Optične komunikacije

Predavanje 2:

Odboj in lom elektromagnetnega valovanja

$$1.\ Ampere \rightarrow \oint_s \vec{H} \cdot d\,\vec{s} = I_{celotni} = \iint_A \vec{J}_{celotni} \cdot d\,\vec{A}$$

Harmonske veličine

$$\frac{\partial}{\partial t} = j\,\omega$$

$$\text{rot}\,\vec{H} = \vec{J}_{celotni} = \vec{J} + \frac{\partial \vec{D}}{\partial t} = \vec{J} + j\,\omega\,\vec{D}$$

$$\text{rot}\,\vec{H} = \nabla \times \vec{H}$$

$$\nabla = \vec{1}_x \frac{\partial}{\partial x} + \vec{1}_y \frac{\partial}{\partial y} + \vec{1}_z \frac{\partial}{\partial z}$$

Kartezične koordinate

$$(x, y, z)$$

$$2.\ Faraday \rightarrow u_i = -\frac{d\Phi}{dt} = \oint_s \vec{E} \cdot d\,\vec{s} = -\frac{\partial}{\partial t} \iint_A \vec{B} \cdot d\,\vec{A} = -\iint_A \frac{\partial \vec{B}}{\partial t} \cdot d\,\vec{A}$$

$$\text{rot}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t} = -j\,\omega\,\vec{B}$$

$$3.\ Gauss \rightarrow \iiint_V \rho\, dV = Q = \oiint_A \vec{D} \cdot d\,\vec{A}$$

$$\text{div}\,\vec{D} = \rho$$

$$\text{div}\,\vec{D} = \nabla \cdot \vec{D}$$

$$\mathrm{rot}\,\vec{H} = \vec{J} + j\,\omega\,\vec{D}$$

$$\mathrm{rot}\,\vec{E} = -\,j\,\omega\,\vec{B}$$

$$\mathrm{div}\,\vec{D} = \rho$$

$$\vec{D} = \epsilon\,\vec{E}$$

$$\vec{B} = \mu\,\vec{H}$$

1. $\mathrm{rot}\,\vec{H} = j\,\omega\,\epsilon\,\vec{E}$

2. $\mathrm{rot}\,\vec{E} = -\,j\,\omega\,\mu\,\vec{H}$

3. $\mathrm{div}\,\vec{E} = \frac{\rho}{\epsilon} \;\rightarrow\; \vec{E} \perp \vec{k}$

$$\check{Z}arek \equiv ravninski\ val\ (brez\ izvorov)$$

$$\vec{J} = 0 \quad brez\ tokov$$

$$\rho = 0 \quad brez\ elektrin$$

$$\vec{E}(\vec{r}, t) = \vec{E}_0\, e^{-j\vec{k}\cdot\vec{r}}\, e^{j\omega t}$$

$$\vec{E} \perp \vec{H} \perp \vec{k} \perp \vec{E} \rightarrow TEM \qquad Z = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu}{\epsilon}}$$

$$\vec{k} = \vec{1}_k\, k \equiv valovni\ vektor\,[rd/m]$$

$$k = \omega\sqrt{\mu\,\epsilon} \equiv valovno\ \check{s}tevilo\,[rd/m]$$

$$\Delta\vec{E} + \omega^2\mu\,\epsilon\,\vec{E} = 0 \qquad \Delta \equiv Laplace$$

$$\omega^2\mu\,\epsilon = k^2$$

Poljubna snov

Prazen prostor

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

$$k_0=\frac{\omega}{c_0} \qquad c_0=\frac{\omega}{k_0}=\frac{1}{\sqrt{\mu_0\epsilon_0}}$$

$$k\lambda=2\pi \qquad \lambda=\frac{2\pi}{k}$$

$$k_0\lambda_0=2\pi \qquad \lambda_0=\frac{2\pi}{k_0}$$

$$\mu=\mu_r\mu_0$$

$$Z_0=\frac{|\vec{E}|}{|\vec{H}|}=\sqrt{\frac{\mu_0}{\epsilon_0}}\approx 120\pi\Omega\approx 377\Omega$$

$$\epsilon=\epsilon_r\epsilon_0$$

$$c_0=2.997\ldots\cdot 10^8\, m/s\approx 3\cdot 10^8\, m/s\equiv izbrana\ definicija\ metra\ MKSA$$

$$\mu_0=4\pi\cdot 10^{-7}\, Vs/Am\equiv stara\ definicija\ ampera\ MKSA(pred\ 2019)$$

$$danes\rightarrow\mu_0\approx 4\pi\cdot 10^{-7}\, Vs/Am$$

Povezave

Učbenik Elektrodinamika: http://antena.fe.uni-lj.si/literatura/ed.pdf

Poglavje 13. Ravninski val

Učbenik Antene in razširjanje valov: http://antena.fe.uni-lj.si/literatura/ar.pdf

