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Changes of transmission characteristics for different optic radiation incidence angles in filters protecting against hazardous infrared radiation

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Abstract: The paper presents the fundamental information concerning the types of protective optical filters used for protection against hazardous radiation within the visible and near-infrared spectrum range. The changes of transmission characteristics for different optic radiation angles of incidence with metallic reflective filters and interference filters have been analyzed. The results demonstrate that such changes exert no effect on the level of protection provided by the filters.

Subjects: Environmental & Health; Laser & Optical Engineering; Technology

Keywords: interference filters; infrared radiation; optical filters

1. Introduction

Protection against infrared radiation is provided by special filters mounted in glasses, goggles, or face protections. Such filters should block hazardous infrared radiation as well as reduce radiation within the visual spectrum range, which can cause dazzle, ensuring good visibility of the object/area of work at the same time.

Three basic types of protective optical filters that use protection against hazardous radiation within the visible (Vis) and near-infrared (NIR) spectrum range can be distinguished:

- Absorption filters,
- Metallic reflective filters, and
- Interference filters.

ABOUT THE AUTHORS

The subject of the Central Institute for Labour Protection – National Research Institute activity is conducting research and development works leading to new technical and organizational solutions in the field of labor protection, related to occupational safety, health, and ergonomics as well as other tasks essential for reaching the goals of the state's socioeconomic policy in this field.

VIGO SL Sp. z o.o. is highly specialized in production of high-quality interference optical coatings. Multilayer optical coatings designed and fabricated in our laboratories were applied in many different ranges of activities as ophthalmic, instrumental optics, spectroscopy, astronomy, medical science, and lightning technology.

PUBLIC INTEREST STATEMENT

This work discusses the information on the possibility of blocking the harmful infrared radiation in hot workstations with thin-film optics methods. The structure of the interference film and the results of laboratory tests on model filter solutions are presented. A new approach to the design of infrared radiation filters consists in developing thin-film coatings blocking the harmful infrared radiation with use of interferences occurring in the multilayered dielectric or metallic–dielectric coatings. The appropriate selection of thin-film structure, materials, their thickness, and sequence allows to produce a filter of highly effective infrared suppression and to control the values of transmittance in the visible range. The primary advantages of such solution are the extended filter life, high suppression of harmful radiation, and low absorption levels.

The absorption filters have been practically withdrawn from use due to an increase of filter temperature as a result of absorption of a large proportion of optic radiation against which they were intended to protect. Consequently, the comfort of their use was considerably deteriorated. In view of low level of use, the absorption filters have been excluded from the study.

The filters currently used in eye and face protection are made of glass or organic materials (mainly polycarbonate) and coated with a single metallic layer reflecting infrared radiation. They take advantage of characteristic properties of the metals used in their production, i.e. high radiation reflection coefficient within the IR spectrum and significant transmission coefficient within the visible spectrum range.

Interference filters (patent number P-401213) developed by the authors (Gralewicz et al., 2012a) making use of the principles of interference, i.e. overlapping of the waves leading to the reduction of the resultant wave amplitude (Feng, Elson, & Overfelt, 2005; Fuentes-Hernandez et al., 2011; Wang & Chen, 2005; Yaremchuk, Fitio, & Bobitski, 2006) are a novel solution designed for use in protective eyewear. In the case of interference filter, based on the theory of interference, there is a need to investigate the effect of changes of optic radiation incidence angle on the changes of filter properties.

In the present study, the selected features of transmission characteristics were tested for the effect of changes of optic radiation incidence angle in metallic reflective and interference filters. The analysis of this study achieved information, or changing the angle of incidence of a beam of optical radiation incident on the tested filters to protect against infrared radiation affects the change in the degree of protection filter.

2. Test samples—filters protecting against hazardous infrared radiation

For comparative analysis of the filters available in the market versus the interference filters developed by the authors, the following samples were prepared for the tests:

- Available on the market—metallic reflective filters on polycarbonate substrates—wafer of 50 mm diameter with a metallic layer of copper (Cu)—protection levels: 4–3, 4–5, 4–7 (the higher the protection level, the higher level of blocked IR radiation and appropriately lower transmission coefficient for visible spectrum radiation),
- Developed by the authors—interference filters on polycarbonate substrates—wafer of 50 mm diameter with interference coating made up of the layers of the following materials: aluminum, substance H4—LaTiO3 and silicon dioxide.

Filter samples used in the study are presented in Table 1.

