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PROBLEMS IN EXPANDING THE WORKING RANGE OF WAVELENGTH-TUNABLE LIGHT FILTERS

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The possibilities for expanding the range of tuning of the wavelength isolated by a tunable interference light filter, based on a combination of a nonuniform multilayer and a reflecting prism, are investigated. The degree of influence of the immersion liquid on the lower limit of wavelength tuning is studied. That influence is shown to be limited. A connection between the scheme for obtaining a nonuniform multilayer and the maximum wavelength of light reflected by the multilayer is demonstrated theoretically. The working range of a wavelength-tunable filter, the nonuniform multilayer of which is based on holographic photographic plates, is expanded by changing the scheme for obtaining the multilayer. The possibility of advancing into the near ultraviolet by using other materials (such as bichromized gelatin) is demonstrated experimentally.

Tunable interference light filters [1, 2] enable one to make light monochromatic in broad light beams and to smoothly vary the isolated wavelength. The tunable interference light filter of [3] consists of a reflecting prism or optical wedge and a nonuniform multilayer with an immersion liquid between them. A reflecting phase hologram on a flat mirror is a particular case of a nonuniform multilayer.

Light filters now being built using LOI-2 photographic plates and a He–Ne laser and constructed with a BU-60 prism reflect light at wavelengths of 420-620 nm with variation of the angle of light incidence on the filter from $-30°$ to $+30°$, with the half-width of the reflection band being 8-10 nm at all wavelengths and the reflection coefficient being 40-80%, depending on the spectral range. The task of the present work is to expand the working range of the wavelengths isolated by the light filter.

EXPERIMENTS WITH LOI-2 SILVER HALIDE HOLOGRAPHIC PLATES

The short-wavelength limit of the working range is explained by the fact that at some positive angle φ of light incidence on the filter, a broad band with a maximum in the green range, henceforth called the background, appears in the reflection spectrum in addition to this selectively reflected band. With increasing φ, the background intensity grows sharply while the intensity of selective reflection falls. The wavelength at which the deflection of the recorder pen corresponding to the selectively reflected band equals the deflection corresponding to the background we have arbitrarily called the lower limit λ_l of wavelength tuning.

The following experiments were carried out to clarify the causes of the short-wavelength limit of the range. We prepared light filters using two lasers: a helium–neon laser (633 nm, "red" filter) and an argon ion laser (476 nm, "violet" filter). Experimentally obtained functions $\lambda(\varphi)$ for both filters are given in Fig. 1 (curves *1* and *2*). It is seen that the lower

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TABLE 1. Ratio of the Intensities of Selective and Nonselective Reflection as a Function of the Index of Refraction of the Immersion Liquid

Immersion liquid	n	I_λ/I_b, %
Chloroform	1,442	29
Olive oil	1,465	41
Camphor oil	1,469	63
Oil No. 1	1,472	80
Linseed oil	1,476	81
Castor oil	1,479	81
Vaseline	1,481	70
Para-xylene	1,491	102
Meta-xylene	1,493	137
Ortho-xylene	1,512	110
Oil of cloves	1,537	27

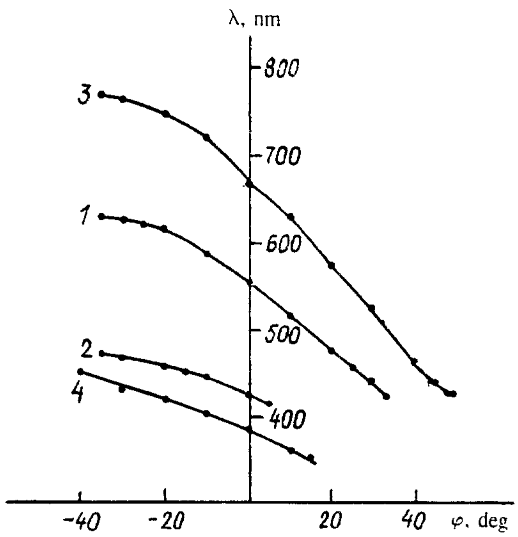

Fig. 1

wavelength limit λ_l is the same for filters obtained with different lasers. For the violet filter the low wavelength is reached at $\varphi \approx$ 5-10°, whereas the red filter permits angles of 30-35°. Hence we conclude that the lower limit is not determined by the limit of the angle of incidence, i.e., by the construction of the filter.

