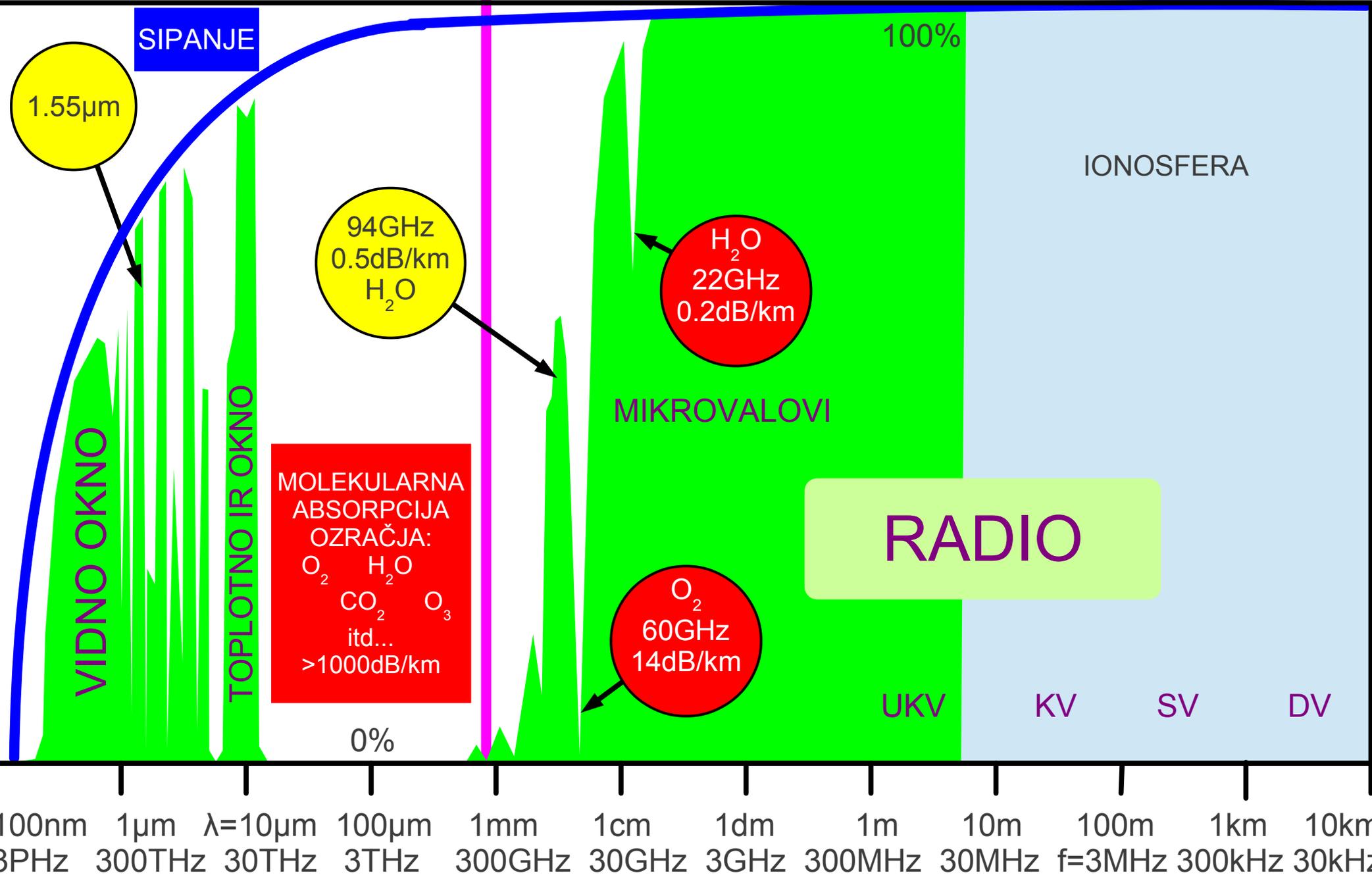


Zenitna prepustnost ozračja

400GHz ITU RR 9kHz



Elektromagnetika

Harmonske veličine:

$$\partial/\partial t = j\omega$$

$$\omega \equiv \text{krožna frekvenca} \quad [\text{rd/s}]$$

$$\text{Ampère: } \text{rot } \vec{H} = \vec{J} + j\omega \epsilon \vec{E}$$

$$\text{Faraday: } \text{rot } \vec{E} = -j\omega \mu \vec{H}$$

$$\text{Gauss: } \text{div } \epsilon \vec{E} = \rho$$

$$\epsilon \equiv \text{dielektričnost} \quad \left[\frac{\text{As}}{\text{Vm}} \right] \rightarrow \vec{D} = \epsilon \vec{E}$$

$$\vec{H} \equiv \text{magnetna poljska jakost} \quad \left[\frac{\text{A}}{\text{m}} \right]$$

$$\vec{J} \equiv \text{gostota toka} \quad \left[\frac{\text{A}}{\text{m}^2} \right]$$

$$\vec{E} \equiv \text{električna poljska jakost} \quad \left[\frac{\text{V}}{\text{m}} \right]$$

$$\rho \equiv \text{gostota elektrine} \quad \left[\frac{\text{As}}{\text{m}^3} \right]$$

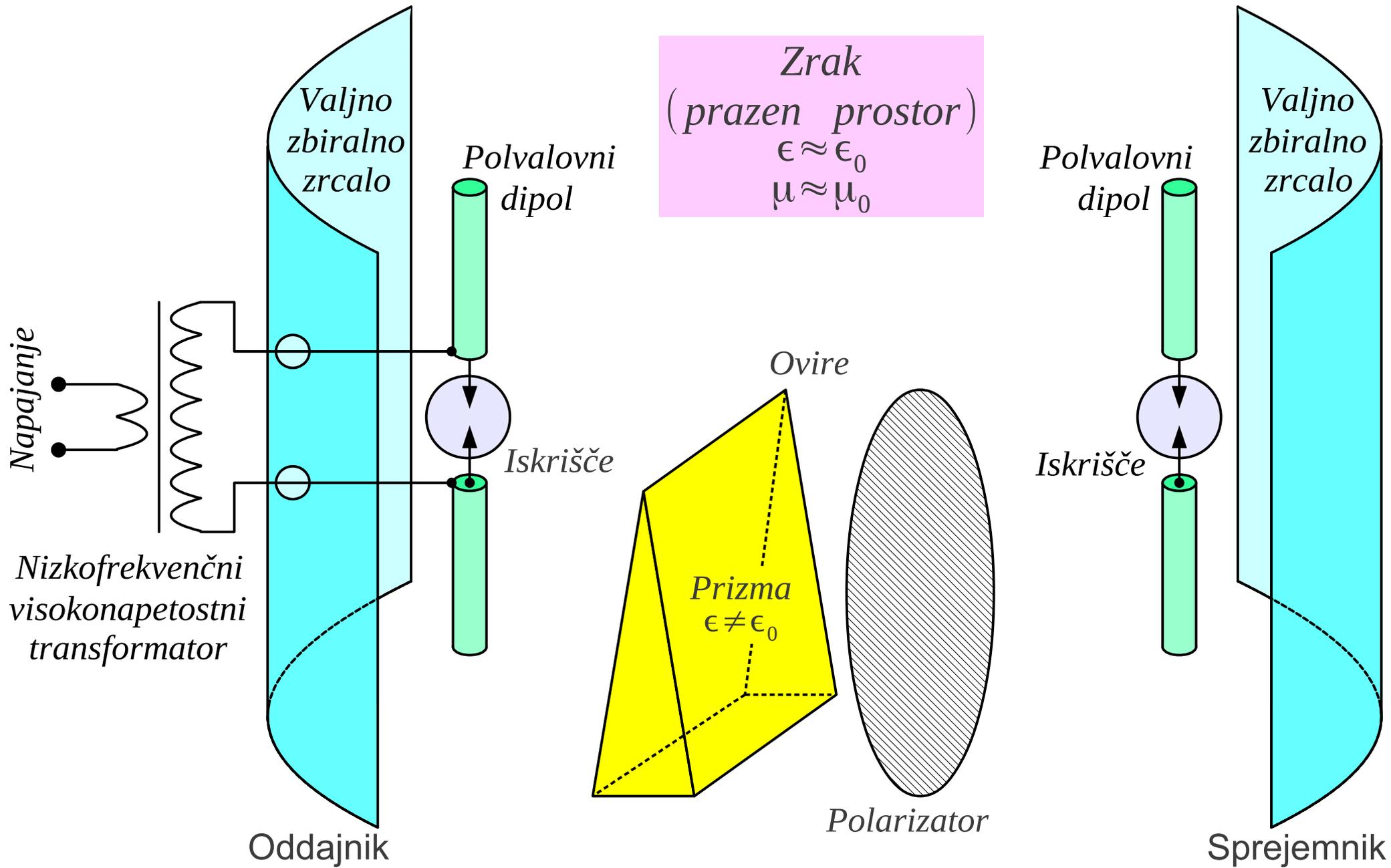
$$\mu \equiv \text{permeabilnost} \quad \left[\frac{\text{Vs}}{\text{Am}} \right] \rightarrow \vec{B} = \mu \vec{H}$$

