsymbol{E}}{\partial t} + \mu \boldsymbol{H} \frac{\partial \boldsymbol{H}}{\partial t}\right) dV = \cdots$$

$$\epsilon \frac{\partial \boldsymbol{E}}{\partial t} = rot\, \boldsymbol{H} - \sigma \boldsymbol{E}$$

$$\mu \frac{\partial \boldsymbol{H}}{\partial t} = -rot\, \boldsymbol{E}$$

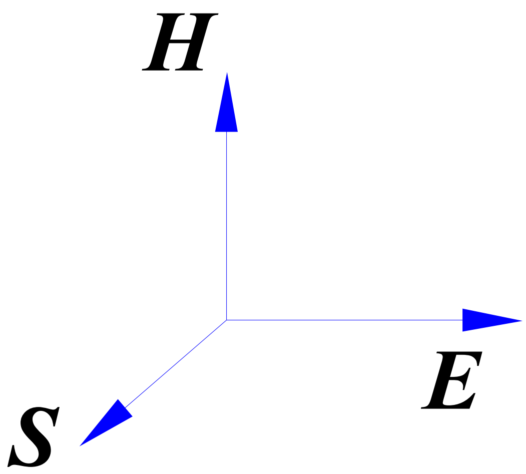
$$\cdots = \int_V \left(\sigma E^2\right) dV + \int_V div\left(\boldsymbol{E} \times \boldsymbol{H}\right) dV = \cdots$$

$$\cdots = \int_V \left(\sigma E^2\right) dV + \oint_s \left(\boldsymbol{E} \times \boldsymbol{H}\right) dS$$

Wektor Poyntinga

$$P = \int_V \left(\sigma E^2 \right) dV + \oint_s \left(\boldsymbol{E} \times \boldsymbol{H} \right) dS$$

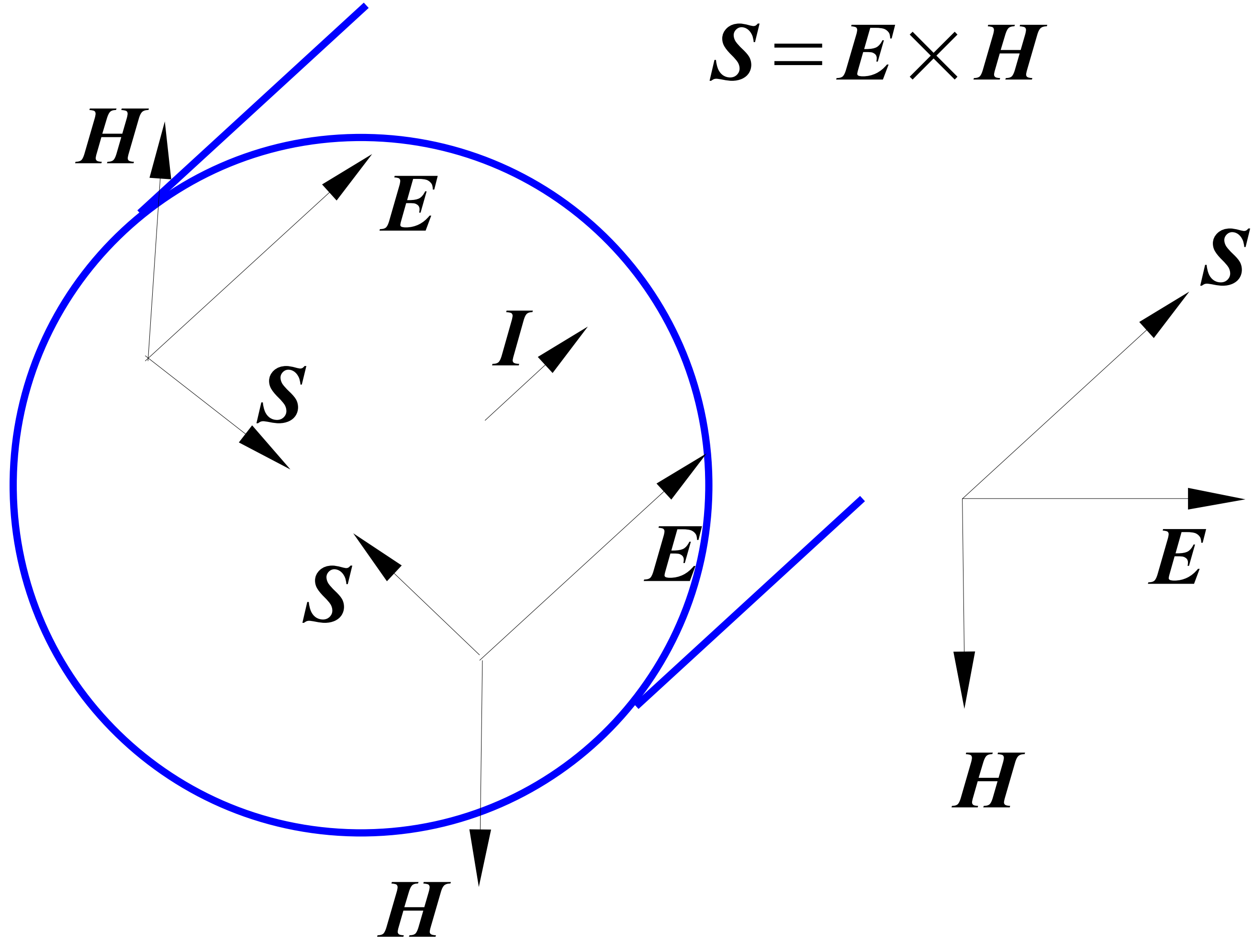
$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H} \qquad \text{[W/m^2]}$$