A metallic reflective filter (Table 1: Numbers 4, 5, and 6) consists of the base: polycarbonate or mineral glass, and metallic coating layer of copper (Cu) or gold (Au). The metals used in their production are characterized by high radiation reflection coefficient within the IR spectrum and significant transmission coefficient within the visible spectrum range.

Table 1. Filter samples used in the study

No	Protection level	Filter type	Comments
1	4–3	Interference filter	Developed by the authors
2	4–5	Interference filter	Developed by the authors
3	4–7	Interference filter	Developed by the authors
4	4–3	Metallic reflective filter	Commercially available
5	4–5	Metallic reflective filter	Commercially available
6	4–7	Metallic reflective filter	Commercially available

An interference optic radiation filter (Table 1: Numbers 1, 2, and 3) consists of the base: polycarbonate or mineral glass, and an appropriate sequence of layers made of dielectric materials with high refractive index and low refractive index, as well as metallic reflective layers (most frequently: silver for the visible portion of the spectrum, aluminum for UV, aluminum for IR), deposited with physical techniques involving evaporation under high vacuum conditions (Macleod, 2001; Sytchkova, 2011).

3. Testing methodology

The tests of filters protecting against hazardous IR radiation were performed using a Cary 5000-type spectrophotometer. The filter samples were positioned, so as to obtain incidence of the beam radiation perpendicular to the filter surface or parallel to the line of vision. Then, the angle of filter positioning was changed (30°, 45°) in relation to the beam radiation (Figure 1).

The measurement data used as the basis for determination of transmission characteristics of the filter were recorded. The characteristics of the tested filters were analyzed within the visible spectrum: 380–780 nm and infrared spectrum range 780–3,000 nm.

For the 380–780 nm range, the transmission coefficients which must meet the requirements specified in the relevant standards (EN 166, 2001; EN 171, 2002), i.e. ensure the required light transmission level, were determined.

For the 780–3,000 nm range, spectrum average IR transmission coefficients, which must meet the requirements specified in the relevant standards (EN 166, 2001; EN 171, 2002), i.e. ensure the required level of infrared radiation blockade were determined. The coefficients were calculated according to the following equations:

- Light transmission coefficient; light transmittance (Equation 1).

$$\tau_v = \frac{\int_{380\,\text{nm}}^{780\,\text{nm}} \tau_F(\lambda) \cdot V(\lambda) \cdot S_{D65\lambda}(\lambda) \cdot d\lambda}{\int_{380\,\text{nm}}^{780\,\text{nm}} V(\lambda) \cdot S_{D65\lambda}(\lambda) \cdot d\lambda} \tag{1}$$

- Transmission coefficient for the 780–1,400 nm spectrum range (Equation 2).

$$\tau_A = \frac{1}{63} \int_{780\,\text{nm}}^{1400\,\text{nm}} \tau(\lambda) \cdot d\lambda \tag{2}$$

- Transmission coefficient for the 780–2,000 nm spectrum range (Equation 3).

$$\tau_N = \frac{1}{123} \int_{780\,\text{nm}}^{2000\,\text{nm}} \tau(\lambda) \cdot d\lambda \tag{3}$$

- Transmission coefficient for the 780–3,000 nm spectrum range (Equation 4).

$$\tau_C = \frac{1}{223} \int_{780\,\text{nm}}^{3000\,\text{nm}} \tau(\lambda) \cdot d\lambda \tag{4}$$

where $S_{A\lambda}(\lambda)$ stands for spectral power distribution of standard illuminant CIE A (or a 3200 K light source for blue signal light). Cf. (ISO/CIE 10526, 1999); $S_{D65\lambda}(\lambda)$ stands for spectral power distribution of standard illuminant CIE D65. Cf. (ISO/CIE 10526, 1999); $V(\lambda)$ stands for the function of relative

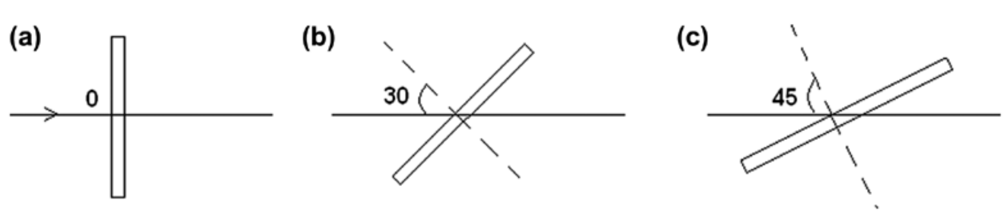


Figure 1. Changes in incidence angle of beam radiation: (a) 0° angle, (b) 30° angle, (c) 45° angle.

spectral luminous efficiency for daytime vision. Cf. (ISO/CIE 10526, 1999); and $\tau_F(\lambda)$ stands for spectral transmission coefficient of the filter.

