

**СПбГУТ им. проф. М.А. Бонч-Бруевича**

***Основы  
радиоэлектроники  
и связи***

**2013 г.**

*Физические каналы*  
*Проводной канал*

# Основные понятия

*Физический канал* — естественная или искусственная среда распространения сигналов

# Физический канал в виде линейного четырёхполюсника



# Физический канал в виде линейного четырёхполюсника



$$\begin{cases} u_1 = A_{11} \cdot u_2 + A_{12} \cdot i_2; \\ i_1 = A_{21} \cdot u_2 + A_{22} \cdot i_2 \end{cases}$$

# Физический канал в виде линейного четырёхполюсника



$$\begin{cases} u_1 = A_{11} \cdot u_2 + A_{12} \cdot i_2; \\ i_1 = A_{21} \cdot u_2 + A_{22} \cdot i_2 \end{cases}$$

$$\begin{bmatrix} u_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{bmatrix} u_2 \\ i_2 \end{bmatrix}$$

$$[A] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$

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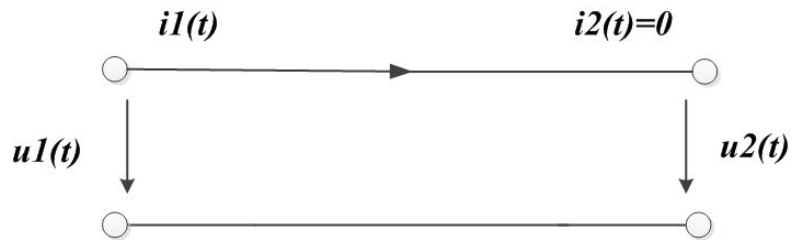
$$A_{11} = \left. \frac{u_1}{u_2} \right|_{i_2=0} \quad \text{ОМ}$$

$$A_{12} = \left. \frac{u_1}{i_2} \right|_{u_2=0}$$

$$A_{21} = \left. \frac{i_1}{u_2} \right|_{i_2=0} \quad \text{СМ}$$

$$A_{22} = \left. \frac{i_1}{i_2} \right|_{u_2=0}$$

# Физический канал в виде линейного четырёхполюсника

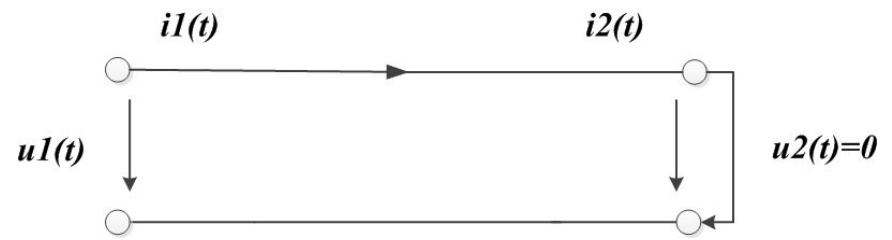
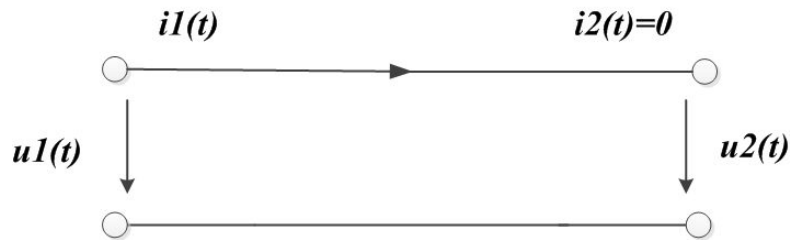


$$A_{11} = \left. \frac{u_1}{u_2} \right|_{i_2=0} = 1; \quad u_1 = u_2;$$

$$A_{21} = \left. \frac{i_1}{u_2} \right|_{i_2=0} = 0; \quad i_1 = 0;$$



# Физический канал в виде линейного четырёхполюсника



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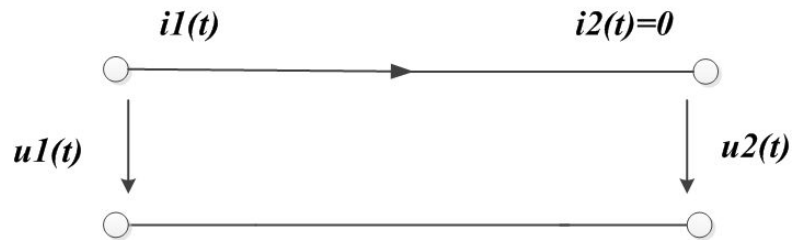
$$A_{12} = \left. \frac{u_1}{i_2} \right|_{u_2=0} = 0; \quad u_1 = u_2 = 0;$$

$$A_{22} = \left. \frac{i_1}{i_2} \right|_{u_2=0} = 1; \quad i_1 = i_2;$$

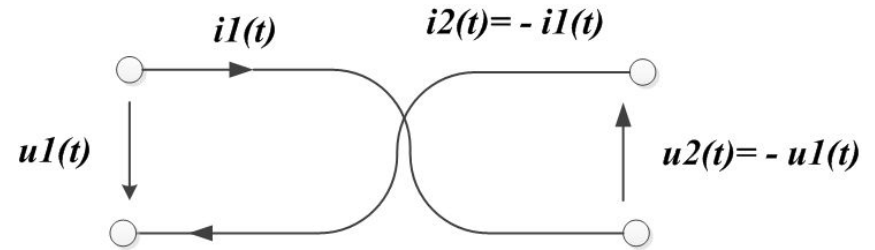
$$[A] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad \Delta A = 1;$$

# Пример физического канала

*"Витая пара"*

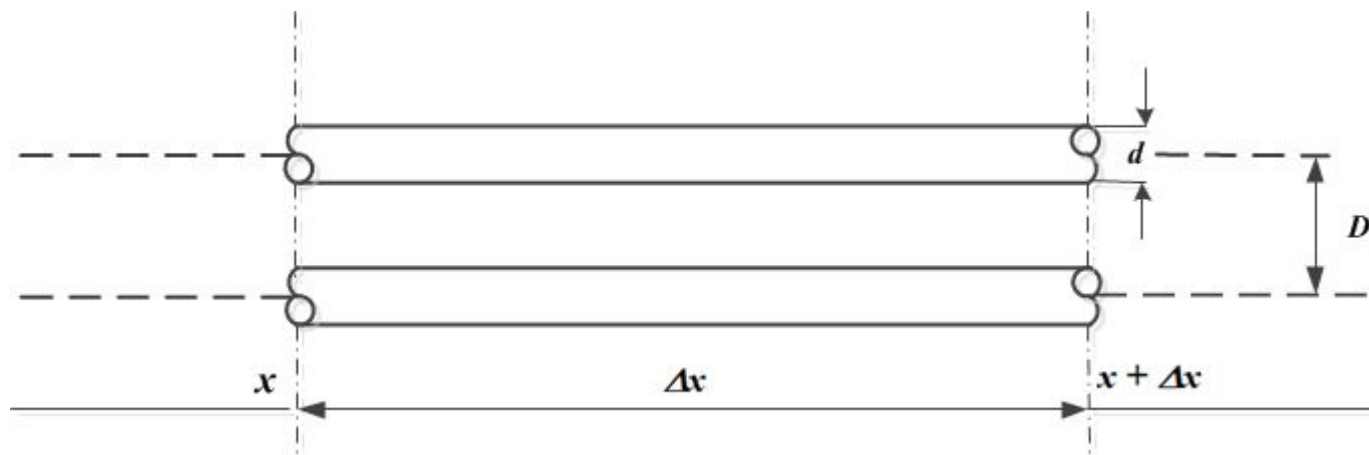


$$[A] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad \Delta A = 1;$$

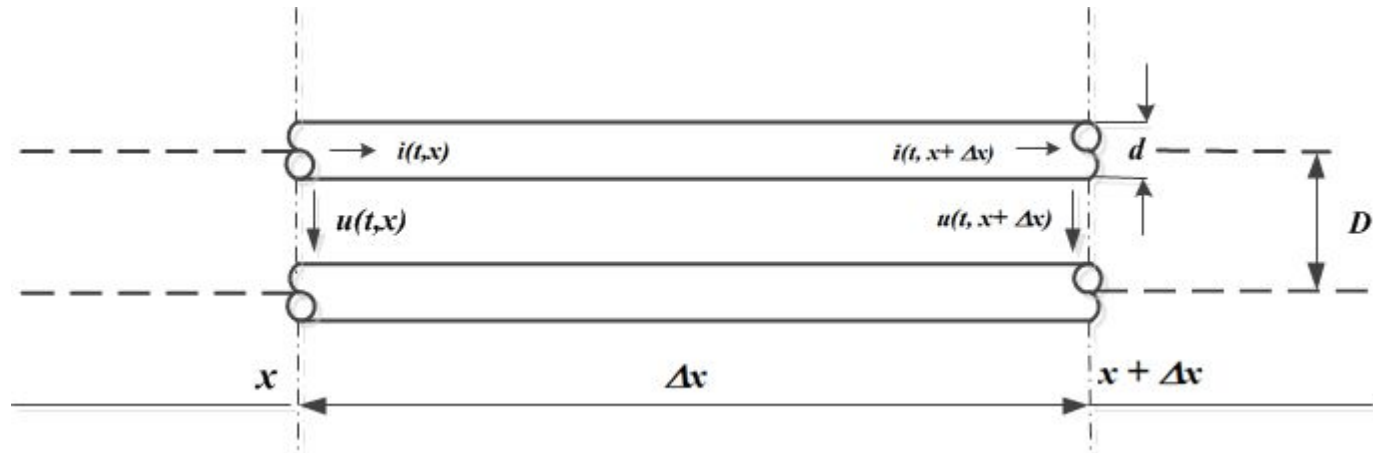


$$[A] = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; \quad \Delta A = 1;$$