Poglavje 15. Odboj valovanja

Poljubna snov $n \equiv$ *lomni količnik snovi* [*neimenovan*]

$$v = \frac{1}{\sqrt{\mu \epsilon}} = \frac{c_0}{\sqrt{\mu_r \epsilon_r}} = \frac{c_0}{n}$$

$$n = \sqrt{\mu_r \epsilon_r}$$

$$Z = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu}{\epsilon}} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}}$$

$$Z = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \equiv \textit{valovna impedanca snovi} \, [\Omega]$$

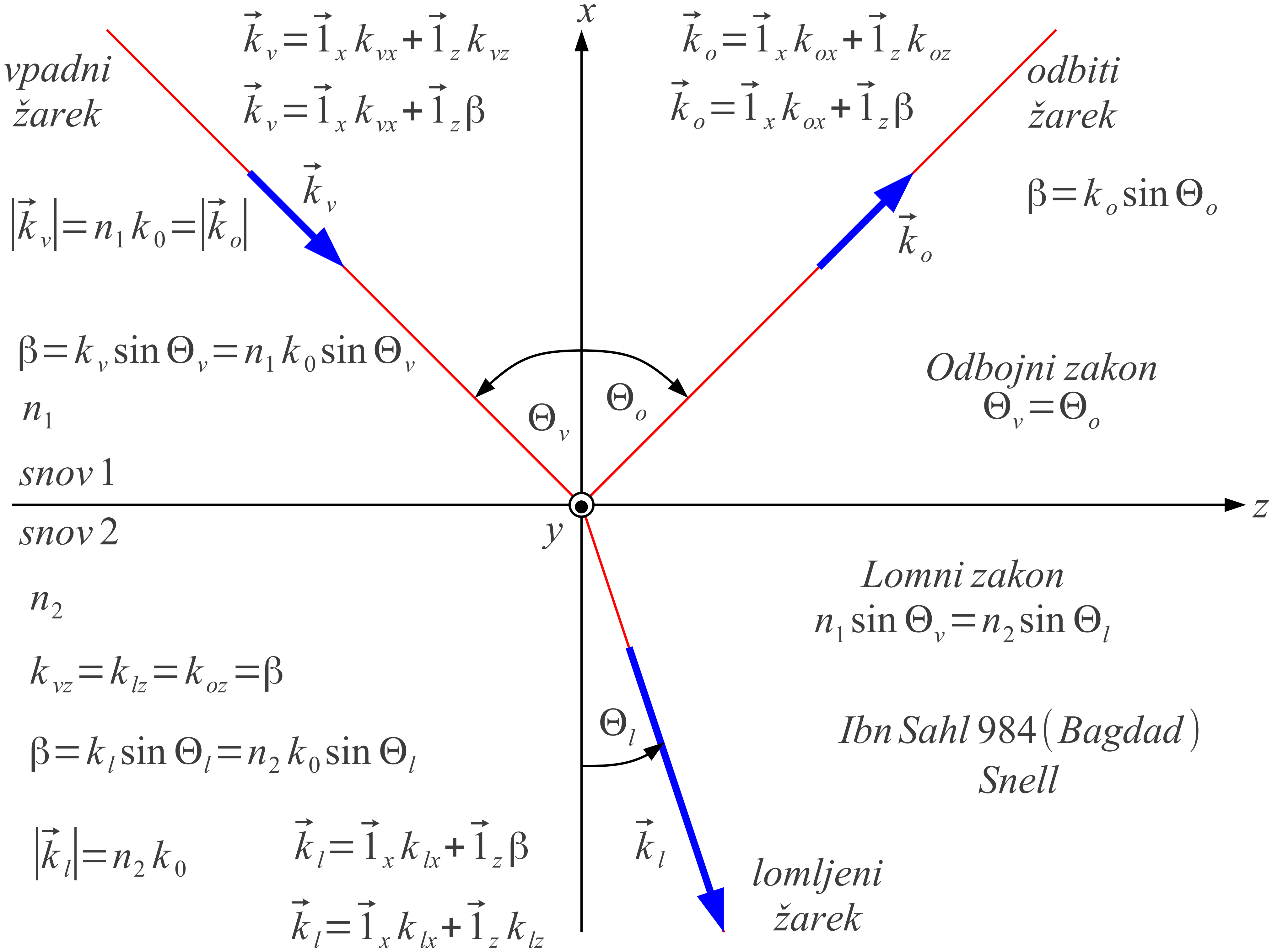
Neferomagnetiki $\mu_r = 1$ ➔ *Poenostavitve???*

$$v = \frac{1}{\sqrt{\mu \epsilon}} = \frac{c_0}{\sqrt{\epsilon_r}} = \frac{c_0}{n}$$

