JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 24, No. 1-2, January – February 2022, p. 9-14

Design of unidirectional energy flow film based on micro-prism structure

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Unidirectional transmission optical elements are mainly designed based on metal surface microstructures, photonic crystals, etc. and the unidirectional ratio can reach 100%. These elements are mainly used in optical communications, optical switch and have unidirectional energy flow in a narrow spectral range. However, in the other cases, such as solar cells and radiative cooling, unidirectional transmission is usually required in a wide spectral range. In this paper, a unidirectional transmission film with micro-prism structure is proposed and demonstrated based on geometrical optics. When the refractive index of the used materials is about 2.0 and the bottom angle of the micro-prism is between 58-65 degrees, the unidirectional energy flow difference of the film is about 55%. Although this structure cannot achieve 100% unidirectional energy flow ratio, its working band is very wide.

(Received March 26, 2021; accepted February 11, 2022)

Keywords: Unidirectional energy flow, Micro-prism structure film, Radiative cooling

1. Introduction

Passive radiation cooling technology is a novel zero energy consumption cooling technology and the corresponding research has made rapid development in recent years. When this technology is used in tropical areas, due to the high air humidity, the radiation heat transfer between cooling materials and the ambient air is fast, and the cooling effect is poor. If a unidirectional film with angle selectivity transmission of heat radiation can be designed and combined with the radiation material, the radiation heat transfer rate between the radiation material and the ambient atmosphere can be effectively suppressed, and the cooling effect of the material can be improved. At present, unidirectional transmission films are usually designed based on surface plasmon structure and photonic crystal structure, and the unidirectional ratio can reach 100% in a narrow band. These structures are mainly used in the region of optical communication [1-5]. However, for solar cells, passive radiative cooling, etc., the unidirectional transmission in a wide spectral range is usually required, and the surface plasmon and photonic crystal structures are not suitable [6-10]. In this paper, a kind of film with a micro-prism structure has been demonstrated to realize a wide spectrum unidirectional net energy flow of the electromagnetic wave.

2. Theoretical basis

At present, the design of unidirectional energy flow film mainly uses surface plasmon effect and interference diffraction effect. The surface plasmon effect requires the material whose real part of dielectric constant is less than zero, and the diffraction effect requires the microstructure size to be in the same order of the wavelength, which limits the spectral width of unidirectional energy flow. In this paper, we use the geometrical optical effect to design films with a micro prism structure, which can obtain the unidirectional energy flow with wide spectrum. This requires that the micro prism structure size is much larger than the optical wavelength, and the absorption of the material is very low in the working wavelength range.

As Fig. 1 shows, the proposed films have a micro-prism structure. The light energy flows out from the inner side is I_{0A}, and the light energy flows in from the outer side is $I_{0B}+I_{0C}$. I_{0B} and I_{0C} are the light energies incident from the B and C sides of the prism respectively, and I_{0A} is defined equal to $I_{0B}+ I_{0C}$. In Fig. 1, the energy fluencies have the following relations: $I_{0AB}+I_{0AC}=I_{0A}$, $I_{0BA}+I_{0BC}=I_{0B}$ and $I_{0CA}+I_{0CB}=I_{0C}$. The net energy flowing in from the outer sider (I_{NET}) is equal to $I_{0BA}+I_{0CA}-I_{0A}$.

