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Filter for TV and video cameras

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Abstract. An infrared-cut filter for TV and video cameras was calculated and fabricated. The filter contains 28 alternating SiO_2 and TiO_2 layers. The filter was calculated using the principle of unequal-thickness layers. This filter has a transmittance of 95 % in 400 to 650 nm range and 1 % in 700 to1150 nm range.

Keywords: interference coating, multilayer interference filter, cut filter.

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It is necessary to use infrared-cut filters to create a high-quality image using TV and video cameras in natural (solar) light. This necessity is caused by the following fact. Human eyes perceive light within the spectral range 400 to 700 nm. However, the photosensitivity of a photodetector (as a rule, is a silicon-target matrix used in TV and video cameras reaches up to 1200 nm. Therefore, the presence of a photocurrent produced by 700 to 1200 nm waves in a total electric signal is undesirable because it does not carry any useful information about image colors. This allows to formulate the following requirements for optical properties of filters: the transmittance in 400 to 650 nm range should be not less than 90 – 95 % and no more than 1 % in 700 to1200 nm range.

In [1], it was reported about the filter provided the transmittance of more than 90 % in 400 to 700 nm range and less than 1 % in 700 to 930 nm one. At the same time, this filter has the very high transmittance (80 – 90 %) in the region of 1000 to 1200 nm. It seems that the role of this transmittance can be ignored because the photosensitivity of silicon in this region is very small. However, a simple calculation shows that it is not so. The solar radiation power in 1000 to 1200 nm range near the Earth surface contains from 18 to 20 % of the solar radiation power in the whole visible region of 400 to 650 nm. Therefore, the contribution into a total photocurrent from 1000 to 1200 nm waves can be appreciable despite the small photosensitivity of silicon in this region. In this article, we describe a filter with the transmittance of about 95 % within the region of 400 to 650 nm and its improved characteristics in the region of 1000 to 1200 nm.

The filter represents the system $(n_H n_L)^N n_H$ of alternating layers with high- and low-refractive indexes and optical thickness $nd = \lambda / 4$ (λ – characteristic wavelength, d – layer thickness). As n_L material we used SiO_2 with the refractive index $n_L = 1.45454$, and as n_H material we used TiO_2 with $n_H = 2.25565$. According to M. Born and E. Wolf [2], the reflection of a multilayer system reaches 99 % at $N = 6$, i.e., a filter must contain 13 alternating layers $n_H, n_L, n_H, n_L, \ldots, n_H$.

A band where the filter has a very high reflection is called the suppression band, designated as R_{100}. The wavelength corresponding to the middle of R_{100} band is designated as λ_0 (reference wavelength). The layers have the optical thickness equal to $\lambda_0 / 4$.

The half-width of R_{100} band in the units $g = \lambda_0 / \lambda$ depends only on the difference between refractive indexes n_H and n_L and is defined by the following expression [3]:

$$\Delta g = \frac{2}{\pi} \arcsin \frac{n_H - n_L}{n_H + n_L} . \qquad (1)$$

Let us define the width of R_{100} band for our data. The high reflection region of our filter should extend from 700 to 1200 nm. The center of this range lies at $\lambda_0 = 950$ nm. Substituting $n_H = 2.25565$ and $n_L = 1.45454$ into (1) we get $\Delta g \approx 0.13$. R_{100} bandwidth has the value of $\lambda_0 \cdot 2\Delta g = 247$ nm. Thus, our materials SiO_2 and TiO_2 can supply only 247 nm R_{100} bandwidth, while the filter bandwidth should have its extent of 1200 – 700 = 500 nm**.** It means that to construct a filter with 500 nm R_{100} bandwidth it is necessary to use two (or three) systems of layers with different reference wavelengths λ_0' and λ_0''. The wavelengths λ_0' and λ_0'' are chosen from the requirement that the bands of high reflection partly overlap. It is clear that the formation of R_{100} band with the width of 500 nm by means of two-layer systems with different λ_0' and λ_0'' using n_{SiO_2} and n_{TiO_2} is a very difficult task. At the same time, the usage of three-layer systems makes the filter design very complex, and its practical realization is very difficult.

We have constructed a filter of two systems such as $(HL)^6H$ with $\lambda_0' = 736$ nm and $\lambda_0'' = 900$ nm and achieved further widening R_{100} band by means of suppression (increasing) of lateral transmittance minima. We obtained the suppression band from 680 to 1050 nm with transmittance of 1 to 1.5 %. However, a large number of lateral transmittance minima arises on the shortwave side of this band in the region of 400 to 650 nm and on the longwave one of 1050 nm. The lateral minima in the region of 400 to 650 nm are generated by the layer system at $\lambda_0' = 736$ nm, and the ones with wavelengths longer than 1050 nm are generated by the layer system at $\lambda_0'' = 900$ nm. The number of these lateral minima is equal to the number of layers in every system, and their depths reach 60 %. Hence, the problem of a filter construction lies in elimination of these minima and preservation of the transmittance in the range of 400 to 600 nm at the level of 95 % and vice versa increasing the depth of transmittance minima down to zero in the region of 1050 to1200 nm.