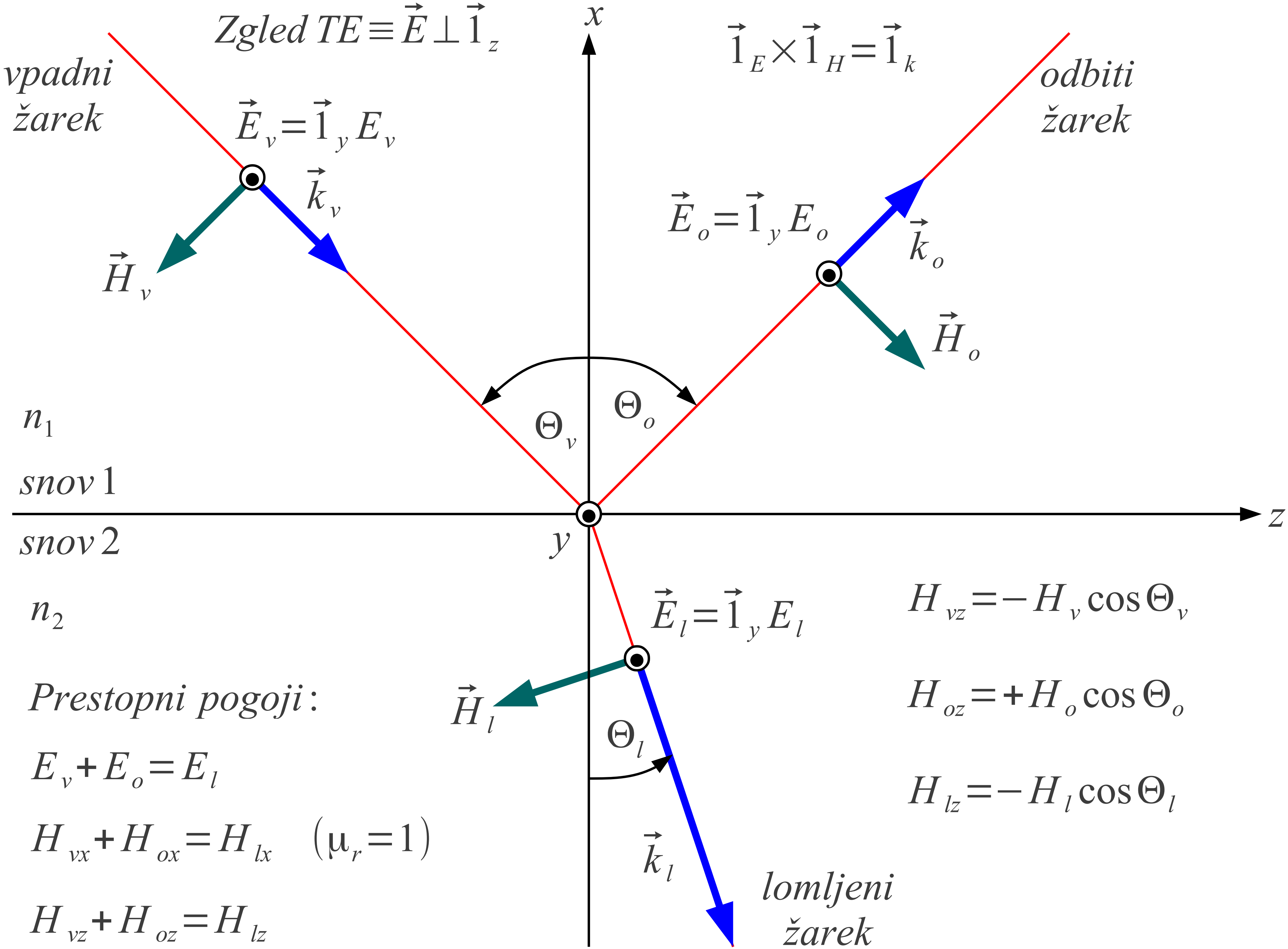
$$n = \sqrt{\epsilon_r}$$

$$Z = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\epsilon}} = \frac{Z_0}{\sqrt{\epsilon_r}}$$

$$Z = \frac{Z_0}{\sqrt{\epsilon_r}} = \frac{Z_0}{n} \quad (\textit{kdaj velja???})$$



x
$\vec{k}_v = \vec{1}_x k_{vx} + \vec{1}_z k_{vz}$
$\vec{k}_v = \vec{1}_x k_{vx} + \vec{1}_z \beta$
$\vec{k}_o = \vec{1}_x k_{ox} + \vec{1}_z k_{oz}$
$\vec{k}_o = \vec{1}_x k_{ox} + \vec{1}_z \beta$
vpadni žarek
odbiti žarek
$\vec{k}_v$
$|\vec{k}_v| = n_1 k_0 = |\vec{k}_o|$
$\beta = k_o \sin\Theta_o$
$\vec{k}_o$
$\beta = k_v \sin\Theta_v = n_1 k_0 \sin\Theta_v$
Odbojni zakon
$\Theta_v = \Theta_o$
Θ_v
Θ_o
n_1
snov 1
snov 2
y
z
Lomni zakon
$n_1 \sin\Theta_v = n_2 \sin\Theta_l$
n_2
$k_{vz} = k_{lz} = k_{oz} = \beta$
Θ_l
Ibn Sahl 984 (Bagdad)
Snell
$\beta = k_l \sin\Theta_l = n_2 k_0 \sin\Theta_l$
$|\vec{k}_l| = n_2 k_0$
$\vec{k}_l = \vec{1}_x k_{lx} + \vec{1}_z \beta$
$\vec{k}_l$
lomljeni žarek
$\vec{k}_l = \vec{1}_x k_{lx} + \vec{1}_z k_{lz}$



