Tunability of optical filter based on fibre-optic ring resonator using polarisation and birefringence effects in the resonator loop

[1]Faramarz E. Seraji,[2]Fatemeh Asghari and [3]Alireza Yekrangi Sendi

[1] Optical Communication Group, Iran Telecom Research Center,
14399 Tehran, Iran, E-mail: feseraji@itrc.ac.ir
[2] Physics Group, Payam Noor University, Shahr Rey, Iran
[3] Physics Group, Islamic Azad University, Tonekaboon Branch, Iran

Received: 24.06.2010

Abstract

We report on tuning characteristics of an optical filter based on fibre-optic ring resonator (FORR), which exploits polarisation and birefringence effects in the resonance loop of the FORR. It is demonstrated that at some operational conditions imposed upon the FORR, the effects of polarisation and birefringence in the resonance loop can become an easy tool for tuning the filter response. In particular, we show that the filtering wavelength can be tuned in to a desired value by simultaneously varying the polarisation and birefringence in the loop fibre. In the case of no polarisation change and the birefringence variations by π rad, the filtering wavelength will not alter. The results of our analysis may be useful for designing optical filters used in various optical systems.

Keywords: optical filter, tunability, polarisation, birefringence, fibre-optic ring resonator

PACS : 42.81.Gs, 42.79.Ci, 42.81.Gs, 42.81.Gs
UDC: 535.5, 535.8

1. Introduction

A great number of optical filters commonly used in optical systems are based on fibre-optic ring resonators (FORR) and Sagnac loops [1–3], fibre Bragg gratings (FBG) [4], long-period gratings (LPG) built on photonic crystal fibres [5] and some other structures such as arrayed waveguide gratings, thin-film dielectric interference structures, fibre Fabry–Pérot resonators, and Mach–Zehnder interferometers [6–8]. Tunability of these filters is an essential element of their work, which is to be carried out, at least, in modern wavelength division multiplexing (WDM) systems with the carrier spacing of less than 50 GHz [8]. Optical filters based on the FORR may be tuned using various methods such as changing of a coupler ratio [9], a Sagnac phase-shift [1], a finesse of a resonator [10], and phase matching conditions of a loop resonator [11]. In a recent work [12], a high-birefringence (HBF) fibre ring resonator with an inline reflector has been proposed where a piece of single-mode fibre is replaced with a piece of HBF in order to obtain a narrow-band filters based on Vernier effect for the use in single-frequency fibre lasers.

In another report [13], a Sagnac loop mirror with an inline HBF ring resonator has been proposed where, due to refractive index difference between the fast and slow axes of the HBF, an equivalent compound ring resonator is realised for the use in narrowband filters employed in single-frequency fibre lasers.

Recently we have reported a novel method for tuning optical filters within a narrow band using the FORR based on Sagnac phase-shift and reciprocal rotations under balanced/unbalanced resonance. It has been shown that the filter response could be tuned by rotating the Sagnac loop coupled to the FORR [1].

In this paper we present a novel method for obtaining tunability of the optical filters based on the FORR by exploiting polarisation and birefringence effects in the resonance loop fibre of the FORR under steady-state condition [14]. In our method, we consider the well-known configuration of the FORR assumed to be made of a directional optical coupler insensitive to the light polarisation. Its loop fibre and the fibre in the embedded polarisation rotator represent single-mode fibres with a low birefringence in the core.

2. Theoretical modelling

A schematic diagram of the FORR is shown in Fig. 1. It consists of a polarisation rotator inserted in the loop at port 3. The following assumptions are made in the analysis. The coupler is assumed to be polarisation insensitive and the losses of each of the two orthogonal polarisation modes due to optical birefringence in the loop fibre are assumed to be the same.

Let κ be the power coupling coefficient of the coupler, α the power transmittance coefficient of the loop fibre, E_{in} the electric field of the input light at port 1, E_c the field cross-coupled to the loop at port 3, E_t the transmitted field in the loop fibre, θ the change in the polarisation angle introduced in the field E_c by the rotator, and ϕ the polarisation angle of the input electric field E_{in} with respect to the x axis, as shown in Fig. 1.