Wektor Poyntinga

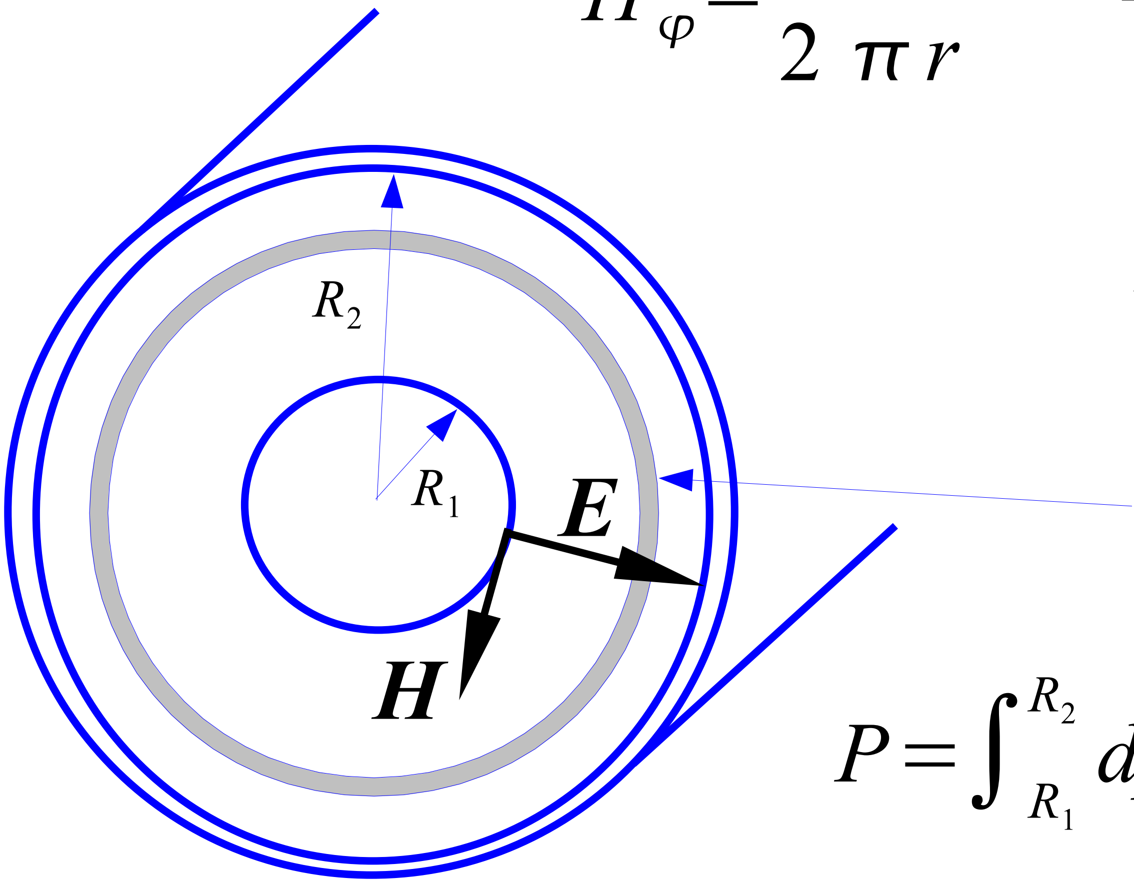
Prosty, długi przewód

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$$



Strumień wektora Poyntinga

Dielektryk



Przewód koncentryczny

$$H_\varphi = \frac{I}{2\pi r}$$

$$E_r = \frac{U}{r \ln(R_2/R_1)}$$

$$S_z = \frac{U I}{2\pi r^2 \ln(R_2/R_1)}$$

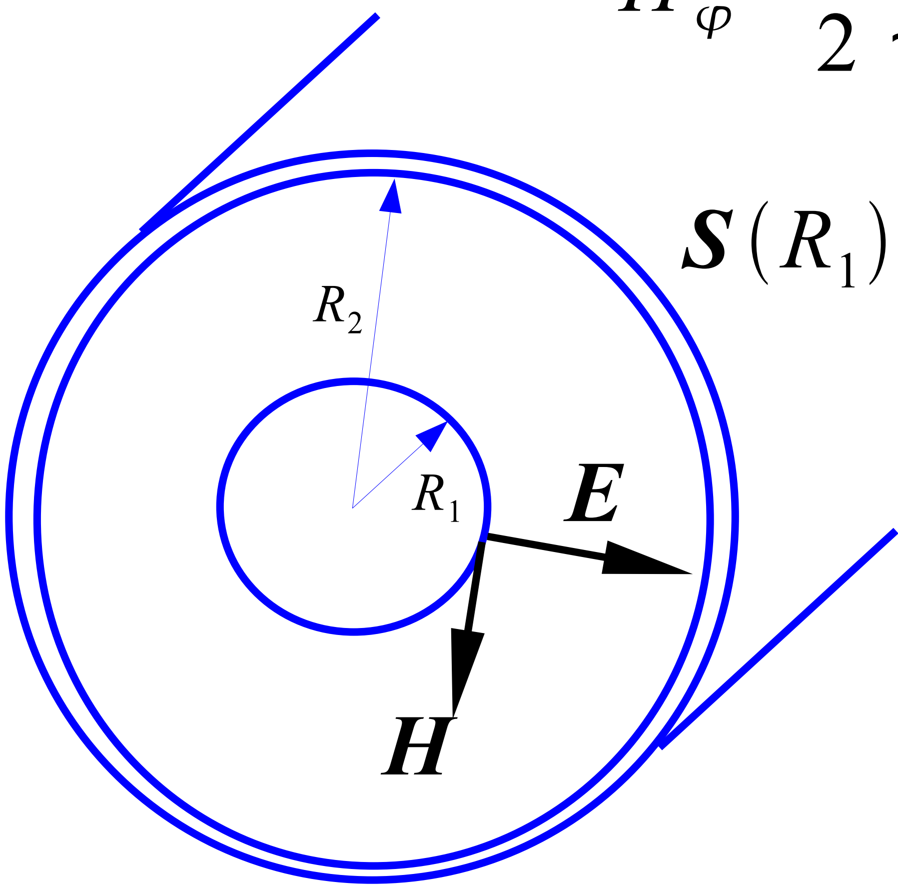
$$dp = S_z 2\pi r\, dr$$

$$P = \int_{R_1}^{R_2} dp = \frac{U I}{\ln(R_2/R_1)} \int_{R_1}^{R_2} \frac{1}{r} dr$$

$$P = U I$$

Strumień wektora Poyntinga

Powierzchnia żyły:



$$H_{\varphi} = \frac{I}{2\pi R_1}$$

$$E_Z = \frac{J}{\sigma} = \frac{I}{\pi R_1^2} \cdot \frac{1}{\sigma}$$

$$\boldsymbol{S}(R_1) = \boldsymbol{E}(R_1) \times \boldsymbol{H}(R_1) = -S_r \mathbf{1}_r + S_z \mathbf{1}_z$$

$$S_r = \frac{I^2}{2\pi^2 \sigma R_1^3}$$

$$X = \frac{1}{I^2}\left[Im \frac{1}{2} \oint_s \left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^* \right) dS \right]$$

Przewód koncentryczny

Wektor Poyntinga w polu harmonicznym

W. Poyntinga

$$\underline{\boldsymbol{S}} = \frac{1}{2}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right) \qquad \underline{\boldsymbol{S}} = \boldsymbol{P} + j\,\boldsymbol{Q}$$

Moc

$$S = P + j\,Q$$

$$Q = Im\,\frac{1}{2}\oint_{s}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right)dS \qquad P = Re\,\frac{1}{2}\oint_{s}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right)dS$$

Parametry obwodowe

$$\underline{Z} = \frac{1}{I^{2}}\left[\frac{1}{2}\oint_{s}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right)dS\right]$$

$$R = \frac{1}{I^{2}}\left[Re\,\frac{1}{2}\oint_{s}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right)dS\right] \qquad X = \frac{1}{I^{2}}\left[Im\,\frac{1}{2}\oint_{s}\left(\underline{\boldsymbol{E}} \times \underline{\boldsymbol{H}}^{*}\right)dS\right]$$

Siły mechaniczne

Pole elektryczne:

$$f_e = \rho\,\boldsymbol{E} - \frac{1}{2} E^2 \, grad\, \epsilon$$

Pole magnetyczne:

$$f_m = \boldsymbol{J} \times \boldsymbol{B} - \frac{1}{2} H^2 \, grad\, \mu$$

Pole elektromagnetyczne:

$$f_{em} = f_e + f_m + \frac{\partial p}{\partial t}$$

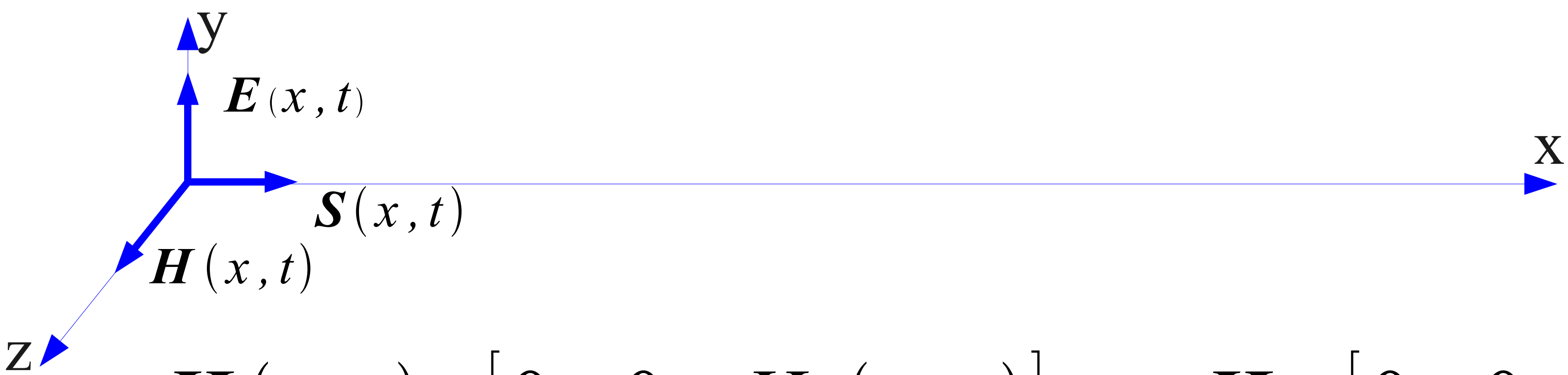
$$p = \epsilon\,\mu\left(\boldsymbol{E} \times \boldsymbol{H}\right) = \frac{1}{\vartheta^2}\left(\boldsymbol{E} \times \boldsymbol{H}\right)$$

Harmoniczna fala płaska (1)

$$\nabla^2 \boldsymbol{H} = \sigma\mu \frac{\partial \boldsymbol{H}}{\partial t} + \epsilon\mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2}$$

$$\nabla^2 \underline{\boldsymbol{H}} = j\omega\sigma\mu \underline{\boldsymbol{H}} - \omega^2 \epsilon\mu \underline{\boldsymbol{H}}$$

$$\nabla^2 \underline{\boldsymbol{H}} = \underline{\Gamma}^2 \underline{\boldsymbol{H}} \qquad \underline{\Gamma} = \alpha + j\beta = \sqrt{j\omega\sigma\mu - \omega^2 \epsilon\mu}$$

