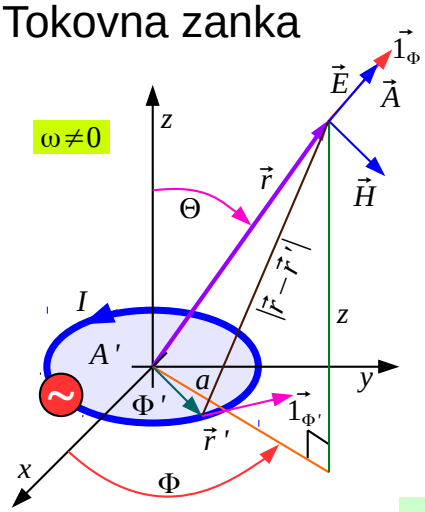
11. Preproste antene

Sevanje Teslovega transformatorja je neučinkovito, ker je naprava zelo majhna $h \ll \lambda \approx 10\,\mathrm{km}$ v primerjavi z valovno dolžino. Gulielmo Marconi je s številnimi poskusi pravilno ugotovil, da sevanje Teslovega transformatorja narašča predvsem z višanjem droga h oziroma večanjem dolžine žice, ki je nanj priključena. Marconi je učinkovitejšo sevalno napravo poimenoval »antena« po latinskem izrazu za tipalke žuželk podobnih oblik in z njo vzpostavil prvo prekooceansko radijsko zvezo leta 1901.

Tokovna zanka



$\rho(\vec{r}\,')=0 \;\rightarrow\; V(\vec{r})=0$

$$\vec{A}(\vec{r})=\frac{\mu}{4\pi}\int_0^{2\pi}\vec{1}_{\Phi'}\,I\,\frac{e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|}\,a\,d\,\Phi'$$

Polmer zanke $a=|\vec{r}\,'|$

$$\vec{1}_\Phi=-\vec{1}_x\sin\Phi+\vec{1}_y\cos\Phi \qquad \vec{1}_{\Phi'}=-\vec{1}_x\sin\Phi'+\vec{1}_y\cos\Phi'$$

$$|\vec{r}-\vec{r}\,'|=\sqrt{\begin{matrix}(r\sin\Theta\cos\Phi-a\cos\Phi')^2+\\+(r\sin\Theta\sin\Phi-a\sin\Phi')^2+(r\cos\Theta)^2\end{matrix}}$$

$a \ll r \;\rightarrow\; |\vec{r}-\vec{r}\,'|\approx r-a\sin\Theta\cos(\Phi-\Phi')$

$$(1)\quad a \ll r \;\rightarrow\; \frac{1}{|\vec{r}-\vec{r}\,'|}\approx\frac{1}{r}\left[1+\frac{a}{r}\sin\Theta\cos(\Phi-\Phi')\right]$$

$$(2)\quad a \ll \lambda \;\rightarrow\; e^{-jk|\vec{r}-\vec{r}\,'|}\approx e^{-jkr}\left[1+jka\sin\Theta\cos(\Phi-\Phi')\right]$$

$$\vec{A}(\vec{r})=\vec{1}_\Phi\frac{\mu\,I\,(\pi a^2)}{4\pi}e^{-jkr}\left(\frac{jk}{r}+\frac{1}{r^2}\right)\sin\Theta$$

Površina zanke $A'=\pi a^2$

$$\vec{E}(\vec{r})=-j\,\omega\,\vec{A}(\vec{r})-\mathrm{grad}\,V(\vec{r})=-\vec{1}_\Phi\frac{j\,\omega\,\mu\,IA'}{4\pi}e^{-jkr}\left(\frac{jk}{r}+\frac{1}{r^2}\right)\sin\Theta=\vec{1}_\Phi\frac{ZIA'}{4\pi}e^{-jkr}\left(\frac{k^2}{r}-\frac{jk}{r^2}\right)\sin\Theta$$

$$\vec{H}(\vec{r})=\frac{1}{\mu}\mathrm{rot}\,\vec{A}(\vec{r})=\vec{1}_\Phi\frac{IA'}{4\pi}e^{-jkr}\left[\vec{1}_r\left(\frac{jk}{r^2}+\frac{1}{r^3}\right)2\cos\Theta+\vec{1}_\Theta\left(-\frac{k^2}{r}+\frac{jk}{r^2}+\frac{1}{r^3}\right)\sin\Theta\right]$$