Assuming the coupler to be lossless and resolving all the complex electric fields (E_{cx} and E_{cy}) along two arbitrary orthogonal x and y axes belonging to the cross section of the input fibre, one can obtain the complex output electric field components under steady-state operation of the FORR after a single trip of the circulating field through the loop as

$$\begin{aligned} E_{ox} &= -i\sqrt{\kappa}E_{in}\cos(\phi) + \sqrt{1-\kappa}\,E_{tx} \\ E_{oy} &= \sqrt{1-\kappa}\,E_{ty} - i\sqrt{\kappa}\,E_{in}\sin(\phi) \end{aligned} . \tag{1}$$

In deriving Eq. (1), we notice that the contribution of the input field E_{in} (or E_t) when coupled to port 4 (or port 3) has the phase shift of $-\pi/2\,\mathrm{rad}$, as compared to a zero phase shift when coupling to port 3 (or port 4). This assumption is required to ensure the law of conservation of energy and remains valid if the coupler loss is nearly zero [15].

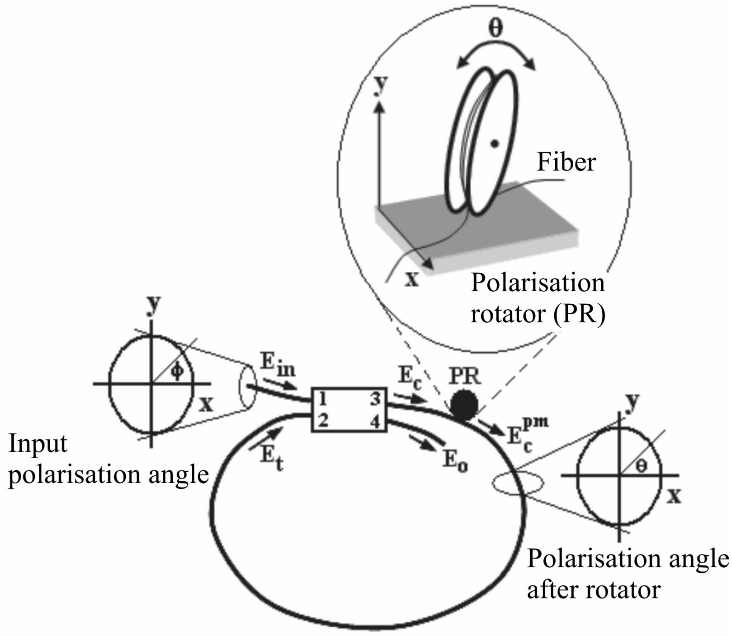


Fig. 1. Schematic diagram of FORR with polarisation rotator in the loop.

Under same condition of deriving Eq. (1), the *x*- and *y*-components (E_{cx} and E_{cy}) of the direct- and cross-coupled complex fields from ports 1 and 2 to port 3 are given by

$$\begin{aligned} E_{cx} &= \sqrt{1-\kappa}\, E_{in} \cos(\phi) - i\sqrt{\kappa}\, E_{tx} \\ E_{cy} &= -i\sqrt{\kappa}\, E_{ty} + \sqrt{1-\kappa}\, E_{in} \sin(\phi) \end{aligned}, \tag{2}$$

where E_{tx} and E_{ty} are the *x*- and *y*-components of the corresponding transmitted fields along the loop fibre.

The polarisation rotator placed in the vicinity of port 3, which imposes the polarisation change of θ rad, will change the coupled fields E_{cx} and E_{cy} respectively along the *x* and *y* axes to E_{cx}^{pm} and E_{cy}^{pm}:

$$\begin{aligned} E_{cx}^{pm} &= E_{cx} \cos(\theta) - E_{cy} \sin(\theta) \\ E_{cy}^{pm} &= E_{cx} \sin(\theta) + E_{cy} \cos(\theta). \end{aligned} \tag{3}$$

