

Interference světla

Skládání světla

Interference světla – dvousvazková
vícesvazková

Podle principu superpozice

Dvojsvazková interference

$$\vec{E}(\vec{r}, t) = \vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t)$$

$$I(\vec{r}) = \vec{E}_0(\vec{r}) \cdot \vec{E}_0^*(\vec{r})$$

$$\vec{E}_j = (\vec{r}, t) = \vec{E}_{0j} \exp[-i(\omega t)] \quad \text{Rovinné vlny na stejné frekvenci}$$

$$\vec{E}_{01}(\vec{r}) = \vec{E}_{01} \exp[i(-\varphi_1 + \vec{k}_1 \cdot \vec{r})] = \vec{E}_{01} \exp[i\Phi_1(\vec{r})]$$

$$\vec{E}_{02}(\vec{r}) = \vec{E}_{02} \exp[i(-\varphi_2 + \vec{k}_2 \cdot \vec{r})] = \vec{E}_{02} \exp[i\Phi_2(\vec{r})]$$

$$I(\vec{r}) = I_1 + I_2 + \vec{E}_{01} \cdot \vec{E}_{02}^* + \vec{E}_{02} \cdot \vec{E}_{01}^* = I_1 + I_2 + 2 \operatorname{Re}\{ \vec{E}_{01} \cdot \vec{E}_{02}^* \}$$

$$I(\vec{r}) = I_1 + I_2 + 2 \vec{E}_{01} \cdot \vec{E}_{02} \cos(\Phi_2 - \Phi_1)$$

$$I(\vec{r}) = I_1 + I_2 + 2 \vec{E}_{01} \cdot \vec{E}_{02} \cos(\Phi_2 - \Phi_1) \quad \delta = \Phi_2 - \Phi_1$$

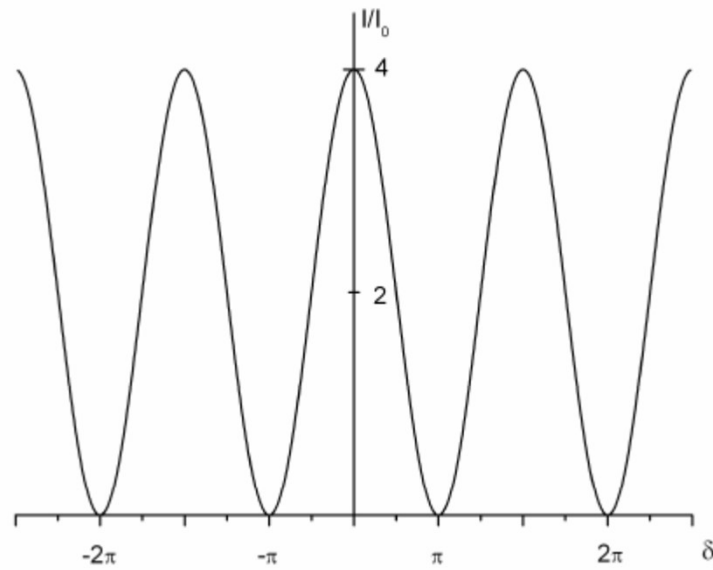
a) případ vlnové vektory leží v rovině y, z , $\vec{E}_{01,02} = (E_{01}, 0, 0), I_1 = I_2$

$$I = 2 I_1 (1 + \cos \delta) = 4 I_1 \cos^2 \left(\frac{\delta}{2} \right)$$

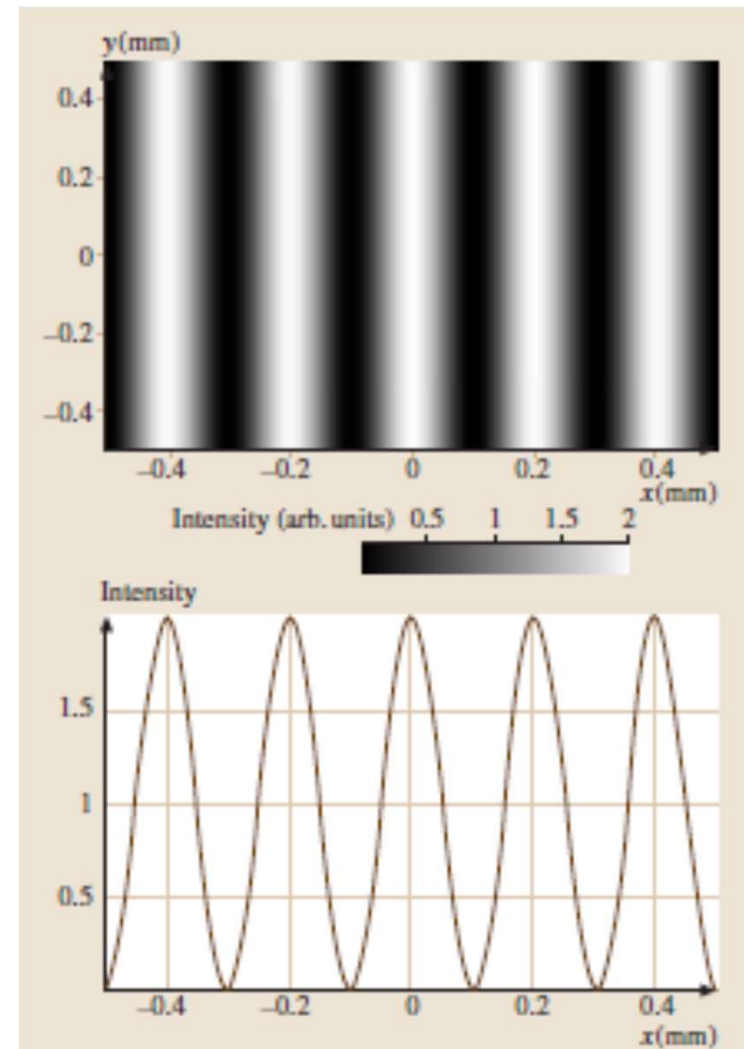
Fázový rozdíl δ může být prostorově závislý !

Interferenční obrazec

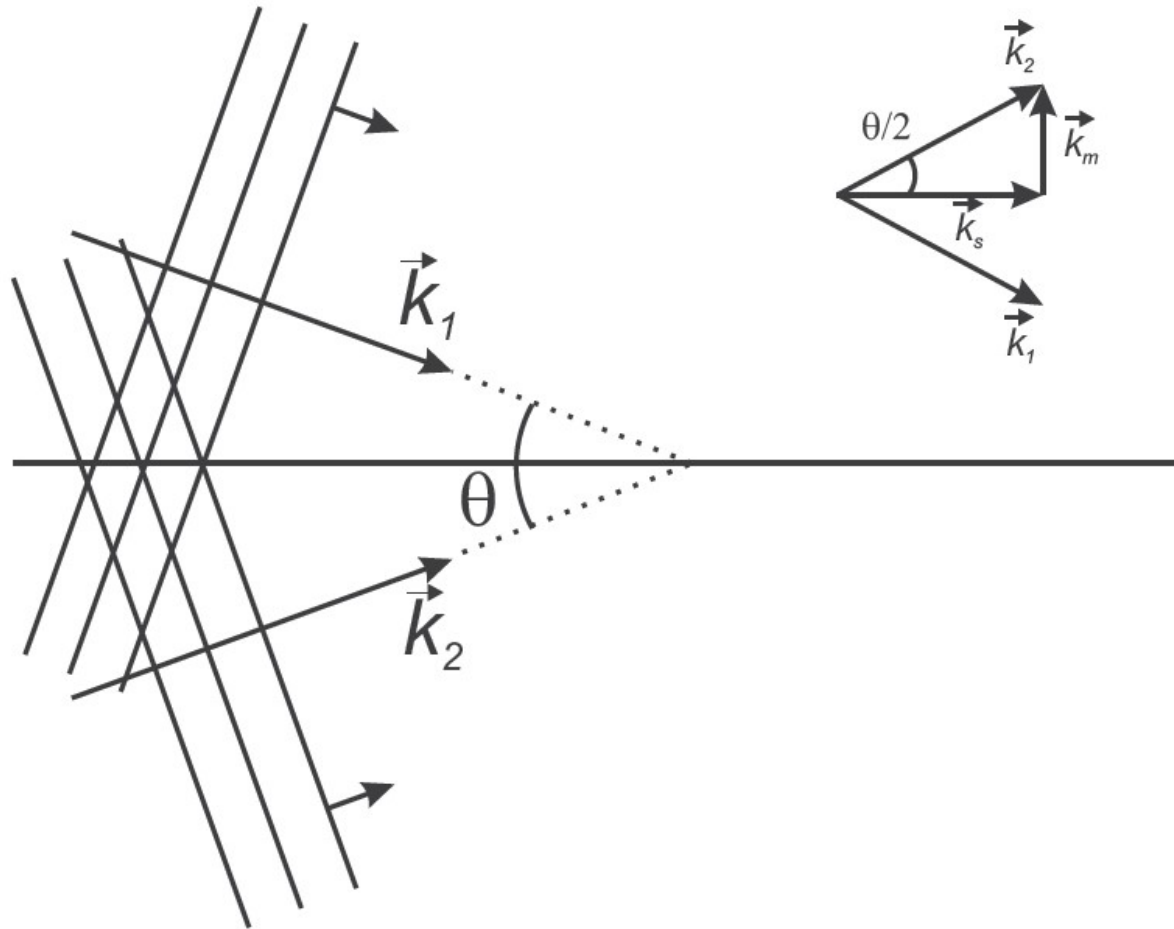
Dvousvazková interference



$$I = 2I_1 [1 + \cos \delta] = 4I_1 \cos^2 \left(\frac{\delta}{2} \right)$$



Prostorová závislost výsledného interferenčního pole (za podmínek výše)



$$\vec{k}_m = \frac{\vec{k}_2 - \vec{k}_1}{2}$$

$$k_m = k_1 \sin\left(\frac{\theta}{2}\right)$$

$$\vec{k}_s = \frac{\vec{k}_2 + \vec{k}_1}{2}$$

$$k_s = k_1 \cos\left(\frac{\theta}{2}\right)$$

$$\varphi_m = \frac{\varphi_2 - \varphi_1}{\gamma}$$

$$\varphi_s = \frac{\varphi_2 + \varphi_1}{2}$$

$$\tilde{E}(\vec{r}, t) = 2 E_0 \cos(\vec{k}_m \cdot \vec{r} + \varphi_m) \exp[-i(\omega t - \vec{k}_s \cdot \vec{r} + \varphi_s)]$$