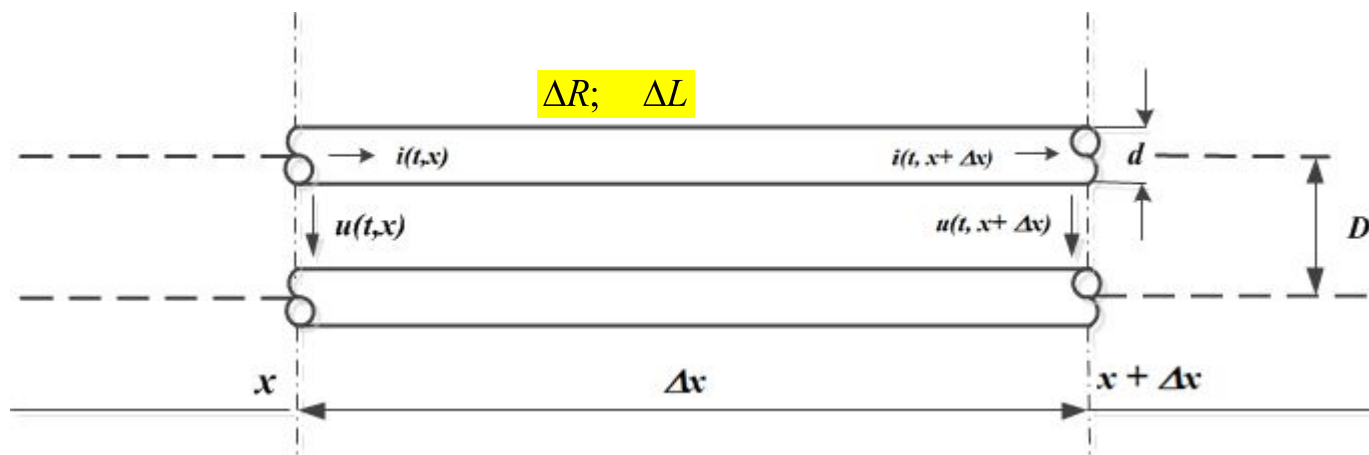
# Проводной канал



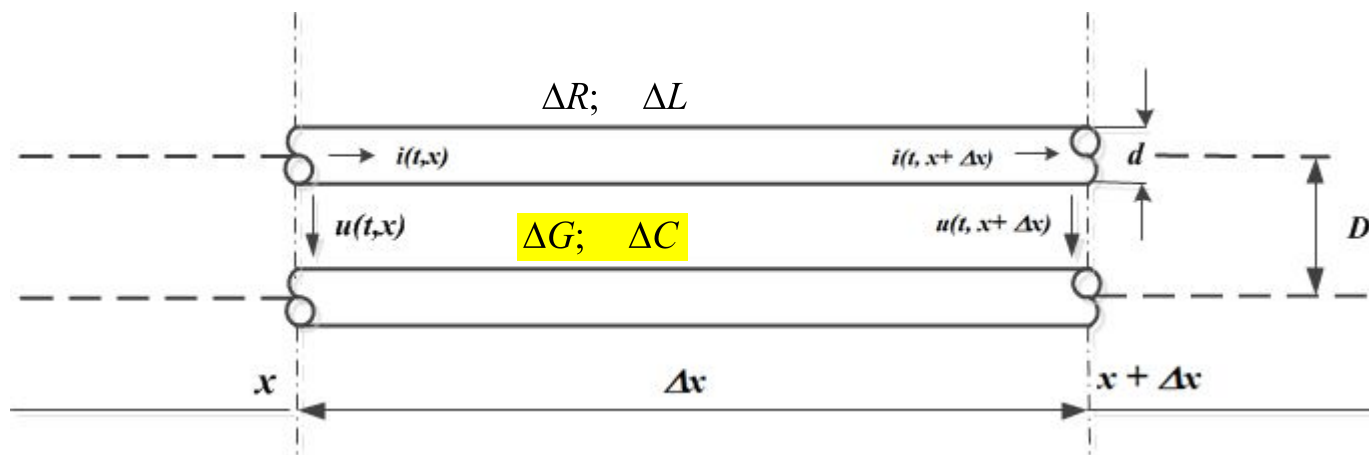
# Проводной канал



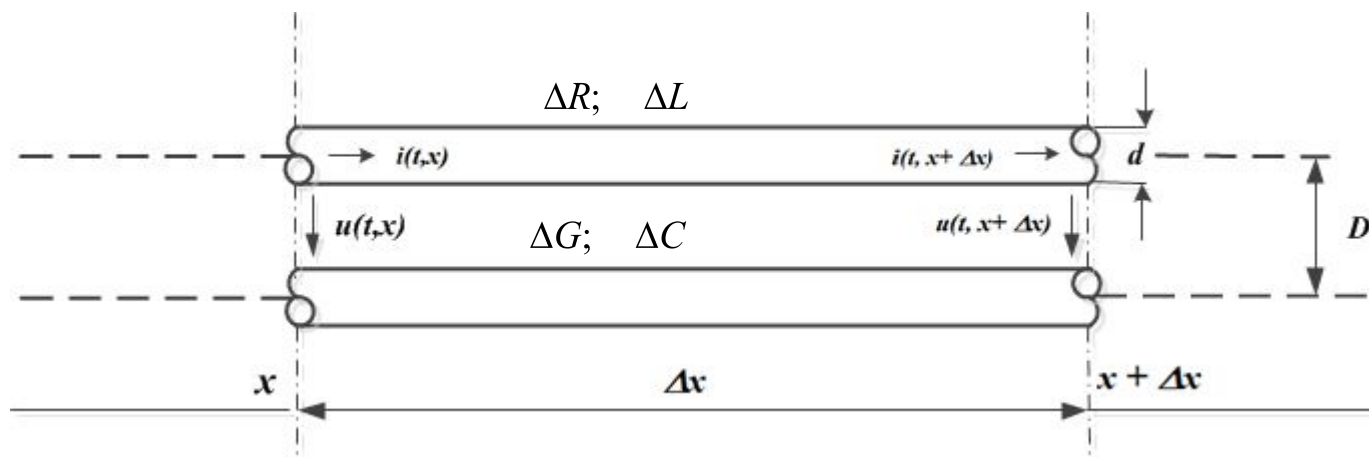
# Проводной канал



# Проводной канал

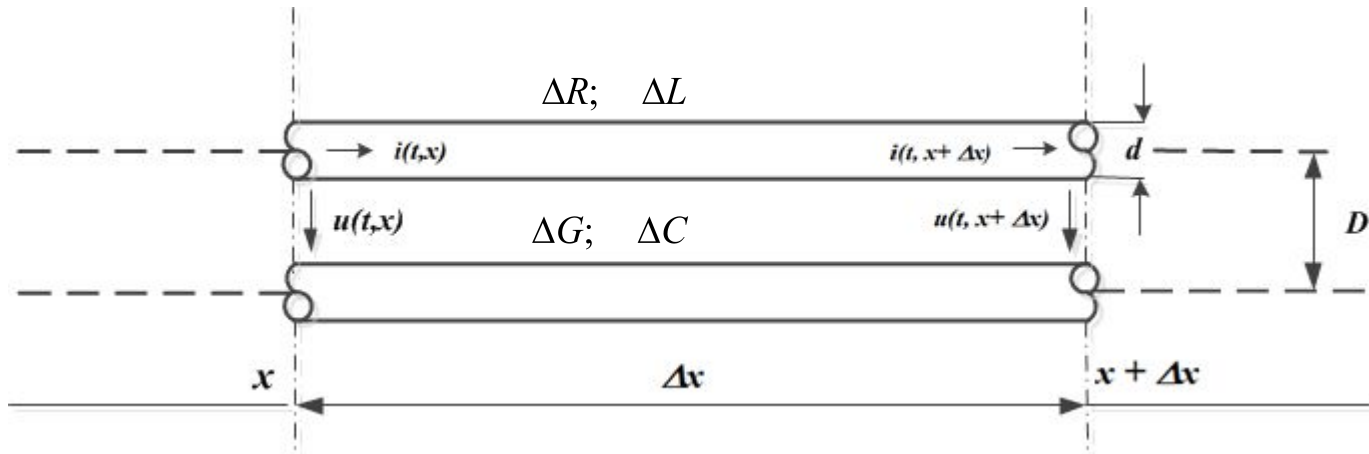


# Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

# Проводной канал

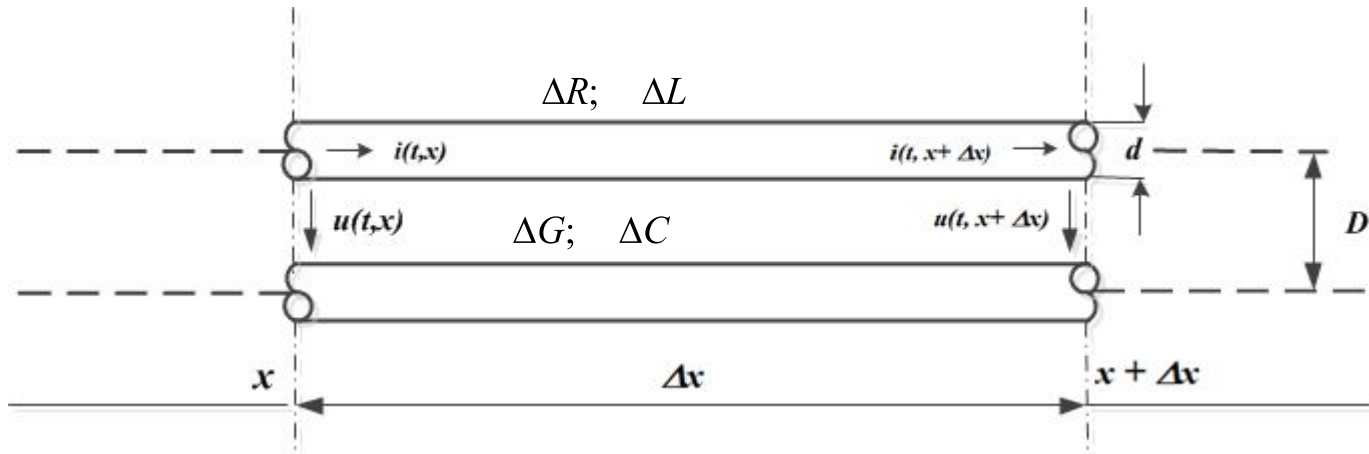


$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

$$R_0 = \rho \cdot \frac{2}{S} = \frac{2 \cdot \rho}{\pi \cdot d^2};$$



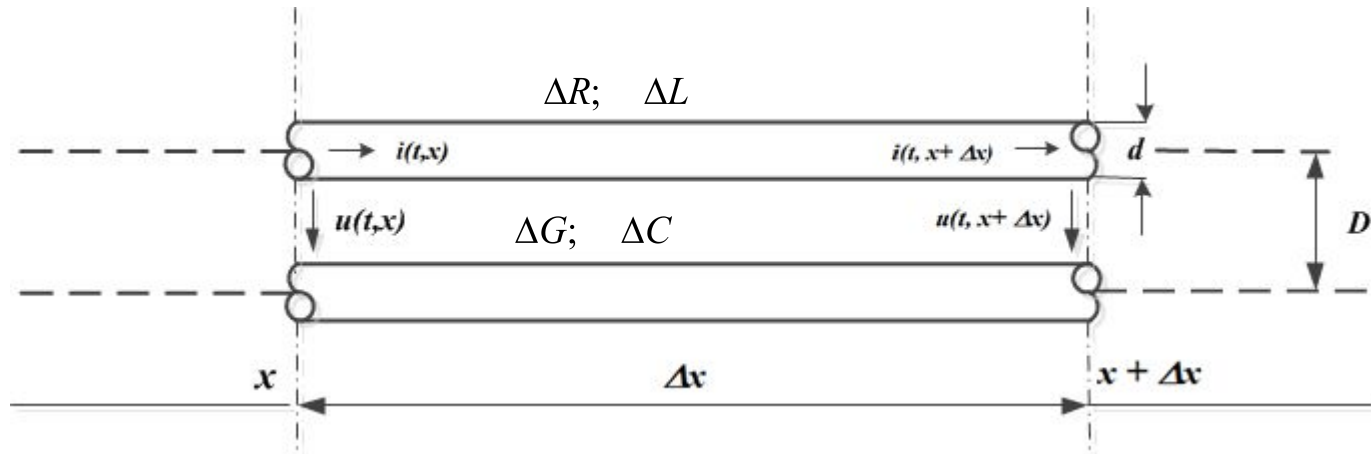
# Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

$$R_0 = \rho \cdot \frac{2}{S} = \frac{2 \cdot \rho}{\pi \cdot d^2}; \quad L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right);$$

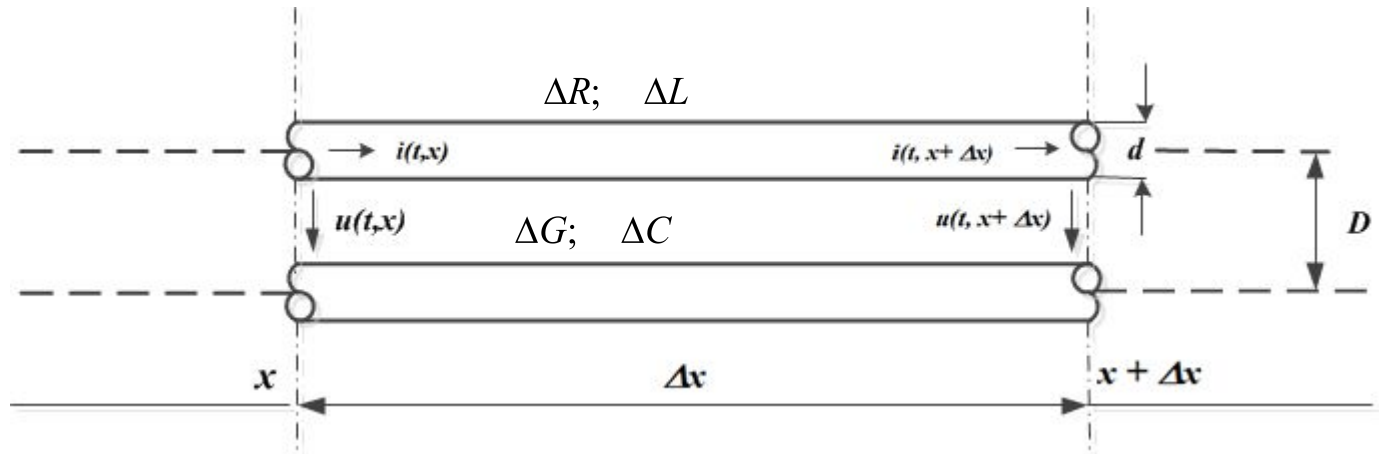
# Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

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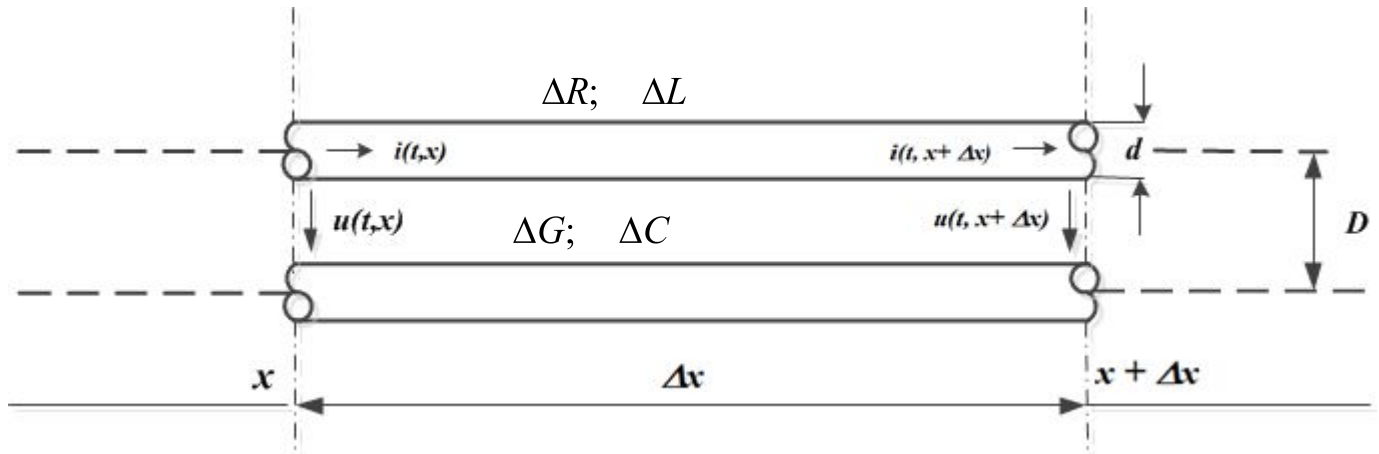
# Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

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# Проводной канал



$$\Delta R = R_0 \cdot \Delta x; \quad \Delta L = L_0 \cdot \Delta x; \quad \Delta C = C_0 \cdot \Delta x; \quad \Delta G = G_0 \cdot \Delta x;$$