There are a few receptions to correct the transmittance on both sides of R_{100} band. One of them is to use layers with unequal optical thicknesses according the condition

$$n_H h_H + n_L h_L = \lambda_0 / 2, \quad (2)$$

where h_H and h_L are geometrical thicknesses of layers with a high- and low-refractive indexes. The transmittance is increased in a shortwave range of R_{100} band and simultaneously is decreased in a longwave range when $n_H h_H / n_L h_L > 1$. The relation $n_H h_H / n_L h_L < 1$ gives the opposite result.

A very effective method for increasing the transmittance of a lateral minimum is creation of the last n_L layer at the optical thickness $\lambda_0 / 8$ on the surface of this multilayer system. However, it should be noted that the use of such layer as well as introduction of matching layers between the substrate and multilayer system does not allow to obtain the transmittance more than 80 % in 400 to 420 nm range.

The range of 400 to 420 nm is shortwave in relation to R_{100} band with the center at $\lambda_0' = 736$ nm. However, it can be considered as the longwave one in relation to R_{100} band with the center at λ_{01}, which satisfies the condition

$$n_H h_H = n_L h_L = (3/4)\lambda_{01} \quad (3)$$

or

$$(3/4)\,\lambda_{01} = (1/4)\,\lambda_0'; \; \lambda_{01} < \lambda_0'. \quad (4)$$

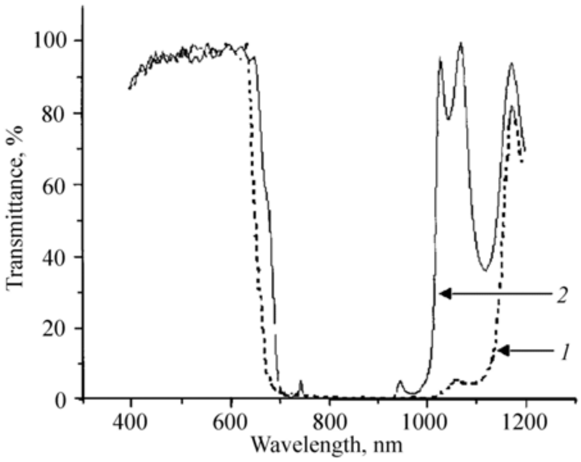

Fig. 1. Optical characteristic of IR-cut filter (simulation): 1 – this work, 2 – filter from [1].

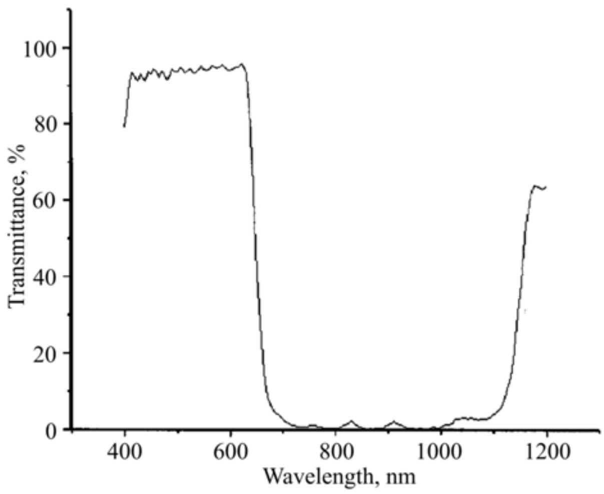

Fig. 2. Optical characteristic of the real IR-cut filter (experiment).

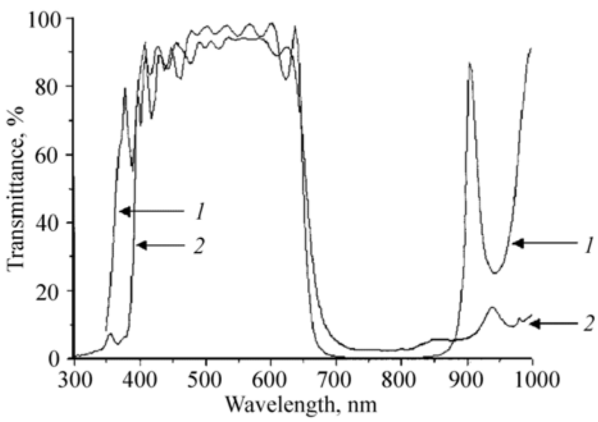

Fig. 3. Optical characteristics of IR-cut filters, produced by Melles Griot (USA) (1) and Taeyoung (Korea) (2).