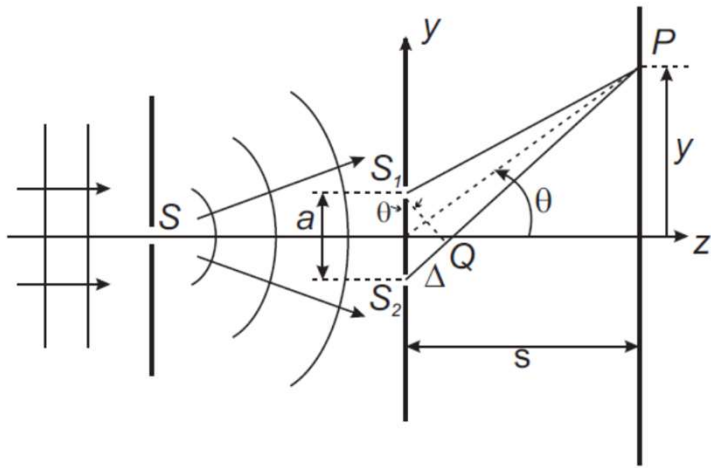
$$\Lambda = \frac{1}{2} \frac{2\pi}{k_m} = \frac{\lambda}{2 \sin\left(\frac{\theta}{2}\right)}$$

$$I(\vec{r}) = 4 I_0 \cos^2(\vec{k}_m \cdot \vec{r} + \varphi_m)$$

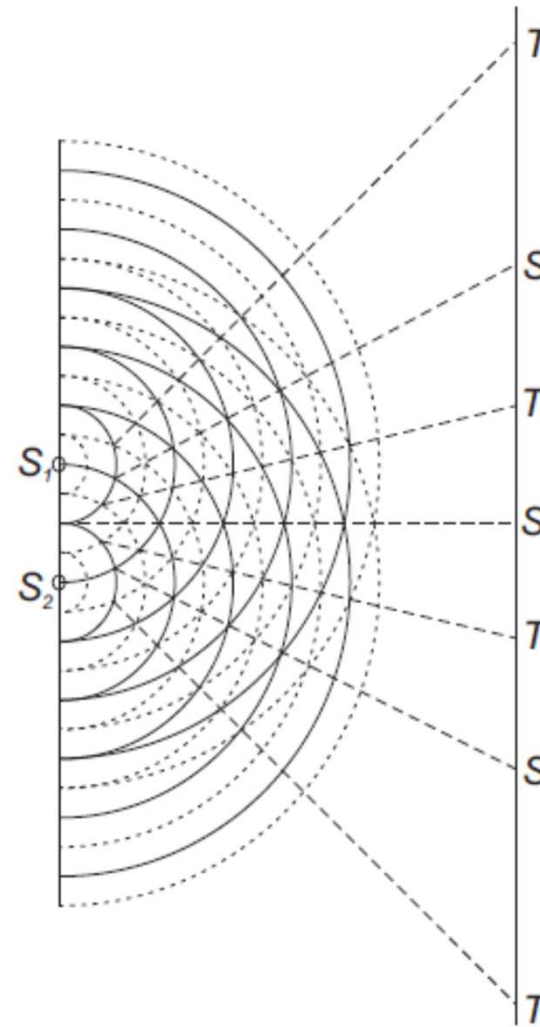
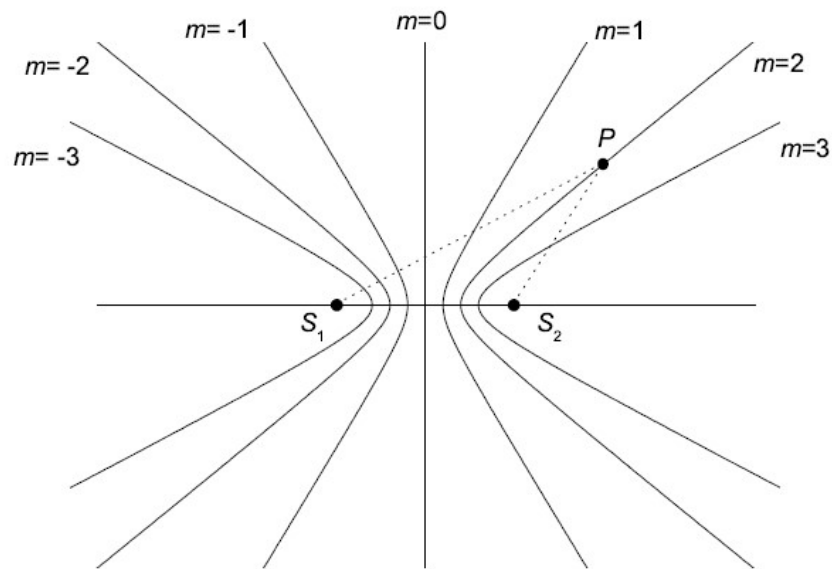
Interference se často vyšetřuje ve skalární aproximaci

Přesné pro lineárně polarizované světlo, dosti přesné obecně

Young's experiment



Thomas Young, 1802



$$|S_1P - S_2P| = m\lambda$$

Součet vln → součet komplexních amplitud

Grafická metoda řešení interference

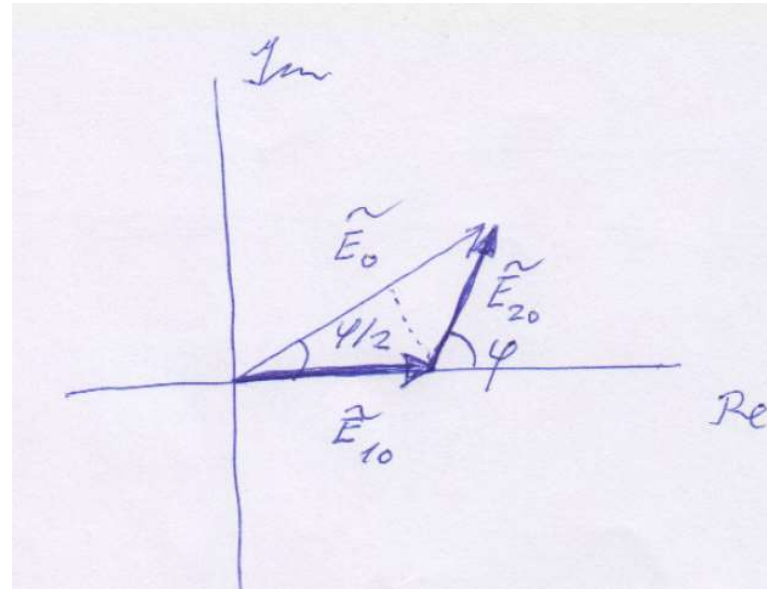
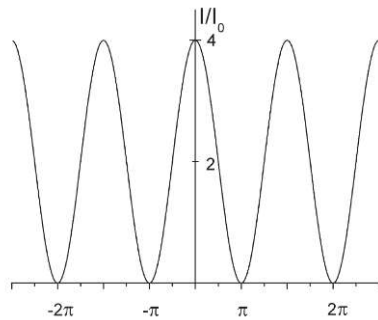
$$\vec{E}(\vec{r}, t) = \vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t)$$

skalárně

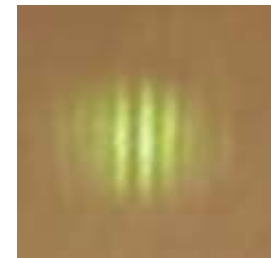
$$\tilde{E}_0 = \sum_p \tilde{E}_{0p}$$

$$\begin{aligned} \tilde{E}_{10} &= E_{10} \\ \tilde{E}_{20} &= E_{20} e^{i\varphi} \end{aligned}$$

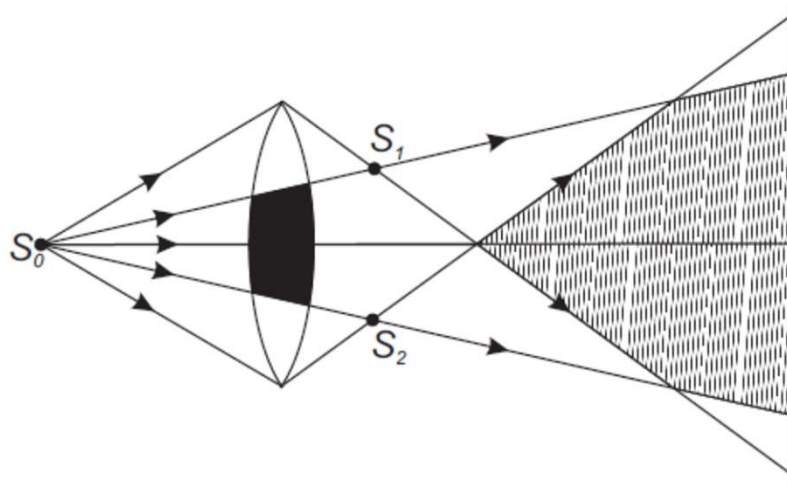
$$|\tilde{E}_0| = 2 E_{10} \cos \frac{\varphi}{2}$$
$$I \propto |\tilde{E}_0|^2 = 4 I_1 \cos^2 \frac{\varphi}{2}$$