The polarisation rotator is inserted in the loop in the vicinity of the port 3 in Fig. 1. It can change the birefringence $n_x - n_y$ in the cross section of the fibre along the loop, thus introducing some phase difference σ between the two orthogonal polarisation modes, E_{cx}^{pm} and E_{cy}^{pm}. For a fibre length of L, we have $\sigma = (2\pi/\lambda)(n_x - n_y)L$, where λ is the light wavelength in a vacuum. Therefore, *x*- and *y*-components of the transmitted field along the loop length with the transmission coefficient α will take the form

$$E_{tx} = \sqrt{\alpha}\, E_{cx}^{pm} \exp(-i\omega\tau)$$
$$E_{ty} = \sqrt{\alpha}\, E_{cy}^{pm} \exp[-i(\omega\tau + \sigma)] \quad , \qquad (4)$$

where ω is the angular optical frequency of the input light, τ the delay time in the loop for the mode polarised along the x axis, and $(\tau + \sigma / \omega)$ the same for the y-axis mode. Here we have assumed that the input light is linearly polarised. Solving the above equations simultaneously, one can show that a following relation holds true:

$$\frac{E_{tx}}{E_{in}} = \frac{N_x}{D_x} \text{ and } \frac{E_{ty}}{E_{in}} = \frac{N_y}{D_y} , \qquad (5)$$

where

$$N_x = C\cos(\theta+\phi)\mathrm{e}^{-i\omega\tau} + iA(E_{ty} / E_{in})\sin(\theta)\mathrm{e}^{-i\omega\tau}$$
$$D_x = 1 + iA\cos(\theta)\mathrm{e}^{-i\omega\tau}$$
$$N_y = C\left\{1 - A\cos(\theta)e^{-i\omega\tau}\right\}\sin(\theta+\phi)\mathrm{e}^{-i(\omega\tau+\sigma)} \qquad (6)$$
$$D_y = -A^2\sin^2(\theta)e^{-i(2\omega\tau+\sigma)} + \left\{1 + iA\cos(\theta)\mathrm{e}^{-i(\omega\tau+\sigma)}\right\}\left\{1 + iA\cos(\theta)\mathrm{e}^{-i\omega\tau}\right\},$$

with $A = \sqrt{\alpha\kappa}$, $B = \alpha\sqrt{\kappa(1-\kappa)}$ and $C = \sqrt{\alpha(1-\kappa)}$ being constants for a given FORR. Substituting Eq. (5) in Eq. (1), one can derive the normalised output field components for the special case of $\phi = 0$:

$$\frac{E_{ox}}{E_{in}} = \frac{i}{\sqrt{\kappa}}\left[\frac{(1-\kappa) + \kappa\sqrt{\alpha}(E_{\mathrm{oy}} / E_{\mathrm{in}})\sin(\theta)\exp(-i\omega\tau)}{1 + i\sqrt{\alpha\kappa}\cos(\theta)\exp(-i\omega\tau)} - 1\right], \qquad (7)$$

$$\frac{E_{oy}}{E_{in}} = \frac{(1-\kappa)\sqrt{\alpha}\sin(\theta)\exp(-i\omega\tau)}{1 - \alpha\kappa\exp(-i2\omega\tau) + i2\sqrt{\alpha\kappa}\cos(\theta)\exp(-i\omega\tau)} . \qquad (8)$$

The x- and y-components of the output intensity, $I_{ox} = |E_{ox}/E_{in}|^2$ and $I_{oy} = |E_{oy}/E_{in}|^2$, may be evaluated using Eqs. (7) and (8), respectively. The normalised output intensity I_o would be a sum of the intensities I_{ox} and I_{oy} along the x and y axes, respectively:

$$I_o = I_{ox} + I_{oy} . \qquad (9)$$

The above equations may be validated by verifying that if the ring is lossless ($\alpha = 1$), the output power should be equal to the input power for all the values of $\omega\tau$, κ, σ, ϕ and θ.

3. Simulation of the response and discussions

Fig. 2 shows the response I_o as a function of loop phase $\omega\tau$ for different values of σ, derived in the assumption that $\alpha = \kappa = 0.9$ and $\theta = 0$. Since the coupler is supposed to be insensitive to the polarisation, the ϕ value is taken to be zero in all the calculations.

When $\theta = 0$, I_{oy} is zero for all the values of σ and $\omega\tau$, and the final value I_o is only due to the I_{ox} component, which dips to zero at the resonance point ($\omega\tau = 2q\pi - \pi/2$), where q is an integer. In fact, the filter response under this parametric condition does not depend on the birefringence, since the filter acts as a stopband one at the resonance point under steady-state condition of the FORR [14].