$$\text{Poynting: } \vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^* \equiv \text{gostota pretoka moči} \quad \left[\frac{\text{W}}{\text{m}^2} \right]$$

$$\vec{A}(\vec{r}) = \frac{\mu}{4\pi} \int_{V'} \vec{J}(\vec{r}') \frac{e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dV' \equiv \text{vektorski potencial} \quad \left[\frac{\text{Vs}}{\text{m}} \right]$$

$$\vec{H} = \frac{1}{\mu} \text{rot } \vec{A}$$

$$V(\vec{r}) = \frac{1}{4\pi\epsilon} \int_{V'} \rho(\vec{r}') \frac{e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dV' \equiv \text{skalarni potencial} \quad [\text{V}] \quad \vec{E} = -j\omega \vec{A} - \text{grad } V$$



Zrak
(prazen prostor)
 $\epsilon \approx \epsilon_0$
 $\mu \approx \mu_0$



Rayleigh $r \gg \frac{\lambda}{2\pi}$

Hertzov poskus

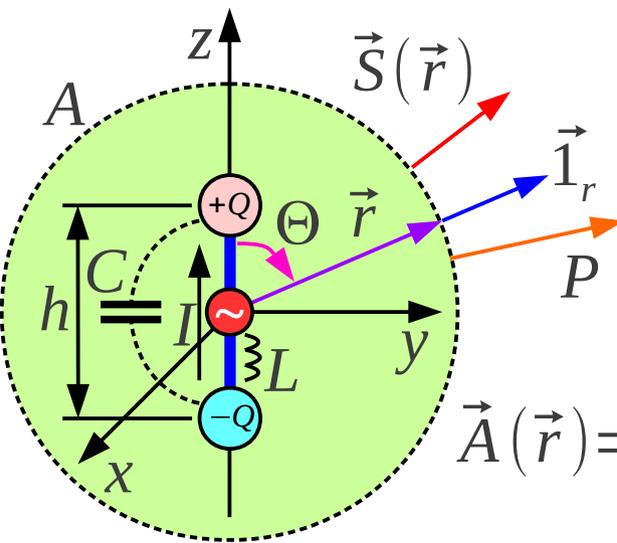
Sevanje kratkega dipola

Poenostavitve:

- (1) $h \ll r$
- (2) $h \ll \lambda$

$\omega \neq 0$

$$k = \omega \sqrt{\mu \epsilon} = \frac{2\pi}{\lambda}$$



$$\vec{A}(\vec{r}) = \frac{\mu}{4\pi} \int_{V'} \vec{J}(\vec{r}') \frac{e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dV' \approx (\vec{1}_r \cos \Theta - \vec{1}_\Theta \sin \Theta) \frac{\mu I h e^{-jkr}}{4\pi r}$$

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

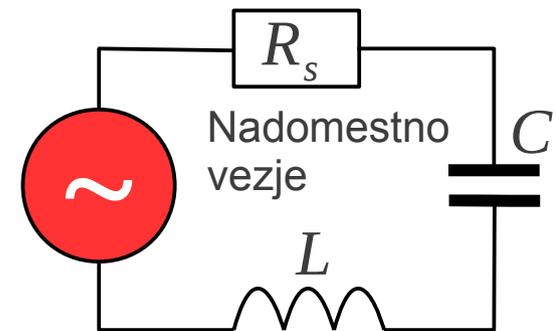
$$\frac{1}{\omega \epsilon} = \frac{1}{\omega \sqrt{\mu \epsilon}} \sqrt{\frac{\mu}{\epsilon}} = \frac{Z}{k}$$

$$\vec{E}(\vec{r}) = \frac{1}{j\omega \epsilon} \text{rot } \vec{H} = \frac{I h}{4\pi j\omega \epsilon} e^{-jkr} \left[\vec{1}_r \left(\frac{jk}{r^2} + \frac{1}{r^3} \right) 2\cos \Theta + \vec{1}_\Theta \left(-\frac{k^2}{r} + \frac{jk}{r^2} + \frac{1}{r^3} \right) \sin \Theta \right]$$