$Zgled\ TE \equiv \vec{E} \perp \vec{1}_z$
x
$\vec{1}_E \times \vec{1}_H = \vec{1}_k$
vpadni žarek
odbiti žarek
$\vec{E}_v = \vec{1}_y E_v$
$\vec{k}_v$
$\vec{H}_v$
$\vec{E}_o = \vec{1}_y E_o$
$\vec{k}_o$
$\vec{H}_o$
Θ_v
Θ_o
n_1
snov 1
snov 2
z
y
n_2
$\vec{E}_l = \vec{1}_y E_l$
$H_{vz} = -H_v \cos\Theta_v$
$\vec{H}_l$
Θ_l
$H_{oz} = +H_o \cos\Theta_o$
$H_{lz} = -H_l \cos\Theta_l$
$\vec{k}_l$
lomljeni žarek
Prestopni pogoji:
$E_v + E_o = E_l$
$H_{vx} + H_{ox} = H_{lx} \quad (\mu_r = 1)$
$H_{vz} + H_{oz} = H_{lz}$

$$E_v + E_o = E_l$$

$$-H_v \cos\Theta_v + H_o \cos\Theta_o = -H_l \cos\Theta_l$$

$$H_i = \frac{E_i}{Z_j}$$

$$\frac{-E_v}{Z_1}\cos\Theta_v + \frac{E_o}{Z_1}\cos\Theta_o = \frac{-E_l}{Z_2}\cos\Theta_l$$

$$\frac{E_v}{Z_1}\cos\Theta_v - \frac{E_o}{Z_1}\cos\Theta_o = \frac{E_v + E_o}{Z_2}\cos\Theta_l$$

$$\frac{1}{Z_1}\cos\Theta_v - \frac{1}{Z_2}\cos\Theta_l = \Gamma\left(\frac{1}{Z_1}\cos\Theta_v + \frac{1}{Z_2}\cos\Theta_l\right)$$

$$\Gamma_{TE} = \frac{\frac{1}{Z_1}\cos\Theta_v - \frac{1}{Z_2}\cos\Theta_l}{\frac{1}{Z_1}\cos\Theta_v + \frac{1}{Z_2}\cos\Theta_l}$$

$$\Gamma_{TE} = \frac{E_o}{E_v}$$

$$\frac{1}{Z_1}\cos\Theta_v - \frac{\Gamma}{Z_1}\cos\Theta_o = \frac{1+\Gamma}{Z_2}\cos\Theta_l$$

$$\Theta_v = \Theta_o = \Theta \qquad \sin\Theta_l = \frac{n_1}{n_2}\sin\Theta$$

$$\cos\Theta_l = \sqrt{1 - \sin^2\Theta_l}$$

$$\cos\Theta_l = \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}$$

$$\Gamma_{TE} = \frac{\frac{1}{Z_1}\cos\Theta - \frac{1}{Z_2}\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}{\frac{1}{Z_1}\cos\Theta + \frac{1}{Z_2}\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}$$