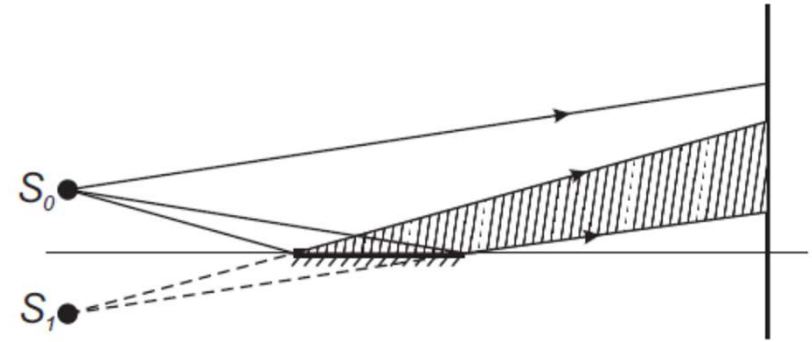
YOUNG. EXP.
 $\varphi = k \Delta l$



Jiné tradiční experimenty pro sledování dvojsvazkové interference

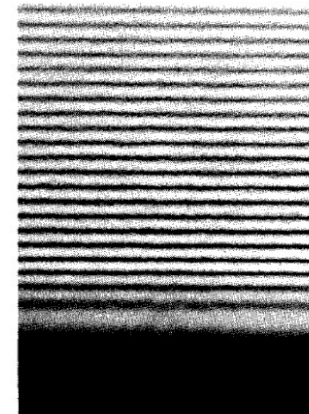


Obr. 5.6 Billetova dvojčochka

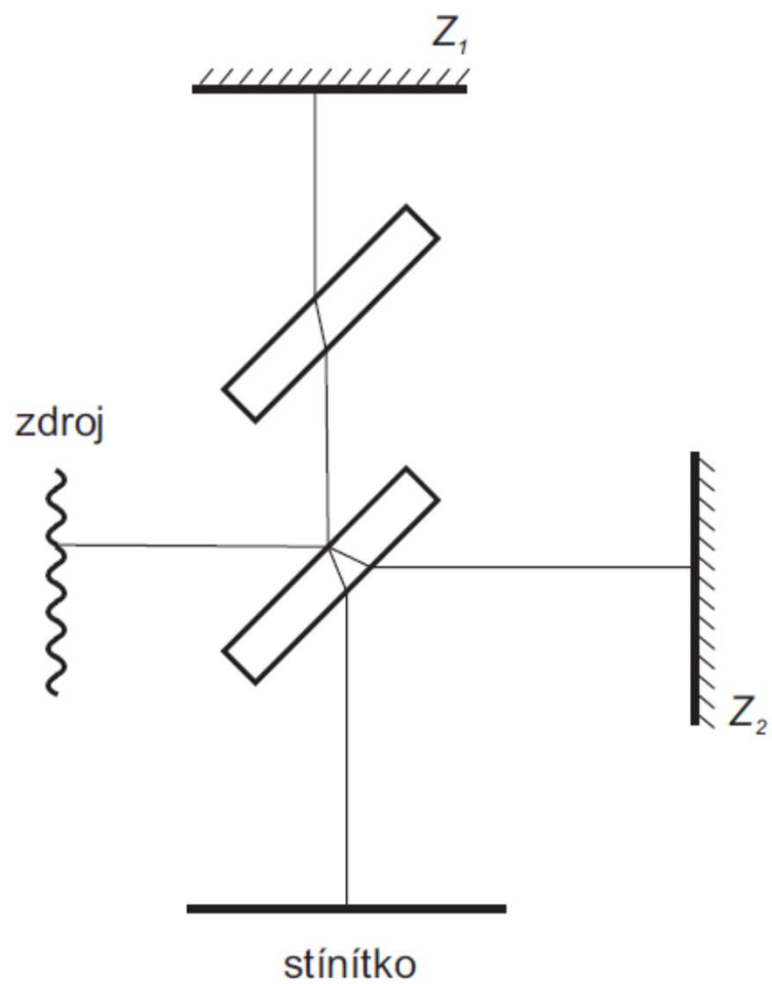


Obr. 5.7 Lloydovo zrcadlo

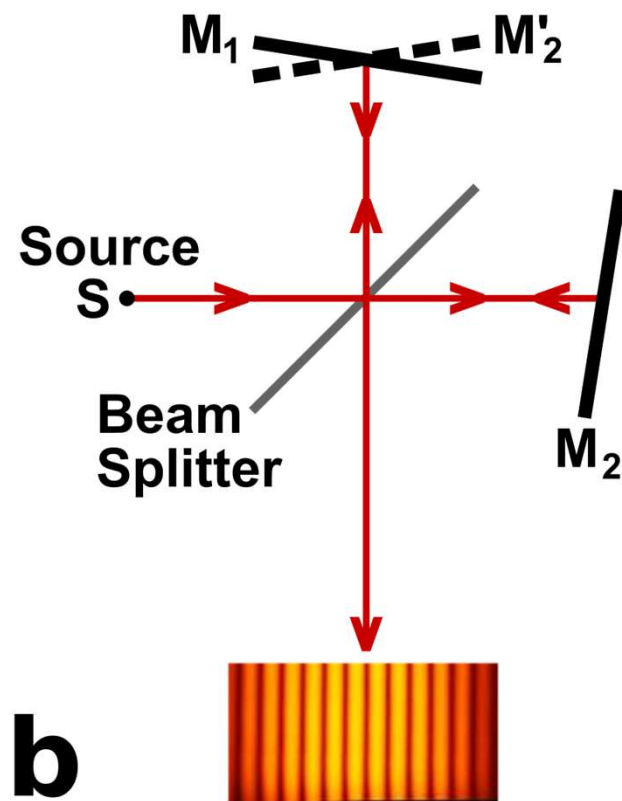
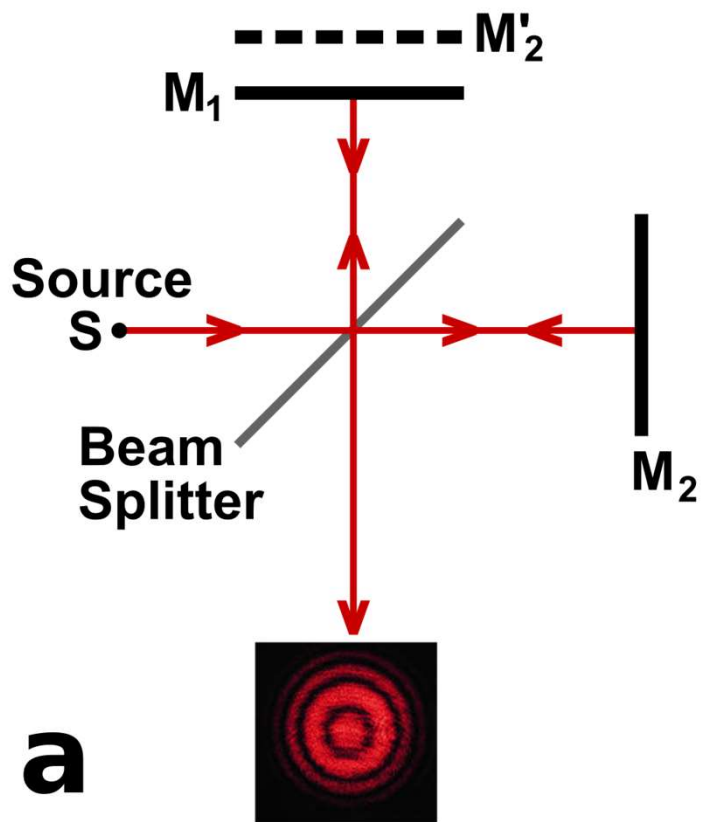
Dělení vlnoplochy