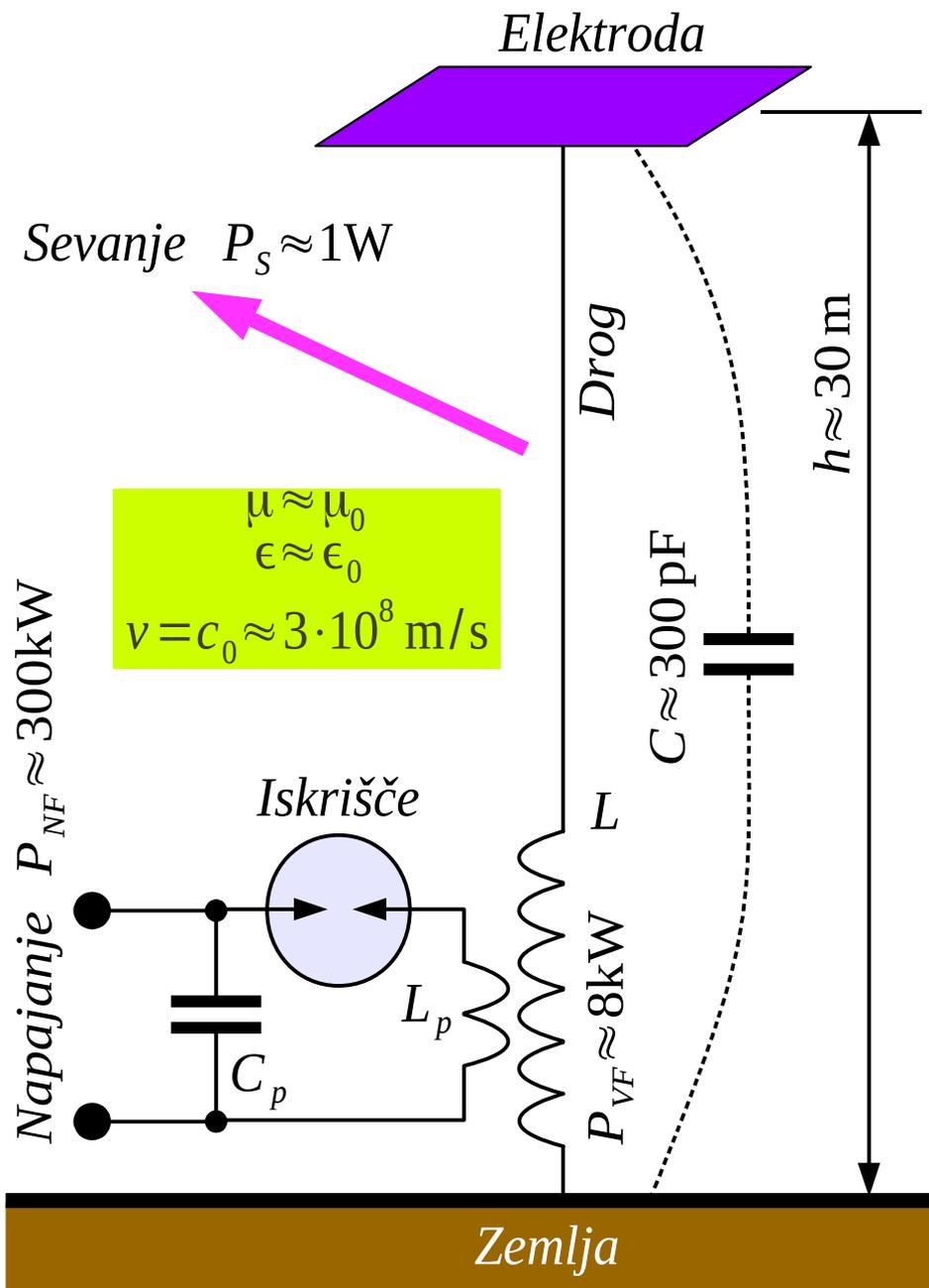
$$\vec{S}(\vec{r}) = \frac{1}{2} \vec{E}(\vec{r}) \times \vec{H}(\vec{r})^* = \frac{|I|^2 h^2}{32\pi^2 \omega \epsilon} \left[\vec{1}_r \left(\frac{k^3}{r^2} - \frac{j}{r^5} \right) \sin^2 \Theta + \vec{1}_\Theta \left(\frac{jk^2}{r^3} + \frac{j}{r^5} \right) 2\cos \Theta \sin \Theta \right]$$

