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Design and manufacture of metal/dielectric long-wavelength cutoff filters

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Thin films of high reflecting metal, such as Ag, have a high reflectance in the long-wavelength region. When they are combined with dielectric layers, it is possible, through thin film interference effects, to induce transmission in certain shorter wavelength regions. Thus, they are useful components for the design of long-wavelength cutoff filters with a broad rejection region. In this paper, metal/dielectric multi-layer designs based on this principle are numerically investigated. Three designs with different cutoff wavelengths and with very broad transmission regions in the visible or near-IR spectral ranges are presented. An excellent rejection on the long-wavelength side extends beyond 20 μm . Experimental results for one of the designs produced in our magnetron sputtering system are given. © 2010 Optical Society of America

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1. Introduction

Cutoff filters are a generic filter type that finds numerous applications in optical instruments. A cutoff filter with an ideal performance will have a very high transmittance in the transmission region and a very low transmittance in the rejection region, both regions being as broad as possible. The transition from one region to the other should occur at the specified wavelength as rapidly as possible. The ideal cutoff filter would be very compact, operate in normally incident transmitted light, and be affordable. Of course, real cutoff filters do not meet the above ideal requirements. More information on the terminology used in the definition of cutoff filters, and on the performance of real devices will be found in Refs. [1–3].

Two basic types of cutoff filters exist: those that remove radiation of short or of long wavelengths. There exist many colored glasses, chemical compounds, semiconductors, and liquids with extinction coefficients that can be used to produce short-wavelength cutoff filters that satisfy almost all of the above requirements.

Unfortunately, the same goals are much harder to achieve for long-wavelength cutoff filters. In long-wavelength cutoff filters based on the intrinsic optical properties of the materials, the transitions between the transmission and rejection regions are much less steep than in the case of short-wavelength cutoff filters.

The first thin film interference long-wavelength cutoff filters with a steep transition between the transmission and rejection regions were essentially two-material quarter-wave stacks with thicknesses that were somewhat modified to remove the reflection ripples in the transmission band [4]. Unfortunately, the rejection region of such a coating is rather narrow. Depositing a second, contiguous reflectance coating onto the first could extend the rejection region. However, this required a doubling of the number of layers, and, in addition, it was at the expense of the width of the transmission region because of the appearance there of higher order reflectance peaks. This narrowing of the transmission region can be avoided through the use of inhomogeneous layer reflectors in which higher order reflectance peaks are suppressed or by employing multilayer coatings consisting of three or more materials, as demonstrated by Thelen [5].

However, such solutions still have a limited rejection region that will depend on the transition wavelength and that will be small compared to the rejection regions offered by the cutoff filters to be described below.

Long-wavelength cutoff filters have been produced in which the light is incident on the multilayer coating at an oblique angle. For example, multilayers embedded between prisms are used for color separation purposes, but usually for these applications, the required transmittance and rejection bands are not very wide and the cone angle at which the devices operate is also not very large. For some parts of the spectrum, it is possible to produce nonnormal incidence long-wavelength cutoff filters with a high transmittance and a broad rejection region that are based on a combination of thin film interference and critical angle effects and absorption [6,7], but these devices are useful only for collimated light. Efficient long-wavelength cutoff filters based on multiple reflections from several identical all-dielectric reflecting coatings can be made, but they are bulky and are difficult to integrate into commercial devices [1].

Broadband blocking is also an issue with narrow-band transmission filters. The problem has been solved long ago through the use of one or more thin silver layers embedded in a dielectric layer stack with the thicknesses of the various dielectric and metal layers selected so that transmittance is induced in the required wavelength region and suppressed elsewhere [8]. Of course, the price for the extended blocking was a reduced transmittance in the transmission region.

Long-wavelength metal/dielectric cutoff filters were reported in 1995, but the main object of that work was to reduce the reflected beam in the visible spectral region through absorption [9]. For this reason, the absorbing metal layers were made of a relatively poorly reflecting material, such as Ni.

In this paper, we are not concerned with low reflectance. The aim is to produce a metal/dielectric cutoff filter with a rejection over a broad spectral region but with as high a transmittance in the transmission region as possible. The metal of choice was, therefore, silver.