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$$R_0 \left\langle \frac{\text{Ом}}{\text{м}} \right\rangle;$$

$$L_0 \left\langle \frac{\text{Гн}}{\text{м}} \right\rangle;$$

$$C_0 \left\langle \frac{\text{Ф}}{\text{м}} \right\rangle;$$

$$G_0 \left\langle \frac{\text{См}}{\text{м}} \right\rangle;$$

$$\rho \left\langle \frac{\text{Ом}}{\text{м}} \right\rangle;$$

$$\mu \left\langle \frac{\text{Гн}}{\text{м}} \right\rangle;$$

$$\varepsilon \left\langle \frac{\text{Ф}}{\text{м}} \right\rangle;$$

$$\delta \langle \text{град} \rangle$$

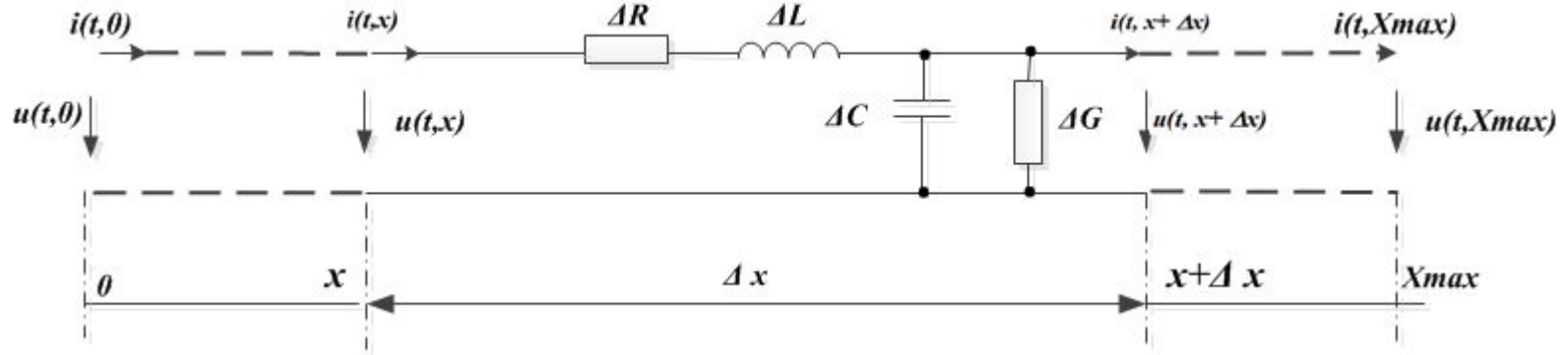
удельное сопротивление

магнитная проницаемость

диэлектрическая проницаемость

угол потерь в диэлектрике

# Проводной канал

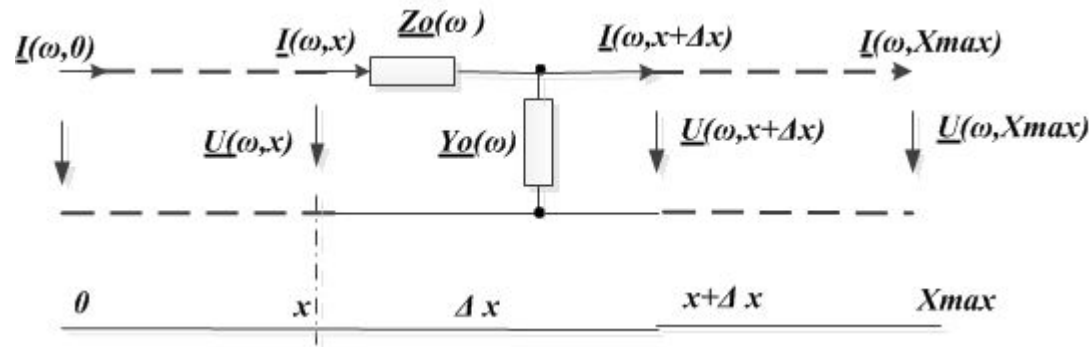


$$\underline{Z}_0(\omega) = [j \cdot \omega \cdot L_0 + R_0] \left\langle \frac{OM}{M} \right\rangle;$$

$$\underline{Y}_0(\omega) = [j \cdot \omega \cdot C_0 + G_0] \left\langle \frac{CM}{M} \right\rangle;$$

$$\begin{cases} \frac{\partial \underline{I}(\omega, x)}{\partial x} = -\underline{Y}_0(\omega) \cdot \underline{U}(\omega, x); \\ \frac{\partial \underline{U}(\omega, x)}{\partial x} = -\underline{Z}_0(\omega) \cdot \underline{I}(\omega, x); \\ \underline{U}_0 = \underline{U}(\omega, 0); \quad \underline{I}_0 = \underline{I}(\omega, 0); \end{cases}$$

# Проводной канал



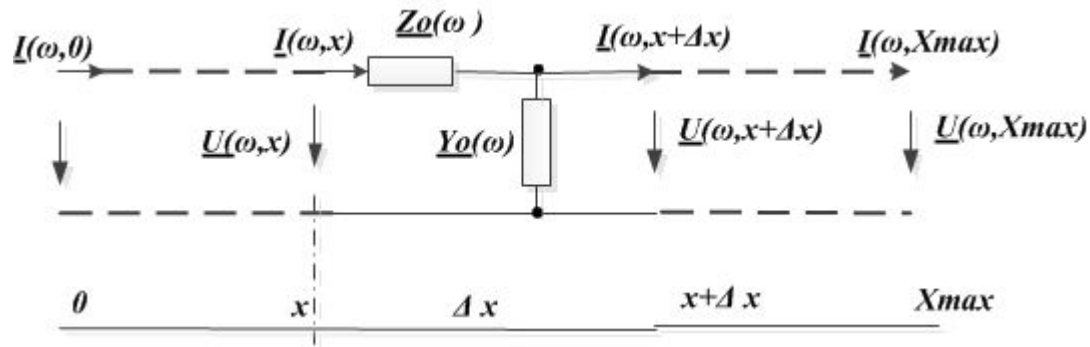
$$\underline{\gamma}_0(\omega) = \sqrt{\underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega)}; \quad \left\langle \frac{1}{M} \right\rangle;$$

$\underline{\gamma}_0(\omega)$  постоянная распространения

$$\frac{\underline{Z}_0(\omega)}{\underline{\gamma}_0(\omega)} = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}} = \underline{Z}_w(\omega) \quad \langle \quad \rangle;$$

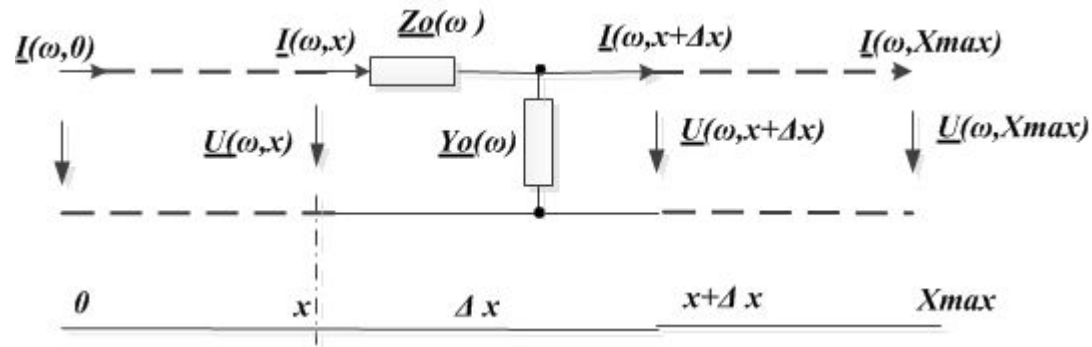
$\underline{Z}_w(\omega)$  - волновое сопротивление

# Проводной канал



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \underline{Z}_w(\omega) \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

# Проводной канал



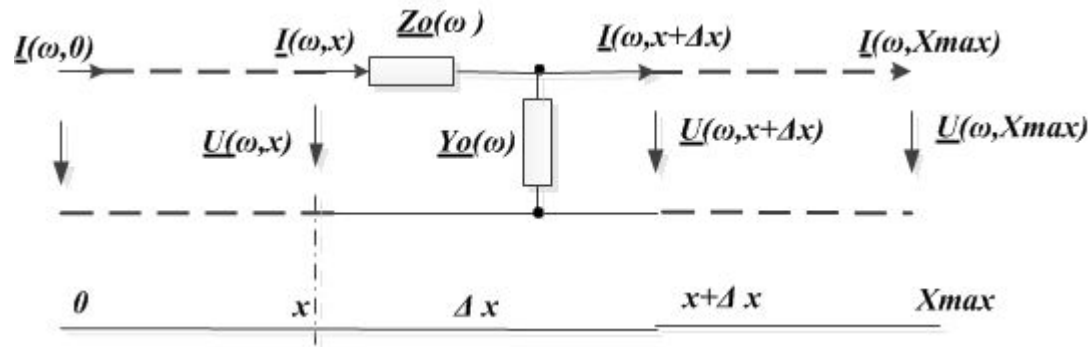
$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \underline{Z}_w(\omega) \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

$$\underline{Z}_w(\omega) = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}} \quad \langle \quad \rangle; \quad \underline{Y}_w(\omega) = \sqrt{\underline{Y}_0(\omega) \cdot \underline{Z}_0(\omega)} \quad \left\langle \frac{1}{\quad} \right\rangle;$$

$$\underline{Z}_0(\omega) = [j \cdot \omega \cdot L_0 + R_0] \quad \left\langle \frac{O_M}{M} \right\rangle; \quad \underline{Y}_0(\omega) = [j \cdot \omega \cdot C_0 + G_0] \quad \left\langle \frac{C_M}{M} \right\rangle;$$

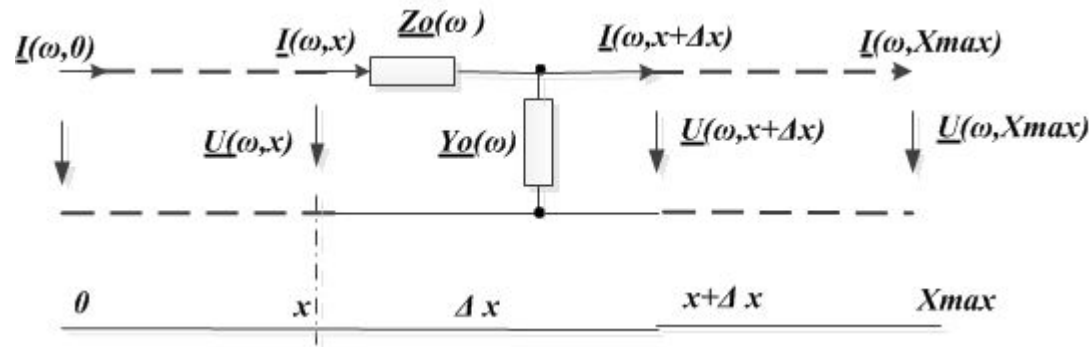


# Проводной канал



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \underline{Z}_w(\omega) \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

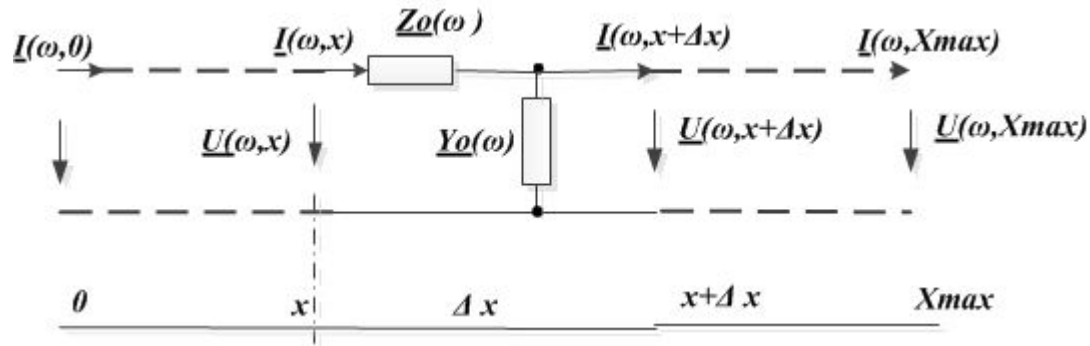
# Проводной канал



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \underline{Z}_w(\omega) \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega, 0) = \underline{U}(\omega, x) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] + \underline{Z}_w(\omega) \cdot \underline{I}(\omega, x) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, 0) = \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, x) \cdot sh[\underline{\gamma}_0(\omega) \cdot x] + \underline{I}(\omega, x) \cdot ch[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

# Проводной канал

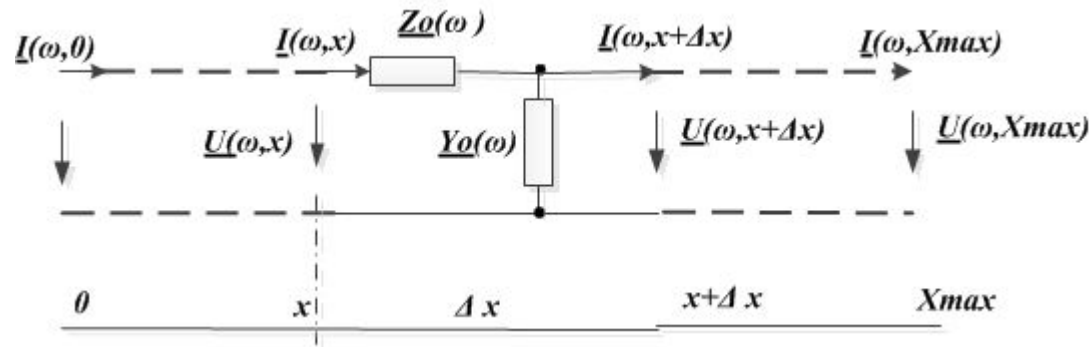


$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \text{ch}[\underline{\gamma}_0(\omega) \cdot x] - \underline{Z}_w(\omega) \cdot \underline{I}(\omega, 0) \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \text{ch}[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, 0) \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega, 0) = \underline{U}(\omega, x) \cdot \text{ch}[\underline{\gamma}_0(\omega) \cdot x] + \underline{Z}_w(\omega) \cdot \underline{I}(\omega, x) \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, 0) = \frac{1}{\underline{Z}_w(\omega)} \cdot \underline{U}(\omega, x) \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x] + \underline{I}(\omega, x) \cdot \text{ch}[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

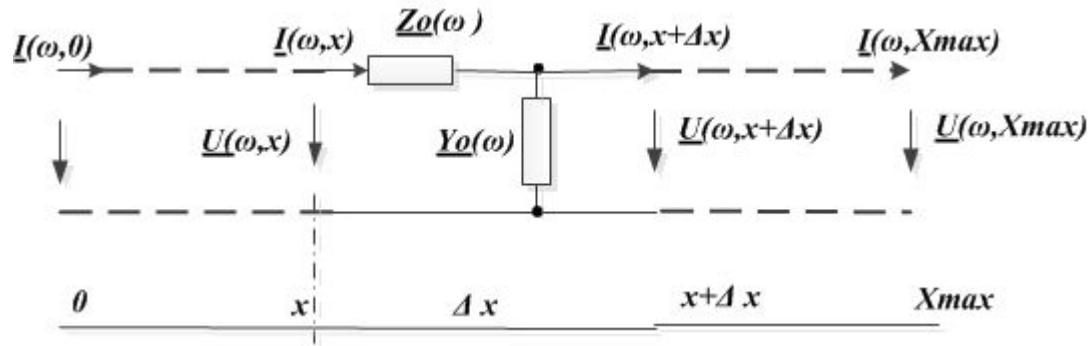
$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \text{ch}[\underline{\gamma}_0(\omega) \cdot x] & \underline{Z}_w(\omega) \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x] \\ \frac{1}{\underline{Z}_w(\omega)} \cdot \text{sh}[\underline{\gamma}_0(\omega) \cdot x] & \text{ch}[\underline{\gamma}_0(\omega) \cdot x] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, x) \\ \underline{I}(\omega, x) \end{bmatrix}$$