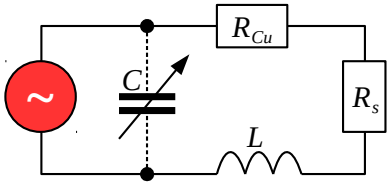
$$Z=\sqrt{\frac{\mu}{\epsilon}}$$

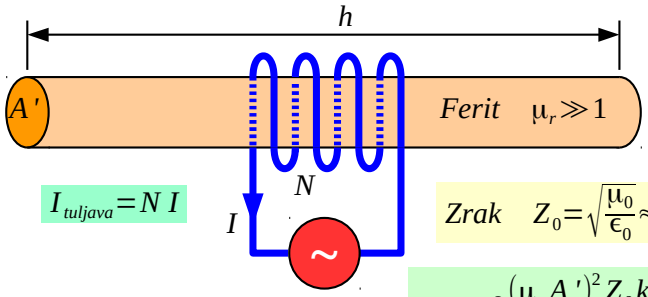
$$\vec{S}(\vec{r})=\frac{1}{2}\vec{E}(\vec{r})\times\vec{H}(\vec{r})^{*}=\frac{|I|^2(A')^2Z}{32\pi}\left[\vec{1}_r\left(\frac{k^4}{r^2}+\frac{jk}{r^5}\right)\sin^2\Theta-\vec{1}_\Theta\left(\frac{jk^3}{r^3}+\frac{jk}{r^5}\right)2\cos\Theta\sin\Theta\right]$$

$$P=\oiint_{A\to\infty}\vec{S}(\vec{r})\cdot\vec{1}_r\,dA=\frac{|I|^2(A')^2Z}{32\pi}k^4\int_o^{\pi}\int_0^{2\pi}\sin^3\Theta\,d\Theta\,d\Phi=\frac{|I|^2(A')^2Z}{32\pi}k^4\frac{4}{3}2\pi=\frac{|I|^2(A')^2Zk^4}{12\pi}$$

$$R_s=\frac{2P}{|I|^2}=\frac{(A')^2Zk^4}{6\pi}=\frac{8\pi^3(A')^2Z}{3\lambda^4}=\frac{8\pi^3Z}{3}\left(\frac{A'}{\lambda^2}\right)^2$$

Sevanje zanke





$h\gg\sqrt{A'}\ \rightarrow\ A_{eff}\approx\mu_r A'$

$f\approx1\,\mathrm{MHz}$
$A'\approx1\,\mathrm{cm}^2$
$h\approx20\,\mathrm{cm}$
$\mu_r\approx100$
$N\approx30$
$R_s\approx0.35\,\mu\Omega$

$I_{tuljava}=N\,I$

Zrak $\quad Z_0=\sqrt{\frac{\mu_0}{\epsilon_0}}\approx377\,\Omega$

$$R_s=N^2\frac{(\mu_r A')^2Z_0k^4}{6\pi}=\frac{8\pi^3(N\mu_r A')^2Z_0}{3\lambda^4}=\frac{8\pi^3Z_0}{3}\left(\frac{N\mu_r A'}{\lambda^2}\right)^2$$