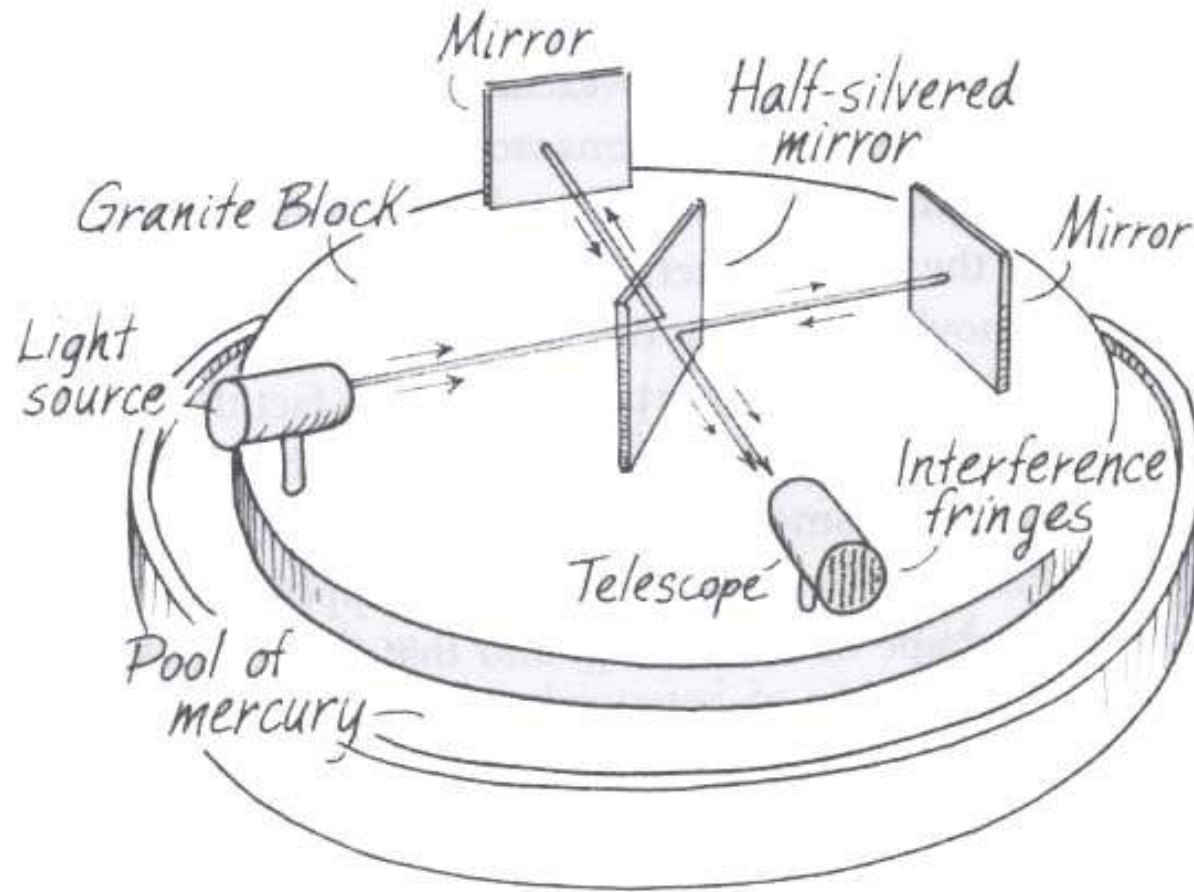


Dělení amplitudy

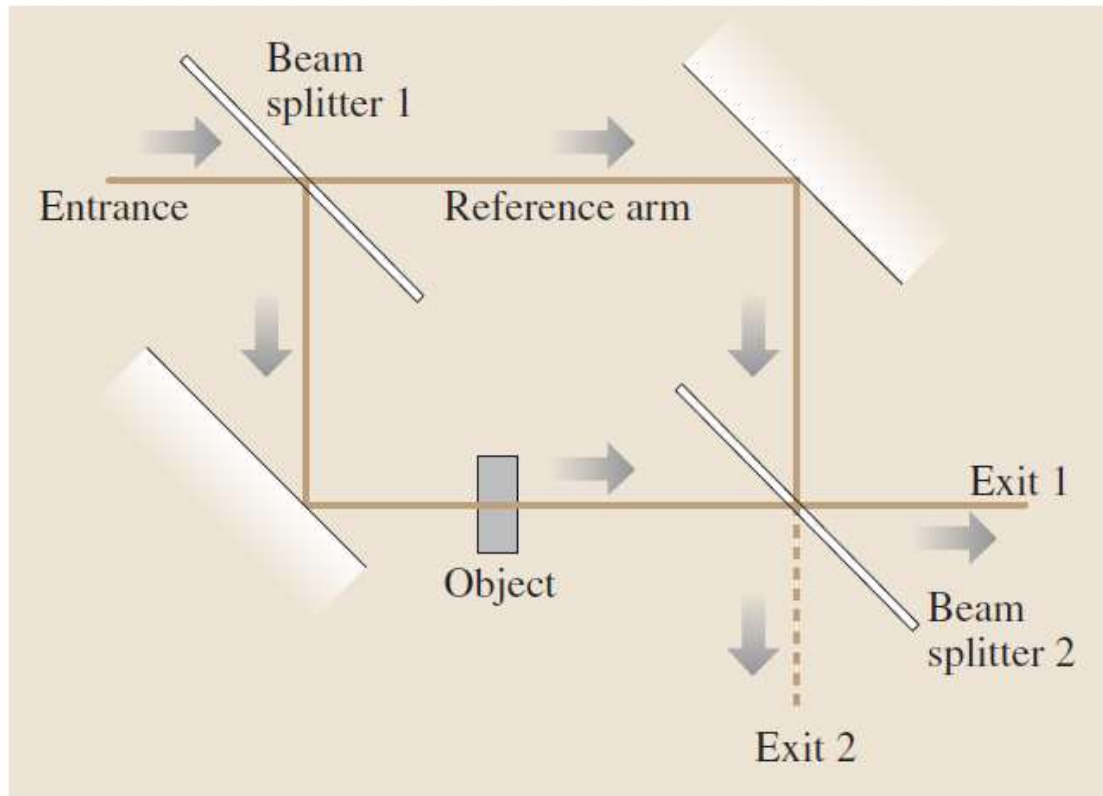


Obr. 5.8 Michelsonův interferometr



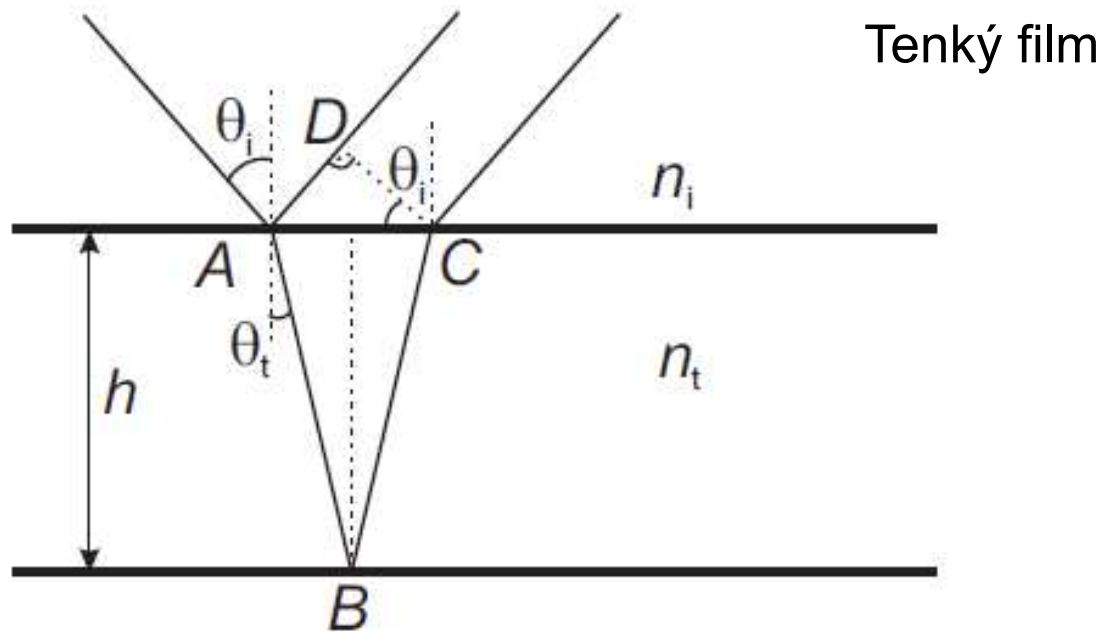


Michelson-Morley's experiment (1887)



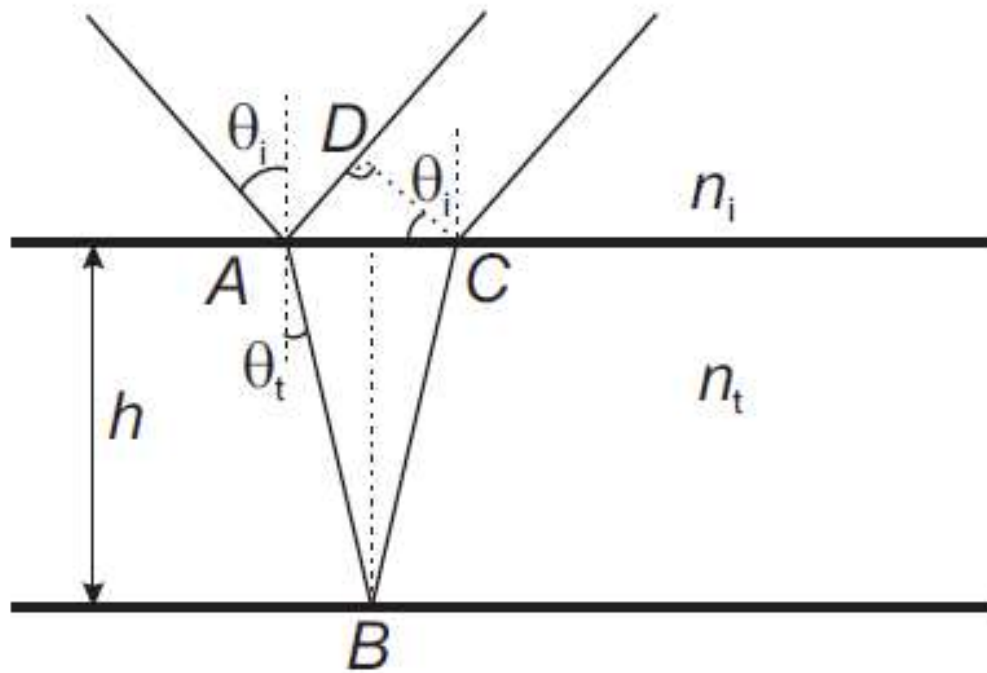
Mach-Zenderův interferometr

Interference na dielektrických vrstvách



Změna fáze při šíření $\delta = k z = k_0 n z$ Zavedeme optickou dráhu $z_{OD} = z n$

$$\delta = z_{OD} k_0$$



$$AB = BC = \frac{h}{\cos \theta_t},$$

$$AD = AC \sin \theta_i,$$

$$AC = 2h \operatorname{tg} \theta_t.$$

Rozdíl optických drah mezi paprskem 1 a 2

$$\Delta_{OD} = n_t (AB + BC) - n_i AD$$

$$\Delta_{OD} = 2h \left[n_t \frac{1}{\cos \theta_t} - n_i \operatorname{tg} \theta_t \sin \theta_i \right]$$

$$\delta = k_0 \Delta_{OD} = \frac{4\pi}{\lambda_0} h n_t \cos \theta_t$$

K fázovým rozdílům nutno přidat možný
Posun fáze při odrazu na rozhraní (Fresnel)

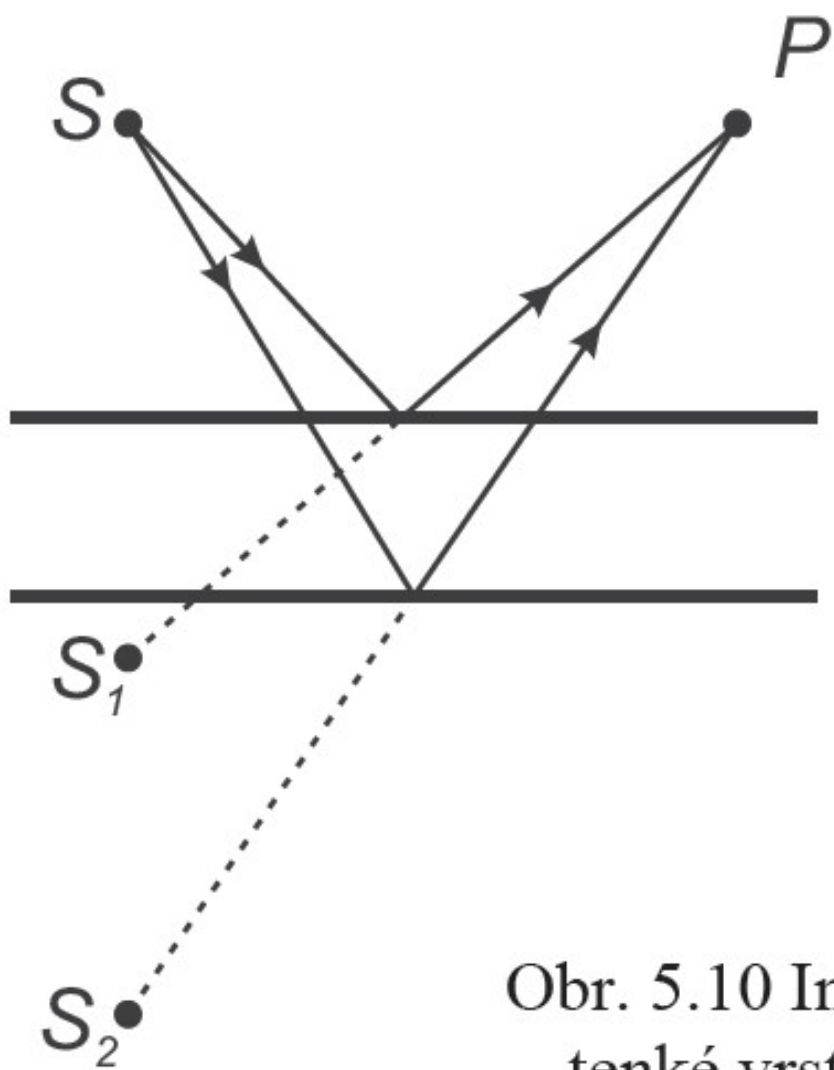
$$\delta_{odr} = 0 \quad \left| \delta_{odr} \right| = \pi$$

$$\Delta_{OD} = 2h n_t \cos \theta_t$$

Interference:

$$\text{maxima} \quad \delta + \delta_{odr} = 2p\pi$$

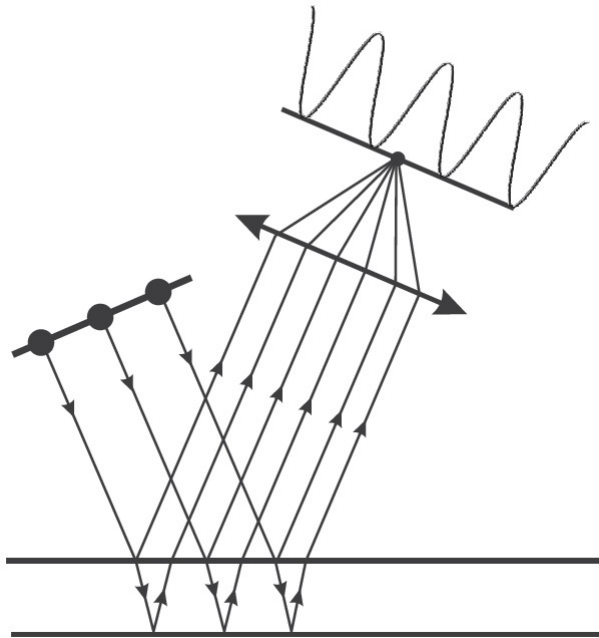
$$\text{minima} \quad \delta + \delta_{odr} = (2p+1)\pi$$