Neferomagnetiki $\mu_r = 1 \rightarrow$ *Poenostavitve???*

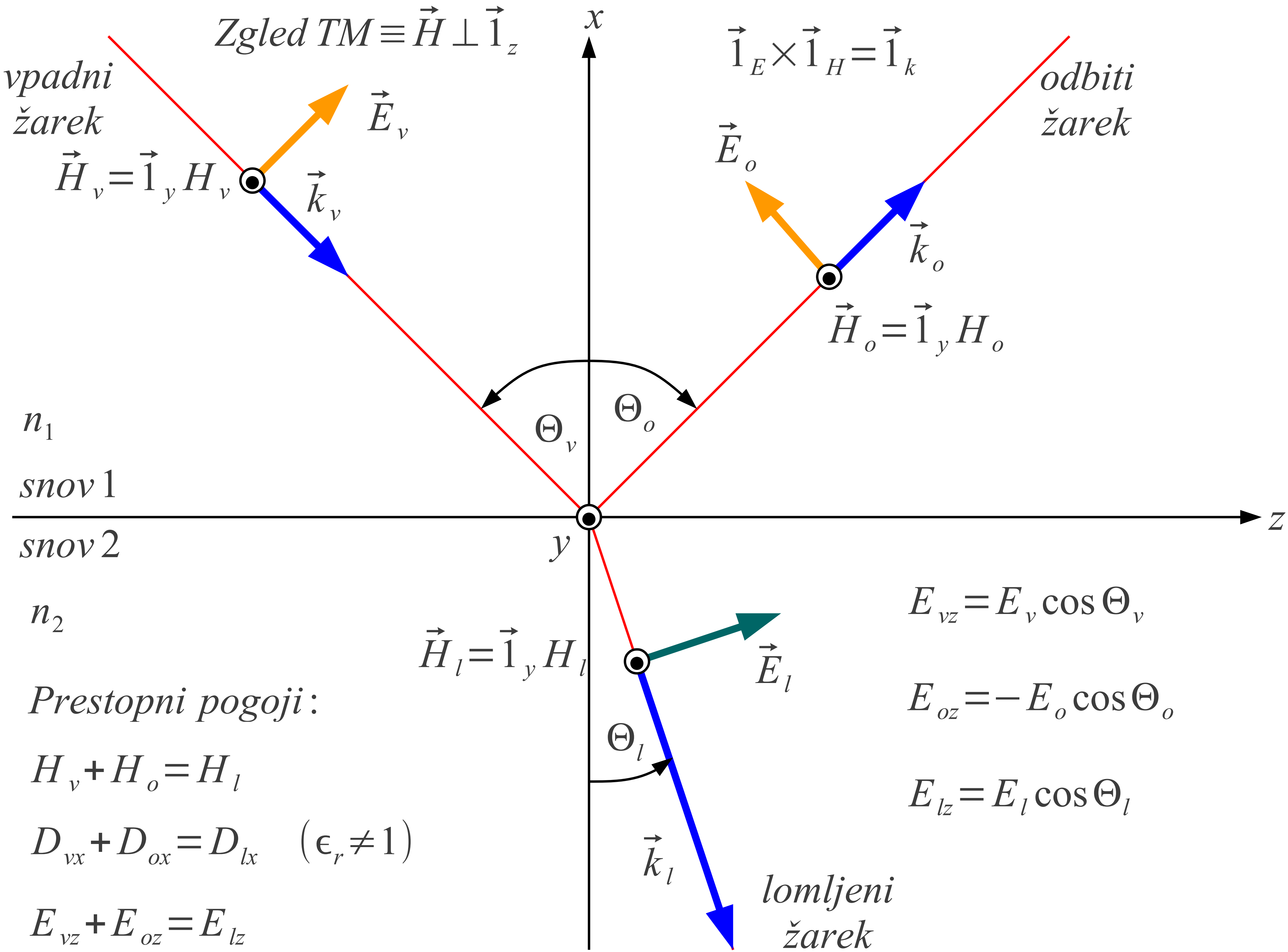
$$Z = \frac{Z_0}{\sqrt{\epsilon_r}} = \frac{Z_0}{n} \quad (kdaj\ velja???)$$

$$\Gamma_{TE} = \frac{n_1 \cos\Theta - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}{n_1 \cos\Theta + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}$$

$$\Gamma_{TE} = \frac{\cos\Theta - \frac{n_2}{n_1} \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}{\cos\Theta + \frac{n_2}{n_1} \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\Theta}}$$

$$\Gamma_{TE} = \frac{\cos\Theta - \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2\Theta}}{\cos\Theta + \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2\Theta}}$$

Fresnelova odbojnost za TE



$Zgled\ TM \equiv \vec{H} \perp \vec{1}_z$
x
$\vec{1}_E \times \vec{1}_H = \vec{1}_k$
vpadni žarek
$\vec{E}_v$
odbiti žarek
$\vec{E}_o$
$\vec{H}_v = \vec{1}_y H_v$
$\vec{k}_v$
$\vec{k}_o$
$\vec{H}_o = \vec{1}_y H_o$
Θ_v
Θ_o
n_1
snov 1
snov 2
z
y
n_2
$E_{vz} = E_v \cos\Theta_v$
$\vec{H}_l = \vec{1}_y H_l$
$\vec{E}_l$
$E_{oz} = -E_o \cos\Theta_o$
Prestopni pogoji:
Θ_l
$H_v + H_o = H_l$
$E_{lz} = E_l \cos\Theta_l$
$D_{vx} + D_{ox} = D_{lx} \quad (\epsilon_r \neq 1)$
$\vec{k}_l$
lomljeni žarek
$E_{vz} + E_{oz} = E_{lz}$

$$\Gamma_{TM}=\frac{Z_1\cos\Theta_v-Z_2\cos\Theta_l}{Z_1\cos\Theta_v+Z_2\cos\Theta_l}$$

$$E_i=H_i Z_j$$

$$\Gamma_{TM}=\frac{Z_1\cos\Theta-Z_2\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\sin^2\Theta}}{Z_1\cos\Theta+Z_2\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\sin^2\Theta}}$$

Neferomagnetiki $\mu_r=1$ → *Poenostavitve ???*

$$\Gamma_{TM}=\frac{n_2\cos\Theta-n_1\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\sin^2\Theta}}{n_2\cos\Theta+n_1\sqrt{1-\left(\frac{n_1}{n_2}\right)^2\sin^2\Theta}}$$

$$\Gamma_{TM}=\frac{\left(\frac{n_2}{n_1}\right)^2\cos\Theta-\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}{\left(\frac{n_2}{n_1}\right)^2\cos\Theta+\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}$$