Feritna antena

Poenostavitve za sevanje

$$\vec{A}(\vec{r})=\alpha\,I\,e^{-jkr}\vec{F}(r,\Theta,\Phi)$$

Daljava $\quad r\gg\frac{1}{k}=\frac{\lambda}{2\pi}\ \rightarrow\ \frac{\partial}{\partial r}\approx-jk\quad\frac{\partial}{\partial\Theta}\approx0\quad\frac{\partial}{\partial\Phi}\approx0$

$$\vec{\nabla}\approx\vec{1}_r(-jk)$$

$$\mathrm{rot}\,\vec{A}(\vec{r})\approx\frac{1}{r^2\sin\Theta}\begin{vmatrix}\vec{1}_r & r\vec{1}_\Theta & r\sin\Theta\vec{1}_\Phi\\ -jk & 0 & 0\\ A_r & rA_\Theta & r\sin\Theta A_\Phi\end{vmatrix}=\vec{\nabla}\times\vec{A}(\vec{r})=\vec{1}_\Theta jkA_\Phi-\vec{1}_\Phi jkA_\Theta$$

Brez A_r

$$\vec{H}(\vec{r})=\frac{1}{\mu}\mathrm{rot}\,\vec{A}(\vec{r})\approx\vec{1}_\Theta\frac{jk}{\mu}A_\Phi-\vec{1}_\Phi\frac{jk}{\mu}A_\Theta$$

$$\vec{E}(\vec{r})=\frac{1}{j\omega\epsilon}\vec{\nabla}\times\left(\frac{1}{\mu}\vec{\nabla}\times\vec{A}(\vec{r})\right)\approx-j\omega\left[\vec{A}(\vec{r})-\vec{1}_r\left(\vec{1}_r\cdot\vec{A}(\vec{r})\right)\right]=-j\omega\left(\vec{1}_\Theta A_\Theta+\vec{1}_\Phi A_\Phi\right)$$

$$\frac{|\vec{E}(\vec{r})|}{|\vec{H}(\vec{r})|}=Z$$

$$\vec{S}(\vec{r})=\frac{1}{2}\vec{E}(\vec{r})\times\vec{H}(\vec{r})^{*}\approx\vec{1}_r\frac{\omega^2}{2Z}\left(|A_\Theta|^2+|A_\Phi|^2\right)$$

Samo delovna moč!

$$\vec{1}_r\perp\vec{H}(\vec{r})\perp\vec{E}(\vec{r})\perp\vec{1}_r$$

Zgled tokovni element

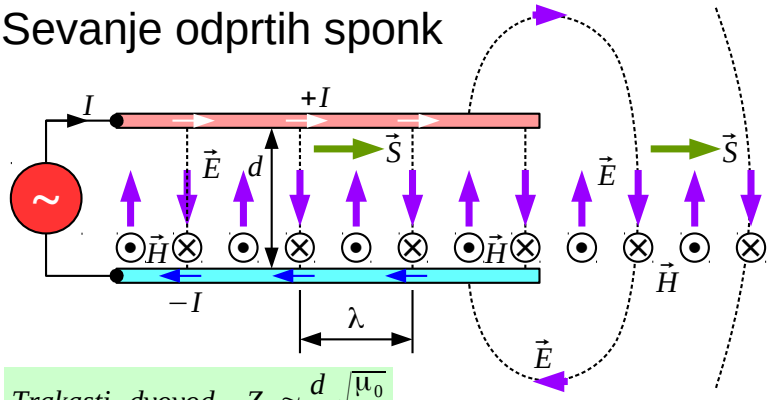
$$\vec{A}(\vec{r})=\left(\vec{1}_r\cos\Theta-\vec{1}_\Theta\sin\Theta\right)\frac{\mu\,I\,h}{4\pi}\frac{e^{-jkr}}{r}$$

$$\vec{H}(\vec{r})\approx\vec{1}_\Phi\frac{jk}{4\pi}I\,h\frac{e^{-jkr}}{r}\sin\Theta$$

$$\vec{E}(\vec{r})\approx\vec{1}_\Theta\frac{jkZ}{4\pi}I\,h\frac{e^{-jkr}}{r}\sin\Theta$$

$$\vec{S}(\vec{r})\approx\vec{1}_r\frac{k^2Z|I|^2h^2}{32\pi^2}\frac{\sin^2\Theta}{r^2}$$