To study the influence of the immersion liquid on the properties of the filter, we investigated different immersion liquids having an index of refraction n of from 1.442 to 1.537 in the visible range. We took one BU-60 quartz prism and one plate with a multilayer made by a helium–neon laser. From them we built a filter with one immersion liquid, investigated it, and then took it apart. The same was done with another immersion liquid. The comparison of these filters consisted in the following.

The wavelength drum of the monochromator was set at 390 nm and then the selective reflection maximum was found by rotating the light filter. The magnitude I_λ of that maximum was measured. Here the filter was set at $\varphi = 20°$. Then, without changing the filter position, the background maximum I_b was found and measured by rotating the monochromator wavelength drum. The ratio I_λ/I_b was calculated. If that ratio is greater than 100%, then the line intensity is greater than the background intensity. For a filter with this immersion liquid, the lower limit is therefore $\lambda_l < 390$ nm. The experiment showed that the ratio I_λ/I_b passes through a maximum as a function of n. The maximum is clear-cut, despite the very large spread of the results (the average results are given in Table 1). A lower limit $\lambda_l < 390$ nm was obtained for xylenes and $\lambda_l > 390$ nm for other

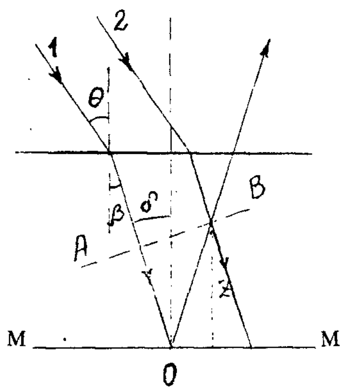

Fig. 2

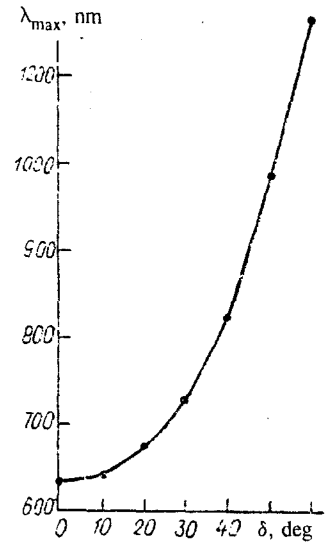

Fig. 3

substances, but at 390 nm a filter with any immersion liquid has a background. Hence it is not only the immersion liquid that is responsible for nonselective reflection.

We then sought the cause of nonselective reflection in the properties of the multilayer. In preparing a multilayer, one creates a periodic structure with a period

$$d = \lambda_0/2n \tag{1}$$

in the material, where λ_0 is the wavelength of the light used to obtain the flat-mirror hologram and n is the average index of refraction of the multilayer. If d for an already prepared multilayer is somehow altered, its tuning range should shift.

To reduce the lower limit, we baked a prepared multilayer for 2 h at 90°C in hopes that the thickness of the emulsion would decrease and, with a constant number of periods, each period d would become smaller, and hence the lower limit of wavelength tuning of the filter would become lower. This experiment demonstrated the following. The upper limit is indeed lowered. The entire $\lambda(\varphi)$ graph for a red filter runs lower by an average of 19 nm, and that for a violet filter by 10 nm. But it is cut off in the short-wavelength range at the same wavelength as an unbaked multilayer, but at a smaller angle φ. The reflection coefficient hardly changed in the process, but I_λ/I_b was smaller for the baked plate than for the unbaked one at the same wavelength.