# Проводной канал



$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} ch[\underline{\gamma}_0(\omega) \cdot X_{\max}] & \underline{Z}_w(\omega) \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}] \\ \frac{1}{\underline{Z}_w(\omega)} \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}] & ch[\underline{\gamma}_0(\omega) \cdot X_{\max}] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_{\max}) \\ \underline{I}(\omega, X_{\max}) \end{bmatrix};$$

# Проводной канал

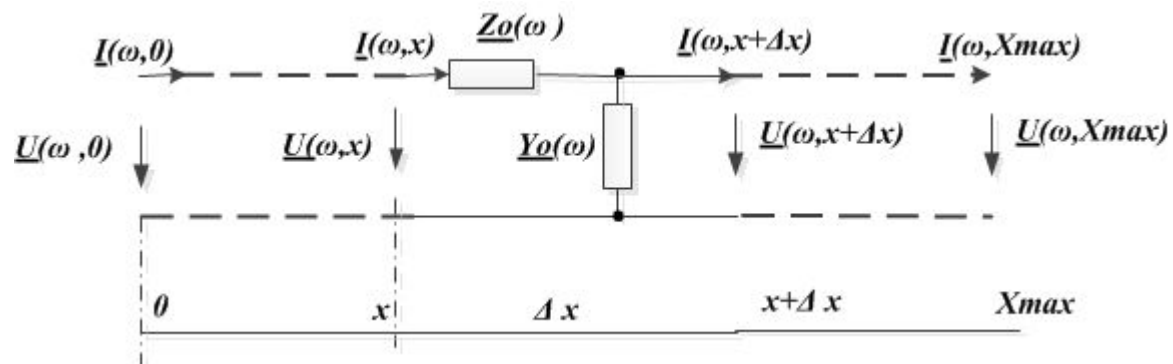


$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} ch[\underline{\gamma}_0(\omega) \cdot X_{\max}] & \underline{Z}_w(\omega) \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}] \\ \frac{1}{\underline{Z}_w(\omega)} \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}] & ch[\underline{\gamma}_0(\omega) \cdot X_{\max}] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_{\max}) \\ \underline{I}(\omega, X_{\max}) \end{bmatrix};$$

$$\begin{aligned} \underline{A}_{11}(\omega) &= ch[\underline{\gamma}_0(\omega) \cdot X_{\max}]; & \underline{A}_{12}(\omega) &= \underline{Z}_w(\omega) \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}]; \\ \underline{A}_{21}(\omega) &= \frac{1}{\underline{Z}_w(\omega)} \cdot sh[\underline{\gamma}_0(\omega) \cdot X_{\max}]; & \underline{A}_{22}(\omega) &= ch[\underline{\gamma}_0(\omega) \cdot X_{\max}]; \end{aligned}$$

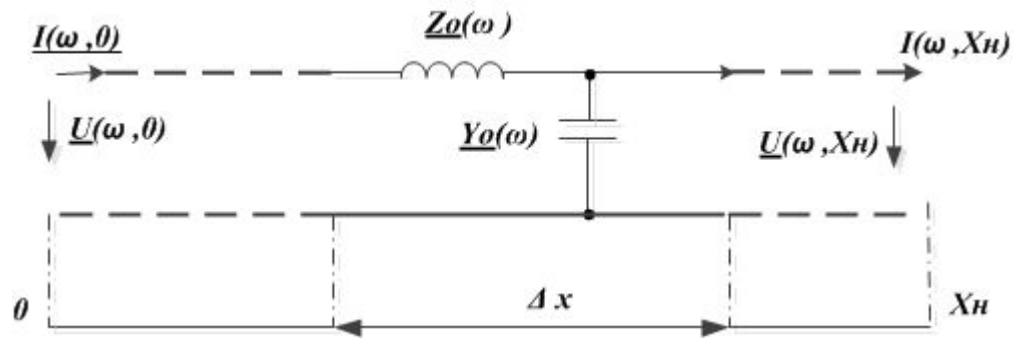
$$\Delta A = \underline{A}_{11}(\omega) \cdot \underline{A}_{22}(\omega) - \underline{A}_{21}(\omega) \cdot \underline{A}_{12}(\omega) = 1$$

# Проводной канал без потерь



$$R_0 = 0; \quad G_0 = 0;$$

# Проводной канал без потерь

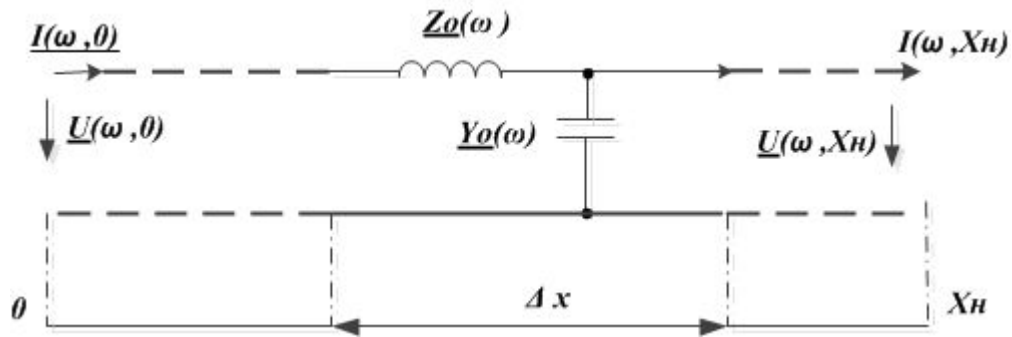


$$R_0 = 0; \quad G_0 = 0;$$

$$\underline{Z}_0(\omega) = j \cdot \omega \cdot L_0 \left\langle \frac{OM}{M} \right\rangle; \quad \underline{Y}_0(\omega) = j \cdot \omega \cdot C_0 \left\langle \frac{CM}{M} \right\rangle;$$

$$\underline{\gamma}_M = \sqrt{\frac{L_0}{C_0}} \left\langle \quad \right\rangle; \quad j \underline{\gamma}_M(\omega) = \omega \sqrt{L_0 \cdot C_0} \left\langle \frac{1}{M} \right\rangle;$$

# Проводной канал без потерь



$$R_0 = 0; \quad G_0 = 0;$$

$$\underline{Z}_0(\omega) = j \cdot \omega \cdot L_0 \left\langle \frac{OM}{M} \right\rangle; \quad \underline{Y}_0(\omega) = j \cdot \omega \cdot C_0 \left\langle \frac{CM}{M} \right\rangle;$$

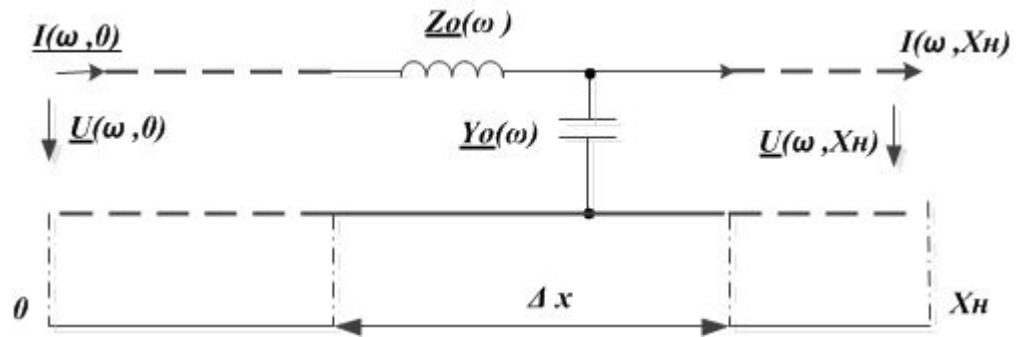
$$\underline{\gamma}_0(\omega) = \sqrt{\frac{L_0}{C_0}} \cdot \omega \left\langle \frac{1}{M} \right\rangle;$$

$$\frac{1}{\sqrt{L_0 \cdot C_0}} \cdot \frac{1}{\sqrt{\frac{L_0}{M} \cdot \frac{C_0}{M}}} = \frac{M}{c} \quad ; \quad L \cdot C^w = \frac{1}{\sqrt{L_0 \cdot C_0}}$$

скорость распр
остранения колебаний в физическом канале

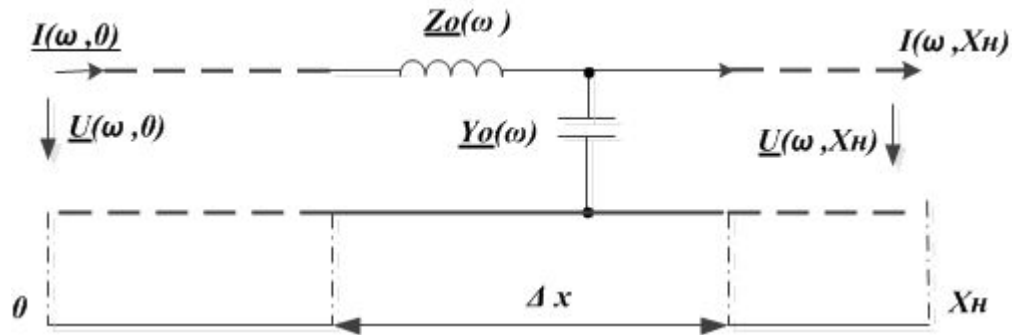


# Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

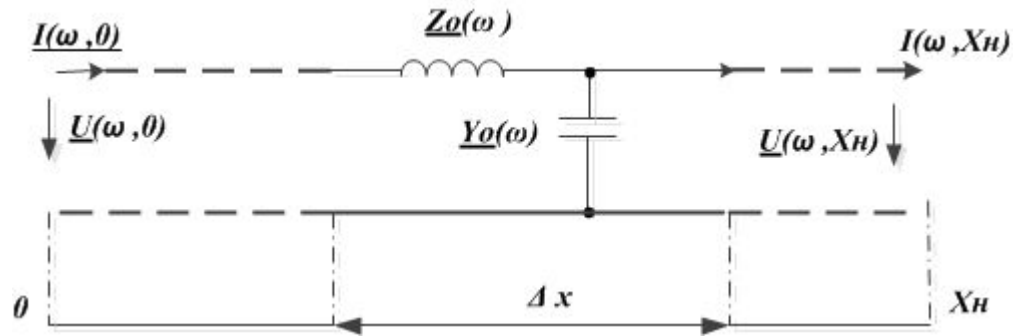
# Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)}$$

# Проводной канал без потерь

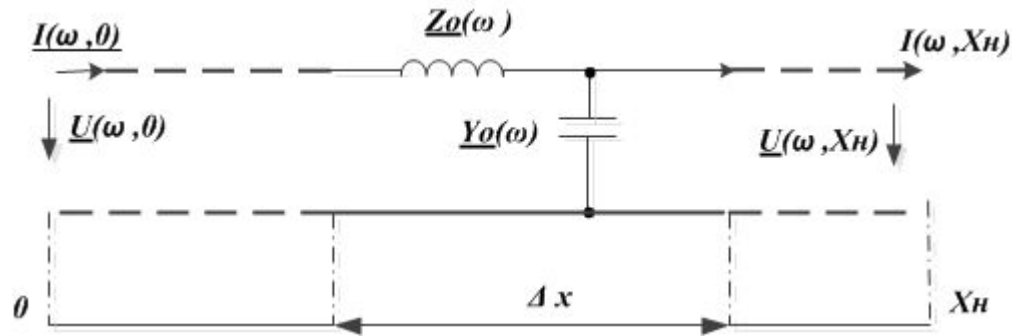


$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)};$$

$$V_w = \frac{1}{\sqrt{\mu \cdot \varepsilon}};$$

# Проводной канал без потерь



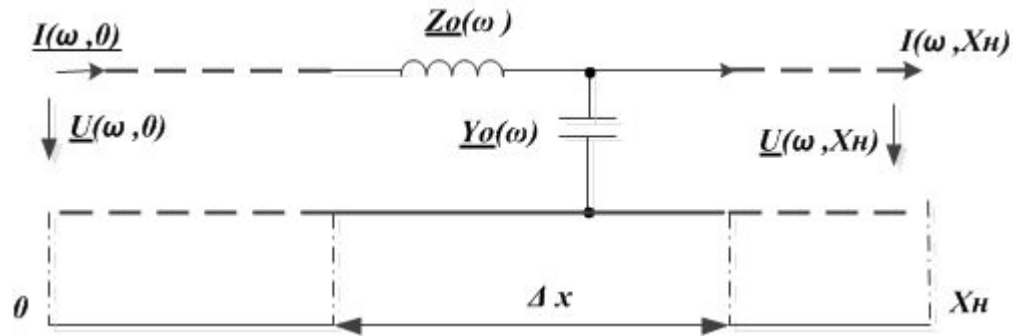
$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}}; \quad L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)}$$

$$V_w = \frac{1}{\sqrt{\mu \cdot \varepsilon}}; \quad \mu = \mu_{отн} \cdot \mu_0 = \mu_{отн} \cdot 4 \cdot \pi \cdot 10^{-7} \frac{\Gamma_H}{M}; \quad \varepsilon = \varepsilon_{отн} \cdot \varepsilon_0 = \varepsilon_{отн} \cdot \frac{10^{-9}}{36 \cdot \pi} \frac{\Phi}{M};$$

$$V_w = \frac{1}{\sqrt{\mu_{отн} \cdot \mu_0 \cdot \varepsilon_{отн} \cdot \varepsilon_0}} = \frac{1}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \cdot \frac{1}{\sqrt{\mu_0 \cdot \varepsilon_0}} = \frac{1}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \cdot 3 \cdot 10^8 \frac{M}{c};$$

$$V_w \leq V_{w0} = \frac{3 \cdot 10^8}{\sqrt{\mu_0 \cdot \varepsilon_0}} \frac{M}{c};$$