Now, if the polarisation angle θ attains a non-zero value after the rotator, the response would render to a dependence of birefringence in the loop fibre. This condition is illustrated in Fig. 3 for the case of $\theta = \pi/4$ rad. We observe that, due to the propagation of the second mode in the resonance loop of the FORR pertaining to non-zero θ, the resonance point shifts away from the initial position. A similar behaviour may appear when there is a slight birefringence σ in the loop fibre. As an example, the resonance dip of the filter can be moved away from a preliminary point by sweeping the loop phase angle when $\sigma = \pi/4$, as illustrated in Fig. 4.

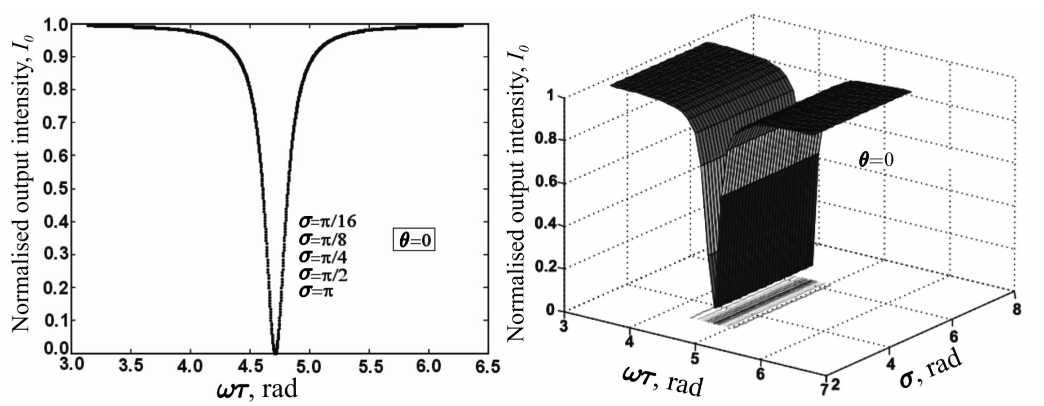


Fig. 2. Filter response for the case of zero polarisation angle for different birefringences in the loop fibre.

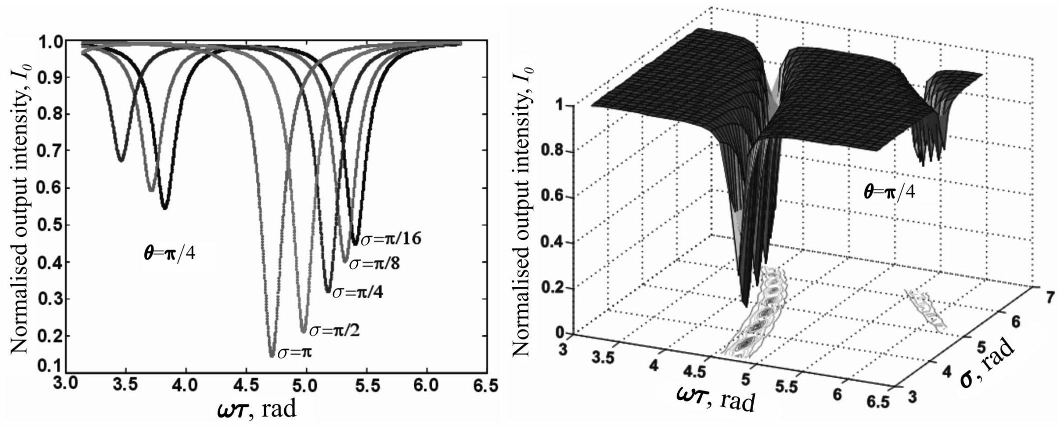


Fig. 3. Dependence of filter response on the birefringence for the case when polarisation is present in the loop.

Two other special cases of $\sigma = 0$ and $\sigma = \pi$ rad are shown in Fig. 5. For non-zero θ, the propagation of the two modes circulating in the loop are likely when $\sigma = 0$ rad, and the resonance dips due to these two modes appear at a distance equal to twice the polarisation angle (2θ), as shown in Fig. 5a.