Sevanje odprtih sponk

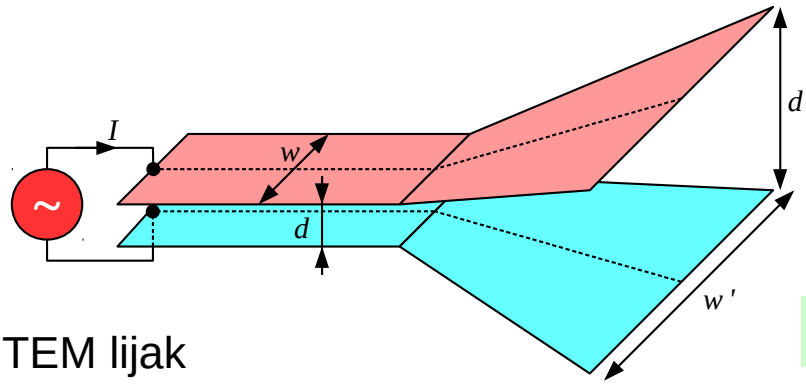


$d \ll \lambda \rightarrow \Gamma \approx +1$

$d \approx \lambda/2 \rightarrow |\Gamma| \approx 0.3$

$d \gg \lambda \rightarrow \Gamma \approx 0$

Trakasti dvovod $Z_K \approx \frac{d}{w}\sqrt{\frac{\mu_0}{\epsilon_0}}$

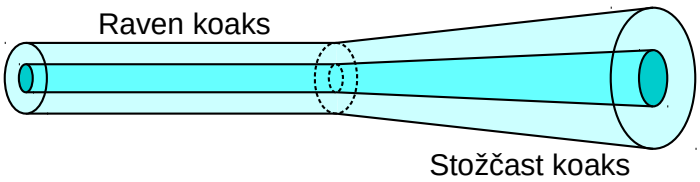


Sevanje

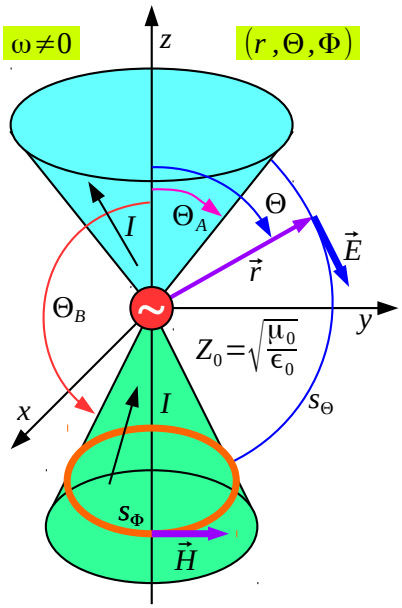
$Z_K \approx \frac{d}{w}\sqrt{\frac{\mu_0}{\epsilon_0}} = \frac{d'}{w'}\sqrt{\frac{\mu_0}{\epsilon_0}}$

TEM lijak

Stožčasti vod



$\omega \neq 0$ (r, Θ, Φ)



Ugibam $\vec{E}(\vec{r}) = \vec{1}_\Theta \frac{C}{r \sin\Theta} e^{-jkr}$

Preverim Gauss $\operatorname{div}(\epsilon \vec{E}(\vec{r})) = 0$

Faraday izračunam $\vec{H}(\vec{r}) = \frac{j}{\omega\mu} \operatorname{rot} \vec{E}(\vec{r}) = \vec{1}_\Phi \frac{C/Z_0}{r \sin\Theta} e^{-jkr}$