# Проводной канал без потерь

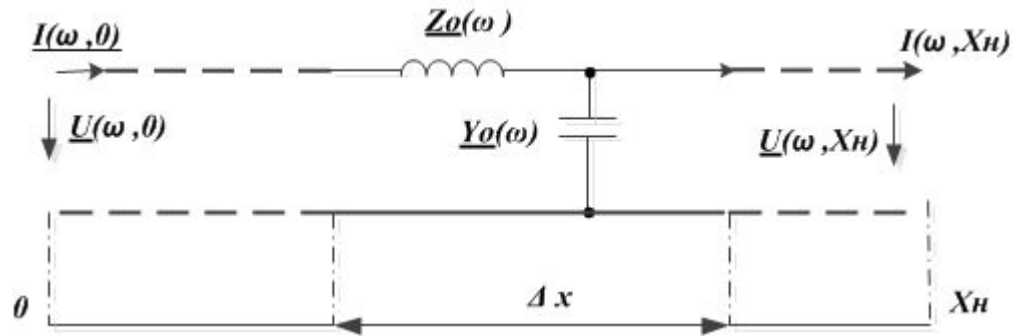


$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{отн} \cdot \varepsilon_{отн}}} \left\langle \frac{M}{C} \right\rangle;$$

# Проводной канал без потерь



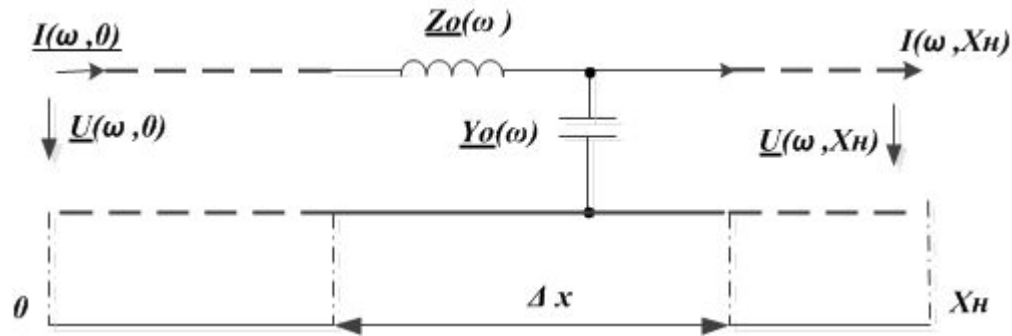
$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{\text{отн}} \cdot \varepsilon_{\text{отн}}}} \left\langle \frac{M}{c} \right\rangle;$$

$$\underline{\gamma}_0(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} = j \cdot \frac{\omega}{M_w} \left\langle \frac{1}{-} \right\rangle;$$

# Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

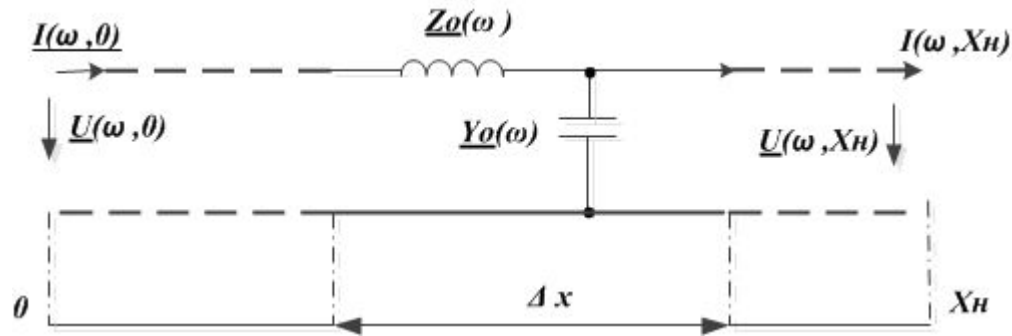
$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)};$$

$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{\text{омн}} \cdot \varepsilon_{\text{омн}}}} \left\langle \frac{M}{c} \right\rangle;$$

$$\underline{\gamma}_0(\omega) = j \cdot \omega \sqrt{L_0 \cdot C_0} = j \cdot \frac{\omega}{M_w} \left\langle \frac{1}{c} \right\rangle;$$

$$\underline{\gamma}_0(\omega) = j \cdot \frac{\omega}{M_w} = j \cdot \frac{2 \cdot \pi \cdot f}{V_w} = j \cdot \frac{2 \cdot \pi}{\lambda_w} \left\langle \frac{1}{c} \right\rangle;$$

# Проводной канал без потерь



$$V_w = \frac{1}{\sqrt{L_0 \cdot C_0}};$$

$$L_0 = \mu \cdot \lg\left(\frac{2 \cdot D}{d}\right); \quad C_0 = \frac{\varepsilon}{\lg\left(\frac{2 \cdot D}{d}\right)};$$

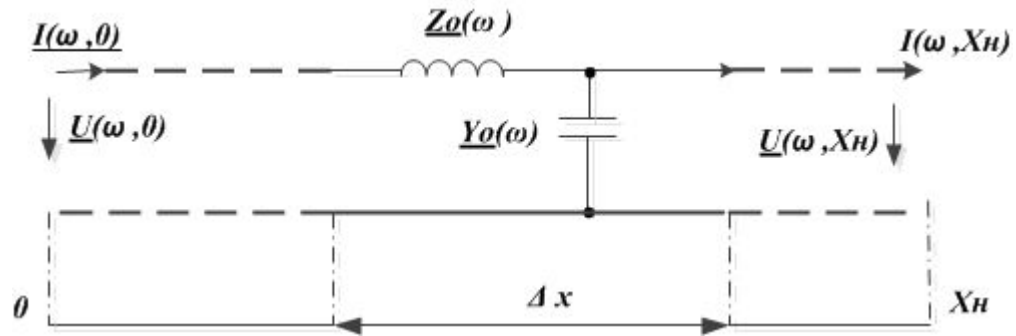
$$V_w = \frac{3 \cdot 10^8}{\sqrt{\mu_{\text{отн}} \cdot \varepsilon_{\text{отн}}}} \left\langle \frac{M}{c} \right\rangle;$$

$$\underline{\gamma}_0(\omega) = j \cdot \frac{\omega}{M_w} = j \cdot \frac{2 \cdot \pi \cdot f}{V_w} = j \cdot \frac{2 \cdot \pi}{\lambda_w} \left\langle \frac{1}{\lambda_w} \right\rangle;$$

$$\underline{\varnothing}_w = \sqrt{\frac{Z_0(\omega)}{Y_0(\omega)}} = \sqrt{\frac{j \cdot \omega \cdot L_0}{j \cdot \omega \cdot C_0}} = \sqrt{\frac{L_0}{C_0}} = \sqrt{\frac{\mu}{\varepsilon}} \cdot \lg\left(\frac{2 \cdot D}{d}\right) \langle \quad \rangle;$$

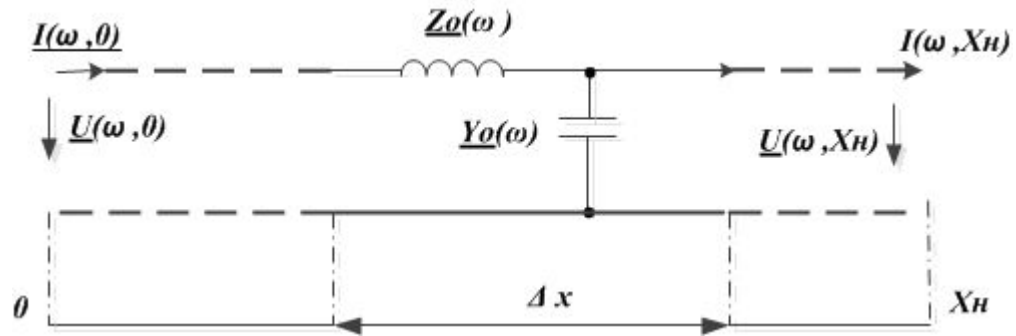


# Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - Z_w \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{Z_w} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

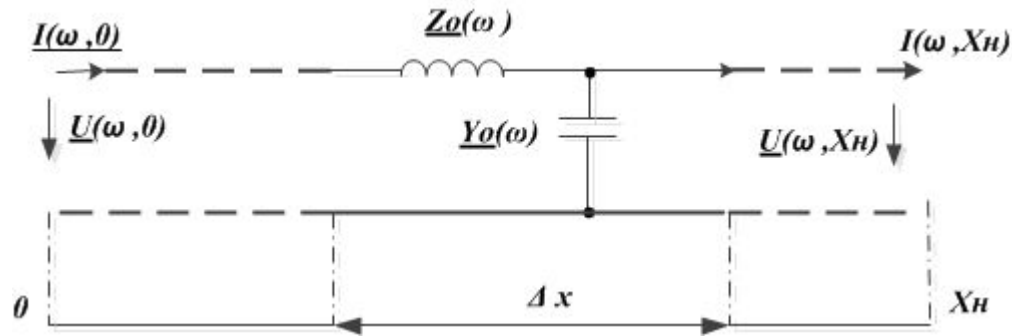
# Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - Z_w \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - Z_w \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases}$$

$$\begin{cases} ch[\underline{\gamma}_0(\omega) \cdot x] = \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right]; \\ sh[\underline{\gamma}_0(\omega) \cdot x] = j \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right]; \end{cases}$$

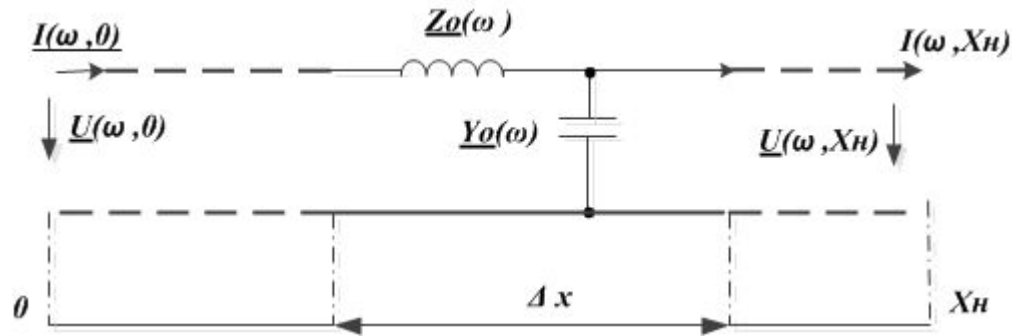
# Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - Z_w \cdot \underline{I}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot ch[\underline{\gamma}_0(\omega) \cdot x] - \frac{1}{Z_w} \cdot \underline{U}(\omega, 0) \cdot sh[\underline{\gamma}_0(\omega) \cdot x]; \end{cases} \quad \begin{cases} ch[\underline{\gamma}_0(\omega) \cdot x] = \text{Cos}\left[\frac{\omega}{V_w} \cdot x\right]; \\ sh[\underline{\gamma}_0(\omega) \cdot x] = j \cdot \text{Sin}\left[\frac{\omega}{V_w} \cdot x\right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \text{Cos}\left[\frac{\omega}{V_w} \cdot x\right] - j \cdot Z_w \cdot \underline{I}(\omega, 0) \cdot \text{Sin}\left[\frac{\omega}{V_w} \cdot x\right]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \text{Cos}\left[\frac{\omega}{V_w} \cdot x\right] - \frac{j}{Z_w} \cdot \underline{U}(\omega, 0) \cdot \text{Sin}\left[\frac{\omega}{V_w} \cdot x\right]; \end{cases}$$

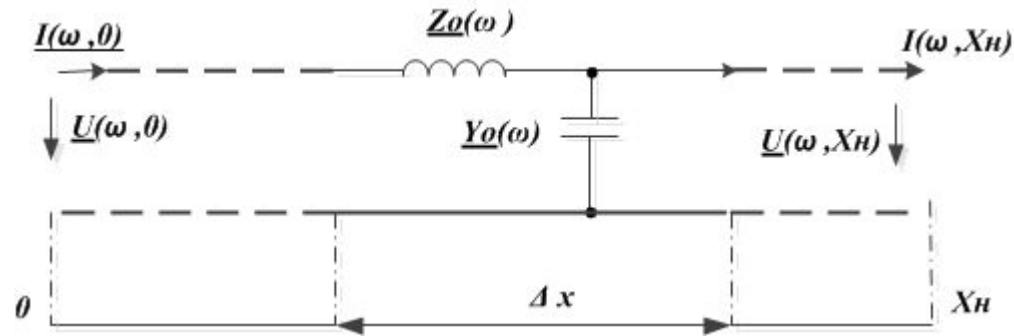
# Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega, x) = \underline{U}(\omega, 0) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] - j \cdot Z_w \cdot \underline{I}(\omega, 0) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right]; \\ \underline{I}(\omega, x) = \underline{I}(\omega, 0) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] - \frac{j}{Z_w} \cdot \underline{U}(\omega, 0) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right]; \end{cases}$$

$$\begin{cases} \underline{U}(\omega, 0) = \underline{U}(\omega, x) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] + j \cdot Z_w \cdot \underline{I}(\omega, 0) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right]; \\ \underline{I}(\omega, 0) = \frac{j}{Z_w} \cdot \underline{U}(\omega, x) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right] + \underline{I}(\omega, x) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right]; \end{cases}$$