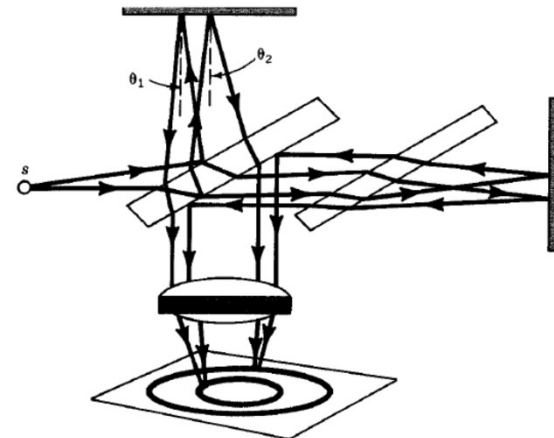
Obr. 5.10 Interference na planparalelní tenké vrstvě – bodový zdroj světla

Proužky stejného sklonu

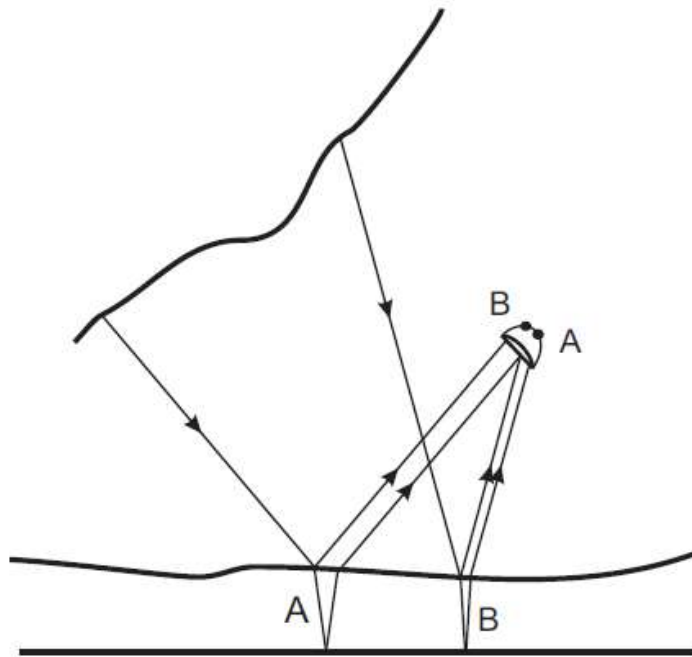
Haidingerovy kroužky.



V Michelsonově interferometru

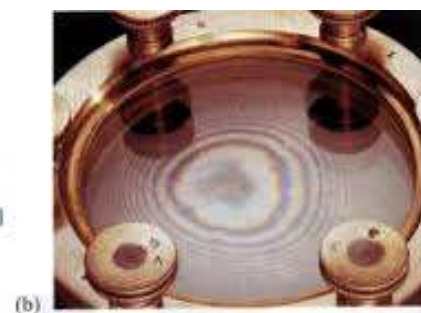
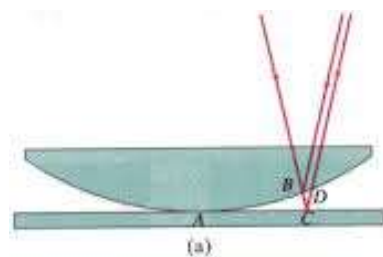
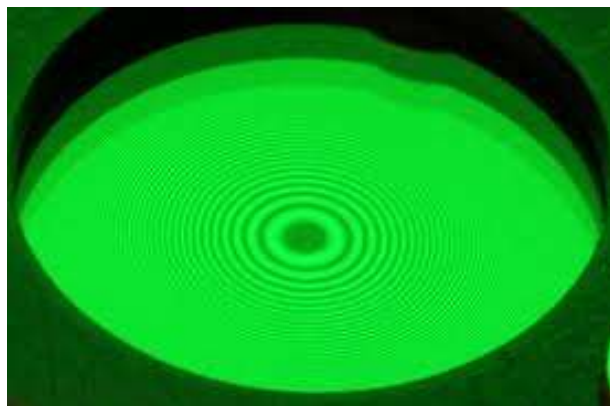
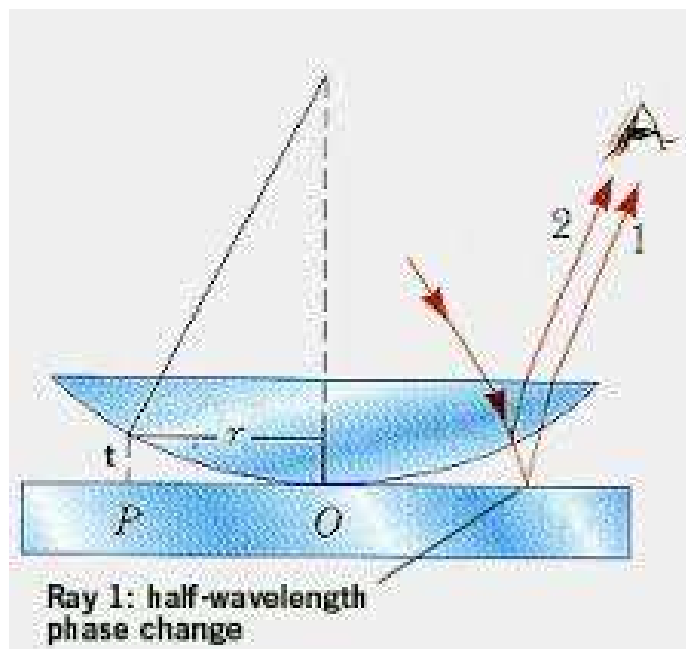


Proužky stejné tloušťky *Fizeauovy proužky.*



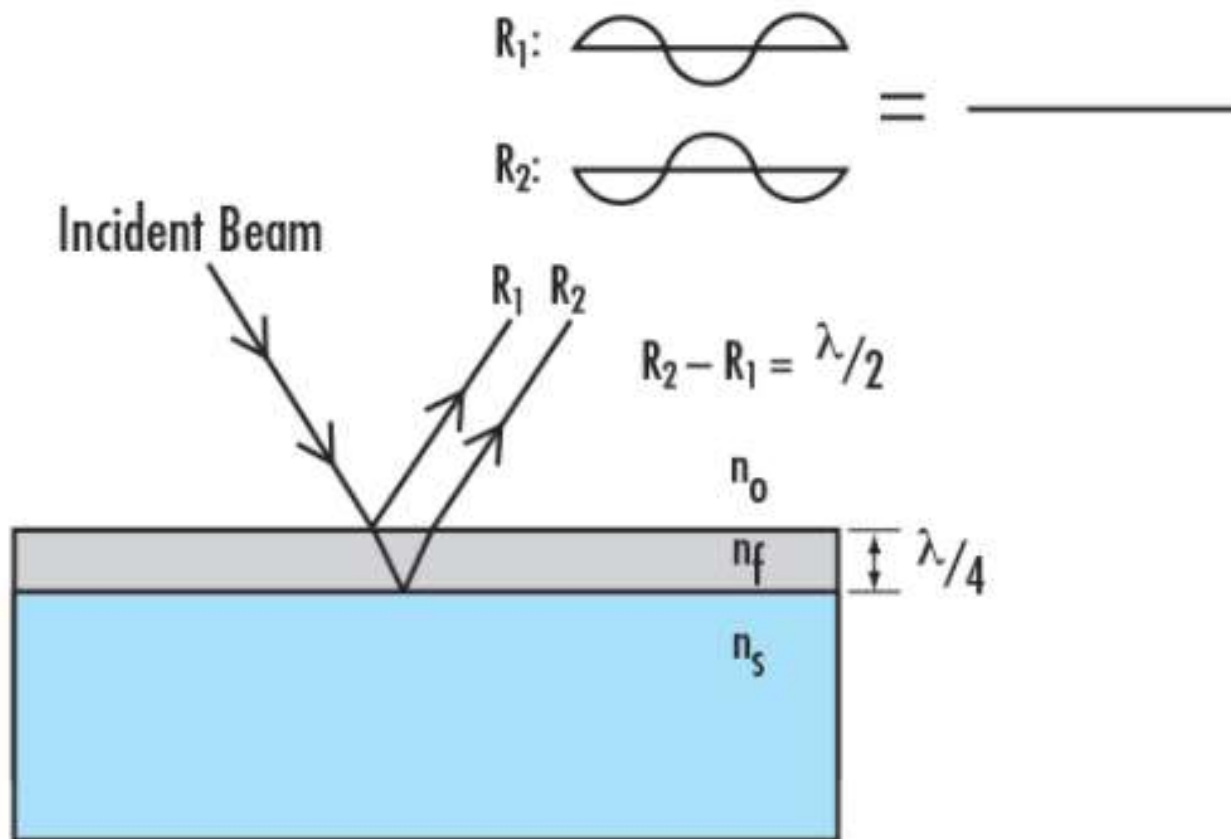
Obr. 5.12 Pozorování proužků stejné tloušťky (obrazy *A*, *B* v oku odpovídají různým místům na vrstvě)