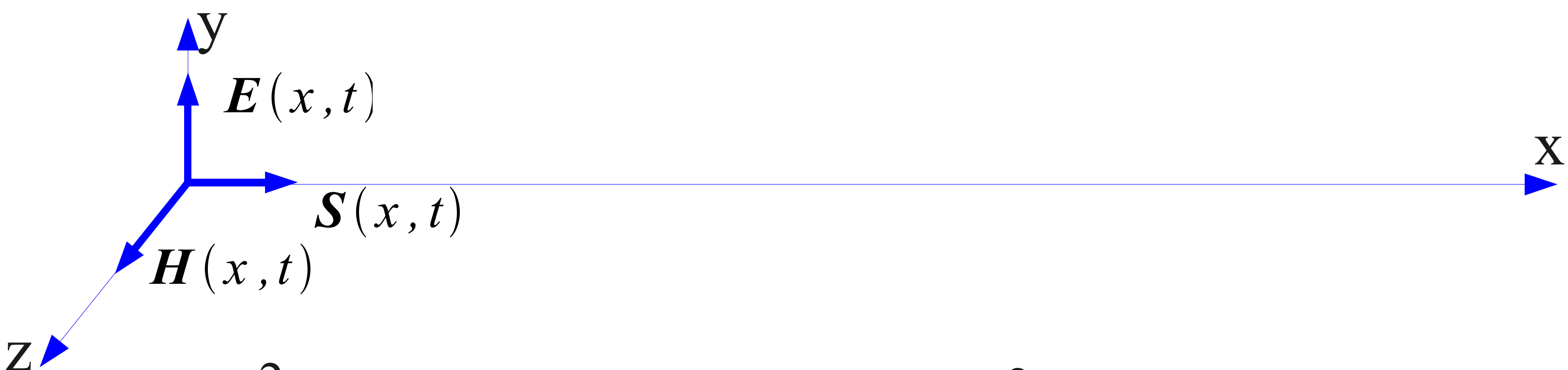


$$\boldsymbol{H}(\boldsymbol{r}, t) = \begin{bmatrix} 0 & 0 & H_z(x, t) \end{bmatrix}, \qquad \underline{\boldsymbol{H}} = \begin{bmatrix} 0 & 0 & \underline{H}_z(x) \end{bmatrix}$$

$$\boldsymbol{E}(\boldsymbol{r}, t) = \begin{bmatrix} 0 & E_y(x, t) & 0 \end{bmatrix}, \qquad \underline{\boldsymbol{E}} = \begin{bmatrix} 0 & \underline{E}_y(x) & 0 \end{bmatrix}$$

Harmoniczna fala płaska (2)

$$\nabla^2 \underline{\boldsymbol{E}} - \underline{\Gamma^2}\, \underline{\boldsymbol{E}} = 0 \qquad \nabla^2 \underline{\boldsymbol{H}} - \underline{\Gamma^2}\, \underline{\boldsymbol{H}} = 0$$



$$\frac{\partial^2 \underline{E_y}}{\partial x^2} - \underline{\Gamma^2}\, \underline{E_y} = 0 \qquad \frac{\partial^2 \underline{H_z}}{\partial x^2} - \underline{\Gamma^2}\, \underline{H_z} = 0$$

$$\underline{E_y}(x) = \underline{E_1}\, e^{-\Gamma x} + \underline{E_2}\, e^{\Gamma x}$$

$$\underline{H_z}(x) = \underline{H_1}\, e^{-\Gamma x} + \underline{H_2}\, e^{\Gamma x}$$

Harmoniczna fala płaska (3)

$$\underline{\Gamma} = \sqrt{j\omega\sigma\mu - \omega^2 \epsilon\mu} = \alpha + j\beta$$

$$\alpha = \omega\sqrt{\frac{\epsilon\mu}{2}\left(\sqrt{1+tan\,\delta_0} - 1\right)} \qquad \tan\delta_0 = \frac{\sigma}{\omega\epsilon}$$

$$\beta = \omega\sqrt{\frac{\epsilon\mu}{2}\left(\sqrt{1+tan\,\delta_0} + 1\right)}$$

$$E_y(x,t) = E_1 e^{-\alpha x}\sin(\omega t - \beta x + \psi_{e1}) + E_2 e^{\alpha x}\sin(\omega t + \beta x + \psi_{e2})$$

$$H_z(x,t) = H_1 e^{-\alpha x}\sin(\omega t - \beta x + \psi_{h1}) + H_2 e^{\alpha x}\sin(\omega t + \beta x + \psi_{h2})$$

Impedancja falowa

$$\nabla \times \underline{\boldsymbol{E}} = -j\omega\mu\underline{\boldsymbol{H}}$$

$$\frac{\partial \underline{E_y}}{\partial x} = -j\omega\mu\underline{H_z}$$

$$\underline{E_y}(x) = \underline{E_1}e^{-\Gamma x} + \underline{E_2}e^{\Gamma x}$$

$$\Gamma\left(-\underline{E_1}e^{-\Gamma x} + \underline{E_2}e^{\Gamma x}\right) = -j\omega\mu\left(\underline{H_1}e^{-\Gamma x} + \underline{H_2}e^{\Gamma x}\right)$$

$$\Gamma\underline{E_1} = j\omega\mu\underline{H_1}$$

$$\frac{E_1}{H_1} = \frac{j\omega\mu}{\Gamma} = \underline{Z_c}$$

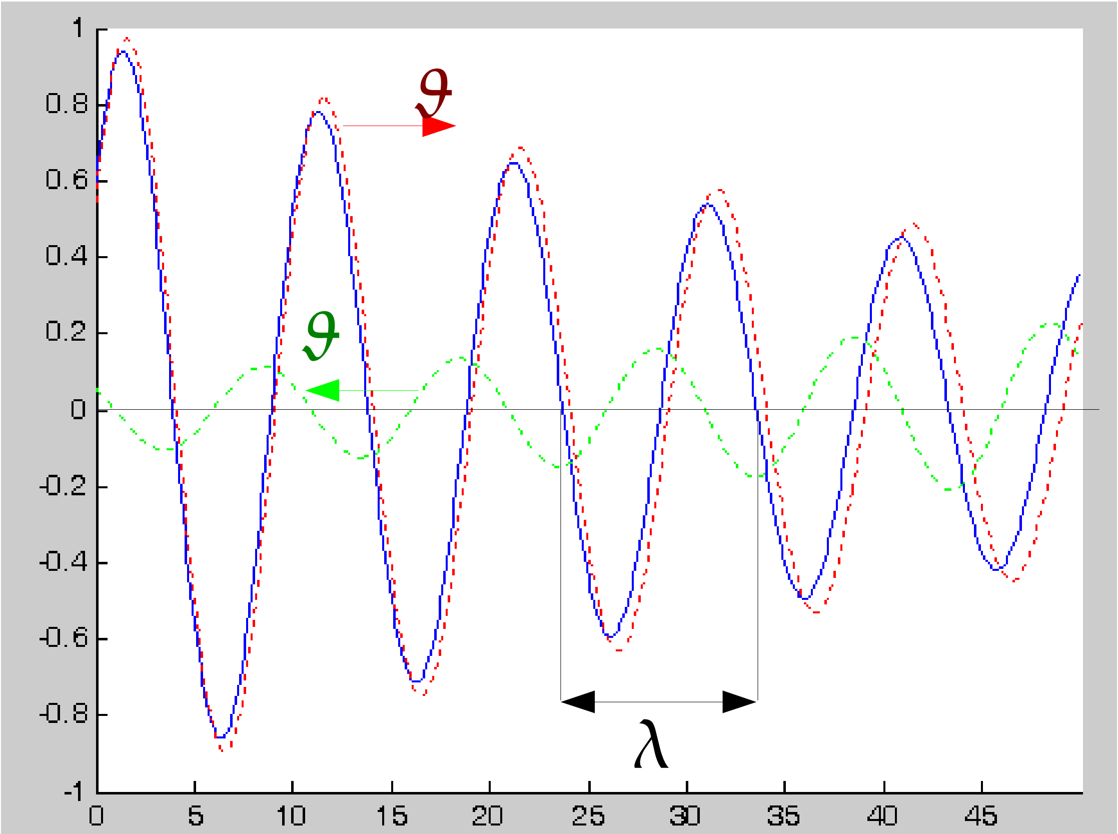
Rozchodzenie się fali

$$E_y(x,t)=E_1\,e^{-\alpha x}\sin(\omega t-\beta x+\psi_{e1})+E_2\,e^{\alpha x}\sin(\omega t+\beta x+\psi_{e2})$$

$$\omega t-\beta x+\psi_{e1}=const,\quad \omega t+\beta x+\psi_{e1}=const$$

$$\vartheta=\frac{\partial x}{\partial t}=\frac{\omega}{\beta}$$

$$\lambda=\vartheta T=\frac{\vartheta}{f}=\frac{\omega}{\beta}T=\frac{2\pi}{\beta}$$