Fresnelova odbojnost za TM

$$\Gamma_{TE}=\frac{\cos\Theta-\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}{\cos\Theta+\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}$$

$$\Gamma_{TM}=\frac{\left(\frac{n_2}{n_1}\right)^2\cos\Theta-\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}{\left(\frac{n_2}{n_1}\right)^2\cos\Theta+\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta}}$$

$vakuum \quad n=1$

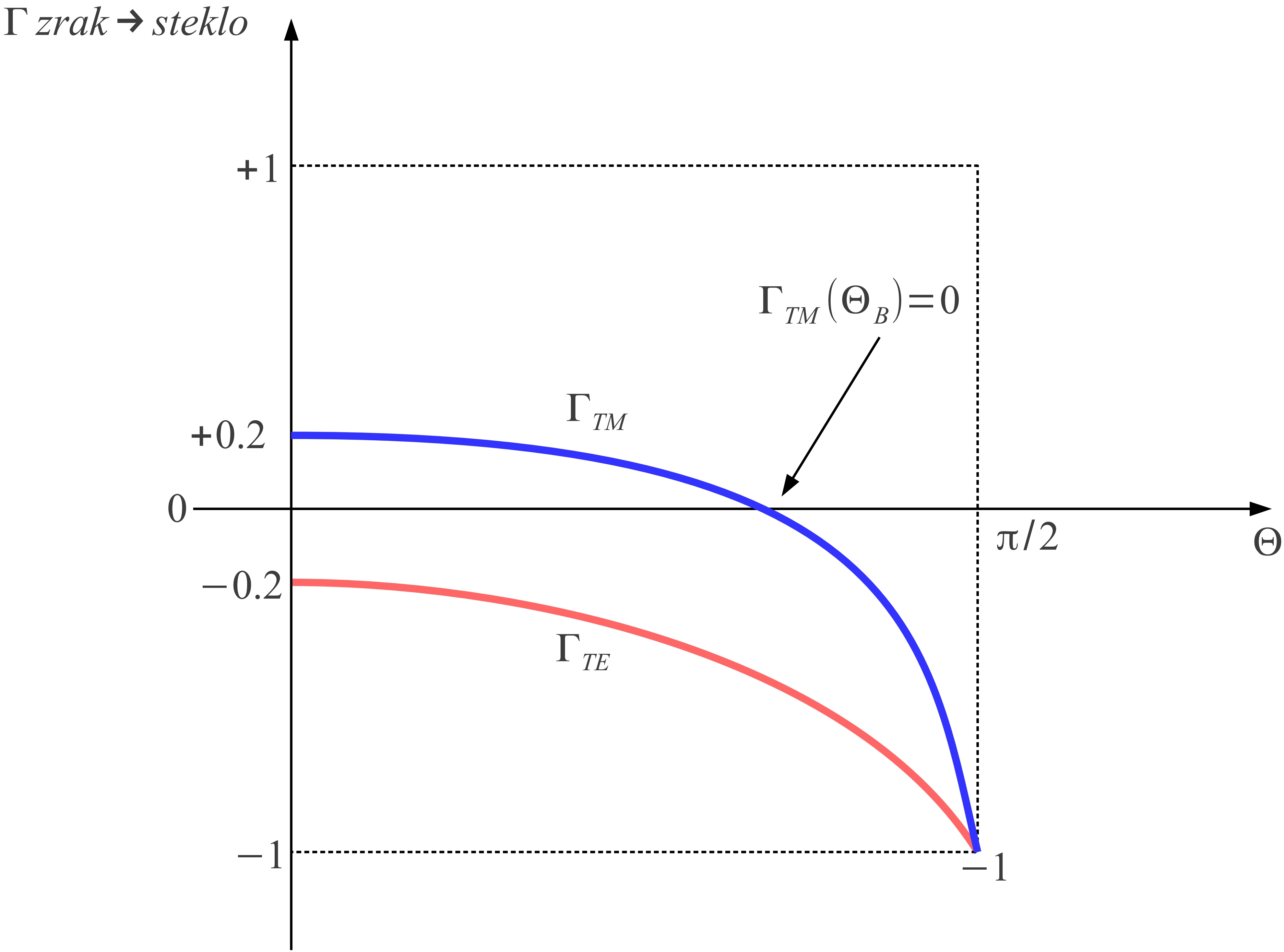
$zrak\ n\approx 1.0003\ radio \quad n\approx 1.00015\ svetloba$