The spectral values of spectral power distribution products ($S_{A\lambda}(\lambda)$, $S_{D65\lambda}(\lambda)$ illuminants, relative spectral luminous efficiency $V(\lambda)$ of the eye, and spectral transmission coefficient $\tau_S(\lambda)$ of street signal light glass are specified in the European standards concerning personal eye protections (EN 166, 2001; EN 171, 2002).

The maximum transmittance (Equation 5) of the filter was also considered in the analysis of transmission characteristics.

$$T_{f\,\max} = \frac{T^2}{(1-R)^2} = \frac{1}{(1 + A/T)} \tag{5}$$

where R is the refraction index; T is the transmission coefficient; and A is the absorption coefficient.

Another value taken into account in the analysis of transmission characteristics of the filters is filter half-width $\Delta\lambda_{1/2}$, for which the transmittance is equal to 1/2 of the maximum transmittance to the following Equation 6 (Fuentes-Hernandez et al., 2011; Macleod, 2001).

$$\Delta\lambda_{1/2} = \frac{\lambda_{\max} \cdot (1-R)}{m \cdot \pi \cdot \sqrt{R}} \tag{6}$$

where $\lambda_{\max}$ is the maximum transmittance; m is the row of interference; and R is the refraction index.

The filter half-width is dependent on the refraction index R and in the case of interference filters—on the order of interference. The higher R and the higher order of interference correlates with the higher filter half-width value.

The changes of transmission characteristics for different optic radiation angles of incidence with filters to the following Equation 7 (Macleod, 2001).

$$\lambda_{\max}(\phi_1) = \frac{2 \cdot n_1 \cdot d_1}{m + \frac{\varepsilon}{\pi}} \cos\phi_1 \tag{7}$$

where n_1 is the transmission coefficient; m is the row of interference; and d is the thickness of the separating layer.

Figure 2 presents a sample of transmission characteristics $T(\lambda)$ of a filter within the 380–780 nm spectrum range, with $T_{f\,\max}$ and $\Delta\lambda_{1/2}$ indicated.

4. Analysis of filters protecting against hazardous infrared radiation

Figures 3 and 4 present examples of transmission characteristics of a metallic reflective filter and the developed interference filter. The interference filters developed by the authors characterized by a steeper depth of characteristics are more significant as far as IR blocking is concerned in comparison with metallic reflective filters. The spectral transmittance values for ranges (780–1,400 and 780–2,000 nm) are in an order of magnitude of the value of the currently manufactured filter. Interference filters have a higher mechanical strength (according to EN 166, 2001; EN 171, 2002). This affects the reduction of costs in the long-term use (Gralewicz et al., 2012b).

Figure 2. Sample transmission characteristics $T(\lambda)$ of a filter within the 380–780 nm spectrum range, with $T_{f\,max}$ and $\Delta\lambda_{1/2}$ indicated.