Harmoniczna fala płaska w dielektryku

$$\underline{\Gamma} = \sqrt{j\omega\sigma\mu - \omega^2\epsilon\mu} = \sqrt{-\omega^2\epsilon\mu} = j\omega\sqrt{\epsilon\mu}$$

$$E_y(x,t) = E_1 \sin(\omega t - \beta x + \psi_{e1}) + E_2 \sin(\omega t + \beta x + \psi_{e2})$$

$$\beta = \omega\sqrt{\epsilon\mu}$$

$$Z_c = \frac{E}{H} = \frac{j\omega\mu}{j\omega\sqrt{\epsilon\mu}} = \sqrt{\frac{\mu}{\epsilon}} \qquad \vartheta = \frac{\omega}{\beta} = \frac{1}{\sqrt{\epsilon\mu}}$$

Dla próżni:

$$\epsilon_0 = 8.85\,10^{-12}, \quad \mu_0 = 4\,\pi\,10^{-7}$$

$$Z_c \approx 377\ \Omega \qquad \vartheta = c \approx 3\,10^8\ m/s$$

Harmoniczna fala płaska w przewodniku

$$\underline{\Gamma}=\sqrt{j\omega\sigma\mu-\omega^2\epsilon\mu}\approx\sqrt{j\omega\sigma\mu}=\sqrt{\frac{\omega\sigma\mu}{2}}+j\sqrt{\frac{\omega\sigma\mu}{2}}$$

$$\alpha=\beta=\sqrt{\frac{\omega\sigma\mu}{2}}$$

$$\vartheta=\frac{\omega}{\beta}=\sqrt{\frac{2\omega}{\sigma\mu}}$$

$$Z_c=\frac{E}{H}=\frac{j\omega\mu}{\Gamma}=\sqrt{\frac{\omega\mu}{\sigma}}e^{j\pi/4}$$

$$\lambda=\frac{2\pi}{\beta}=2\sqrt{\frac{\pi}{f\sigma\mu}}$$

$$E_y(x,t)=E_1 e^{-\alpha x}\sin(\omega t-\beta x+\psi_{e1})$$

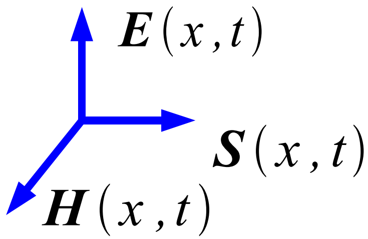
$$u=\frac{1}{\alpha}=\sqrt{\frac{2}{\omega\sigma\mu}}=\sqrt{\frac{2}{2\pi f\sigma\mu}}=\frac{\lambda}{2\pi}$$

$$e^{-2\pi}\approx 0.0018$$

Harmoniczna fala płaska w przewodniku

Materiał	σ [S/m]	μ_r	ε_r	Zastępcza głębokość wnikania [mm]			
				50 Hz	10 kHz	1 MHz	10 GHz
Srebro	$6{,}2 \cdot 10^7$	1	1	9,05	0,64	0,064	0,64 μm
Miedź	$5{,}6 \cdot 10^7$	1	1	9,7	0,67	0,067	0,67 μm
Aluminium	$3{,}7 \cdot 10^7$	1	1	11,7	0,83	0,083	0,83 μm
Stal	$1 \cdot 10^7$	10^3	1	0,71	0,05	0,005	0,05 μm
Woda morska	4	1	81	35,6	2,51 m	251	2,5
Woda czysta	$1 \cdot 10^{-3}$	1	81	2,26 km	160 m	x	x
Grunt suchy	$\approx 1 \cdot 10^{-3}$	1	10	2,26 km	160 m	x	x
Grunt mokry	$\approx 1 \cdot 10^{-5}$	1	3	22,6 km	1,6 km	x	x

HFP na granicy środowisk



Z_{c1} | Z_{c2}

$$\underline{E}_{1}=\underline{E}_{1\mathrm{p}}e^{-\Gamma_1 x}+\underline{E}_{1\mathrm{o}}e^{\Gamma_1 x}$$

$$\underline{H}_{1}=\underline{H}_{1\mathrm{p}}e^{-\Gamma_1 x}+\underline{H}_{1\mathrm{o}}e^{\Gamma_1 x}$$

$$\underline{E}_{1}/\underline{H}_{1}=Z_{c1}$$

$$\underline{E}_{2}=\underline{E}_{2\mathrm{p}}e^{-\Gamma_2 x}$$

$$\underline{H}_{2}=\underline{H}_{2\mathrm{p}}e^{-\Gamma_2 x}$$

$$\underline{E}_{2}/\underline{H}_{2}=Z_{c2}$$

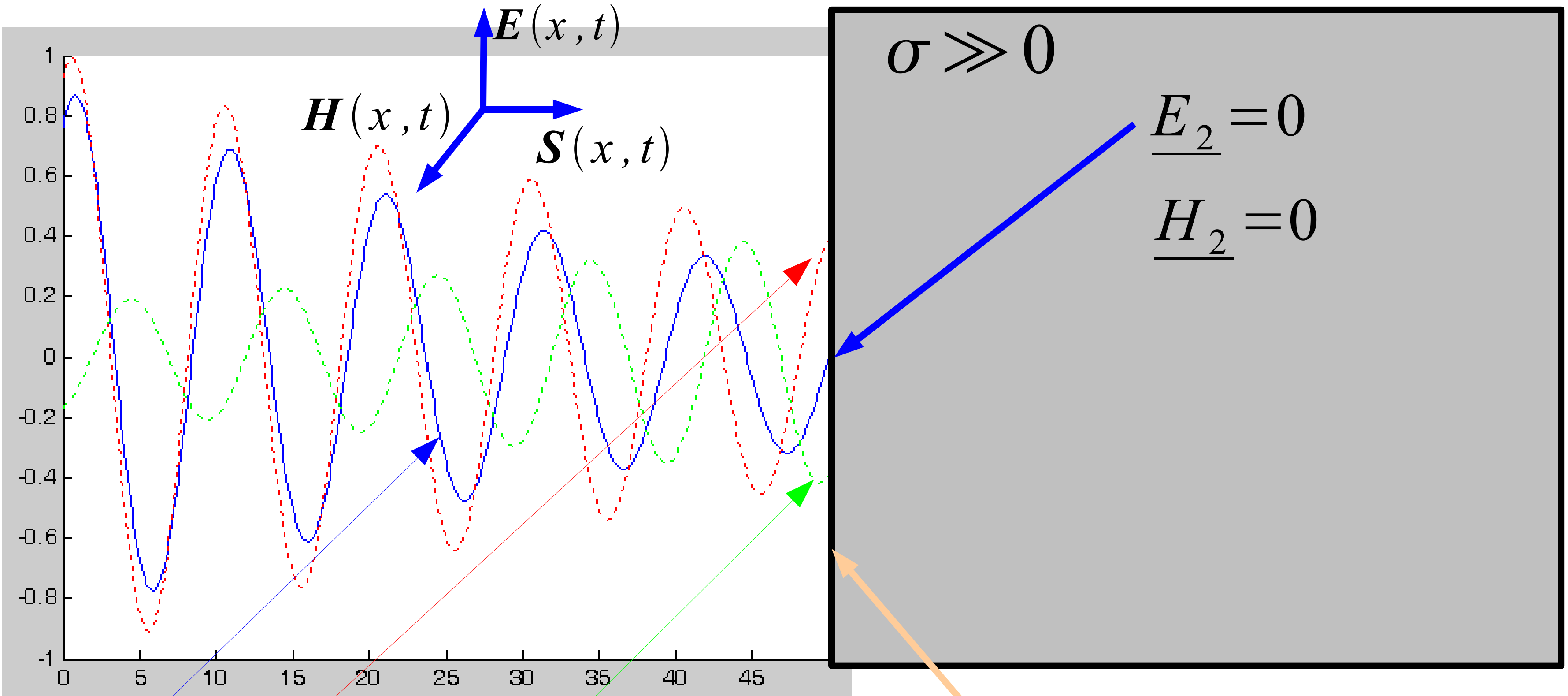
$$\underline{E}_{1\mathrm{p}}+\underline{E}_{1\mathrm{o}}=\underline{E}_{2\mathrm{p}}$$