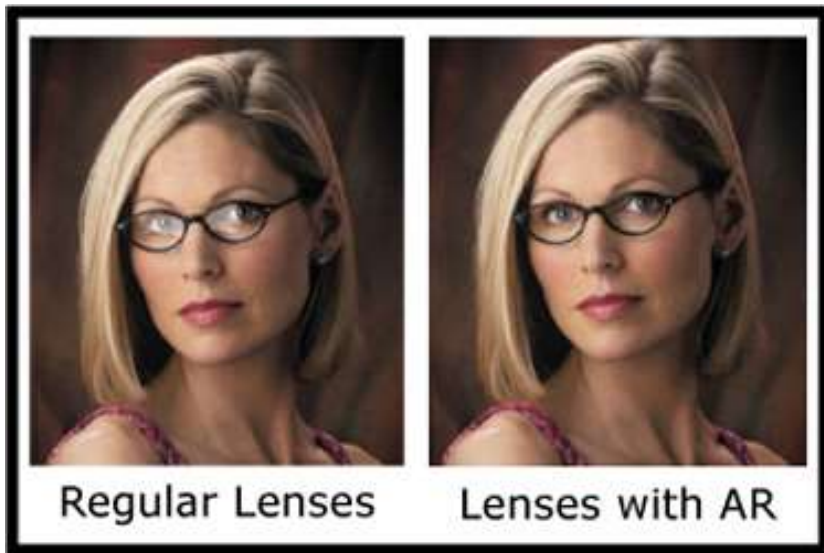
Newtonovy kruhy

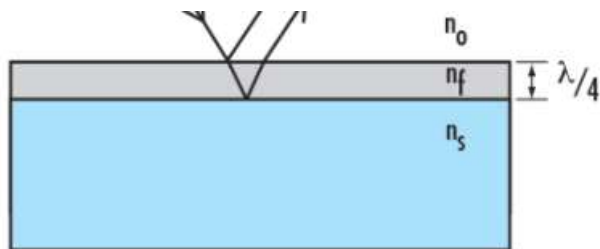


Antireflexní vrstvy

idea (obr podle Edmund Optics)







lomu vzduchu n_v , filmu n_f , a skla n_s takové, že $n_v < n_f < n_s$,

Odraz na rozhraní $n_1 < n_2$ změna fáze π , celkový fáz. rozdíl dvou odr. vln = 0

$$\theta = 0 \quad \delta_{odr} = 0$$

minimum $\frac{4\pi}{\lambda_0} h n_f = (2p + 1)\pi$

Nejmenší tloušťka ($p = 0$) $n_f h = \frac{\lambda_0}{4}$

Aby se dvě vlny odečetly na nulu, musí mít stejné amplitudy – viz Fresnelovy vzorce

$$\left(\frac{n_v - n_f}{n_v + n_f} \right)^2 = \left(\frac{n_f - n_s}{n_f + n_s} \right)^2,$$

$$\left(\frac{1 - \frac{n_f}{n_v}}{1 + \frac{n_f}{n_v}} \right)^2 = \left(\frac{1 - \frac{n_s}{n_f}}{1 + \frac{n_s}{n_f}} \right)^2 \quad \rightarrow \quad \frac{n_f}{n_v} = \frac{n_s}{n_f} \quad n_f = \sqrt{n_v n_s}$$

Například pro $n_v = 1$, $n_s = 1,5$, vychází $n_f \approx 1,22$. Používá se často vrstva MgF_2 s blízkým indexem lomu 1,38. Nedojde ovšem k úplnému potlačení odrazu.⁷ Její minimální tloušťka pro $\lambda_0 = 550$ nm podle (5.35) vychází asi 100 nm.

Zrcadlo: vysoká odrazivost, odražené vlny ve fázi

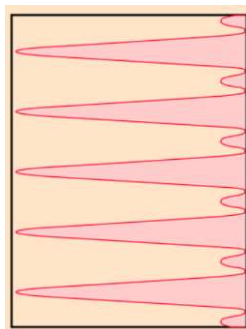
1 vrstva, jako antireflexní vrstva, ale maximum

$$\delta + \delta_{odr} = 2 p \pi$$

$$n_f h = \frac{\lambda_0}{2}$$

VÍCESVAZKOVÁ INTERFERENCE – stejné amplitudy vln

součet N vln, stejná absolutní hodnota, mezi nimi konstantní fázový posun



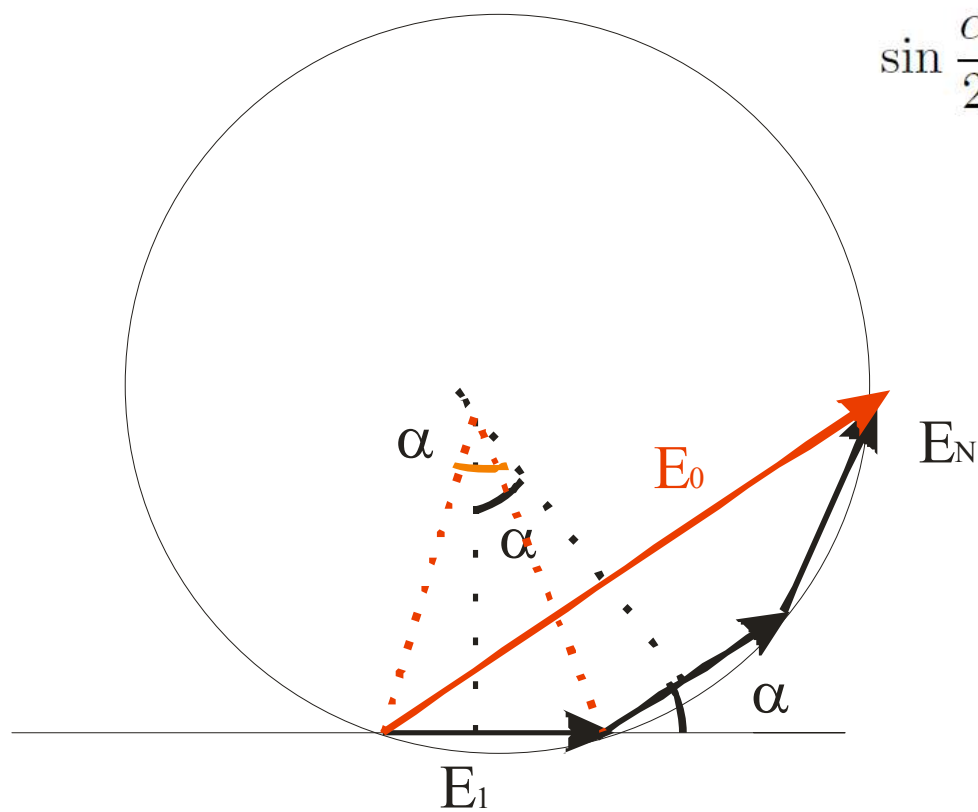
$$E_1, E_1 \exp [i\alpha], E_1 \exp [2i\alpha], \dots, E_1 \exp [i(N-1)\alpha]$$

na obr. - 3 vlny

výsledek součtu E_0 , z geometrie (r poloměr kružnice) :

$$\sin \frac{N\alpha}{2} = \frac{E_0}{2r}$$

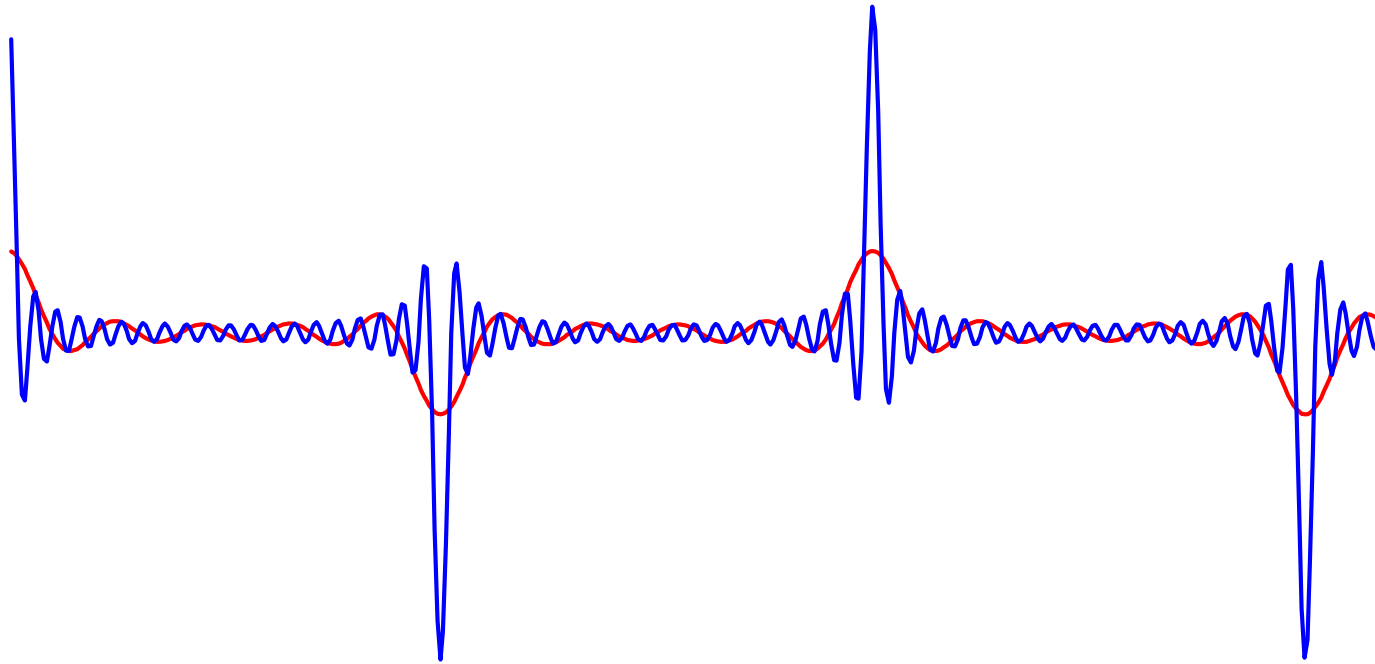
$$\sin \frac{\alpha}{2} = \frac{E_1}{2r}$$



$$E_0 = E_1 \frac{\sin \frac{N\alpha}{2}}{\sin \frac{\alpha}{2}}$$

$$I = I_1^2 \left\{ \frac{\sin \frac{N\alpha}{2}}{\sin \frac{\alpha}{2}} \right\}^2$$

Pole E0 pro N=10 a N=40



$$E_0 = E_1 \frac{\sin \frac{N\alpha}{2}}{\sin \frac{\alpha}{2}}$$

pozn.

$$\lim \left(\frac{\sin x}{x} \right) \rightarrow 1 \text{ pro } x \rightarrow 0$$

$$\lim \left(\left| \frac{\sin \frac{N\alpha}{2}}{\sin \frac{\alpha}{2}} \right| \right) \rightarrow N \text{ pro } x \rightarrow 0$$