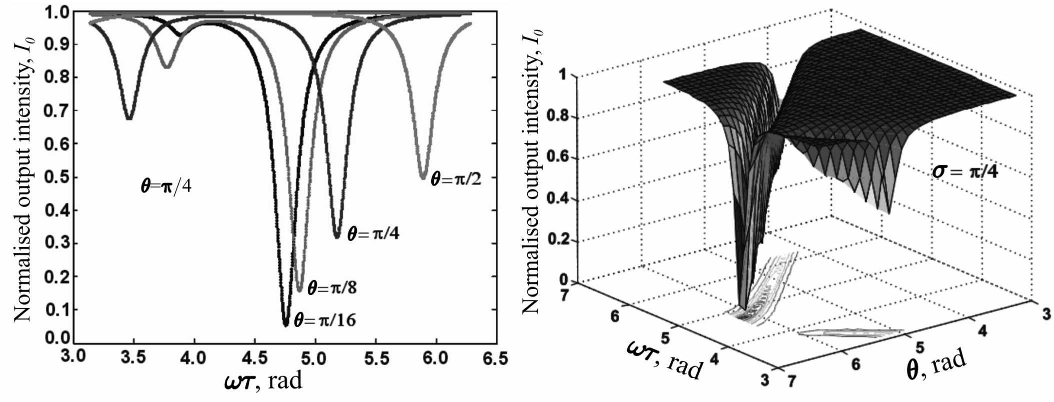
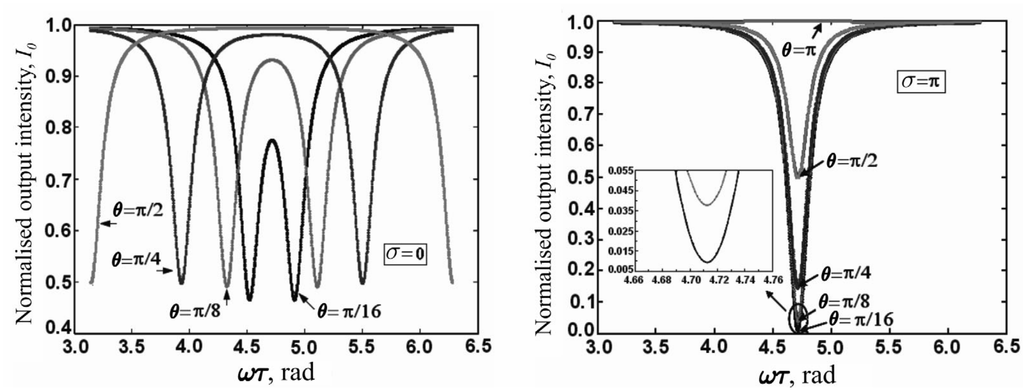


Fig. 4. Dependence of filter response on the polarisation for non-zero birefringence in the loop.



(a) (b)

Fig. 5. Filter response under conditions (a) $\sigma = 0$ and (b) $\sigma = \pi$ rad for different polarisation angles θ.

If we have $\sigma = 0$ rad and $\theta = \pi / 2$ rad, the filter works in a wideband regime, as shown in Fig. 5a. On the other hand, when $\sigma = \pi$ rad, the behaviour of the filter is restricted to propagation of a single mode in the loop at the resonance point, where the depth of resonance dip depends only on the polarisation change in the loop fibre (see Fig. 5b). For instance, when $\theta = \pi / 2$ rad, the response dips to 3 dB down the normalised value, as shown in Fig. 5b. For a typical case of $\sigma = \theta = \pi$ rad, an all-pass optical filter covering a wide range of wavelengths can be designed.

In our calculations we have taken the overall range $\sigma = \pi / 16$ to π for the phase difference between the two orthogonal polarisation modes. Then the birefringence variations are of the order of 10^{-9} on a fibre length of a few hundred loops.

4. Conclusion

Summing up, this paper reports a tunability of response of the optical filter based on the FORR which is obtained using the polarisation and birefringence effects in the loop fibre of its resonator. The filter response has been calculated by including a polarisation rotator and a birefringence in the resonance loop of the resonator.

Under steady-state conditions, the response of the filter based on the FORR is derived for the conditions when the both polarisation and birefringence effects are considered in the loop fibre. It is shown that the filter response does not depend on the birefringence when the polarisation angle remains constant in the loop fibre, whereas for a zero birefringence the filter response could change, due to polarisation variations in the loop. If we have $\sigma = \theta = \pi / 4$, the filter response may include propagation of two modes, depending upon variations of either the polarisation or the birefringence in the loop fibre. In the typical cases of $\sigma = 0$, $\sigma = \pi / 2$ and $\sigma = \theta = \pi$, the filter responds in wideband or all-pass regimes. We have noticed that simultaneous variations of the polarisation and the birefringence in the loop fibre can tune the filtering wavelength to a desired value.