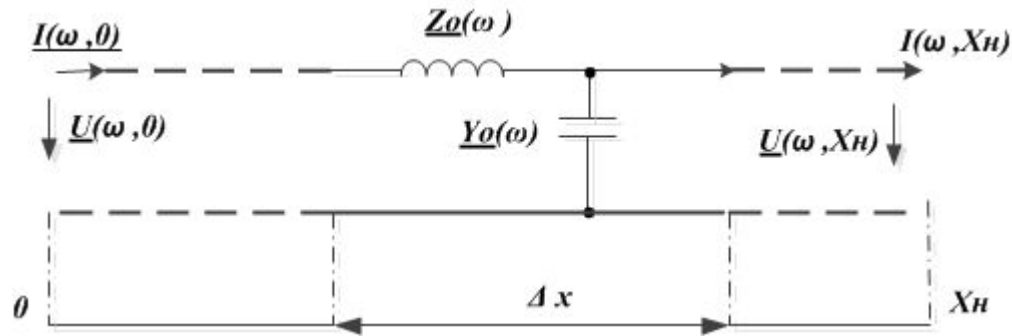
# Проводной канал без потерь



$$\begin{cases} \underline{U}(\omega, 0) = \underline{U}(\omega, x) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] + j \cdot Z_w \cdot \underline{I}(\omega, 0) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right]; \\ \underline{I}(\omega, 0) = \frac{j}{Z_w} \cdot \underline{U}(\omega, x) \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right] + \underline{I}(\omega, x) \cdot \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right]; \end{cases}$$

$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] & j \cdot Z_w \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right] \\ \frac{j}{Z_w} \cdot \text{Sin} \left[ \frac{\omega}{V_w} \cdot x \right] & \text{Cos} \left[ \frac{\omega}{V_w} \cdot x \right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, x) \\ \underline{I}(\omega, x) \end{bmatrix}$$

# Проводной канал без потерь

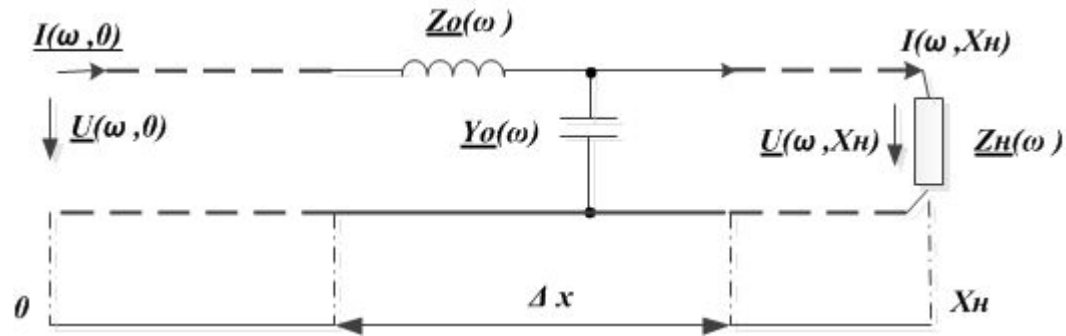


$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot x\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] & \cos\left[\frac{\omega}{V_w} \cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, x) \\ \underline{I}(\omega, x) \end{bmatrix}$$

$$\underline{A}_{11}(\omega) = \cos\left[\frac{\omega}{V_w} \cdot x\right]; \quad \underline{A}_{12}(\omega) = j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right];$$

$$\underline{A}_{21}(\omega) = \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right]; \quad \underline{A}_{22}(\omega) = \cos\left[\frac{\omega}{V_w} \cdot x\right];$$

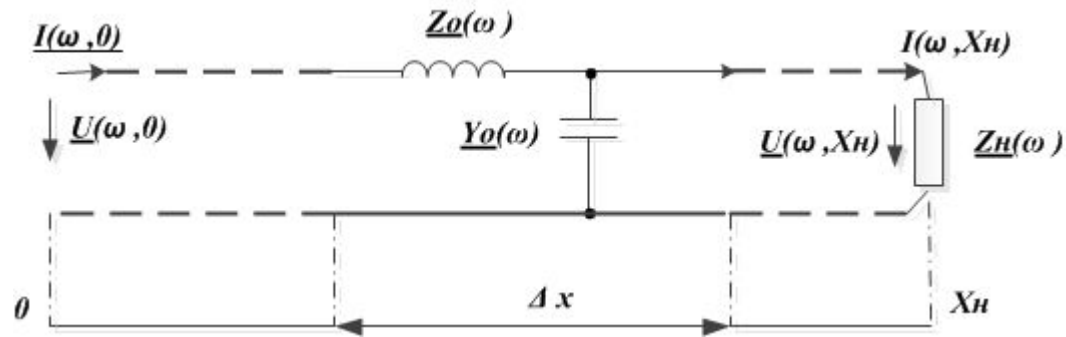
# Проводной канал без потерь



$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot x\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] & \cos\left[\frac{\omega}{V_w} \cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, x) \\ \underline{I}(\omega, x) \end{bmatrix}$$

$$\underline{Z}_H(\omega) = \frac{\underline{U}(\omega, X_H)}{\underline{I}(\omega, X_H)}$$

# Проводной канал без потерь



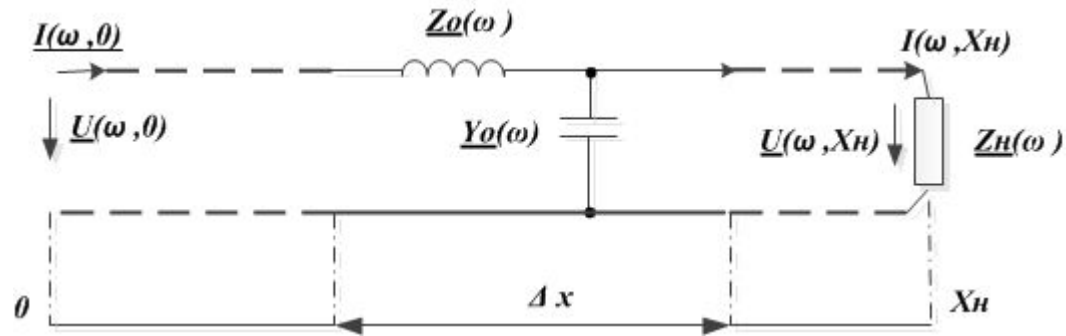
$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot x\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot x\right] & \cos\left[\frac{\omega}{V_w} \cdot x\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, x) \\ \underline{I}(\omega, x) \end{bmatrix} \quad \underline{Z}_H(\omega) = \frac{\underline{U}(\omega, X_H)}{\underline{I}(\omega, X_H)}$$

$$\underline{U}(\omega, 0) = \left[ \cos\left(\frac{\omega}{V_H} \cdot X_H\right) + j \cdot \frac{Z_w}{\underline{Z}_H(\omega)} \cdot \sin\left(\frac{\omega}{V} \cdot X_H\right) \right] \cdot \underline{U}(\omega, X_H);$$

$$\underline{I}(\omega, 0) = \left[ \cos\left(\frac{\omega}{V_w} \cdot X_H\right) + j \cdot \frac{\underline{Z}_H(\omega)}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \right] \cdot \underline{I}(\omega, X_H);$$



# Проводной канал без потерь



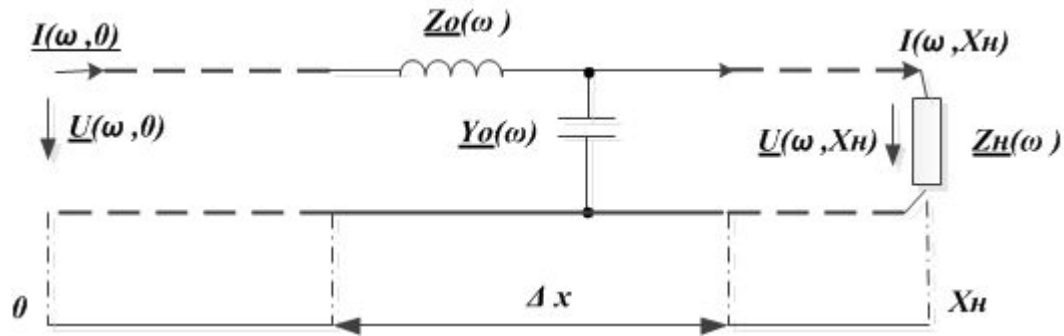
$$\underline{U}(\omega, 0) = \left[ \cos\left(\frac{\omega}{V_H} \cdot X_H\right) + j \cdot \frac{Z_w}{Z_w(\omega)} \cdot \sin\left(\frac{\omega}{V} \cdot X_H\right) \right] \cdot \underline{U}(\omega, X_H);$$

$$\underline{I}(\omega, 0) = \left[ \cos\left(\frac{\omega}{V_w} \cdot X_H\right) + j \cdot \frac{Z_H(\omega)}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \right] \cdot \underline{I}(\omega, X_H);$$

$$\underline{U}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_H} \cdot X_H\right) - j \cdot \frac{Z_w}{Z_w(\omega)} \cdot \sin\left(\frac{\omega}{V} \cdot X_H\right) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_w} \cdot X_H\right) - j \cdot \frac{Z_H(\omega)}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \right] \cdot \underline{I}(\omega, 0);$$

# Проводной канал без потерь



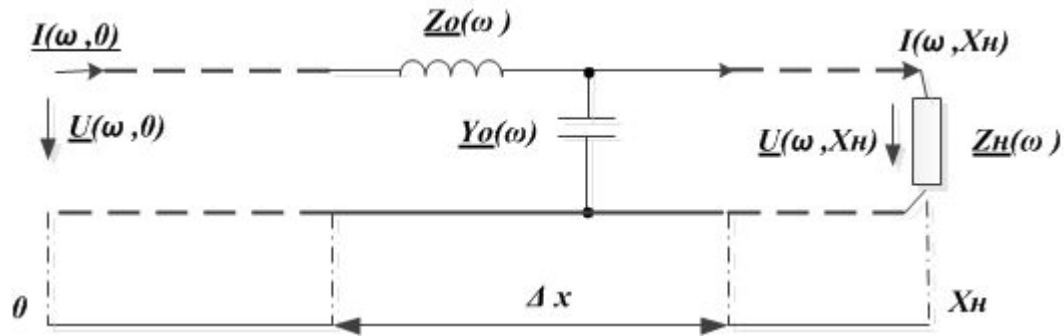
$$\underline{U}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_H} \cdot X_H\right) - j \cdot \frac{Z_w}{Z_w(\omega)} \cdot \sin\left(\frac{\omega}{V} \cdot X_H\right) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_w} \cdot X_H\right) - j \cdot \frac{Z_H(\omega)}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

$\tau_p$  время распространения ЭМК

# Проводной канал без потерь



$$\underline{U}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_H} \cdot X_H\right) - j \cdot \frac{Z_w}{Z_w(\omega)} \cdot \sin\left(\frac{\omega}{V} \cdot X_H\right) \right] \cdot \underline{U}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

$$\underline{I}(\omega, X_H) = \left[ \cos\left(\frac{\omega}{V_w} \cdot X_H\right) - j \cdot \frac{Z_H(\omega)}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \right] \cdot \underline{I}(\omega, 0);$$

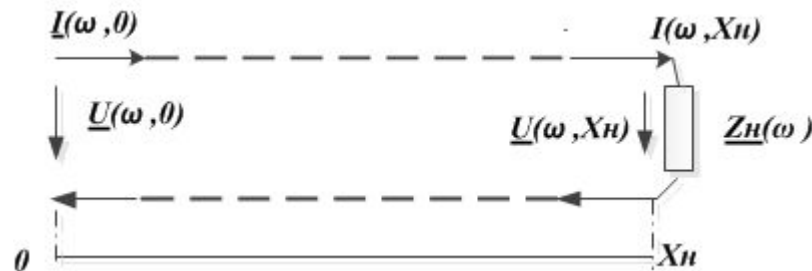
$\tau_p$  время распространения ЭМК

$$\underline{U}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{Z_w}{Z_H(\omega)} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{Z_H(\omega)}{Z_w} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{Z_w(\omega)}{\underline{Z}_H(\omega)} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{\underline{Z}_H(\omega)}{Z_w(\omega)} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

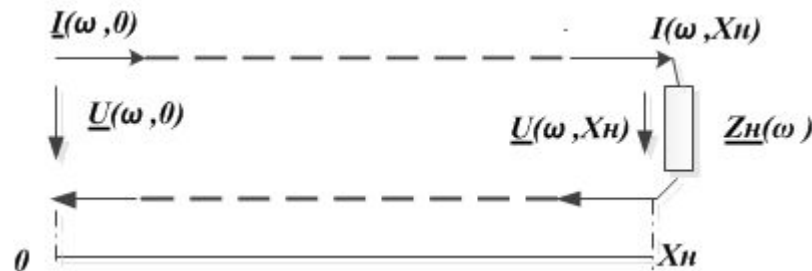
$\tau_p$  время распространения ЭМК

$$\underline{U}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{Z_w(\omega)}{\underline{Z}_H(\omega)} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \frac{\underline{Z}_H(\omega)}{Z_w(\omega)} \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

$$\frac{\omega}{V_w} \cdot X_H = \omega \cdot \tau_p$$

$\tau_p$  время распространения ЭМК

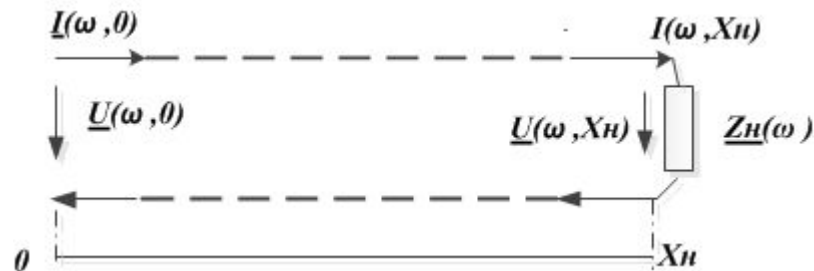
$$\underline{U}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = \left[ \cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) \right] \cdot \underline{I}(\omega, 0);$$

$$\underline{Z}_{\text{ex}}(\omega) = \frac{\underline{U}(\omega, 0)}{\underline{I}(\omega, 0)} = \frac{\underline{U}(\omega, X_H)}{\underline{I}(\omega, X_H)} = Z_w;$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{U}(\omega, 0);$$

$$\underline{I}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{I}(\omega, 0);$$