We also carried out experiments with swelling the photoemulsion before exposure (the photographic plate was kept for a day in water vapor at room temperature in an exsiccator) and normal drying after developing. In this case, at $\lambda_0 = 633$ nm the upper limit was reduced but the lower limit did not change, while at $\lambda_0 = 476$ nm the light filter did not work at all. These experiments can be explained by the fact that by wetting and drying the photographic emulsion, we act only on the gelatin but do not change the sizes of the silver halide (AgHal) grains. In drying the gelatin, the layers of the multilayer are brought together, and since the grains retain their former size, scattering from grains of the multilayer, rather than specular reflection from the layers, occurs at short wavelengths, as before. At $\lambda_0 = 476$ nm, upon drying of the emulsion the ratio of the distance between layers to the grain size becomes such that the whole pattern of the periodic structure becomes indistinct and the filter does not work. That is, a smaller emulsion grain size is needed to move into the shorter-wavelength range, so that light is not scattered from the grains. The processing technique also affects the grain size of the processed emulsion. The next experiments were therefore aimed at improving the parameters of the light filters by introducing changes into the standard technique of processing the photographic material, consisting of developing, fixing, and decolorizing, but they did not yield positive results. When we treated the photographic plates before preparing the holograms and the prepared holograms with Na sulfide, the reflection coefficient was increased and the profile of the reflection band was improved, but the lower limit was not lowered.

We also carried out experiments for the purpose of expanding the wavelength tuning range by increasing the upper limit. Before exposure, the photographic plates were cooled to about −20°C, so that the emulsion layer became thinner. They were then exposed in cooled form and then processed at room temperature, as usual. They yielded a narrower spectral band than unfrozen ones. The same reflection coefficient and working range were obtained. The next experiment consisted in drying the plates in a vacuum drying cabinet for a day at 60°C before exposure. The dried plates were then exposed with an argon ion laser. The wavelength of this laser (476 nm) is the upper limit of the tuning range for a filter made from undried plates. For filters made from dried plates we obtained an upper limit of 520 nm, i.e., it was raised by more than 40 nm. The reflection coefficient decreased slightly in the process. The other parameters were hardly changed.

We also moistened the multilayer before taking the light filter apart. The plates were first placed in a room with 60% humidity for a day. The control group of plates was kept in a room with 40% humidity. We found that upon moistening the multilayer, the wavelength tuning range increased by about 50 nm due to an increase in the upper limit. The lower limit remained virtually as before.

The virtual constancy of the lower limit shows that the short-wavelength limit of the tuning range is related to the properties of the AgHal contained in the LOI-2 photographic plates with which all these experiments were conducted.

INFLUENCE OF THE SCHEME FOR OBTAINING A FLAT-MIRROR HOLOGRAM

The upper limit of the wavelength tuning range of a light filter can also be increased in a fundamentally different way, that is, by changing the scheme for recording the flat-mirror hologram. Equation (1) was obtained under the condition that when recording the hologram, light falls normally onto the flat mirror and the surface of the light-sensitive material parallel to it. If the light is not perpendicular but falls at an angle δ, then the distance d between nodes of the standing wave will be greater than $\lambda_0/2n$ [see (1)]. Let us find d in this case. In Fig. 2, $M-M$ is the flat mirror; *1* and *2* are two beams incident on the mirror, and δ is the angle of incidence. The result of interference between these two beams will be observed at the point B. We designate the distance from the mirror to the point B as z. We draw the incident wave front AB through B. At B the path difference between rays *1* and *2* is determined by the travel of ray *1* from A to B and by the loss of a half-wave in reflection,

$$\Delta x = AO + OB + \lambda_0/2n. \tag{2}$$

We express AO and OB in terms of z and δ:

$$OB = z/\cos \delta, \tag{3}$$

$$AO = OB\cos 2\delta = z\cos 2\delta/\cos \delta. \tag{4}$$

Substituting (3) and (4) into (2), we obtain

$$\Delta x = [z(1 + \cos 2\delta)/\cos \delta] + \lambda_0/n. \tag{5}$$

Imposing the condition of an interference maximum (a whole number of waves) on Δx, we obtain the location of the maxima of the standing waves:

$$z = (\kappa - 1)\lambda_0\cos \delta/(1 + \cos 2\delta)n. \tag{6}$$

The distance d between adjacent nodes of the standing waves will then be

$$d = \lambda_0\cos \delta/n(1 + \cos 2\delta). \tag{7}$$

Equation (1) follows from (7) as a special case for $\delta = 0$. The wavelength of light reflected by the multilayer is related to the period of the multilayer by the equation

$$\lambda = 2dn\cos \alpha. \tag{8}$$

Using Eqs. (7) and (8), we obtain the relationship between the wavelength of light reflected by the multilayer and the conditions for obtaining the multilayer (λ_0, δ) and the angle α of light incidence on the finished multilayer:

$$\lambda = 2\lambda_0 \cos \alpha \cos \delta/(1 + \cos 2\delta). \tag{9}$$

Since λ_{max} corresponds to $\alpha = 0$, from (9) we obtain the dependence of λ_{max} on δ and λ_0:

$$\lambda_{max} = 2\lambda_0 \cos \delta/(1 + \cos 2\delta). \tag{10}$$

The result of a calculation based on Eq. (10) is given in Fig. 3.

