Three-band interference filters for open flame sensors

Evgeniy Kotlikov, *Natalia* Lavrovskaya*, and *Georgy* Tereshchenko

Saint Petersburg State University of Aerospace Instrumentation, 67, Bol'shaya Morskaya st., Saint-Petersburg, 190000, Russian Federation

Abstract. This paper describes a methodology of synthesizing of interference filters for open flame sensors for the absorption line of 4.4 µm. Its feature is the simultaneous use of reference lines at two wavelengths: 4 and 5 µm. In addition, the paper provides calculations of the transmission spectra of the interference filter at these wavelengths on a sapphire substrate, which blocks long-wave radiation above 6 µm. The use of such filters will increase the reliability of detection of open flames by sensors.

1 Introduction

The detection of open flames is the basis of fire safety systems. Currently, a number of techniques are being developed to detect fire sources at different stages. A large place among them is occupied by optical systems that work on the principle of registering the excess of infrared and/or ultraviolet radiation coming from the flame at certain wavelengths. Such systems are not effective in the case of a slow smoldering fire, but are quite effective for a rapidly spreading fire, i.e. when burning gases and liquids. As a rule, these are various hydrocarbons and their mixtures. Their combustion is accompanied by the release of gaseous or finely dispersed products such as CO_2, H_2O, C (soot), CO, unburned hydrocarbon molecules, etc. [1-4]. Registration of radiation from these substances is the basis of flame detection.

2 The problem

This paper considers sensors that can register radiation of heated CO_2 gas in the infrared range of the spectrum. Their peculiarity is the use of compensating filters allowing to reduce stray light at wavelengths that do not coincide with the radiation of the main flame spectrum at the wavelength of 4.4 µm.

The electromagnetic energy emitted by a flame is located in various spectral ranges: ultraviolet (UV), visible, infrared (IR). The emission spectrum of the flame is determined by the resulting combustion products. Figure 1 shows a schematic spectrum of a hydrocarbon flame in air [1].

* Corresponding author: adele1993@mail.ru

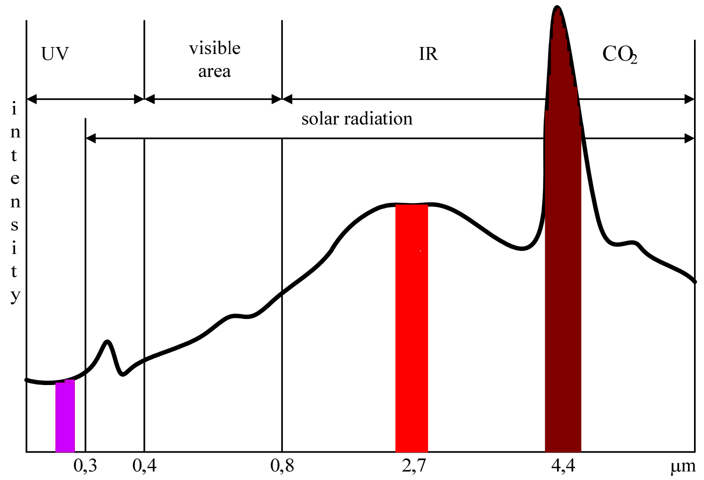

Fig. 1. Characteristic areas in emission spectrum of a hydrocarbon flame.

The solid black curve shows the emission spectrum of an open flame. The darkened areas are parts of the spectrum that can be used in flame detectors. Solar radiation in the UV region of the spectrum with a wavelength of less than 0.28 µm is completely absorbed by air, which eliminates background illumination. Therefore, the appearance of radiation in the 0.20-0.25 µm region indicates an open flame. The radiation peak in the region of 2.5-3.0 µm is strongly absorbed by atmospheric moisture and is not very effective in detecting an open flame. In the region of 4.30-4.45 µm there is a radiation peak characteristic of a flame caused by heated carbon dioxide. Despite the absorption of this radiation by the atmosphere, it can be detected at distances of several tens and hundreds of meters. The registration of this radiation is the basis for the structures described below. The radiation spectrum also includes the spectrum of carbon dioxide lying in the range of 4.20-4.30 µm.