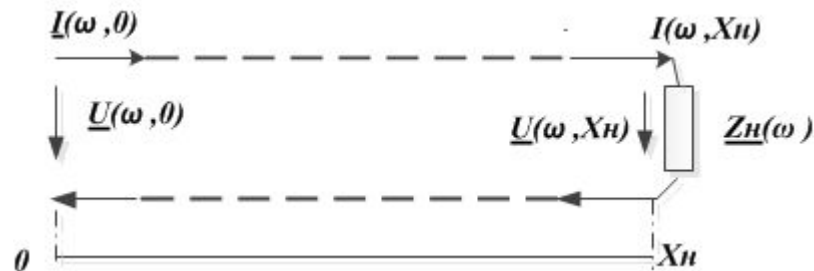
$$\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{U}(\omega, 0);$$

$$\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

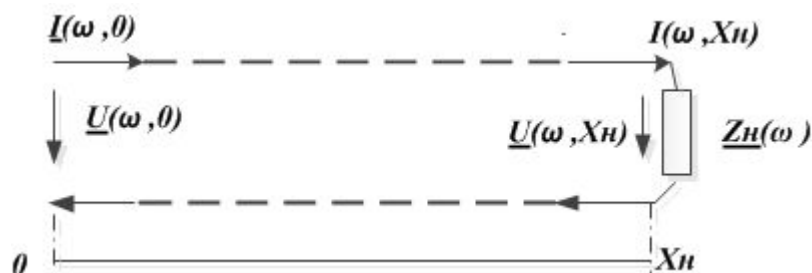
$$\underline{I}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{I}(\omega, 0);$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{U}(\omega, 0);$$

$$\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{I}(\omega, 0);$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

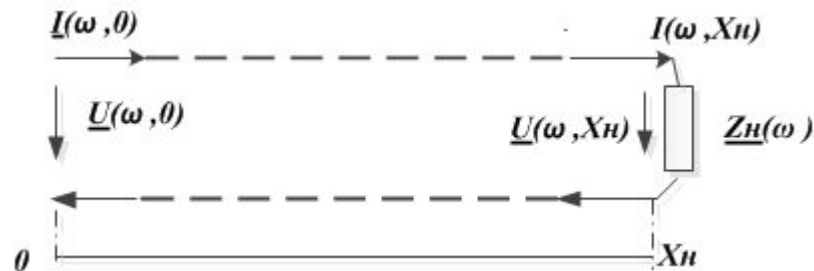
$$\underline{T}_u(\omega, X) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{T}_I(\omega, X) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$



# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{U}(\omega, 0);$$

$$\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{I}(\omega, 0);$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{T}_u(\omega, X) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

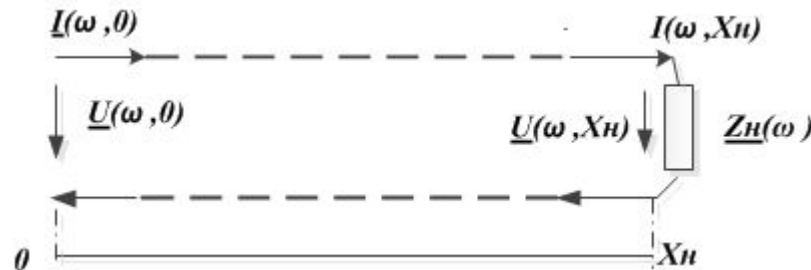
$$\underline{T}_i(\omega, X) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

$$u(t, X_H) = u(t - \tau_p, 0);$$

$$i(t, X_H) = i(t - \tau_p, 0);$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{U}(\omega, 0);$$

$$\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p) = e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = [\cos(\omega \cdot \tau_p) - j \cdot \sin(\omega \cdot \tau_p)] \cdot \underline{I}(\omega, 0);$$

$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-j \cdot \omega \cdot \tau_p};$$

$$\underline{T}_u(\omega, X) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

$$u(t, X_H) = u(t - \tau_p, 0);$$

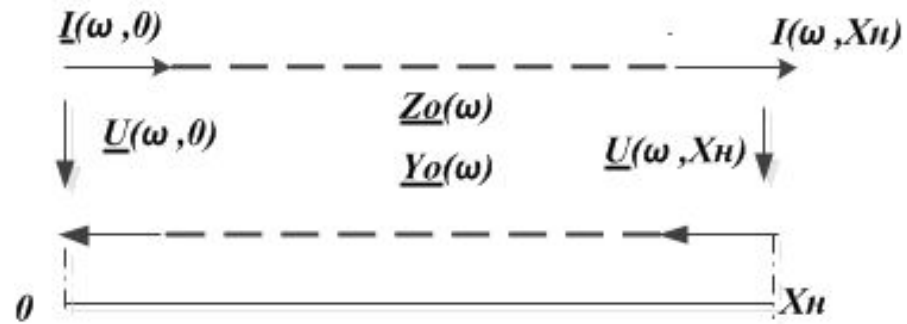
$$p(t, X_H) = p(t - \tau_p, 0);$$

$$\underline{T}_i(\omega, X) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-j \cdot \omega \cdot \tau_p};$$

$$i(t, X_H) = i(t - \tau_p, 0);$$

# Режим холостого хода

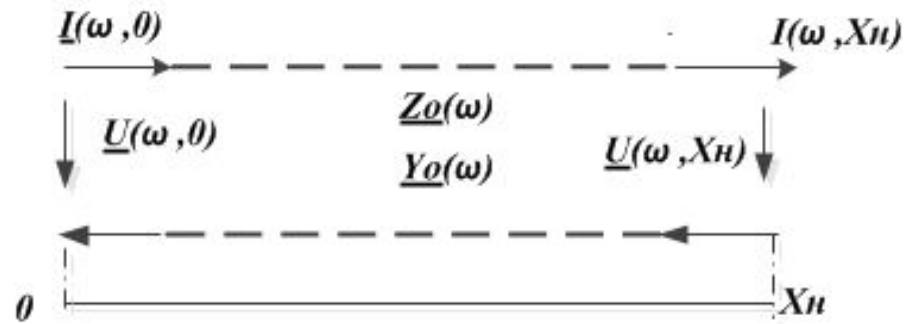
$$\underline{Z}_H(\omega) \rightarrow \infty$$



$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot X_H\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] & \cos\left[\frac{\omega}{V_w} \cdot X_H\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_H) \\ \underline{I}(\omega, X_H) \end{bmatrix}$$

# Режим холостого хода

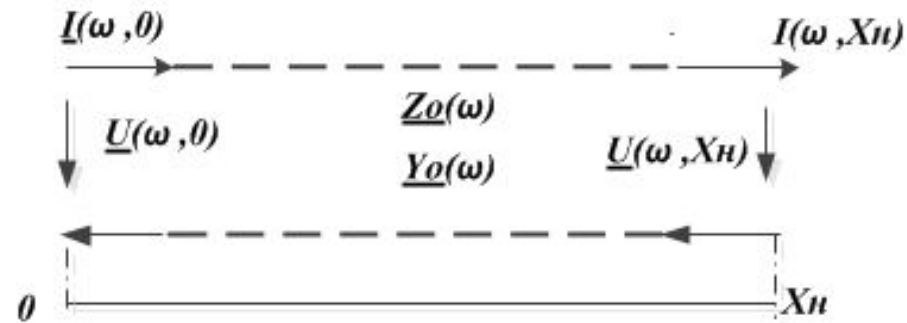
$$\underline{Z}_H(\omega) \rightarrow \infty$$



$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot X_H\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] & \cos\left[\frac{\omega}{V_w} \cdot X_H\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_H) \\ \underline{I}(\omega, X_H) \end{bmatrix}$$

# Режим холостого хода

$$\underline{Z}_H(\omega) \rightarrow \infty$$



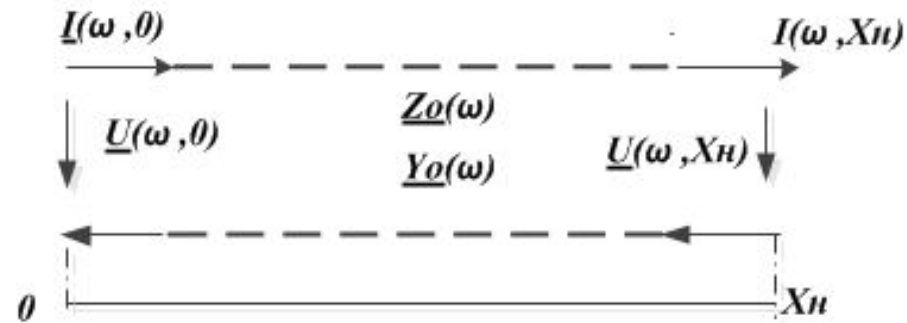
$$\begin{bmatrix} \underline{U}(\omega, 0) \\ \underline{I}(\omega, 0) \end{bmatrix} = \begin{bmatrix} \cos\left[\frac{\omega}{V_w} \cdot X_H\right] & j \cdot Z_w \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] \\ \frac{j}{Z_w} \cdot \sin\left[\frac{\omega}{V_w} \cdot X_H\right] & \cos\left[\frac{\omega}{V_w} \cdot X_H\right] \end{bmatrix} \cdot \begin{bmatrix} \underline{U}(\omega, X_H) \\ \underline{I}(\omega, X_H) \end{bmatrix}$$

$$\underline{U}(\omega, 0) = \cos\left(\frac{\omega}{V_w} \cdot X_H\right) \cdot \underline{U}(\omega, X_H);$$

$$\underline{I}(\omega, 0) = \frac{j}{Z_w} \cdot \sin\left(\frac{\omega}{V_w} \cdot X_H\right) \cdot \underline{U}(\omega, X_H);$$

# Режим холостого хода

$$\underline{Z}_H(\omega) \rightarrow \infty$$

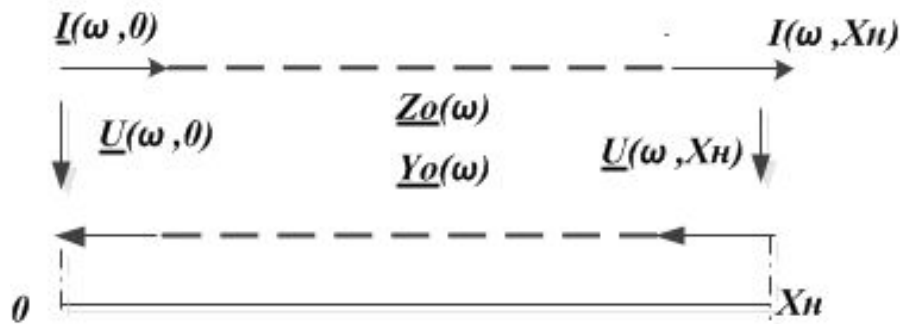


$$\underline{U}(\omega, 0) = \text{Cos}\left(\frac{\omega}{V_w} \cdot X_H\right) \cdot \underline{U}(\omega, X_H);$$

$$\underline{I}(\omega, 0) = \frac{j}{Z_w} \cdot \text{Sin}\left(\frac{\omega}{V_w} \cdot X_H\right) \cdot \underline{U}(\omega, X_H);$$

$$\underline{Z}_{ex}(\omega) = \frac{\underline{U}(\omega, 0)}{\underline{I}(\omega, 0)} = -j \cdot Z_w \frac{\text{Cos}\left(\frac{\omega}{V_w} \cdot X_H\right)}{\text{Sin}\left(\frac{\omega}{V_w} \cdot X_H\right)} = -j \cdot Z_w \cdot \text{ctg}\left(\frac{\omega}{V_w} \cdot X_H\right);$$

# Режим холостого хода

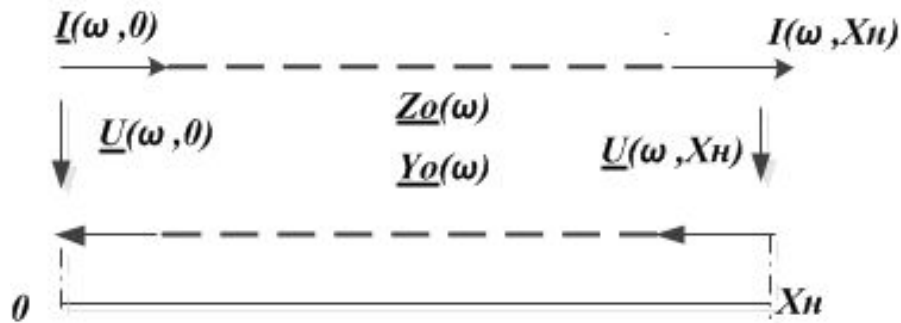


$$\underline{Z}_{ex}(\lambda_w) = -j \cdot Z_w \cdot ctg \left( 2 \cdot \pi \cdot \frac{X_H}{\lambda_w} \right);$$

$$-ctg \left( 2 \cdot \pi \cdot \frac{X_H}{\lambda_w} \right)$$



# Режим холостого хода



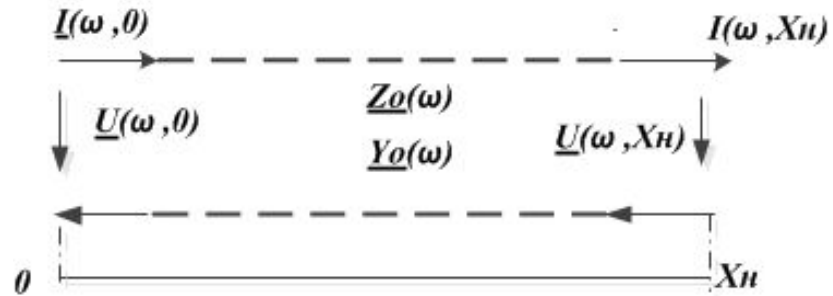
$$\underline{Z}_{ex}(\lambda_w) = -j \cdot Z_w \cdot \text{ctg} \left( 2 \cdot \pi \cdot \frac{X_H}{\lambda_w} \right);$$

$$\varphi \left[ \frac{Z_{ex} \left( \frac{X_H}{\lambda_w} \right)}{Z_w} \right]$$