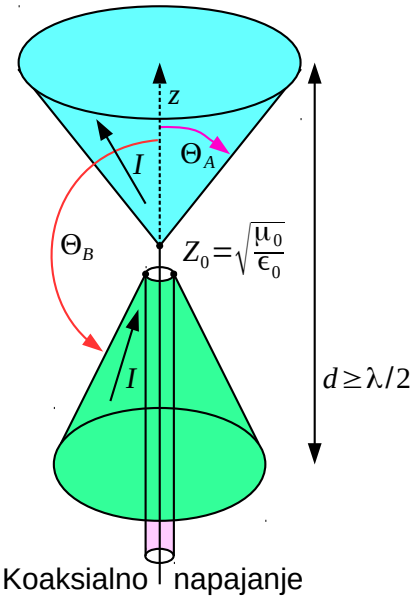
Preverim Ampère $\vec{J}(\vec{r}) = \operatorname{rot} \vec{H}(\vec{r}) - j\omega\epsilon \vec{E}(\vec{r}) = 0$

$$I = \oint_{s_\Phi} \vec{H} \cdot d\vec{s}_\Phi = \int_0^{2\pi} \vec{1}_\Phi \frac{C/Z_0}{r \sin\Theta} e^{-jkr} \cdot \vec{1}_\Phi r \sin\Theta \, d\Phi = \frac{2\pi C}{Z_0} e^{-jkr}$$

$$Z_K = \frac{U}{I} = \frac{Z_0}{2\pi} \ln\left(\frac{\operatorname{tg}(\Theta_B/2)}{\operatorname{tg}(\Theta_A/2)}\right) \approx 60\,\Omega \ln\left(\frac{\operatorname{tg}(\Theta_B/2)}{\operatorname{tg}(\Theta_A/2)}\right)$$

$$U = \int_A^B \vec{E} \cdot d\vec{s}_\Theta = \int_{\Theta_A}^{\Theta_B} \vec{1}_\Theta \frac{C}{r \sin\Theta} e^{-jkr} \cdot \vec{1}_\Theta r \, d\Theta = C e^{-jkr} \int_{\Theta_A}^{\Theta_B} \frac{d\Theta}{\sin\Theta} = C e^{-jkr} \ln\left(\frac{\operatorname{tg}(\Theta_B/2)}{\operatorname{tg}(\Theta_A/2)}\right)$$

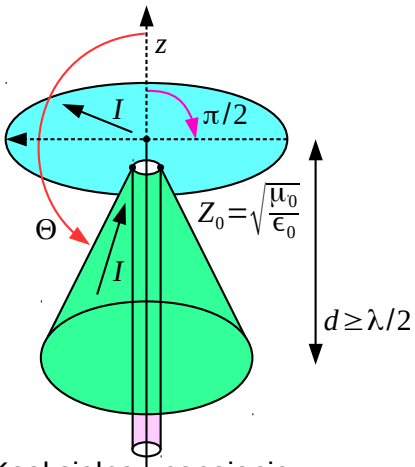
Bikonična antena



Koaksialno napajanje

$$Z \approx 60\,\Omega \ln\left(\frac{\mathrm{tg}(\Theta_B/2)}{\mathrm{tg}(\Theta_A/2)}\right)$$

Discone antena



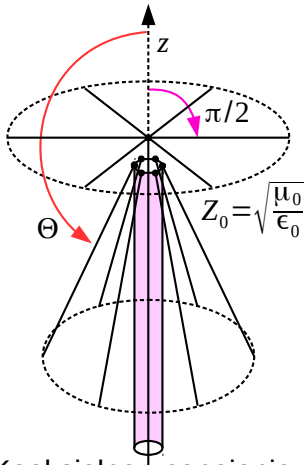
Koaksialno napajanje

$$Z \approx 60\,\Omega \ln\left(\mathrm{tg}(\Theta/2)\right)$$

$$\Theta \approx 2\,\mathrm{arctg}\left(e^{Z/60\Omega}\right)$$

$$Z = 50\,\Omega \;\rightarrow\; \Theta \approx 133^{\circ}$$

Discone iz palčk



Koaksialno napajanje

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