$svetloba\ steklo \quad n\approx 1.5$

$svetloba\ SiO_2 \quad n\approx 1.463$

$svetloba\ kristalno\ steklo \quad n\approx 1.8$

$svetloba\ polprevodniki\ Si\ ,\ InGaAsP \quad n\approx 3.5\ldots 4$



Γ zrak → steklo
+1
+0.2
0
−0.2
−1
Γ_{TM}
Γ_{TE}
$\Gamma_{TM}(\Theta_B)=0$
π/2
−1
Θ

$$\Gamma_{TM}=\frac{\left(\frac{n_2}{n_1}\right)^2\cos\Theta_B-\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta_B}}{\left(\frac{n_2}{n_1}\right)^2\cos\Theta_B+\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta_B}}=0$$

$$\left(\frac{n_2}{n_1}\right)^2\cos\Theta_B-\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta_B}=0$$

$$\left(\frac{n_2}{n_1}\right)^2\cos\Theta_B=\sqrt{\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta_B}$$

$$\left(\frac{n_2}{n_1}\right)^4\cos^2\Theta_B=\left(\frac{n_2}{n_1}\right)^2-\sin^2\Theta_B$$

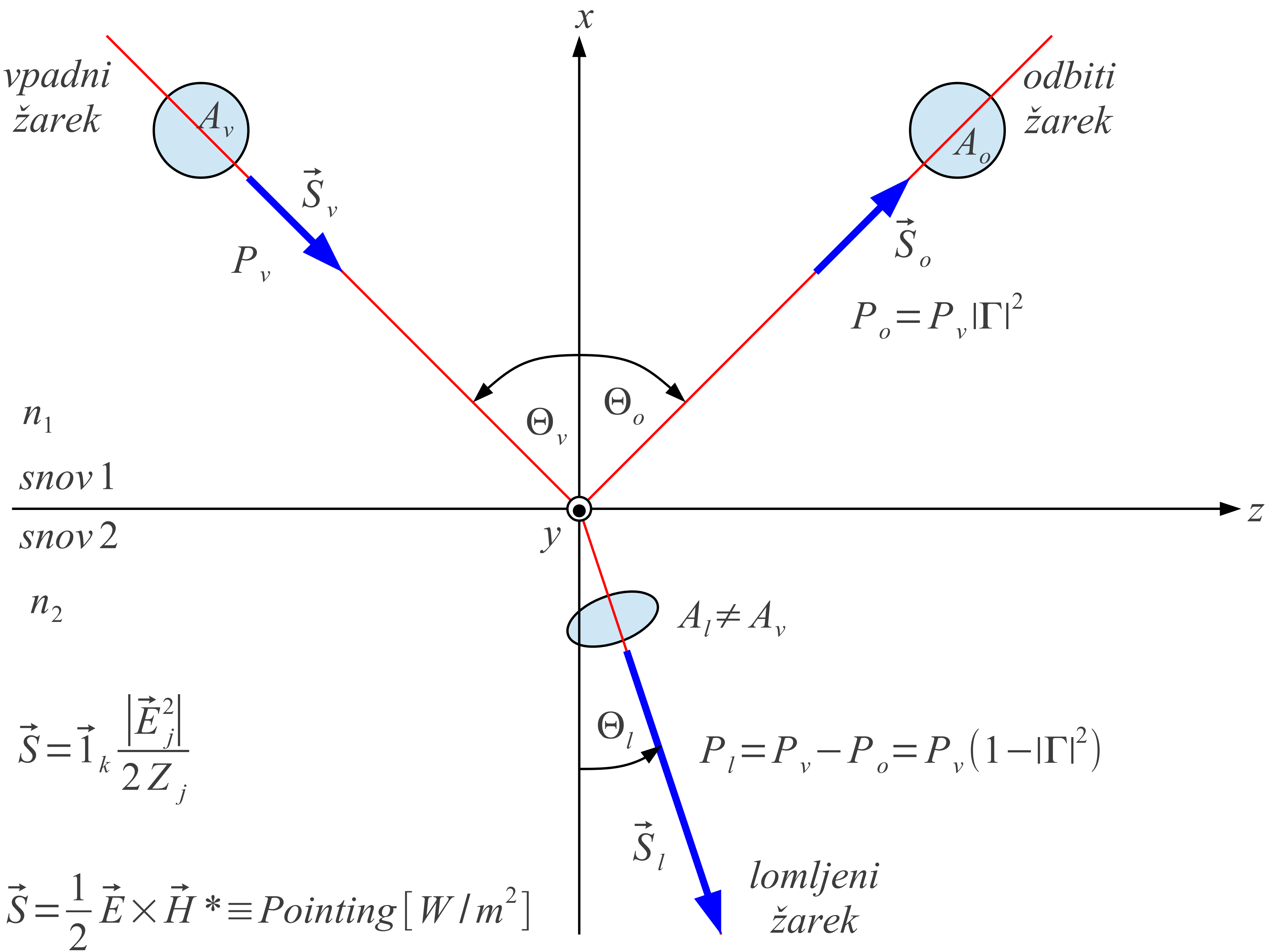
$$\left(\frac{n_2}{n_1}\right)^2=\alpha$$

$$\cos^2\Theta_B=\frac{1}{1+\alpha}$$

$$\sin^2\Theta_B=\frac{\alpha}{1+\alpha}$$

$$\tan^2\Theta_B=\alpha$$

$$\Theta_B=\arctan\frac{n_2}{n_1}$$


x
vpadni
žarek
A_v
odbiti
žarek
A_o
$\vec{S}_v$
P_v
$\vec{S}_o$
$P_o = P_v |\Gamma|^2$
n_1
Θ_v
Θ_o
snov 1
snov 2
z
y
n_2
$A_l \neq A_v$
$\vec{S} = \vec{1}_k \frac{|\vec{E}_j^2|}{2 Z_j}$
Θ_l
$P_l = P_v - P_o = P_v (1 - |\Gamma|^2)$
$\vec{S}_l$
lomljeni
žarek
$\vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^* \equiv Pointing\, [W/m^2]$