$$\underline{H}_{1\mathrm{p}}+\underline{H}_{1\mathrm{o}}=\underline{H}_{2\mathrm{p}}$$

$$\underline{E}_{1\mathrm{o}}=M\,\underline{E}_{1\mathrm{p}} \qquad \underline{H}_{1\mathrm{o}}=-M\,\underline{H}_{1\mathrm{p}} \qquad M=\frac{Z_{c2}-Z_{c1}}{Z_{c2}+Z_{c1}}$$

$$\underline{E}_{2\mathrm{p}}=N\,\underline{E}_{1\mathrm{p}} \qquad \underline{H}_{2\mathrm{p}}=Z_{c1}/Z_{c2}\,N\,\underline{H}_{1\mathrm{p}} \qquad N=\frac{2\,Z_{c2}}{Z_{c2}+Z_{c1}}$$

HFP na powierzchni przewodnika



$$\underline{E}_1 = \underline{E}_{1\mathrm{p}} e^{-\Gamma_1 x} + \underline{E}_{1\mathrm{o}} e^{\Gamma_1 x}$$

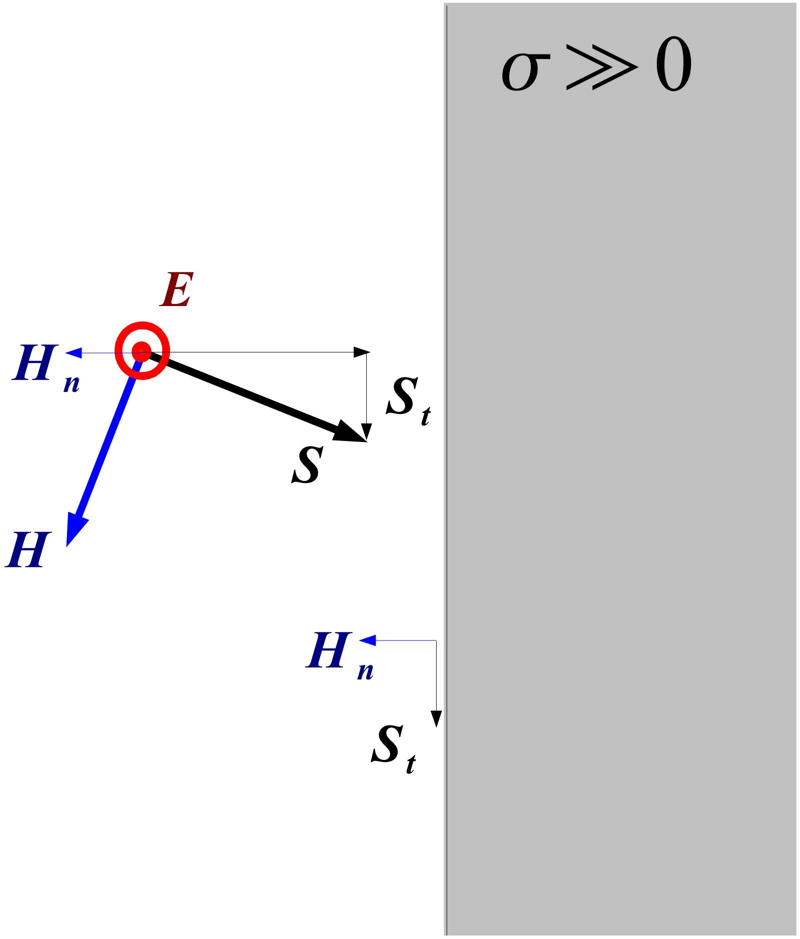
$$\underline{H}_1 = \underline{H}_{1\mathrm{p}} e^{-\Gamma_1 x} + \underline{H}_{1\mathrm{o}} e^{\Gamma_1 x}$$

$$\underline{E}_{1\mathrm{p}} + \underline{E}_{1\mathrm{o}} = \underline{E}_{2\mathrm{p}}$$

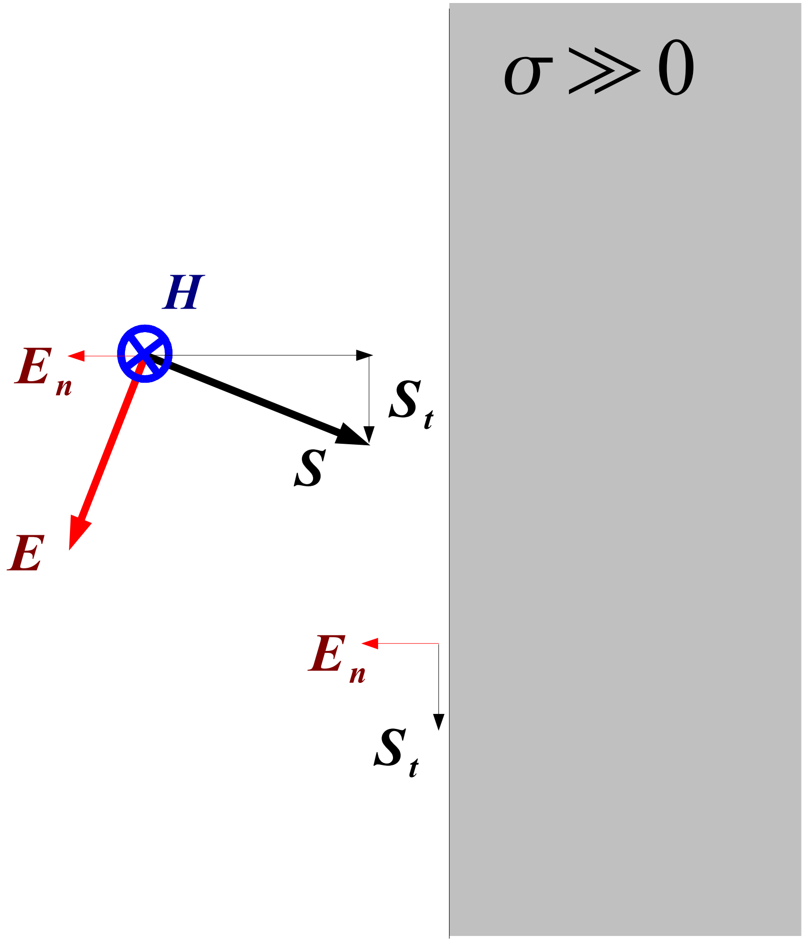
$$\underline{H}_{1\mathrm{p}} + \underline{H}_{1\mathrm{o}} = \underline{H}_{2\mathrm{p}}$$