Section 2 of this paper deals with the design of the long-wavelength cutoff filters. In Section 3, the implementation of one such filter is described. Section 4 contains a discussion of the results and some conclusions.

2. Design of Metal/Dielectric Long-Wavelength Cutoff Filters

A. General Remarks on Materials and the Design Approach

The three coating materials used in all the multilayer designs in this paper are SiO_2 , Nb_2O_5 , and Ag. The substrate is made of BK7 glass. The refractive indices of SiO_2 and Nb_2O_5 were experimentally determined in our laboratory (see Table 1). These values may be different from those in other published

data, but, because the two materials are very stable, the differences will be small enough so that they will not affect any conclusions in this paper. The case of silver is different. The optical constants of Ag are much more sensitive to the deposition method and to process parameters. To make things worse, the optical constants of Ag layers are also a function of the film thickness. It is hard to find consistency in published thin film Ag optical constants. In this paper, we chose to use the bulk optical constants for silver given by Palik [10]. These constants do not depend on the deposition method, and it is our experience that the optical constants of good Ag films are close to the bulk values, and so the multilayer designs presented in this paper should be of use to others. Another problem with Ag films is that silver forms islands during its initial growth. This also means that the effective optical constants of very thin Ag layers are strongly dependent on their thickness. The optical constants of such discontinuous layers are very different from those of bulk Ag. Such layers are much more absorbing than a continuous silver layer. Using very thin Ag films in the multilayer therefore causes complications in the design process. Because such layers do

Table 1. Optical Constants of Nb_2O_5 , SiO_2 , and Ag Used in This Paper^a

Wavelength (nm)	Nb_2O_5	SiO_2	Ag	Ag
	n	n	n	k
400	2.427	1.484	0.173	1.950
450	2.346	1.478	0.151	2.470
500	2.297	1.474	0.130	2.918
550	2.264	1.470	0.125	3.339
600	2.241	1.468	0.124	3.732
650	2.224	1.466	0.139	4.129
700	2.212	1.464	0.142	4.523
750	2.203	1.463	0.146	4.899
800	2.196	1.462	0.144	5.289
850	2.190	1.461	0.152	5.678
900	2.186	1.460	0.170	6.052
950	2.182	1.460	0.196	6.404
1000	2.179	1.459	0.214	6.757
1050	2.176	1.459	0.231	7.113
1100	2.174	1.459	0.244	7.475
1150	2.172	1.458	0.267	7.680
1200	2.170	1.458	0.301	7.818
1250	2.169	1.458	0.333	7.957
1300	2.167	1.457	0.363	8.095
1350	2.166	1.457	0.392	8.233
1400	2.165	1.457	0.418	8.370
1450	2.164	1.457	0.434	8.742
1500	2.164	1.457	0.451	9.013
1550	2.163	1.457	0.469	9.320
1600	2.162	1.456	0.489	9.636
1650	2.162	1.456	0.509	9.952
1700	2.161	1.456	0.529	10.260
1750	2.161	1.456	0.548	10.571
1800	2.160	1.456	0.569	10.923
1850	2.160	1.456	0.589	11.245
1900	2.160	1.456	0.609	11.545
1950	2.159	1.456	0.629	11.883

^aThe Ag data fit the bulk optical constants given by Palik [10].

not reflect as well as bulk Ag, this results in a degradation of the blocking performance. For this reason, in this paper all Ag layers used have a layer thickness that is not less than 15 nm.

Designs of long-wavelength cutoff filters with different performances were found numerically. The commercial OptiLayer program [11] and proprietary software developed at the National Research Council of Canada [12] were used for the calculations. Both programs contain refinement and the needle synthesis method routines that were applied to different starting designs. In the calculations, the constant target transmittance in the transmission region started at a rather high value and was gradually reduced in different sets of calculations until a value was found for which a cutoff filter with a good performance could be obtained.

There are obvious limitations on the number of metal layers, the thickness of an individual metal layer, and the total thicknesses of all the metal layers that can be used in the multilayer designs: the greater these quantities are, the lower the transmittance in the rejection region, but also in the transmission region. So, a compromise solution must be found that depends on the particular application or design target. In order to reduce the absorption in the transmission region, the metal layers must be placed at positions within the multilayer stack at which the electric field is small. This is done automatically by the numerical design programs, which adjust the thicknesses and positions of the metal layers as well as those of the dielectric layers to achieve the best approximation to the desired design target. In the following multilayer stack design examples, two to four Ag layers are used, each with a thickness no less than 15 nm.