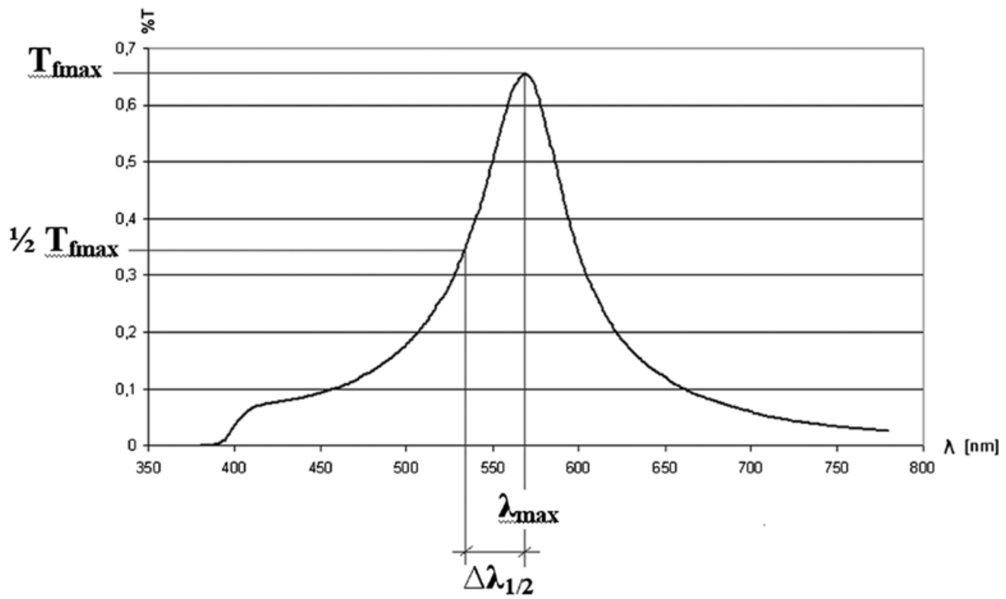
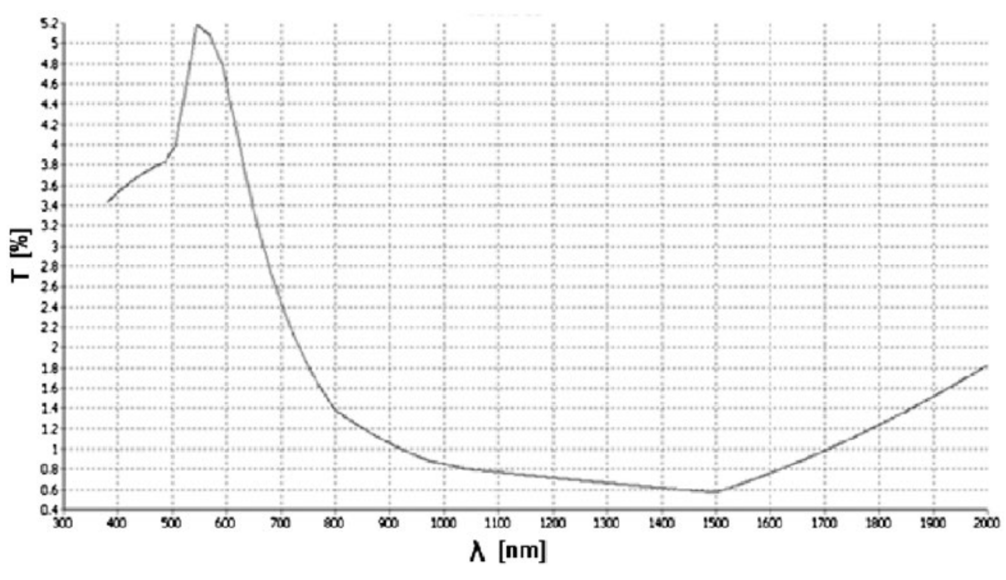


Figure 3. Transmission characteristics $T(\lambda)$ of a metallic reflective filter (protection level 4–5).



4.1. Results

A change of optic radiation incidence angle with the filter results in the change of $T_{f\,max}$ and $\Delta\lambda_{1/2}$. A shift of λ_{max} towards shorter wavelengths is observed. Figure 5 presents sample transmission characteristics of an interference filter, providing protection level of 4–5 for incidence angles: (a) 0°, (b) 30°, (c) 45°. Besides the shift of λ_{max} towards shorter wavelengths, broadening of the transmitted radiation beam corresponding to an increase of $\Delta\lambda_{1/2}$ occurs.

In Tables 2 and 3, maximum transmittance of the filter—$T_{f\,max}$ and filter half-width $\Delta\lambda_{1/2}$ corresponding with the change of optic radiation incidence angle with metallic reflective and interference filters are presented.

It is noteworthy that irrespectively of the angle at which the tested filter is positioned in relation to the beam radiation on spectrophotometer, the filter properties with respect to protection against IR radiation within the 780–2,000 nm spectrum range remain unaffected.