$$P = \iint_{r \rightarrow \infty} \vec{S}(\vec{r}) \cdot \vec{1}_r r^2 \sin \Theta d\Theta d\Phi \approx \frac{|I|^2 h^2 Z k^2}{12\pi}$$

$$R_s = \frac{2P}{|I|^2} = \frac{h^2 Z k^2}{6\pi} = \frac{2\pi Z}{3} \left(\frac{h}{\lambda} \right)^2$$



Teslov transformator



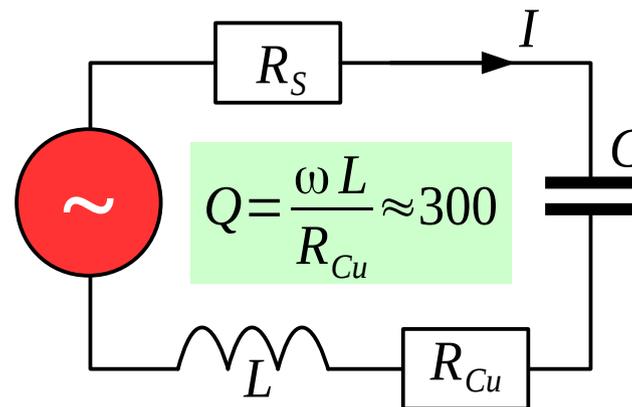
$$f \approx 30 \text{ kHz}$$

$$\omega = 2\pi f \approx 1.885 \cdot 10^5 \text{ rd/s}$$

$$\lambda = \frac{c_0}{f} \approx 10 \text{ km}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 120 \pi \Omega$$

$$R_s = \frac{2\pi Z_0}{3} \left(\frac{h}{\lambda}\right)^2 \approx 80 \pi^2 \Omega \left(\frac{h}{\lambda}\right)^2 \approx 7.1 \text{ m}\Omega$$



$$\omega L = \frac{1}{\omega C} \approx 17.68 \text{ k}\Omega$$

$$R_{Cu} = \frac{\omega L}{Q} \approx 58.9 \Omega$$

$$\eta = \frac{P_s}{P_{VF}} = \frac{P_s}{P_s + P_{Cu}} = \frac{R_s}{R_s + R_{Cu}} \equiv \text{sevalni izkoristek}$$

$$\eta \approx \frac{0.0071 \Omega}{0.0071 \Omega + 58.9 \Omega} \approx 1.2 \cdot 10^{-4}$$

Fraunhofer:
daljne polje

$$|\vec{E}| = \alpha r^{-1}$$

$$\frac{|\vec{E}|}{|\vec{H}|} = Z_0$$

Dve polarizaciji
 $C/B \leq 10 \text{ bit}$

MIMO:
 $C/B \approx 20 \text{ bit}$

Fresnel:
sevano polje

Večrodovni prenos
 $C/B \geq 50 \text{ bit}$

$$r = \frac{2d^2}{\lambda}$$

$$r = \frac{\lambda}{2\pi}$$

Samo tu obstajajo:

$$D, G, F(\Theta, \Phi),$$

Friisova enačba

**Gulielmo
Marconi**

$$\frac{|\vec{E}|}{|\vec{H}|} \approx Z_0$$

$$\frac{|\vec{E}|}{|\vec{H}|} \neq Z_0$$

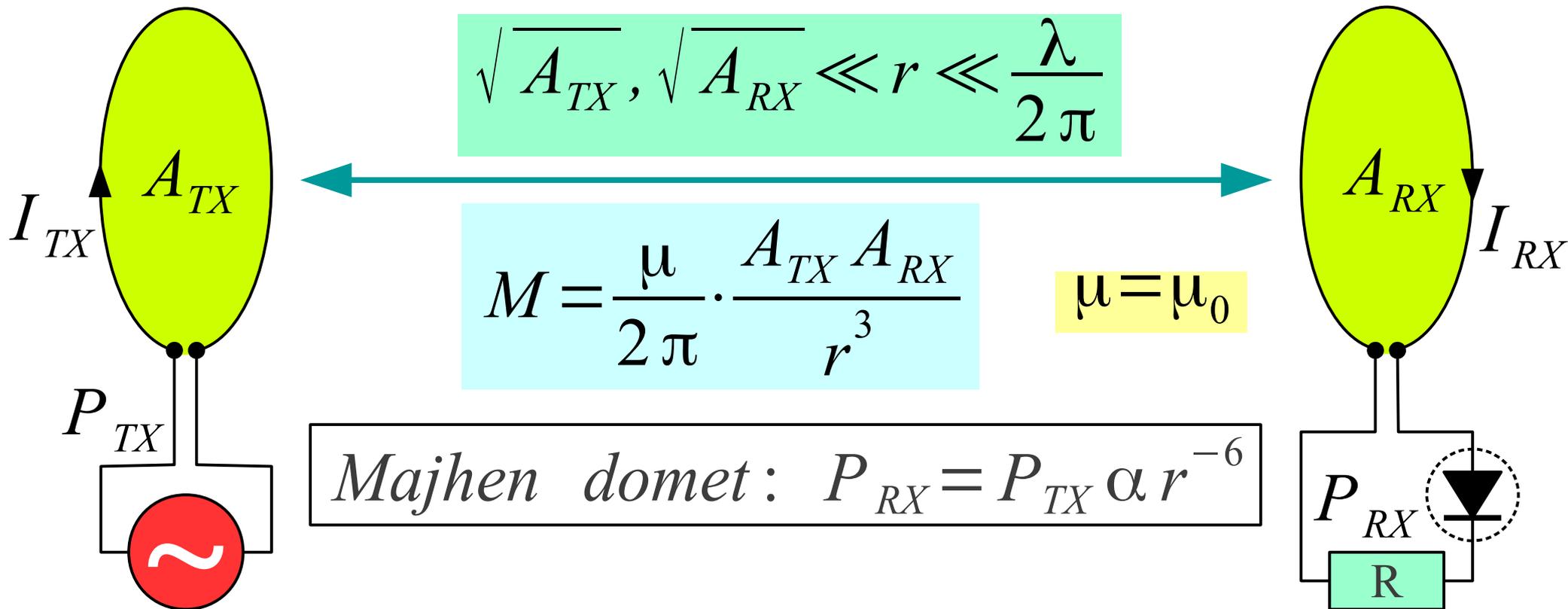
**Nikola
Tesla**

Statika:
bližnje polje

Vir sevanja

d

$\frac{E}{H} \neq Z_0 \rightarrow$ Potrebna ločena meritev \vec{E} ter \vec{H}



$\text{Re}[\vec{S}] = f(I_{TX}, I_{RX})$
Brez sevanja!

Uporaba:

RFID in druge zveze kratkega dosega
 Prenos energije (brezžično polnjenje)

Induktivni sklop v bližnjem polju

Zmogljivost radijske zveze

Informacija $I = \frac{1}{2} \cdot \log_2 \left(1 + \frac{W_S}{W_N} \right)$ [bit] (Claude Shannon 1948)

$W_S \equiv$ energija signala

$W_N \equiv$ energija šuma

$T \equiv$ perioda signala

Pasovna širina $B = \frac{1}{2T}$ [Hz] (Harry Nyquist 1924)

$P_S \equiv$ moč signala

$P_N \equiv$ moč šuma

$N_0 \equiv$ spektralna gostota šuma

Zmogljivost $C = m \cdot B \cdot \log_2 \left(1 + \frac{P_S}{P_N} \right) = m \cdot B \cdot \log_2 \left(1 + \frac{P_S}{B \cdot N_0} \right)$ [bit/s = bps]