B. Long-Wavelength Cutoff Filter Designs

1. Visible Transmission Region

Figure 1(a) shows the refractive index profile of a 32-layer design. It contains three Ag layers, and the other layers are made of SiO_2 or Nb_2O_5 . The calculated transmittance (solid curve) and absorption (dashed curve) of the layer system are plotted in Fig. 1(b). The transmission region covers the entire visible range (400 to 700 nm), and the final target transmittance is 50%. The average deviation from the target transmittance is about 1.5% in the transmission region. The transmittance in the rejection region is small, but it depends on the wavelength and is generally decreasing as the wavelength increases. Between 800 and 2000 nm, the calculated transmittance is less than 3.0×10^{-4} and the average transmittance in this wavelength range is 9.5×10^{-5} . The calculations were only performed up to 2000 nm because of a lack of optical constants for the layer materials at longer wavelengths. However, from actual transmittance measurements on the samples produced in our laboratory (see next section), we

know that the good rejection extends well into the far-IR spectral region. In Fig. 1(b) we can see that absorption in the rejection region is quite small (less than 10%). This means that more than 90% of the rejection in the rejection region can be attributed to reflection.

2. Near-IR Transmission Region

It is possible to design a long-wavelength cutoff filter with a transmission region located in a wavelength range longer than the visible part of the spectrum. How far the transition between transmission and rejection regions can be shifted toward longer wavelengths depends on the thickness of the Ag layers. Generally, for the same desired transmission region transmittance, thinner Ag layers will be needed for transmission regions located at longer wavelengths. It will be the discontinuous growth mode of very thin Ag layers that will set a limit on the upper wavelength at which the transition from transmission to rejection regions can occur in this type of filter. Figure 2(a) represents the refractive index profile of a long-wavelength cutoff filter with a transmission region transmittance of 44% extending from 1200 to 1580 nm. Only two Ag layers are needed in this multilayer because the transmission region is relatively narrow. There are 36 layers in the multilayer. The total metric thickness of the multilayer is $7.60 \mu\text{m}$. This is much thicker than for the long-wavelength

Fig. 1. (Color online) Long-wavelength cutoff filter design with a 50% transmittance in the visible.

cutoff filter for the visible transmission region. In the rejection region (up to 3000 nm), the calculated maximum and average transmittances are about 2.8×10^{-4} and 1.0×10^{-4} , respectively. The absorption in the rejection region is also relatively small, as in the case for the filter with the visible transmission region.

3. Broad Transmission Region

By using more Ag layers, we can design a filter with an even broader transmission region. Figure 3 shows such a design. The transmission region extends from 390 to 1000 nm with a transmittance of about 36%. The width of the rejection region is expected to be similar to those of the above two examples. We can see from the refractive index profile in Fig. 3(a) that the much broader transmission region is not at the expense of a more complicated multilayer structure. Actually there are 33 layers in the multilayer, and the total metric thickness is only $1.74 \mu\text{m}$. However, because the total thickness of Ag is larger, there is more absorption and, therefore, it was necessary to accept a lower transmission region transmittance. For a given transmission region transmittance, having more Ag layers also means that the thicknesses of individual Ag layers have to be thinner. So, in this case, the minimum requirement on the thickness of the Ag layers limits the width of the transmission region. The transmittance in the rejection region

Fig. 2. (Color online) Long-wavelength cutoff filter design with a 44% transmittance in the near-IR spectral region.

Fig. 3. (Color online) Long-wavelength cutoff filter design with a 36% transmittance in the visible and near-IR.

(1100 to 2000 nm) of this filter decreases monotonically from 3.0×10^{-3} to 1.3×10^{-5} .