Fale poprzeczne

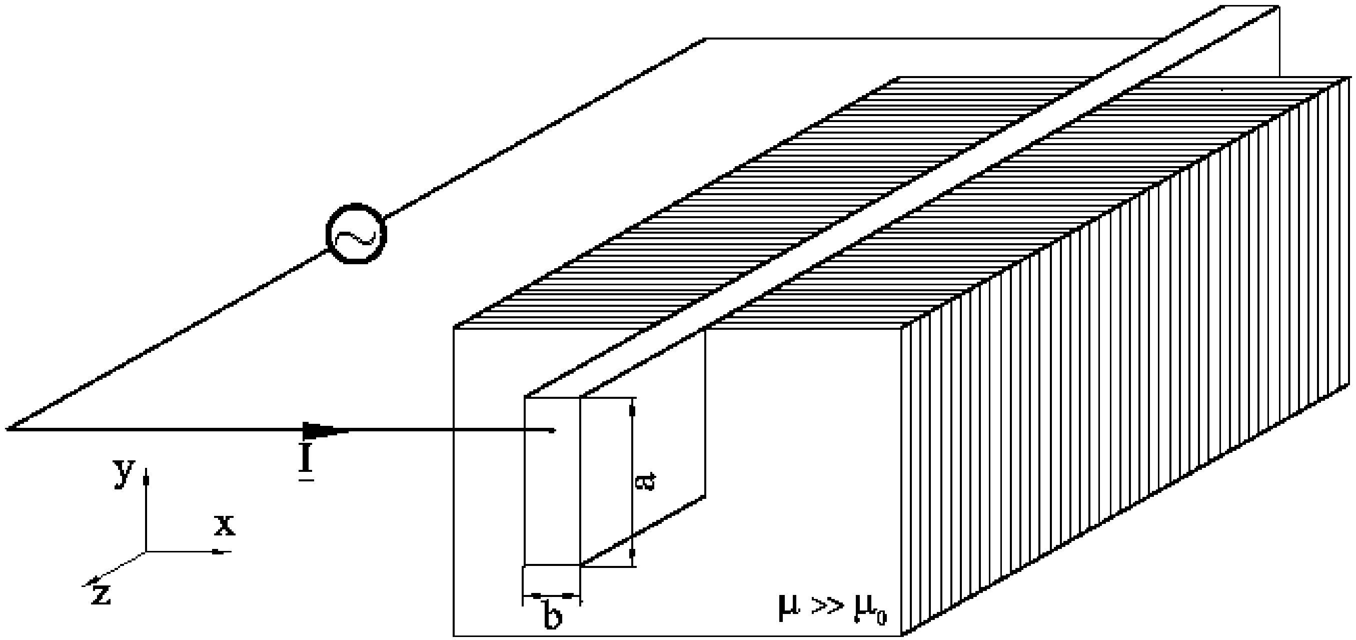
Fala magnetyczna
(poprzeczna elektryczna TE)



Fala elektryczna
(poprzeczna magnetyczna TM)



Zjawisko naskórkowości



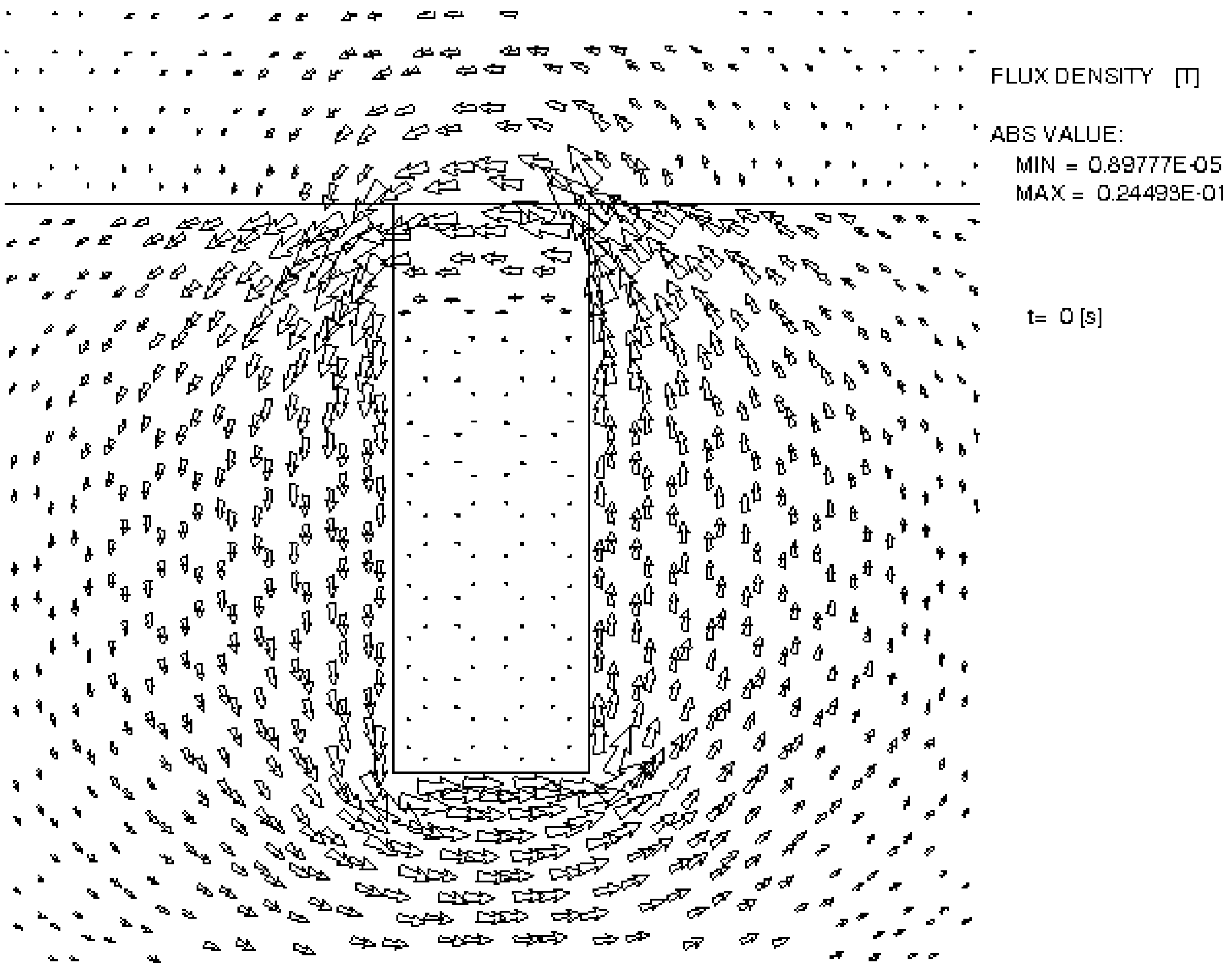
$$\frac{\partial^2 \underline{H}}{\partial y^2} - \underline{\Gamma}^2 \underline{H} = 0$$

$$\underline{H}(y) = \frac{\underline{I}\sinh(\underline{\Gamma}\, y)}{b\sinh(\underline{\Gamma}\, a)}$$

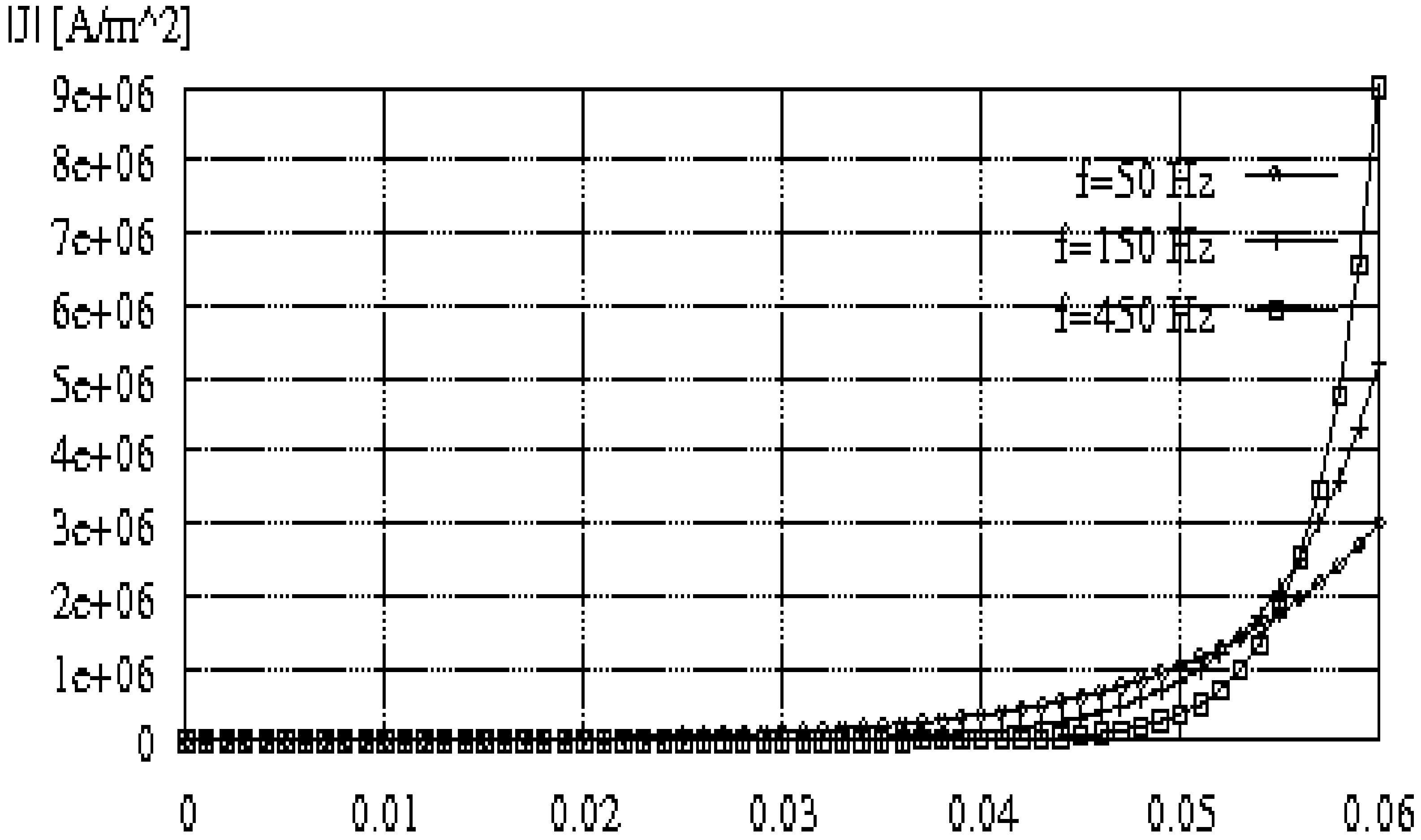
$$\underline{H}(0) = 0, \qquad \underline{H}(a) = \frac{\underline{I}}{b}$$