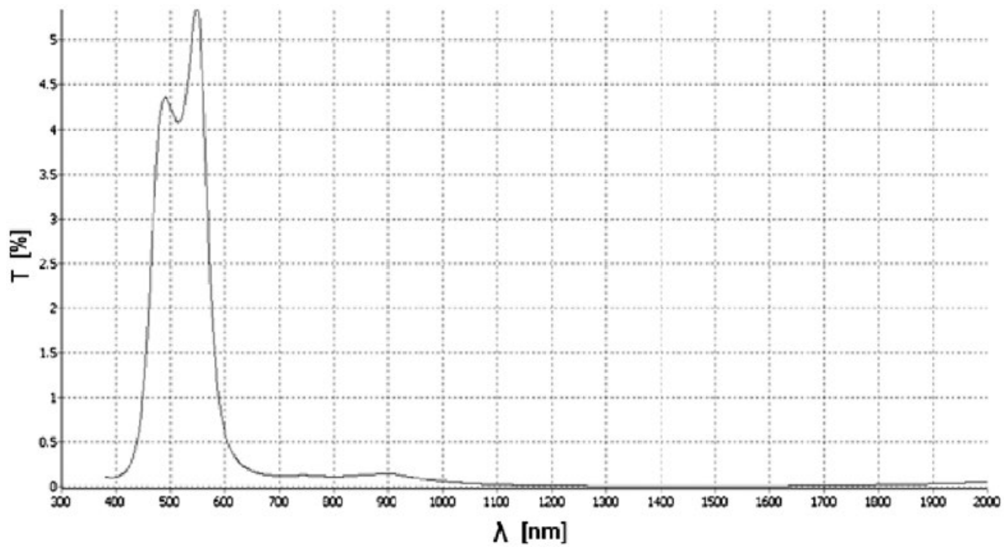


Figure 4. Transmission characteristics *T*(λ) of an interference filter (protection level 4–5).

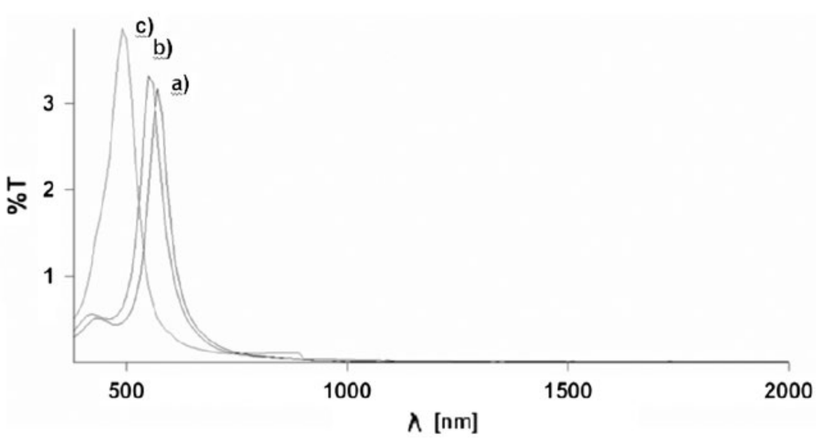


Figure 5. Sample transmission characteristics of an interference filter providing protection level of 4–5 for incidence angles: (a) 0°, (b) 30°, (c) 45°.

Table 2. Maximum filter transmittance values $T_{f\,max}$ correlated with the change of optic radiation incidence angle

$T_{f\,max}$ 380–780 nm	Optic radiation incidence angle		
	0°	30°	45°
	Protection level 4–3		
Metallic reflective	18.784	18.409	17.341
Interference	13.654	15.493	15.401
	Protection level 4–5		
Metallic reflective	2.937	2.622	2.055
Interference	3.944	4.617	5.898
	Protection level 4–7		
Metallic reflective	0.600	0.473	0.312
Interference	0.319	0.323	0.439

Tables 3–5 present the results concerning light transmission coefficients and mean IR transmission coefficients within the 780–1,400 nm and 780–2,000 nm spectrum ranges for optic radiation incidence angles: 0°, 30°, 45°.

Table 3. Light transmission coefficients for optic radiation incidence angles: 0°, 30°, 45°—metallic reflective and interference filters

τ_v 380–780 nm	Optic radiation incidence angle		
	0°	**30°**	**45°**
	Protection level 4–3		
Metallic reflective	14.133	14.333	14.750
Interference	9.082	10.546	12.319
	Protection level 4–5		
Metallic reflective	2.021	1.857	1.594
Interference	1.470	2.887	3.199
	Protection level 4–7		
Metallic reflective	0.353	0.292	0.203
Interference	0.160	0.212	0.219

Table 4. Mean IR transmission coefficients within the 780–1,400 nm range for optic radiation incidence angles: 0°, 30°, 45°—metallic reflective and interference filters

τ_A 780–1,400 nm	Optic radiation incidence angle		
	0°	**30°**	**45°**
	Protection level 4–3		
Metallic reflective	1.486	1.428	1.658
Interference	1.003	0.575	0.681
	Protection level 4–5		
Metallic reflective	0.216	0.190	0.190
Interference	0.038	0.008	0.003
	Protection level 4–7		
Metallic reflective	0.043	0.032	0.033
Interference	0.037	0.039	0.039