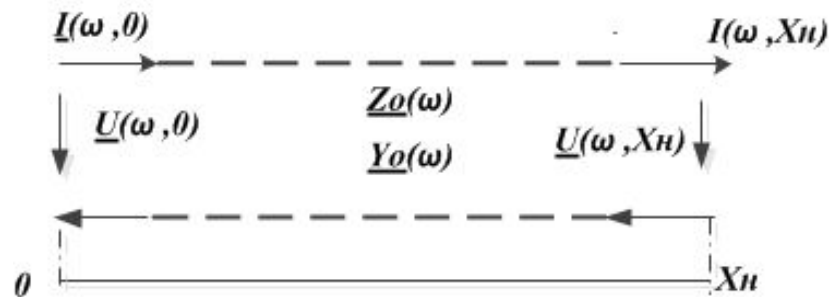


# Проводной канал с малыми потерями



$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

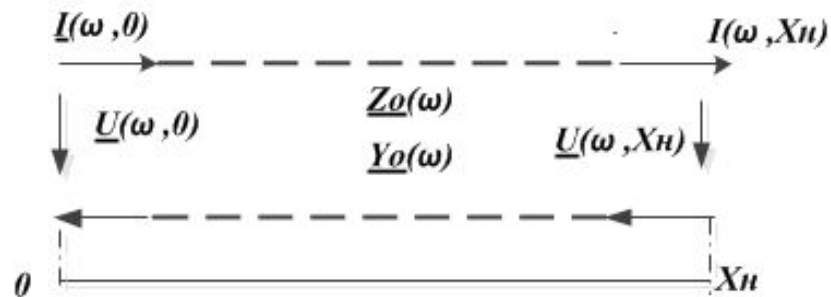
# Проводной канал с малыми потерями



$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{\gamma}_0^2(\omega) = \underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[ -1 + j \cdot \left( \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

# Проводной канал с малыми потерями

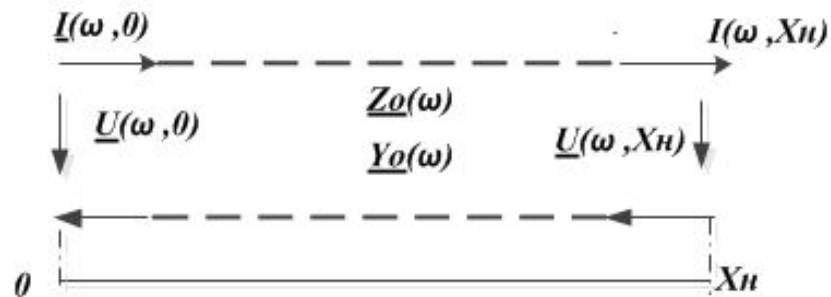


$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{\gamma}_0^2(\omega) = \underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[ -1 + j \cdot \left( \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

$$V_0 = \frac{1}{\sqrt{L_0 \cdot C_0}} \text{ м/с};$$

# Проводной канал с малыми потерями



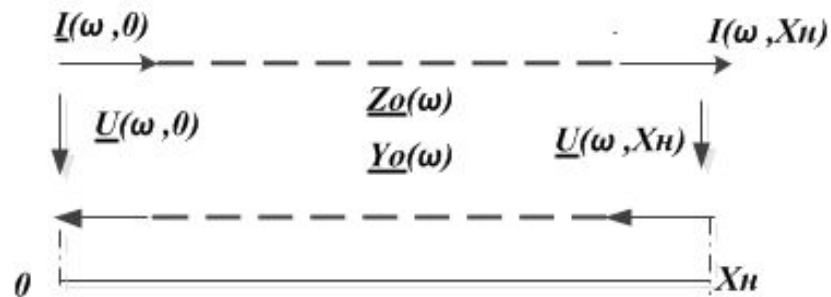
$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{\gamma}_0^2(\omega) = \underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[ -1 + j \cdot \left( \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

$$V_0 = \frac{1}{\sqrt{L_0 \cdot C_0}} \text{ м/с};$$

$$\text{tg}(\delta_\omega) = \frac{G_0}{\omega \cdot C_0} + \frac{R_0}{\omega \cdot L_0}$$

# Проводной канал с малыми потерями



$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

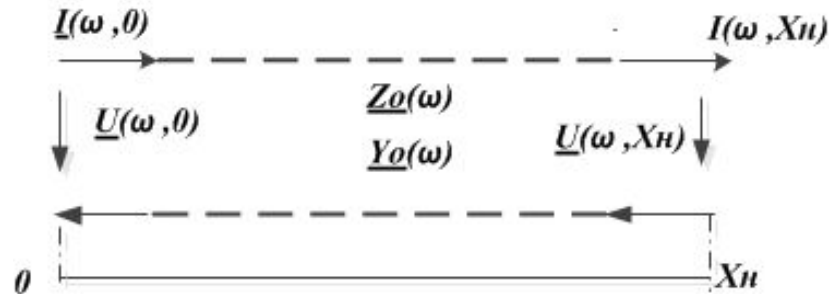
$$\underline{\gamma}_0^2(\omega) = \underline{Z}_0(\omega) \cdot \underline{Y}_0(\omega) \approx \omega^2 \cdot L_0 \cdot C_0 \cdot \left[ -1 + j \cdot \left( \frac{R_0}{\omega \cdot L_0} + \frac{G_0}{\omega \cdot C_0} \right) \right];$$

$$V_0 = \frac{1}{\sqrt{L_0 \cdot C_0}} \text{ м/с};$$

$$\text{tg}(\delta_\omega) = \frac{G_0}{\omega \cdot C_0} + \frac{R_0}{\omega \cdot L_0}$$

$$\underline{\gamma}_0^2(\omega) = \frac{\omega^2}{V_0^2} \cdot [-1 + j \cdot \text{tg}(\delta_\omega)];$$

# Проводной канал с малыми потерями

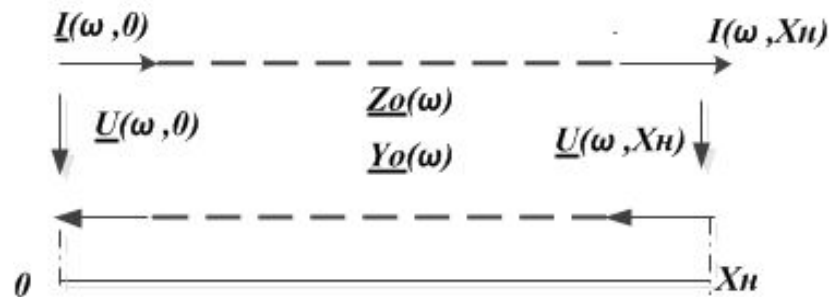


$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{\gamma}_0^2(\omega) = \frac{\omega^2}{V_0^2} \cdot \frac{e^{j(\pi - \delta_\omega)}}{\cos(\delta_\omega)} = -\frac{\omega^2}{V_0^2} \cdot \frac{e^{-j\delta_\omega}}{\cos(\delta_\omega)};$$

$$\underline{\gamma}_0(\omega) = j \cdot \frac{\omega}{V_0} \cdot e^{-j \frac{\delta_\omega}{2}} \sqrt{\frac{1}{\cos(\delta_\omega)}} = \frac{\omega}{V_0 \cdot \sqrt{\cos(\delta_\omega)}} \left[ \sin\left(\frac{\delta_\omega}{2}\right) + j \cdot \cos\left(\frac{\delta_\omega}{2}\right) \right];$$

# Проводной канал с малыми потерями



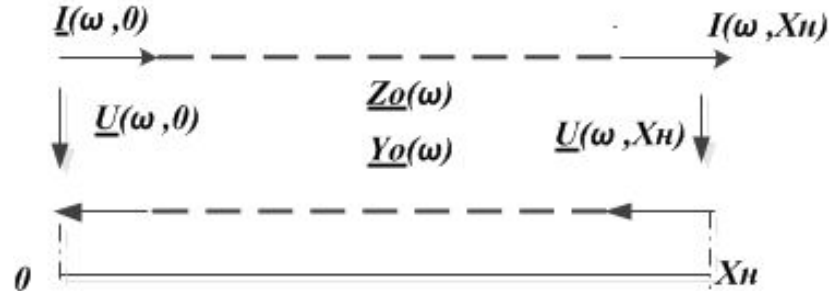
$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{Z}_w(\omega) = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}}$$

$$\underline{Z}_0(\omega) = [j \cdot \omega \cdot L_0 + R_0];$$

$$\underline{Y}_0(\omega) = [j \cdot \omega \cdot C_0 + G_0];$$

# Проводной канал с малыми потерями



$$\omega \cdot L_0 \gg R_0; \quad \omega \cdot C_0 \gg G_0;$$

$$\underline{Z}_w(\omega) = \sqrt{\frac{\underline{Z}_0(\omega)}{\underline{Y}_0(\omega)}}$$

$$\underline{Z}_0(\omega) = [j \cdot \omega \cdot L_0 + R_0];$$

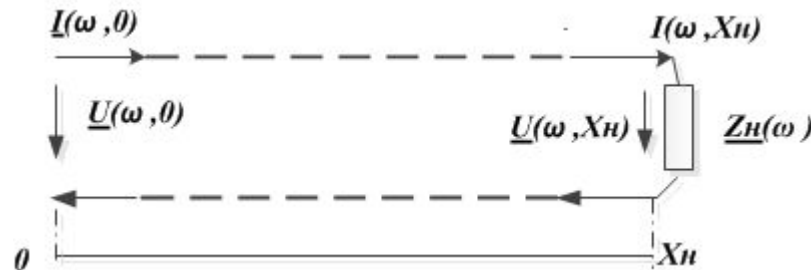
$$\underline{Y}_0(\omega) = [j \cdot \omega \cdot C_0 + G_0];$$

$$\underline{Z}_w(\omega) = \sqrt{\frac{L_0}{C_0}} \cdot \sqrt{\frac{1 - j \cdot \frac{R_0}{\omega \cdot L_0}}{1 - j \cdot \frac{G_0}{\omega \cdot C_0}}} \approx \sqrt{\frac{L_0}{C_0}} = Z_w$$



# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H}; \quad \underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{\varphi}_u(\omega, X_H) = \left| \underline{T}_u(\omega, X_H) \right| = e^{-\alpha(\omega) \cdot X_H}; \quad \varphi_T = \beta(\omega) \cdot X_H \quad \langle \quad \rangle;$$

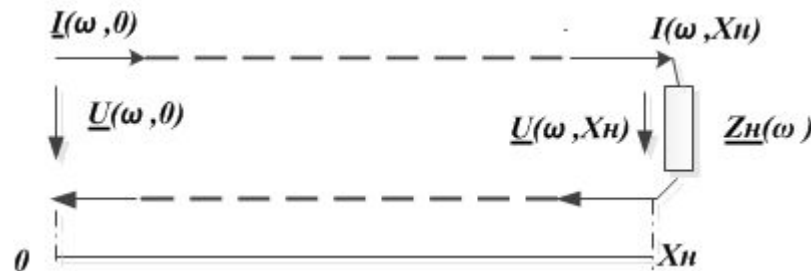
$$\underline{\varphi}_i(\omega, X_H) = \left| \underline{T}_i(\omega, X_H) \right| = e^{-\alpha(\omega) \cdot X_H}; \quad \varphi_T = \beta(\omega) \cdot X_H \quad \langle \quad \rangle;$$

$$T_P(\omega, X_H) = T_u(\omega, X_H) \cdot T_i(\omega, X_H) = e^{-2 \cdot \alpha(\omega) \cdot X_H};$$

$$\Delta B(\omega, X_H) = 10 \cdot \lg[T_P(\omega, X_H)] = -20 \cdot \lg(e) \cdot \alpha(\omega) \cdot X_H = -8.86 \cdot \alpha(\omega) \cdot X_H \quad \langle \quad \rangle;$$

# Согласованная нагрузка

$$\underline{Z}_H(\omega) = Z_w$$



$$\underline{U}(\omega, X_H) = \underline{U}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{I}(\omega, X_H) = \underline{I}(\omega, 0) \cdot e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

$$\underline{T}_u(\omega, X_H) = \frac{\underline{U}(\omega, X_H)}{\underline{U}(\omega, 0)} = e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H}; \quad \underline{T}_i(\omega, X_H) = \frac{\underline{I}(\omega, X_H)}{\underline{I}(\omega, 0)} = e^{-\alpha(\omega) \cdot X_H} \cdot e^{-j \cdot \beta(\omega) \cdot X_H};$$

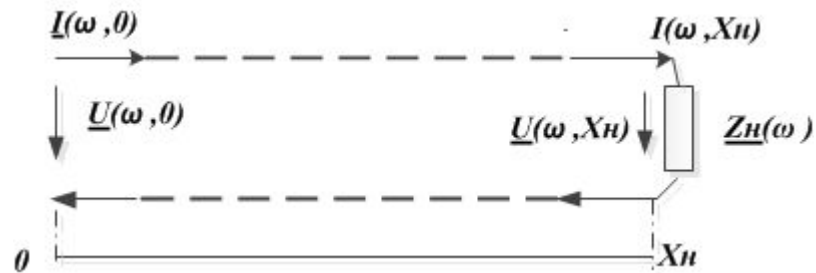
$$\underline{\varphi}_u(\omega, X_H) = \left| \underline{T}_u(\omega, X_H) \right| = e^{-\alpha(\omega) \cdot X_H}; \quad \varphi_T = \beta(\omega) \cdot X_H \quad \langle \quad \rangle;$$

$$\underline{\varphi}_i(\omega, X_H) = \left| \underline{T}_i(\omega, X_H) \right| = e^{-\alpha(\omega) \cdot X_H}; \quad \varphi_T = \beta(\omega) \cdot X_H \quad \langle \quad \rangle;$$

$$T_P(\omega, X_H) = T_u(\omega, X_H) \cdot T_i(\omega, X_H) = e^{-2 \cdot \alpha(\omega) \cdot X_H};$$

$$\Delta B(\omega, X_H) = 10 \cdot \lg[T_P(\omega, X_H)] = -20 \cdot \lg(e) \cdot \alpha(\omega) \cdot X_H = -8.86 \cdot \alpha(\omega) \cdot X_H \quad \langle \quad \rangle;$$

# Пример расчёта потери мощности



Тип кабеля: *PK50-06-11*

$\varnothing_M = 50 \text{ X}$  ;  $M_H = 100$  ;  $\delta_w = 0,02$