Flames are not the only source of IR radiation. Radiation in this range is also produced by any heated surface and the Sun. This radiation can coincide with the flame radiation, which causes false triggering of the sensor and reduces the sensitivity of the devices. Filtering of the received radiation is required to increase the reliability of the device. For this purpose, receivers sensitive to radiation with a wavelength less than 0.25 µm are used in the UV region. To register radiation in the required IR spectral region of 4.2-4.5 µm, interference filters are widely used [2-6]. Their use is primarily due to their low cost for mass production.

3 Method and results of interference filter synthesis

This paper considers sensors that allow to register the radiation of heated CO_2 gas in the IR range of the spectrum. Their peculiarity is the use of compensating filters allowing to reduce stray light at wavelengths that do not coincide with the emission of the main flame spectrum at the wavelength of 4.4 µm.

Narrowband interference filters (NIFs) [5, 6] have high maximum transmission, high contrast and the required width. With these filters, it is possible to select spectral intervals of different widths, from hundreds of nanometers to fractions of a nanometer.

The original program *"FilmAnalysis*" [7] was used to calculate these and subsequent structures, which allows synthesizing transmission, reflection and absorption spectra in which experimental data of optical constants of films and materials were entered.

Figure 2 and 3 show the transmission spectra of the interference filters in the 4 - 5 µm region. Figure 2 shows the 8-layer NIF at different angles of incidence. The filter design has a SLHLH2LHLH structure, where quarter-wavelength films with high (H) and low (L) refractive indices are used for the 4.3 μm wavelength. The substrate (S) is made of silicon, since it transmits radiation well in the range of 1.3-8 μm. The low refractive index substance is barium fluoride (BaF_2) and the high refractive index substance is zinc selenide (ZnSe). Refractive indices n_{sub}=3.42; n_L=1.40; n_H=2.45.

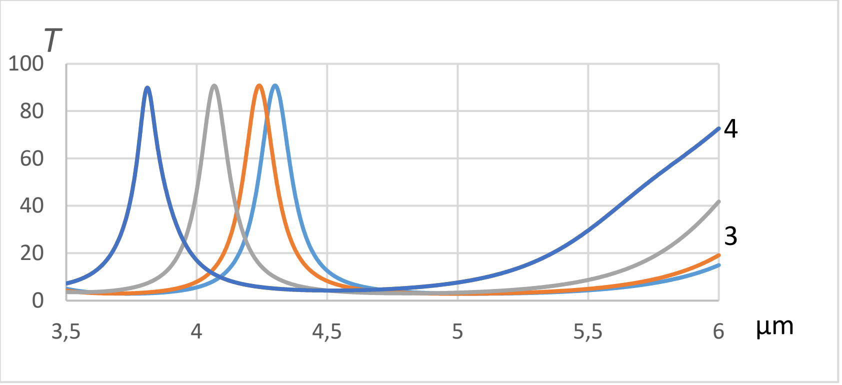

Fig. 2. Transmission spectra of a narrow-band interference filter: 1 – incidence angle 0°, 2 – incidence angle 15°, 3 – incidence angle 30°, 4 – incidence angle 45°.

These filters are reliable and practical at normal radiation incidence. However, it can be seen that as the angle of incidence increases, the transmittance at the desired wavelength of 4.3 μm drops sharply; the filter stops responding to an open flame due to the shift of the transmission peak to the short-wave region of the spectrum. The signal drops by half at an angle of incidence of radiation greater than 30°. If the radiation falls at an angle greater than 30°, the filter will not detect it.

To obtain an optimal signal-to-noise ratio, the transmission spectrum of the IF must coincide with the emission spectrum, so bandpass interference filters (BIFs) are optimal. They have a bell-shaped transmission spectrum. Such filters represent a system consisting of two or three coupled UIFs with the same center wavelength and a separating intermediate layer.

The transmission spectrum of the BIF from two coupled filters is shown in Figure 3. It has a structure of the form SLHL2HLHLHL2HLHL.

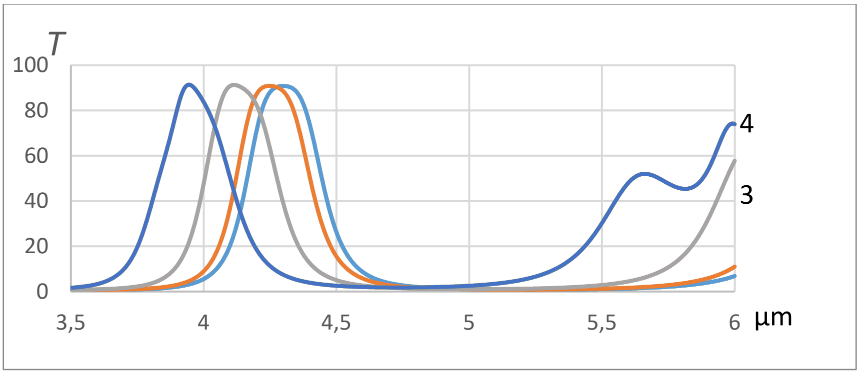

Fig. 3. Transmission spectrum of a bandpass (two-section) interference filter: 1 – incidence angle 0°, 2 – incidence angle 15°, 3 – incidence angle 30°, 4 – incidence angle 45°.