C. Electric Fields and Suppression and Enhancement of Transmission

For metal/dielectric multilayers, the electric field within the multilayer structure is very critical to the filter performance. The electric field at a metal layer is directly related to the loss or absorption in the layer, and this is almost always a focal point when designing a multilayer with absorbing layers. For a cutoff filter, high transmission in the transmission region requires that the electric field be as low as possible at the metal layers at the corresponding wavelengths. In the rejection region, higher absorption is helpful for rejection, but rejection can also be realized by the high reflection. So, in a rejection region, a high electric field is not necessarily an issue for cutoff filters. As we see in Figs. 1–3, the absorption in the rejection region is actually lower than it is in the transmission region, which suggests a lower electric field. To visualize the electric field distribution, we calculate the square of the electric field normalized to the incident electric field as a function of position within the multilayer. Figure 4 plots this quantity for the 50% visible transmission region design (Fig. 1) at two representative wavelengths in the transmission region. The vertical bars in the figure indicate positions of the Ag layers inside the multilayer. In this and the following diagram, 0 and 2200 nm on the x scale correspond to the

Fig. 4. (Color online) Electric field in the transmission region of a long-wavelength cutoff filter of Fig. 1. In this and the following diagram, 0 and 2200 nm on the x scale correspond to the substrate/multilayer and the multilayer/air interfaces. Light is incident from the air side.

substrate/multilayer and the multilayer/air interfaces. Light is incident from the right side. We see that at both wavelengths, one at the center of the transmission region (550 nm) and the other at the cutoff edge (700 nm), there is a significant electric field distribution over the entire multilayer, although the field is generally larger on the right side of the Ag layers. Another noticeable feature for these two distributions is that the electric field distribution has minimum values at the positions of the metal layers. This is also the case for almost every wavelength in the transmission region. It suggests that the numerical procedures optimized the multilayer structure to minimize the loss and therefore to enhance the transmission in the transmission region. However, it should be noted that because the optimization is for a broad wavelength range, the positions of Ag layers are not exactly located at the electric field minima. In Fig. 5, the square of the electric field is plotted at two wavelengths in the rejection region. We see that the electric field only fluctuates significantly on the right side of the Ag layers. The field progressively decreases in the Ag layers along the incident direction; i.e., less and less light penetrates each Ag layer. So, the rejection in a rejection region is much like the reflection from a mirror. The most significant contribution of absorption comes from the first Ag layer where the electric field is the largest among the three Ag layers. At 1067 nm, the electric field is much larger than that at 900 nm. This also means that there is a higher field in the Ag layers at 1067 nm and, therefore, more absorption at this wavelength. The small peak at 1067 nm of the absorption curve in Fig. 1(b) is the result of this high electric field.

We thus see that the rejection in the rejection region is mainly due to reflection and that the trans-

Fig. 5. (Color online) Electric field in the rejection region of a long-wavelength cutoff filter of Fig. 1.

mittance in the transmission region relies on induced transmission. It would be interesting to know how effective the multilayer stack is in enhancing these two effects. In Fig. 6(a) are plotted the transmittances of the 50% transmission region cutoff filter and that of a single Ag layer on a BK7 sub-

Fig. 6. (Color online) (a) Calculated transmittances in the transmission and rejection regions of the 50% long-wavelength cutoff filter and of a single Ag layer on a BK7 substrate. The total Ag thickness in the 50% transmission region filter is the same as that of the single Ag layer. (b) Ratio of the above two transmittances.

strate. The thickness of the single Ag layer equals the total Ag thickness in the 50% transmission region cutoff filter. We can see that in the transmission region, the transmittance of the 50% transmission region filter is much higher than that of the single Ag layer. The ratio of the two transmittances varies from 8 to 100 in the transmission region, with the largest ratio located at the cutoff edge. In the rejection region, the transmittance ratio varies between 0.2 and 0.03. Thus, the multilayer stack, compared to a single Ag layer, enhances both the transmittance and the rejection in the corresponding regions by 1 or 2 orders of magnitude.

D. Some Interesting Properties of the Solutions

The metal/dielectric long-wavelength cutoff filter designs described in the above sections have some interesting properties. With not much more than a change of the metal layer thicknesses, one can obtain new long-wavelength cutoff designs with different transmission and rejection region transmittances. We use the visible transmission region cutoff filter to demonstrate this property. For this purpose, a series of filters was designed with the average transmittances in the transmission region varying from 50% to 0.0001%. The refractive index profiles of three of these filters are shown in Fig. 7. We can see from this figure that the most significant difference in the multilayer structure of these designs is in the Ag layer thicknesses. This is also true for the other two filter designs described in this paper. The design process is quite simple: start with an existing design, set a new

Fig. 7. Multilayer refractive index profiles for visible transmission region long-wavelength cutoff filters with different transmission region transmittances.

target by reducing or increasing the transmittance in the transmission region, and then optimize the multilayer. This usually results in an equally good new design of different transmission and rejection region transmittances. Figure 8 shows the transmittances of these filters on a logarithmic scale. Except for the absolute values, the shapes of these transmittance curves are very similar, even though the transmittances in the transmission regions differ by many magnitudes.