Table 5. Mean IR transmission coefficients within the 780–2,000 nm range for optic radiation incidence angles: 0°, 30°, 45°—metallic reflective and interference filters

τ_N 780–2,000 nm	Optic radiation incidence angle		
	0°	**30°**	**45°**
	Protection level 4–3		
Metallic reflective	0.942	0.935	1.167
Interference	0.563	0.367	0.528
	Protection level 4–5		
Metallic reflective	0.134	0.118	0.131
Interference	0.006	0.021	0.013
	Protection level 4–7		
Metallic reflective	0.023	0.0037	0.0038
Interference	0.039	0.042	0.042

Mean IR transmission coefficients for filters protecting against hazardous infrared radiation are determined for 780–1,400 nm and 780–2,000 nm spectrum range, according to the standard requirements (EN 166, 2001; EN 171, 2002), whereas the hazard levels at worksites exposed to infrared radiation are assessed for up to 3,000 nm range. In view of the above, the mean IR transmission coefficients were determined for the 780–3,000 nm spectrum range (Table 6).

Table 6. Mean IR transmission coefficients within the 780–3,000 nm range for optic radiation incidence angles: 0°, 30°, 45°—metallic reflective and interference filters

τ_C 780–3,000 nm	Optic radiation incidence angle		
	0°	30°	45°
Protection level 4–3			
Metallic reflective	0.524	0.527	0.678
Interference	0.362	0.258	0.414
Protection level 4–5			
Metallic reflective	0.055	0.043	0.053
Interference	0.013	0.037	0.008
Protection level 4–7			
Metallic reflective	0.018	0.052	0.053
Interference	0.050	0.054	0.055

5. Discussion

In the present research of transmission characteristics changes at different optic radiation incidence angles for metallic reflective and interference filters, the analysis was divided into two spectrum ranges: visible spectrum (380–780 nm) and IR spectrum (780–3,000 nm).

Within the visible 380–780 nm spectrum, on the basis of transmission characteristics, the light transmission coefficients τ_v and maximum transmittance $T_{f\,max}$ of the analyzed filters were determined for optic radiation incidence angles of 0°, 30°, 45°. For metallic reflective filters (protection levels: 4–3, 4–5, 4–7), an increase of the optic radiation incidence angle results in an increase of light transmission coefficients τ_v and a decrease of maximum transmittance $T_{f\,max}$ of the filter. In the case of interference filters (protection levels: 4–3, 4–5, 4–7), an increase of the optic radiation incidence angle results in an increase of light transmission coefficients τ_v and an increase of maximum transmittance $T_{f\,max}$ of the filter. A shift λ_{max} towards shorter wavelengths occurs, as well as broadening of the transmitted radiation band—an increase of $\Delta\lambda_{1/2}$. Higher transmittance of the visible spectrum in comparison with metallic reflective filters was observed for all the analyzed cases of interference filters.

For the 780–3,000 nm IR spectrum, IR transmission coefficients τ_A, τ_N, τ_C for optic radiation incidence angles: 0°, 30°, 45° were determined on the basis of transmission characteristics. The values of transmission coefficients obtained for the interference filters developed by the authors are lower by an order of magnitude in comparison with the values demonstrated for metallic reflective filters. The above finding provides evidence for more effective blocking of hazardous IR radiation by the developed interference filters.

6. Conclusions

- The investigated metallic reflective and interference filters comply with the requirements specified in the EN 166 and EN 171 standards.
- The values of transmission coefficients obtained for interference filters within the IR spectrum range from 780 to 2,000 nm are lower by an order of magnitude in comparison with the values demonstrated for metallic reflective filters.
- When the beam radiation is incident obliquely on the tested filters, $T_{f\,max}$ and $\Delta\lambda_{1/2}$ are changed. A shift of λ_{max} towards shorter wavelengths, as well as broadening of the transmitted beam (increase of $\Delta\lambda_{1/2}$) is observed.

- Irrespectively of the angle at which the tested filters are positioned in relation to beam radiation on spectrophotometer, the filter properties with respect to protection against IR radiation within the spectrum range up to 3,000 nm remained unaffected.
- Changes in optic radiation incidence angle in relation to the tested filters protecting against IR radiation cause no alterations in the protection level.

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