Acknowledgement

The authors wish to thank Tonekabbon Branch of the Islamic Azad University (Iran) for supporting this project.

References

1. Seraji F E and Asghari F, 2010. Tunable optical filter based on Sagnac phase-shift using single optical ring resonator. Opt. & Laser Technol. **42**: 115–119.
2. Talebi N, Shahabadi M and Hafner C, 2006. Analysis of a lossy microring using the generalized multipole technique. Prog. Electromag. Res. (PIER). **66**: 287–299.
3. Pang F, Liu F, Han X, Cai H, Qu R and Fang Z, 2006. Analysis of a second order polarization independent filter made of a single ring resonator and a Sagnac interferometer. Opt. Commun. **260**: 567–570.
4. Mohammad N, Szyszkowski W, Zhang WJ, Haddad EI, Zou J, Jamroz W and Kruzelecky R, 2004. Development and analysis of a tunable fibre Bragg grating filter based on axial tension/compression of FBG. J. Lightwave Technol. **22** (**8**): 2001–2003.
5. Seraji F E, Anzabi L C and Farsinezhad S, 2009. Design of compact long-period gratings imprinted in optimized photonic crystal fibers. Appl Phys. B. **97**: 425–429.
6. Lenz G, Eggleton B J, Giles C R, Madsen C K and Slusher R E, 1998. Dispersive properties of optical filters for WDM systems. IEEE J. Quantum Electron. **34** (**8**): 1390–1402.
7. Madsen C K and Zhao JH, Optical Filter Design and Analysis: A Signal Processing Approach, John New York: Wiley & Sons, Inc. (1999).
8. Sadot D and Boimovich E, 1998. Tunable optical filters for dense WDM networks.

IEEE Commun. Mag. **36** (**12**): 50–55.
9. Vázques C, Vargas S E and Pena J M S, 2005. Sagnac loop in ring resonators for tunable optical filters. J. Lightwave Technol. **23**: 2555–2567.
10. Chew Y H, Tjhung T T and Mendis F V C, 1997. An optical filter of adjustable finesse using an amplified fiber ring resonator. J. Lightwave Technol. **15**: 364–370.
11. Seraji F E and Pandian G S, 1991. Dynamic response of a fiber ring resonator with sinusoidal phase modulation of the loop. J. Mod. Opt. **38**: 671–676.
12. Sun Guoyong, Moon Dae Seung and Chung Youngjoo, 2007. High birefringence fiber ring resonator with an inline reflector for single-frequency fiber lasers. Opt. Commun. **280**: 157–160.
13. Sun Guoyong, Zhou Yingwu, Hu Yihui and Chung Youngjoo, 2010. Theoretical analysis of Sagnac loop mirror with an inline high birefringence fiber ring resonator: Application in single-frequency fibre lasers. Opt. Fiber Technol. **16**: 86–89.
14. Seraji F E, 2009. Steady-state performance analysis of fiber-optic ring resonator. Prog. Quant. Electron. **33**: 1–16.
15. Mizumoto T and Naito Y, 1990. Dependence of the output phase on the asymmetry of 3-dB directional couplers. IEEE J. Lightwave Technol. **8**: 1571–1576.

Faramarz E. Seraji, Fatemeh Asghari and Alireza Yekrangi Sendi, 2010. Tunability of optical filter based on fibre-optic ring resonator using polarisation and birefringence effects in the resonator loop. Ukr.J.Phys.Opt. **11**: 185–192.

Анотація. *В роботі описані керуючі характеристики оптичного фільтру, який базується на волоконно-оптичному кільцевому резонаторі і використовує поляризаційні ефекти і двозаломлення в резонаторному кільці. Показано, що за певних умов поляризаційні ефекти і двозаломлення можуть бути простим засобом перестроювання фільтра. Зокрема показано, що необхідна фільтрована довжина хвилі може бути досягнутою шляхом одночасної зміни поляризації і двозаломлення у волоконному кільці. У даному випадку при незмінному стані поляризації і зміні різниці фаз (двозаломлення) на* π *рад, фільтрована довжина хвилі не змінюється. Результати даного аналізу можуть бути корисними при проектуванні фільтрів для різних оптичних систем.*