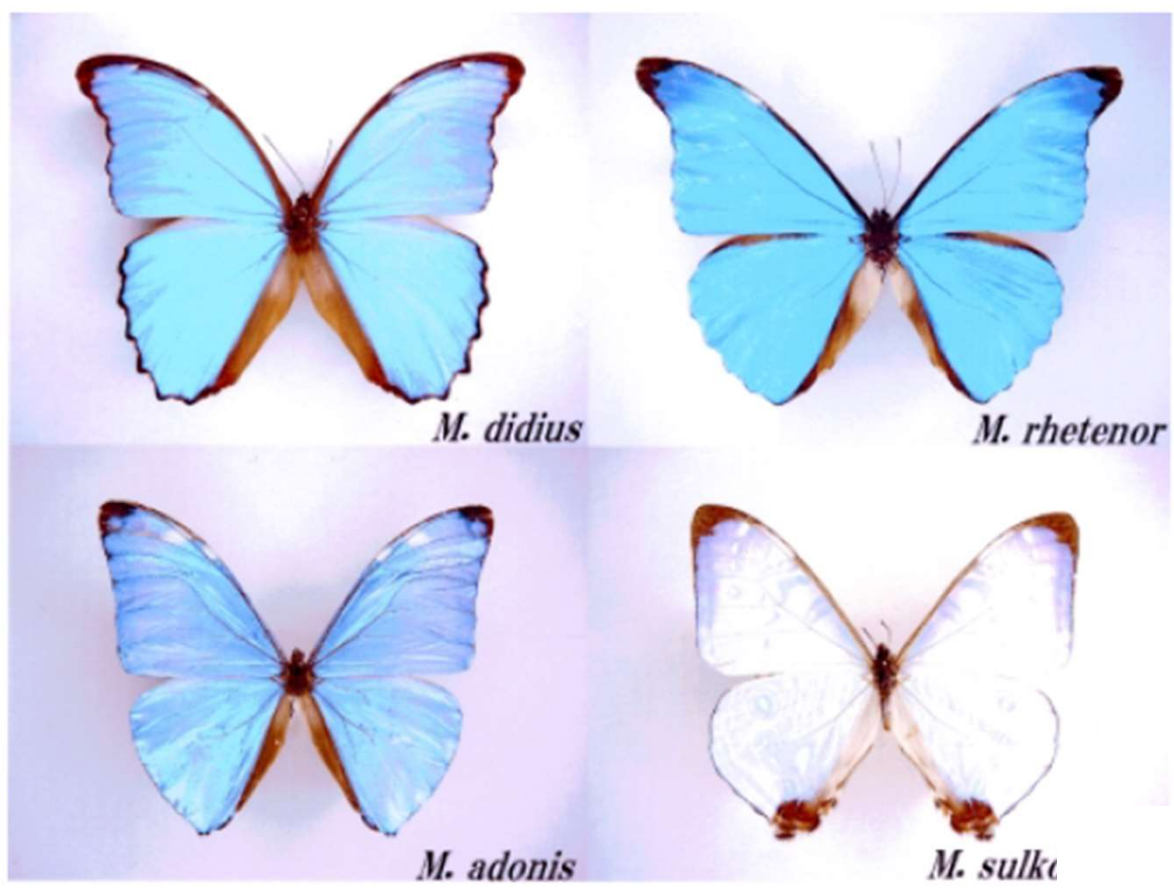


Fig. 2. Photographs of the male *Morpho* butterflies, *M. didius*, *M. rhetenor*, *M. adonis*, and *M. sulkowskyi*.



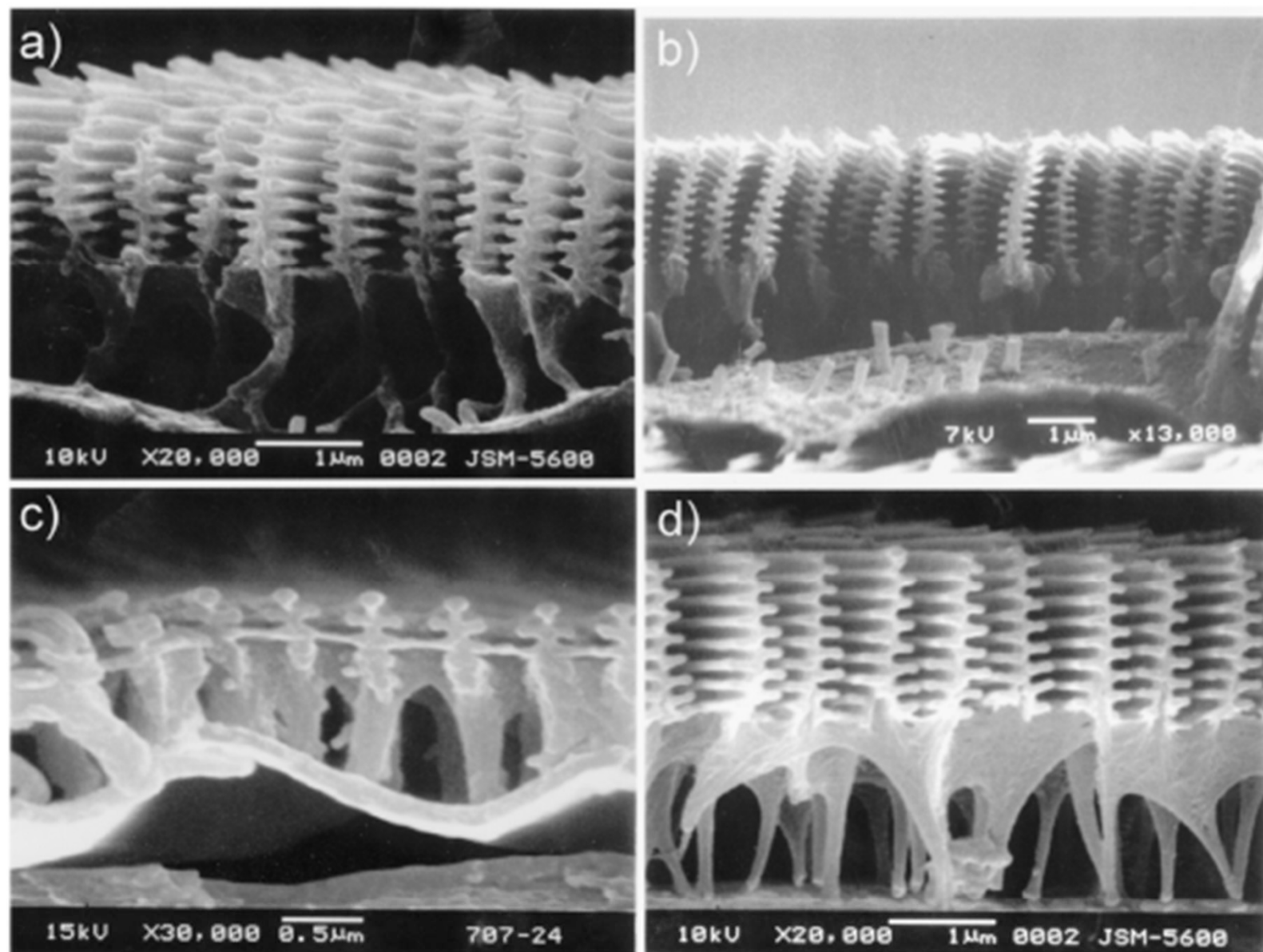


Fig. 3. Scanning electron microscope images of the cross sections of the iridescent scales of *Morpho* butterflies: (a) a ground scale of *M. didius*, (b) a scale of *M. rhetenor*, (c) a cover scale of *M. adonis* and (d) a scale of *M. suikowskyi*.

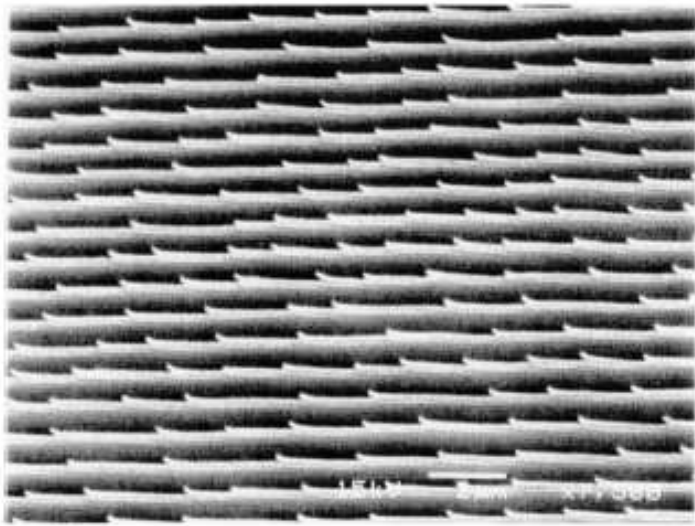


Fig. 4. Oblique view of the scanning electron microscope images of the ground scale of *M. didius*.

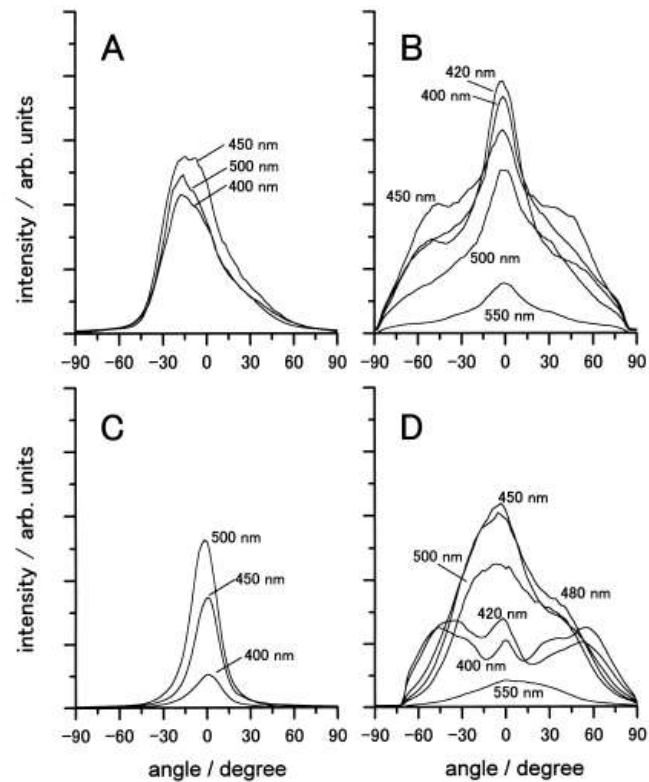


Fig. 6. Angular dependence of reflected light intensity in a plane perpendicular to the ridges for various wavelengths from B) an intact wing and D) a wing without cover scales of the male *M. didius* under normal incidence. Also shown is the angular dependence of reflected light intensity in a plane parallel to the ridges for A) an intact wing and C) a wing without cover scales.

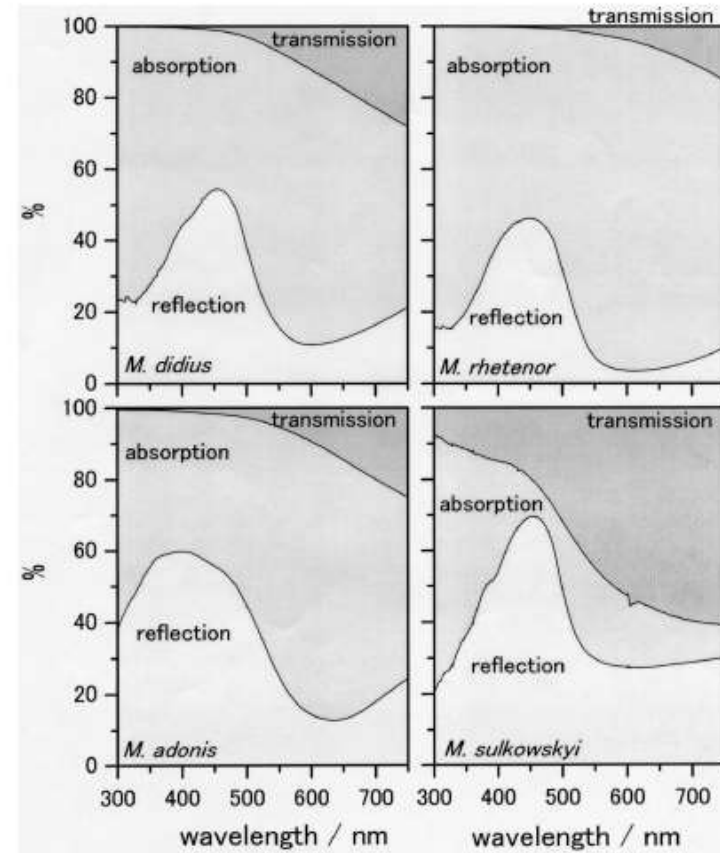


Fig. 5. Percentages of transmission, absorption and reflection of the wings of a) *M. didius*, b) *M. rhatenor*, c) *M. adonis* and d) *M. sulkowskyi*.