$$\underline{J}(y) = \frac{\underline{I}\,\underline{\Gamma}\cosh(\underline{\Gamma}\, y)}{b\sinh(\underline{\Gamma}\, a)}$$

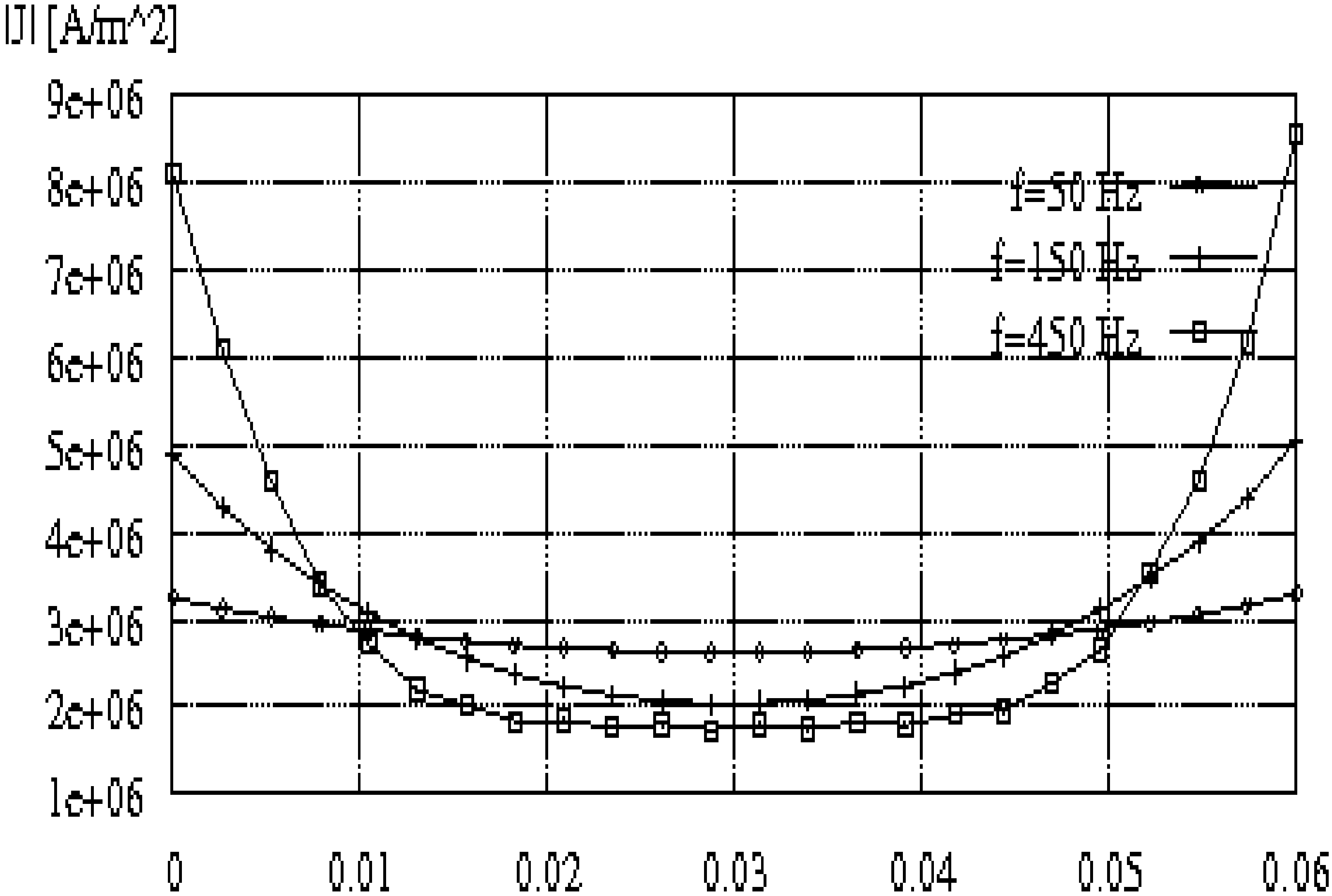
Zjawisko naskórkowości



Zjawisko naskórkowości



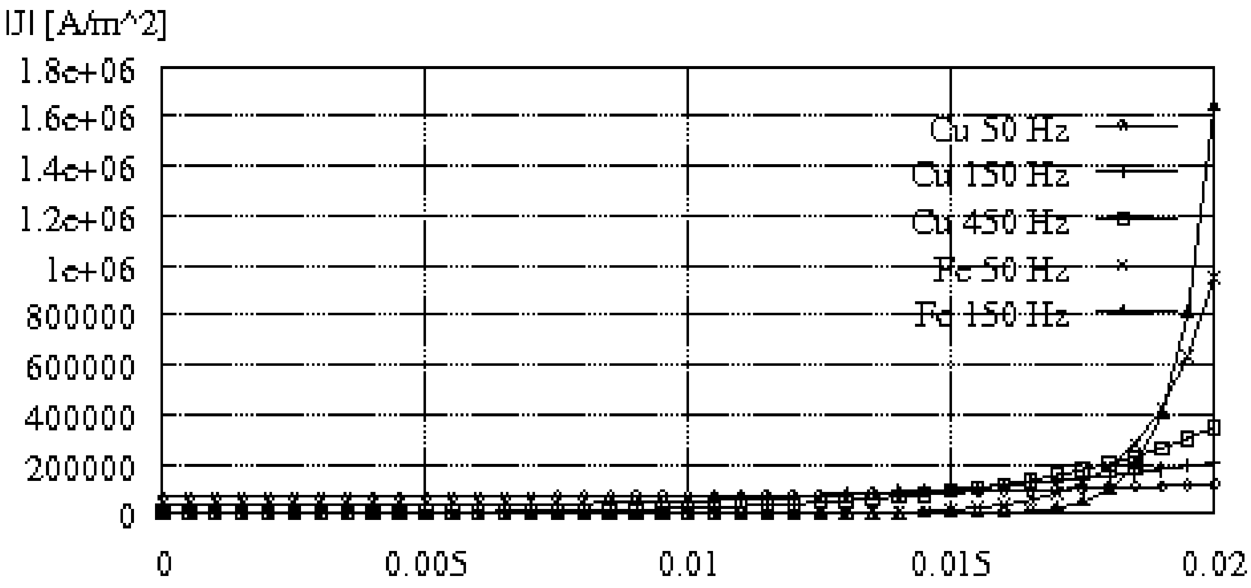
Zjawisko naskórkowości



Przewód kołowy

$$\frac{d^2 \underline{J}}{d r^2} + \frac{1}{r}\frac{d \underline{J}}{d r} - j\omega\sigma\mu\underline{J} = 0$$

$$\underline{J}(r) = \frac{\underline{I}\sqrt{(-j\omega\sigma\mu)}\,J_0(\sqrt{(-j\omega\sigma\mu)})}{2\pi R J_1(\sqrt{(-j\omega\sigma\mu)})}$$