A comparison of the calculated spectra of the NIF and the BIF shows that the radiation energy generated during the combustion process passing through the BIF is more than twice the amount of energy transmitted by the NIF. In addition, it is less critical at high angles of incidence.

An essential point when recording flame spectra is that near the 4 µm wavelength region there is radiation from outside sources. The radiation of these sources overlaps with the flame radiation and interferes with the registration of the useful signal. To reduce the interference and increase the sensitivity, in [5] it was proposed to additionally install a sensor designed for a wavelength close to 4.4 µm. It is proposed to use the sensor wavelength of 4.0+0.2 µm (or 5.0+0.2 µm). The use of a differential scheme for comparing signals at 4.0 and 4.3 µm will reduce the influence of flame radiation fluctuations in the 4.3 µm region.

Examples of the proposed interference filter with transmission maxima of about 4 and 5 µm are shown in Figure 4 and 5. The radiation recorded from them is compared with the working radiation at 4.2-4.4 µm.

To implement such a filter with two transmission maxima, it is proposed to use the following structures. A sapphire plate with transmittance in the region of 3-7 µm is used as a substrate. A filter with transmittance of 4 and about 5 µm is applied on one side of the plate (see Figure 4, curve 1). The structure of the coating has the form shown in Table 1 (λ_0=2.53 µm). Thickness of film $\lambda_0/4$.

Table 1. Filter structure on the front side of the substrate.

Number of layer	Film material	Number of layer	Film material
1	Ge	6	BaF_2
2	BaF_2	7	Ge
3	Ge	8	BaF_2
4	BaF_2	9	Ge
5	Ge	-	-

The spectrum of this filter is shown in Figure 4.

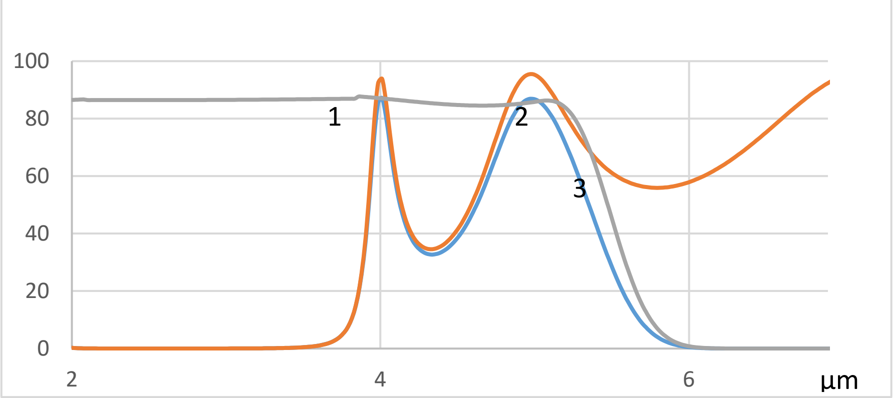

Fig. 4. Transmission spectra of the first filter. 1 - transmission spectrum of a sapphire plate, 2 - filter transmission spectrum without taking into account absorption by the sapphire plate, 3 - transmission spectrum of the first filter on a sapphire plate.

The structure has a narrow transmission peak at a wavelength of 4 µm and a wide one at 5 µm. Suppression above 6 µm is provided by a sapphire plate.

The second filter, which is also applied to the sapphire, has the structure shown in Table 2.

Table 2. Filter structure on the back side of the substrate.

Number of layer	Film material	Number of layer	Film material
1	Si CZ	7	Si CZ
2	ZnSe	8	ZnSe
3	Si CZ	9	Si CZ
4	ZnSe	10	ZnSe
5	Si CZ	11	Si CZ
6	ZnSe	-	-

The spectrum is shown in Figure 5.