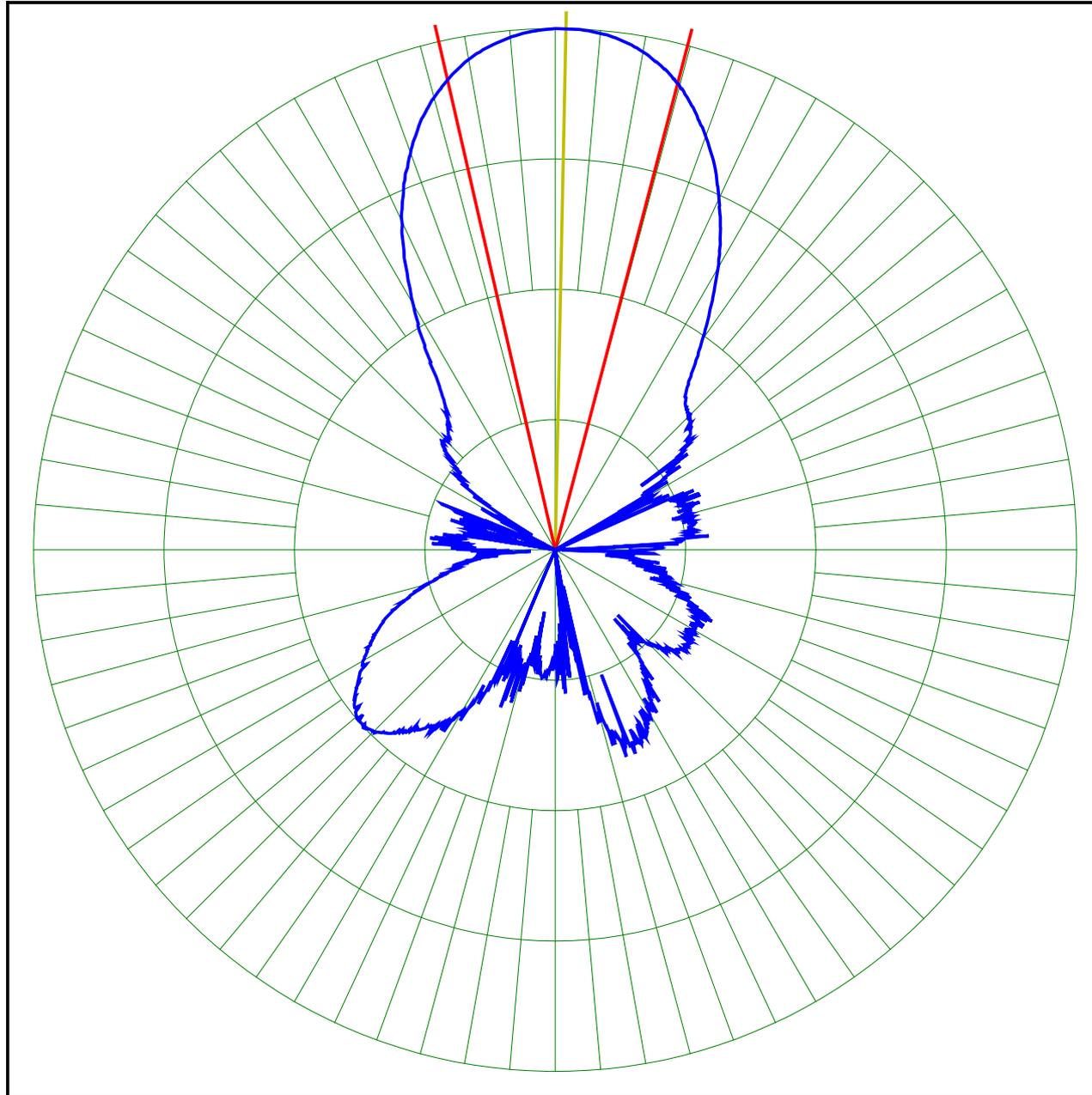
$m \equiv$ število rodov

Spektralna učinkovitost $C/B = m \cdot \log_2 \left(1 + \frac{P_S}{B \cdot N_0} \right)$ [bit/s/Hz = bit]

Leto	Vrsta radijske zveze	Pasovna širina B	Zmogljivost C	Spektralna učinkovitost C/B
~1910	Telegrafija s sprejemom na sluh	500Hz	10bit/s	0.02bit/s/Hz
~1950	Radioteleprinter	250Hz	50bit/s	0.2bit/s/Hz
~1990	GSM telefon	200kHz	271kbit/s	1.355bit/s/Hz
~2010	WiFi 802.11n ($m=2$)	40MHz	300Mbit/s	7.5bit/s/Hz

Wed Sep 27 12:34:32 2017
SBFA13cm 2360MHz ravnina E

Logaritemsko radialno merilo (razpon 40dB)



Sirina -3dB: 27.6 Odklon: -1.2 Smernost: 47.9 = 16.80 dBi