The average transmission region (400 to 700 nm) and average rejection region (800 to 2000 nm) transmittances are plotted in Fig. 9(a) as a function of total Ag thickness. We see that on a logarithmic scale, both the average transmission and rejection region transmittances appear to lie on straight lines. In other words, both quantities depend on the total Ag thickness exponentially.

It is very interesting that such a relationship, which is similar to the behavior of a single absorbing layer, even exists for absorbing layers embedded in a complicated dielectric multilayer structure. To see some further implications of this feature, we introduce the concept of an average blocking power, which is defined to be the ratio of the average transmission to the average rejection region transmittances. This quantity describes the capability of the cutoff filter to block the unwanted radiation intensity relative to the desired radiation intensity. The blocking power is again plotted in Fig. 9(b) as a function of total Ag thickness. In view of Fig. 9(a), it is not surprising that the blocking power has also an exponential relationship to the total Ag thickness. This can be clearly seen by the least-squares fit to an exponential function [red line in Fig. 9(b)]. The blocking power increases with the Ag thickness, and for these visible transmission region long-wavelength cutoff filters, the blocking power converges toward a limiting value of 2.12×10^4 [Fig. 9(b)]. For the 50% filter, the blocking power is about 5000. Clearly, thicker Ag layers

Fig. 8. Set of visible long-wavelength cutoff filters with different transmittances in the transmission region.

Fig. 9. (Color online) (a) Transmission and rejection region transmittances as a function of total Ag thickness in the visible long-wavelength cutoff filters. (b) Blocking power as a function of total Ag thickness of the visible long-wavelength cutoff filters. The line is an exponential fit to the data points.

result in higher blocking powers. However, long-wavelength cutoff filters with blocking powers close to the saturation value or very large Ag thickness will have such small transmission region transmittances that they will not be useful.

3. Deposition of the Long-Wavelength Cutoff Filters

As already mentioned, the transmittance in both the transmission and rejection regions depends critically on the optical constants of the Ag layers. The challenge in making the cutoff filters is to produce Ag layers with low n and high k values. Because the optical constants of the Ag layer are sensitive to deposition conditions and are also thickness dependent, it is necessary to fully characterize the Ag layers before the multilayer design is finalized. Another problem related to the Ag layers is that an Ag layer can be oxidized during the deposition of the next layer. This would result in a high absorption and could completely destroy the effectiveness of the Ag layer. To prevent this from happening, it is usually necessary to deposit a buffer layer to prevent oxidation. For example, a very thin amorphous silicon layer can be used for such a purpose. The thickness of the silicon layer is such that it is just fully oxidized during the deposition of the next dielectric layer [13].

The cutoff filters were made in our magnetron sputtering system. A general description of a similar

apparatus can be found in Ref. [14]. As described in the cited paper, a broadband optical monitor was used for an *in situ* determination of the layer thicknesses after the deposition of each layer. But since that paper was written, the magnetrons can now also be run with pulsed DC power supplies. It is this process that was used to produce the SiO_2 and Nb_2O_5 layers by reactive sputtering of Si and Nb targets, respectively. An oxygen and argon gas mixture was used in the reactive sputtering of these two materials. The total pressure for the SiO_2 and Nb_2O_5 deposition processes was 2.3 and 3.1 mTorr, respectively. The Ar partial pressure was about 1.0 mTorr for both materials. The Ag layers were deposited in pure Ar gas at a pressure of 0.8 mTorr. The pulsed DC power supply provided about 2 to 3 kW for the deposition of the dielectric layers and much less for Ag. The actual power used depended on the deposition rate required in the process. As stated above, the optical properties of the Ag layers are both thickness and process dependent. However, one can also expect different Ag properties when one switches to a different multilayer design. It is important to converge onto the correct optical constants of the various thicknesses of Ag required. The Ag layers are first deposited on separate substrates, and then they are accurately measured with a spectrophotometric