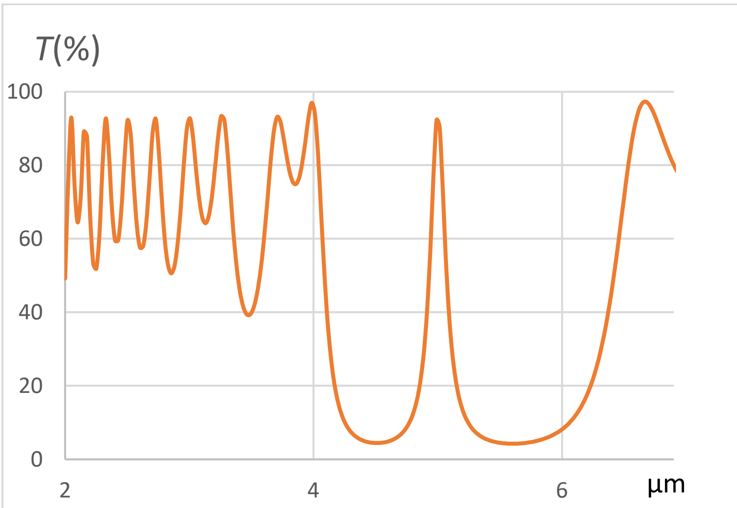

Fig. 5. Transmission spectrum of the second filter.

The filter has a narrow transmission peak at 5 µm. At 4 µm the transmittance is also high.

Collectively, the interference coatings on the sapphire substrate on both sides have the transmittance shown in Figure 6. There are narrow transmittance bands at 4 µm and 5 µm.

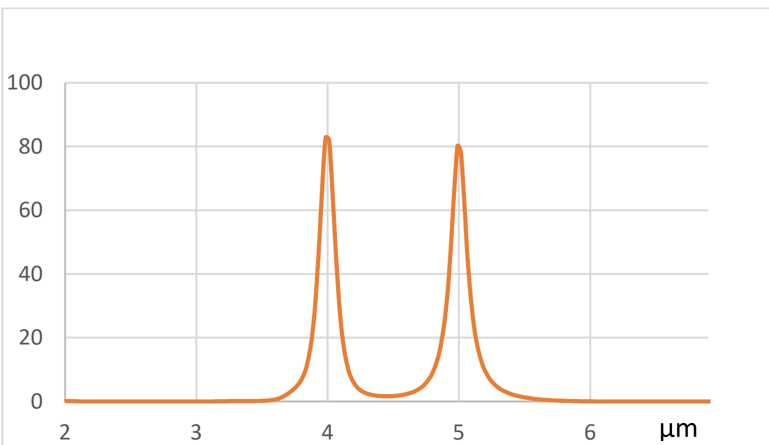

Fig. 6. Transmission of a sapphire substrate with coatings on both sides.

4 Conclusion

The paper describes the synthesis of interference filters for open flame sensors for the 4.4 µm flame absorption line. Their peculiarity is the use of a comparison filter providing simultaneous selection of reference lines at 2 wavelengths: 4 and 5 µm. The transmission spectra of the interference filter were calculated simultaneously at these wavelengths. The use of such comparison sensors will increase the reliability of registration of open flame sources by the sensors.

References

1. B.P. Starshinov, *Fire safety systems* (Handbook, 2003).
2. N.P. Kopylov, V.V. Pivovarov, D.G. Pronin, Fire and Explosion Safety **26**, 5-14 (2017).
3. O.M. Troyanov, Yu.V. Reva, V.I. Komachinsky, Bull. of St. Petersburg university of the state fire service of the ministry of emergency situations of Russia **2018,** 9-14 (2018).
4. Yu.S. Katnikova, T.V. Kononenko, O.G. Lyubskaya, Int. J. of Humanities and Natural Sciences **2-1**, 31-33 (2021).
5. A.V. Tikhonravov, *Design of Optical Coatings* In: Kaiser, N., Pulker, H.K. (eds) Optical Interference Coatings. Springer Series in Optical Sciences, vol 88 (Springer, Berlin, Heidelberg, 2003.
6. W.L. Wolfe, G.J. Zissis, The Infrared Handbook, Eds., ERIM, Ann Arbor, Mich., revised edition, 4th Printing (1993).
7. E.N. Kotlikov, Yu.A. Novikova, I.I. Kovalenko, Information and control systems **3**, 51-59 (2015).