One must allow for the fact that Eq. (7) was obtained without allowance for the difference between the indices of refraction of air and the light-sensitive material. To allow for this difference, we rewrite Eq. (7) in the form

$$d=\lambda_0/2n\sqrt{1-\sin^2\delta}. \tag{11}$$

If the light is incident from air, we must allow for the relationship between the angles of incidence θ and refraction β. For a plane-parallel layer of light-sensitive material, we have $\beta = \delta$. In this case, d is expressed in terms of the angle of incidence θ as follows:

$$d=\lambda_0/2\sqrt{n^2-\sin^2\theta}. \tag{12}$$

It is seen from the graph (see Fig. 3) that a change in the angle δ from 0 to 30° changes λ_{max} little, and only by changing δ substantially (more than 30°) can one significantly increase the maximum wavelength. But at large angles of incidence there will be large losses to reflection at the boundary between air and the light-sensitive material. The experiment also shows that when the angles δ are too large, a large background appears in the light isolated by the filter.

This can be avoided by placing a reflecting prism in front of the light-sensitive material in optical contact with it. If we use an AR-90 prism and direct the reference light beam at one of its adjacent faces, then for normal incidence on the prism the light falls at a 45° angle onto the light-sensitive material with virtually no loss. As a calculation shows (and experiment confirms), a maximum wavelength of more than 800 nm is obtained in this case if a He–Ne laser is used.

If light is incident on an adjacent face of the AR-90 prism not normally but at an angle θ, then we have

$$\delta = 45° - \beta. \tag{13}$$

With allowance for this, from (10) we obtain

$$\lambda_{max} = \lambda_0\sqrt{2}(n + \sin \theta)/(n + 2\sin \theta). \tag{14}$$

The authors experimented in the process of obtaining multilayers, varying the angle δ with and without an AR-90 prism. The best result was obtained when LOI-2 plates were illuminated by a He–Ne laser through an AR-90 prism, but light fell on the prism at an angle $\theta = 15°$ rather than normally. The angle of refraction was then $\beta = 10°$, while the angle of incidence on the light-sensitive material was $\delta = 35°$. The filter made in this way had an isolated band with a good triangular profile, a spectral width of 9-10 nm at the half-maximum level, and a wavelength tuning range of 350 nm. A working graph of this light filter is given in Fig. 1 (curve *3*).

USE OF OTHER THAN SILVER HALIDE LIGHT-SENSITIVE MATERIALS

In concluding that the large silver halide (AgHal) grain size limits an advance into the short-wavelength range, we decided to try photographic materials not containing silver halides. Experiments were carried out with photopolymerizing composites [4, 5] and bichromized gelatin (BCG). Flat-mirror holograms in BCG were obtained using a method presented in

[6]. A Cd laser (442 nm) was used. The photographic material was illuminated normally in obtaining the flat-mirror hologram. We prepared FBU-60 filters for the near-IR range based on BCG holograms. In Fig. 1 (curve *4*) we give the dependence of the wavelength of such a filter on the angle of light incidence on it. The spectral band width of this filter is smaller than for AgHal filters.

The experiments with BCG confirm that it is precisely the AgHal photographic material that set the lower limit of 420 nm obtained with LOI-2 plates. With other holographic materials it is possible to advance into the UV range.

CONCLUSION

Thus, a working range of wavelength tuning of 420-770 nm can now be obtained using LOI-2 plates. The lower limit of the tuning range of working wavelengths of the light filter can be reduced to 370 nm using BCG.

The use of different lasers, different holographic materials, and different schemes for obtaining flat-mirror holograms can yield different working long-wavelength ranges for a light filter.

The filter's geometrical configuration (the use of one or another reflecting prism) also influences the filter's working range, but clarifying this question is a task for future research.

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