Silne zjawisko naskórkowości

Kiedy?

grubość przewodnika >> u

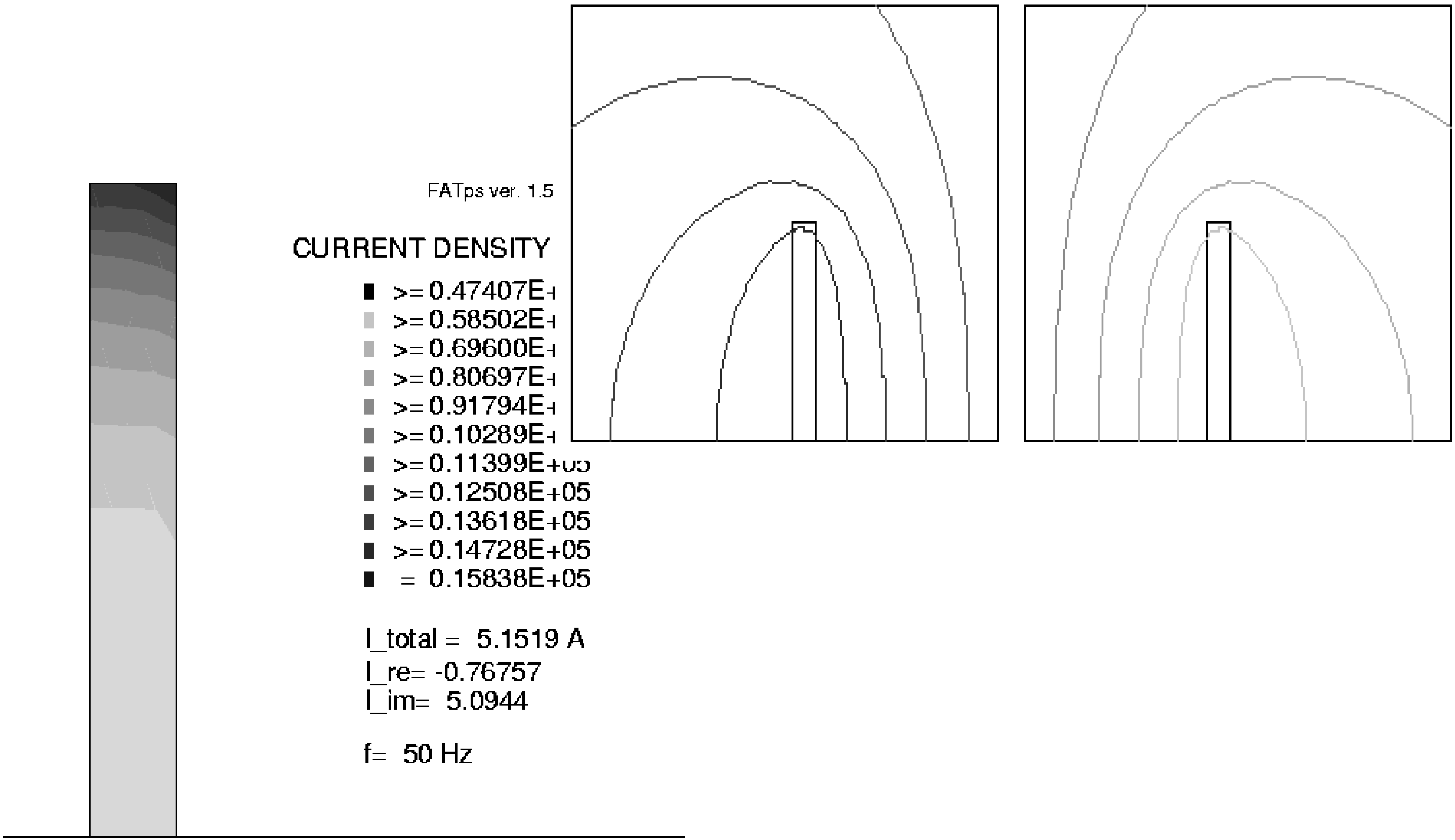
Jak: wnikanie fali w nieograniczony przewodnik.

$$u=\sqrt{\frac{2}{\omega\sigma\mu}}$$

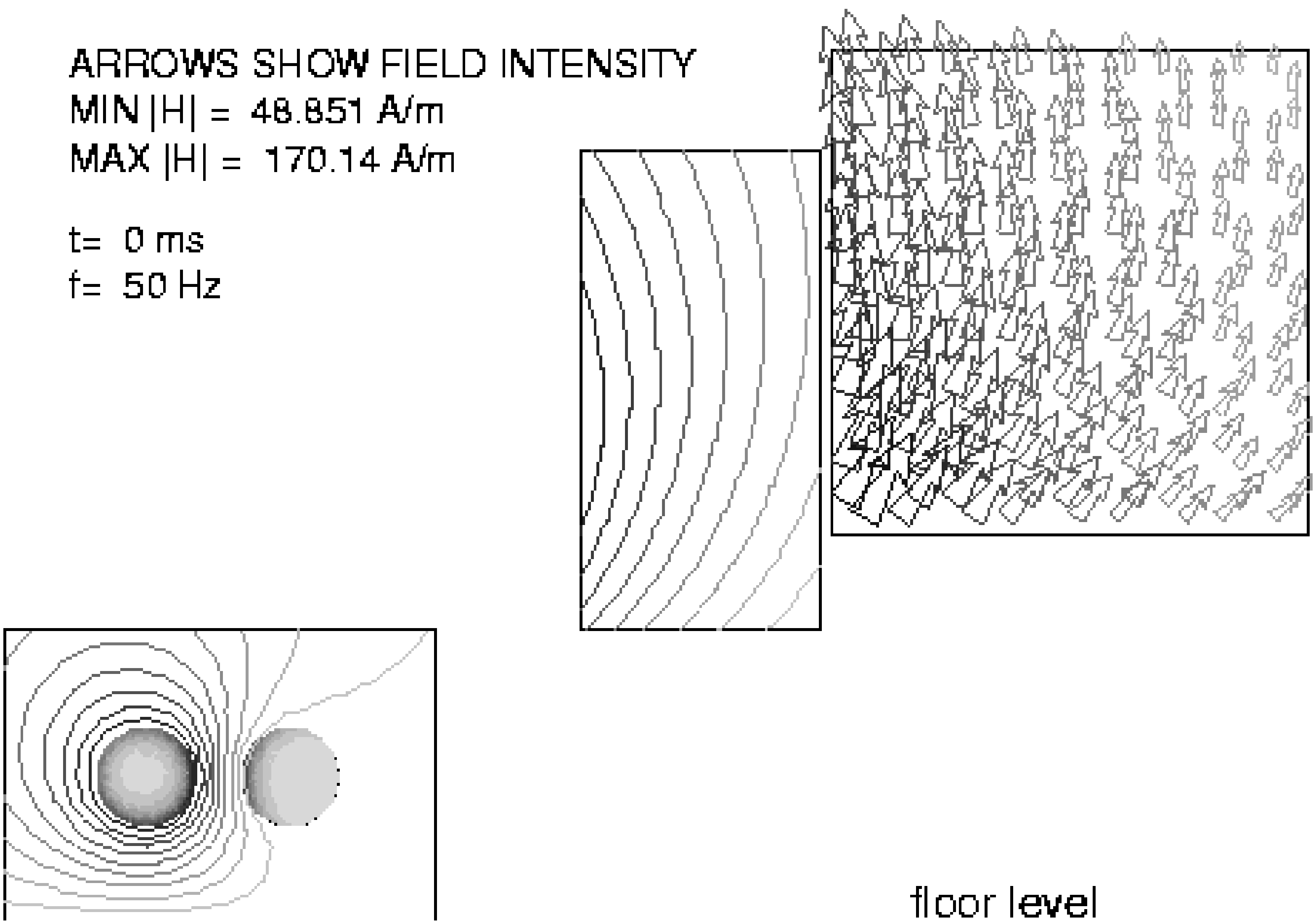
$$\underline{H}(r)=\underline{H}_s e^{-\underline{\Gamma}(R-r)} \qquad \underline{H}_s=\frac{\underline{I}}{2\pi R}$$

$$\underline{J}(r)=\underline{H}_s\sqrt{\omega\sigma\mu}\,e^{j\pi/4}\,e^{-\underline{\Gamma}(R-r)}$$

Zjawisko zbliżenia



Zjawisko zbliżenia



Ekran elektromagnetyczny