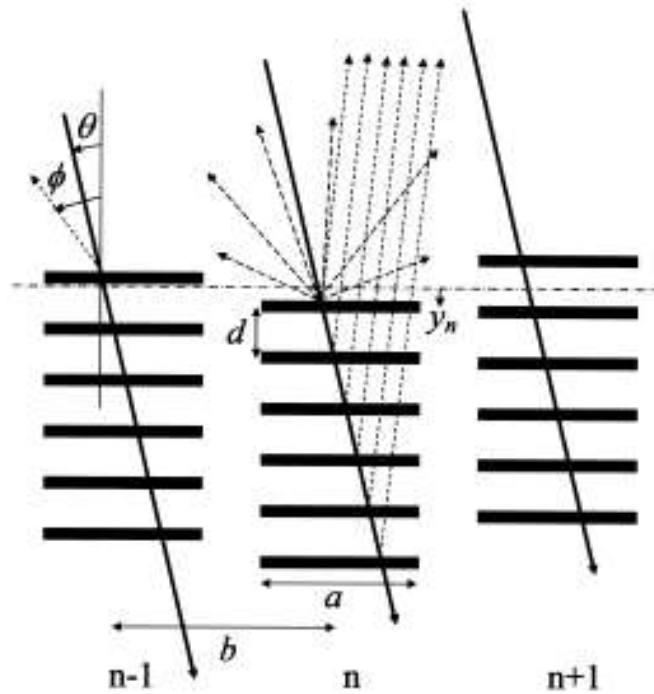


Fig. 7. A simple model for the lamellar structure on the scale. A plane wave is incident on N separate with different heights.

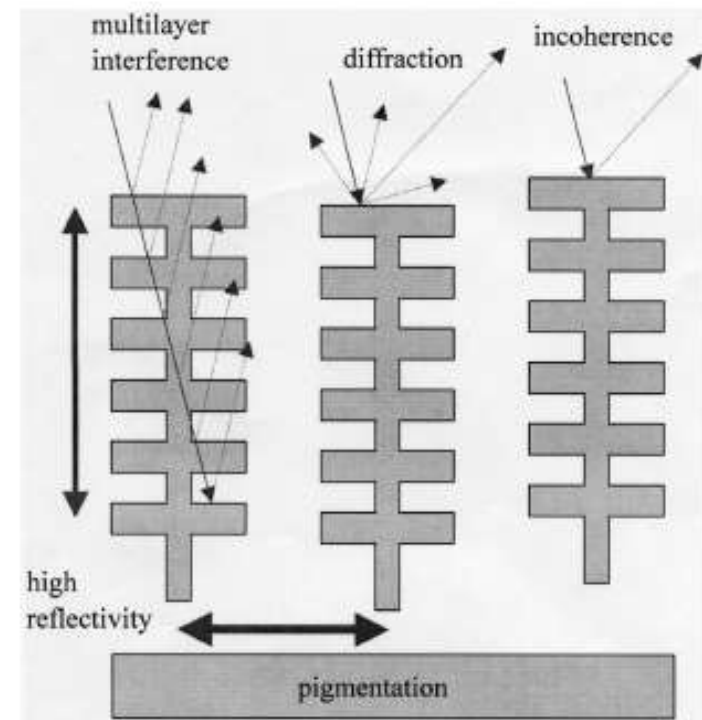


Fig. 11. Schematic view of the factors related to the structural color of the *Morpho* butterflies.

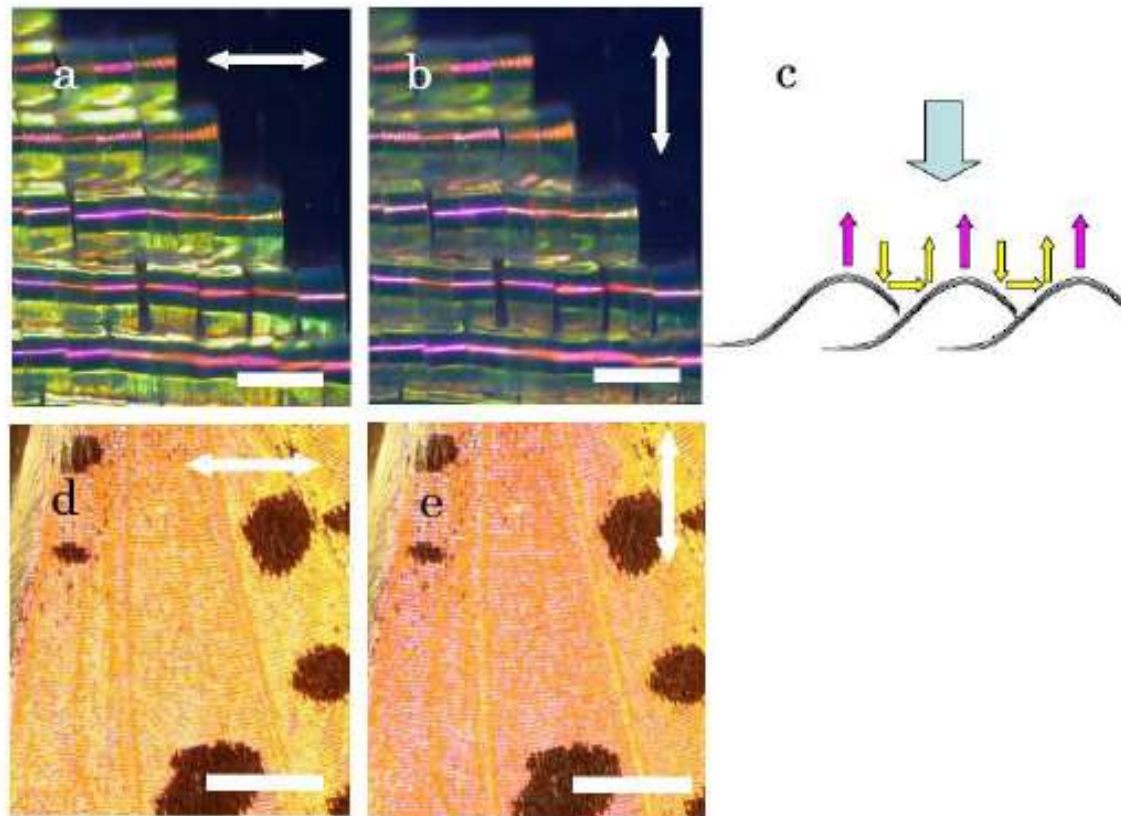
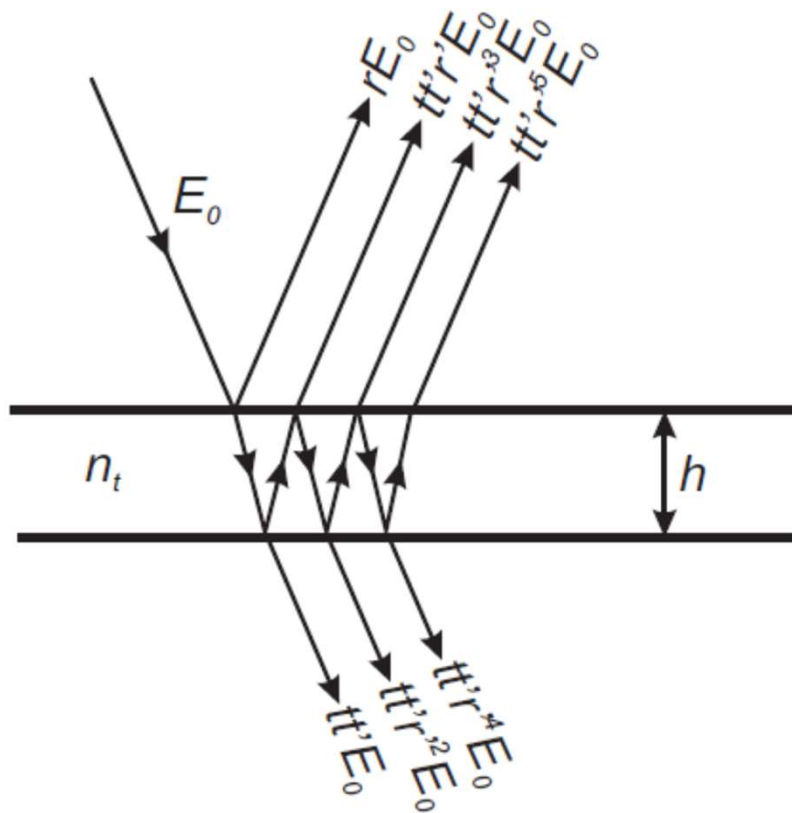


Fig. 4. Polarization dependence of the red purplish part of the ventral hind wing and a schematic illustration of the reflection mechanism. (a) and (b): Polarization-dependent images of the scale arrangement taken with the same exposure time. White arrows show the analyzing direction of the reflected light, while the illuminating light is unpolarized. The right upper black area corresponds to the wing area of the black patch. Scale bar: 200 μm . (c): Schematic illustration showing the two paths of reflection under normal incidence. One path is the direct reflection from the top flat part of the scales (purplish red arrow) and the other path is the dual reflection between adjacent scales (yellow arrows). (d) and (e): Wing-color change depending on the analyzer direction, indicated by white arrows, under unpolarized light illumination. Scale bar: 3 mm

MNOHOSVAZKOVÁ INTERFERENCE



$$r = -r'$$

$$r^2 + tt' = 1$$

Stokesovy vztahy

1. $tt' E_0 \exp(i\delta_0)$
2. $tt' r'^2 E_0 \exp(i\delta_0) \exp(i\delta)$
3. $tt' r'^4 E_0 \exp(i\delta_0) \exp(i2\delta)$
4. $tt' r'^6 E_0 \exp(i\delta_0) \exp(i3\delta)$

$$I_t = I_0 \frac{1}{1 + F \sin^2 \frac{\delta}{2}}$$

$$F = \frac{4R}{(1-R)^2}$$

$$R_d + T_d = 1$$

Airyho funkce