Fig. 10. (Color online) Measured transmittance of an experimentally produced long-wavelength cutoff filter of 50% transmittance in visible spectral region: (a) from 0.4 to 2.0 μm , measured with a spectrophotometer (the dashed curve is the calculated transmittance based on the layer thicknesses determined in the deposition run) and (b) from 2.0 to 20 μm , measured with an IR ellipsometer.

ellipsometer. The multilayer thicknesses are then adjusted for best performance, and the whole layer system is deposited and evaluated. Usually, several such deposition-characterization-design loops are needed before satisfactory results are obtained.

The measurements on a long-wavelength cutoff filter with 50% transmission region transmittance in the visible spectral region will be described below. Figure 10(a) shows the measured transmittance (solid line) in the 0.4 to 2.0 μm spectral region of the filter. The transmittance was measured with a Perkin-Elmer Lambda 900 spectrophotometer. The dashed curve in this figure is the calculated transmittance based on the layer thicknesses determined during the deposition run. We see that the general agreement between the measured and the calculated transmittances is good, with all the spectral features in the measured curve explained by the calculated curve. The largest difference is in the transmission region, and it is somewhat larger than for an all-dielectric multilayer with a structure of similar complexity that is produced in the same deposition system. This is mainly because of the sensitivity of the multilayer to the uncertainty in the Ag optical constants. The transmittance in the rejection region is very small, as predicted by the calculations. For longer wavelengths, the transmittance at normal incidence was measured using an IR ellipsometer (IR-VASE, J. A. Woollam Co., Inc.). The results between 2.0 and 20 μm are shown in Fig. 10(b). The transmittance in this spectral region is certainly less than 0.4%, because the curve is essentially the same as the noise level curve obtained when the sample was removed and the measurement beam was blocked. The fluctuations in the curve at the longer wavelength end cannot possibly be explained by interference effects in the multilayer. So the only conclusion that we can draw from the IR measurements is that the transmittance is small and that it well below the instrument noise level in this part of the spectrum.

4. Conclusions

We have shown in this paper that using the high reflectivity of Ag and the concept of induced transmission, it is possible to design high-performance long-wavelength cutoff filters with wide transmission and rejection regions. The broad rejection regions are mostly due to high reflection, but absorption in the Ag also plays a part. To maximize the transmittance in the transmission region, the Ag layers are placed in locations within the multilayer structure at which the electric field strength is a minimum for wavelengths within the transmission region in order to minimize absorption losses. The width of the transmission region depends on the number of Ag layers used in the design, more layers generally giving rise to a wider transmission region. The thicker the combined thickness of the Ag layers in a design, the lower the transmittance will be in the rejection region. A lower average transmittance in the rejection region is always accompanied by a lower average transmittance in the transmission region.

We define the ratio of these two average transmittances to be the blocking power of the long-wavelength cutoff filter. The practical limit on the blocking power will be set by the minimum acceptable average transmittance in the transmission region. We have shown that only the thicknesses of the Ag layers need to be scaled in a long-wavelength cutoff filter design to obtain another filter with the same transmission region width but with higher or lower average transmittances in both the transmission and rejection regions.

In our experimental work, we avoided the use of Ag films thinner than 15 nm in order to ensure that the optical constants of the films are close to those of the bulk metal. In fact, the biggest challenge in the manufacture of such metal/dielectric coatings was to develop a repeatable and accurate deposition process for Ag layers with good optical constants, as also pointed out by other researchers [15]. We used DC pulsed magnetron sputtering to produce one of the long-wavelength cutoff filters and found good agreement between the calculated and the measured transmittance data. The measurements showed that blocking is good for wavelengths at least as high as 20 μm , and probably much higher.

In the Introduction, we referred to prior work on narrow bandpass filters based on induced transmittance. Because Ag has a significant extinction coefficient throughout the UV, visible, and IR spectral regions, the methods described here should be equally applicable to the design of wide bandpass filters with good rejection on both sides of the transmission region.

All our design and experimental work was based on the use of thin Ag films. For long-wavelength cutoff filters with a near-UV or -IR transmission region, Al or Au films may be more suitable.

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