The design and layer thicknesses of the IR cut-filter.

Layer	Material	Refractive index	Optical thickness (in λ_0)
1	SiO_2	1.45454	0.170
2	TiO_2	2.25565	0.332
3	SiO_2	1.45454	0.335
4	TiO_2	2.25565	0.329
5	SiO_2	1.45454	0.332
6	TiO_2	2.25565	0.325
7	SiO_2	1.45454	0.331
8	TiO_2	2.25565	0.316
9	SiO_2	1.45454	0.330
10	TiO_2	2.25565	0.316
11	SiO_2	1.45454	0.330
12	TiO_2	2.25565	0.316
13	SiO_2	1.45454	0.330
14	TiO_2	2.25565	0.316
15	SiO_2	1.45454	0.295
16	TiO_2	2.25565	0.250
17	SiO_2	1.45454	0.270
18	TiO_2	2.25565	0.250
19	SiO_2	1.45454	0.270
20	TiO_2	2.25565	0.250
21	SiO_2	1.45454	0.265
22	TiO_2	2.25565	0.235
23	SiO_2	1.45454	0.270
24	TiO_2	2.25565	0.240
25	SiO_2	1.45454	0.275
26	TiO_2	2.25565	0.235
27	SiO_2	1.45454	0.285
28	TiO_2	2.25565	0.285
Substrate	Glass	1.51218	

It means that we can consider a band with the center λ_{01} as a band of the next order concerning the band with the center λ_0'. Therefore, if we change the transmittance of the filter in the longwave range for λ_0' band, we simultaneously in the same way change the transmittance in the longwave range for λ_{01} band, i.e., in 400 – 420 nm range. On this basis, we have used layers of an unequal optical thickness for increasing the transmittance in the longwave range of $\lambda_0' = 736$ nm. Choosing the layer geometrical thickness we used the relationship

$$\alpha \cdot n_H h_H + (2 - \alpha)\, n_L h_L = \lambda_0' / 2, \qquad (5)$$

where the coefficient $\alpha < 1$ and $n_H h_H = n_L h_L = \lambda_0'/4$. For optimizing the value of α, we used the geometrical thicknesses h_H' and h_L' with the relation $n_L h_L' / n_H h_H' = 1.2$. The transmittance of 90 to 95 % in the range 400 to 420 nm was obtained for these layer thicknesses. However, the transmittance in the range of 550 to 650 nm was decreased. We have tried to improve the reduction of transmittance in the range of 500 to 650 nm introducing the additional and matching layers. The deposition of the latter layer with $\lambda_0'/8$ optical thickness allowed to increase the transmittance in this range up to 80 %. Further magnification was achieved by the introduction of the matching $\lambda_0'/4$ layer between the substrate and multilayer system.

The refractive index of the matching layer can be found from the relationship [4]

$$n = \sqrt{N_E n_S}\ , \qquad (6)$$

where N_E is the effective refractive index of the multilayer system, and n_S is the refractive index of the substrate. It may happen so that a substance with refractive index n is nonexistent in nature. In this case, it is possible to construct system of three layers such as (aHbLaH) that will play functionally the same role as well as a quarter-wave layer with refractive index n. Coefficients a and b can be determined by the method of effective layers [5]. For our case, the refractive index of the matching layer and its design was calculated in [1].

The filter was constructed on the basis of two-layer systems with the reference waves $\lambda_0' = 736$ nm and $\lambda_0'' = 900$ nm. After the combination of these systems on the substrate, the optimization of the layer thickness at the interface of these systems was carried out using a computer. The final filter contains 28 layers and has the structure (0.44L, 0.88H, 0.44L)0.5L$(HL)^{12}$H0.5L. The layer thicknesses are summarized in Table. The transmittance of the calculated filter and filter from [1] is shown in Fig. 1. It is seen that, in the visible range, the transmittance is nearly the same for both filters and reaches 95 % in 450 to 620 nm range. The transmittance of the calculated filter averages about 2 to 3 % higher than that of the filter in [1]. In the infrared region, however, the distinction of transmittance is drastic. The calculated filter has the transmittance close to zero in the region from 700 to 1030 nm, 5 % – in the region of 1050 to 1120 nm, and, only for 1150–1200 nm, the transmittance band of more than 80 % is observed.

The transmittance of the obtained filter manufactured using the above-mentioned design is shown in Fig. 2. The small (~ 3 %) transmittance reduction of the real filter as compared with the simulated one is caused by monitoring errors for layer thicknesses during manufacturing. The accuracy of the latter was ± 2 nm. For comparison, the transmittance of available commercial filters comprising 29 to 30 layers and manufactured by Taeyoung (Korea) and Melles Griot (USA), which are used in modern TV and video cameras, are shown in Fig. 3.

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