Γ *zrak* → *steklo*

$P_l = P_v - P_o = P_v\left(1 - |\Gamma|^2\right) \approx 0.96$

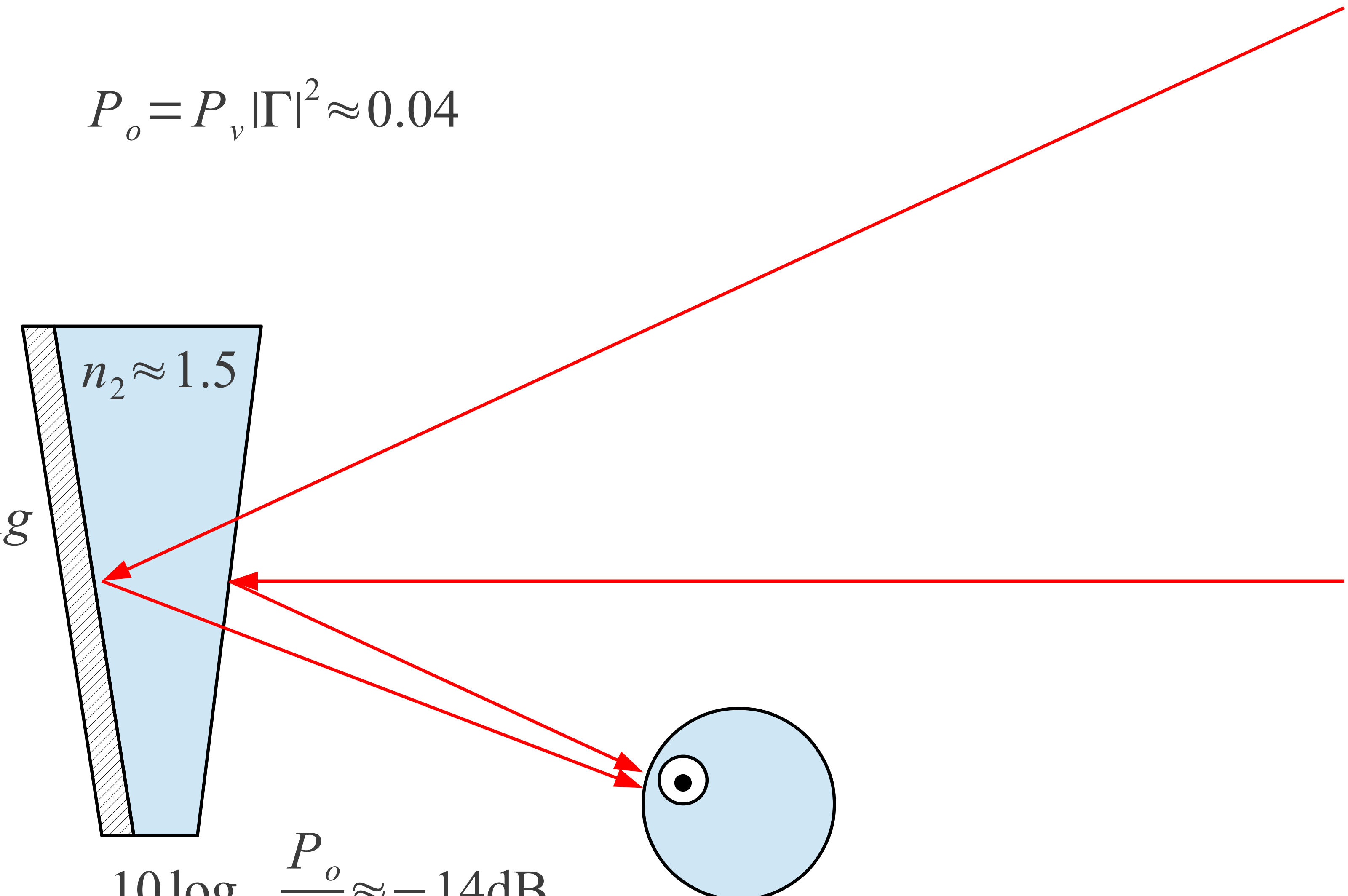
$|\Gamma| \approx 0.2$

$P_o = P_v |\Gamma|^2 \approx 0.04$

Kovina Ag

$|\Gamma| \approx 0.8$

-1dB



$10\log_{10}\dfrac{P_o}{P_v} \approx -14\text{dB}$