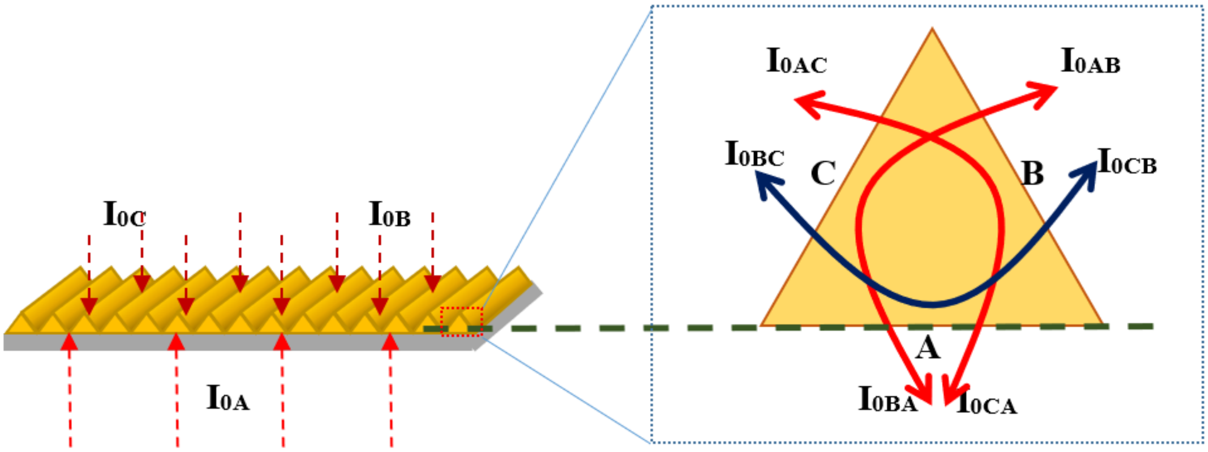
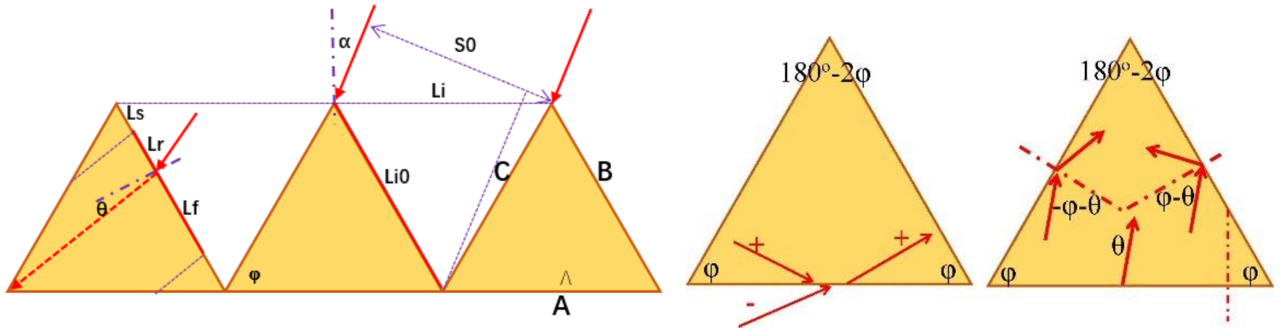


Fig. 1. Schematic diagram of the film and the energy flow of the electromagnetic wave when the refractivity is larger than 2 .0 and the base angle of the prism is 60 degree. To the film, the A side of the micro-prism is definded as the inner side, and the B and C sides of the micro-prism are defined as the outer side (color online)

To evaluate the net energy flowing in from the outer sider, firstly, the irradiation intensity is defined as $I=I_0*\wedge*\cos\alpha$ from a plate radiator, in which the I_0 is the irradiation intensity per unit length perpendicular to the prism extension direction. $\wedge$ is the bottom length of the prism cross section. α is the incident angle of the light. Here, a two dimentional section model is used. As Fig. 2(a) shows, when the light is incident from the outer side, the energy will disttribute on the B and C sides of the prism. In the calculation, base on the structural symmetry, only the light energy incident from the B side of the prism is considered. The energy distribution tatio (r_1) on the B side and the irradiation length (L_{i0}) of the B sides are definced as bellow: when α is smaller than minus 30°, r_1 is equal to 0 and L_{i0} is equal to 0; when α is larger than 30°, r_1 is equal to 1 and L_{i0} is equal to $\wedge*\cos(\alpha)/\cos(\varphi-\alpha)$, in which φ is the base angle of the prim; when α is larger than minus 30° and smaller than 30°, r_1 is equal to $Li/\wedge=0.5*\cos(\varphi-\alpha)/\cos(\alpha)/\cos(\varphi)$, and L_{i0} is equal to $0.5*\wedge/\cos(\varphi)$. The light energy incident from the A side of the prism has a mirror relationship to that incident from the B side. When the light is incident from the inner side (from bottom), the energy will disttribute evenly on the A side of the prism.



(a) *(b)*

Fig. 2. The incident energy distribution on the B side of the prism cross section (a). The definition of the symbol and the incident angle of the light transmitting in the prism (b). $\wedge$ is the bottom length of the prism cross section. α is the incident angle of the light. θ is the refractive angle. φ is the base angle of the prim. L_{i0} is the light irradiation length (color online)

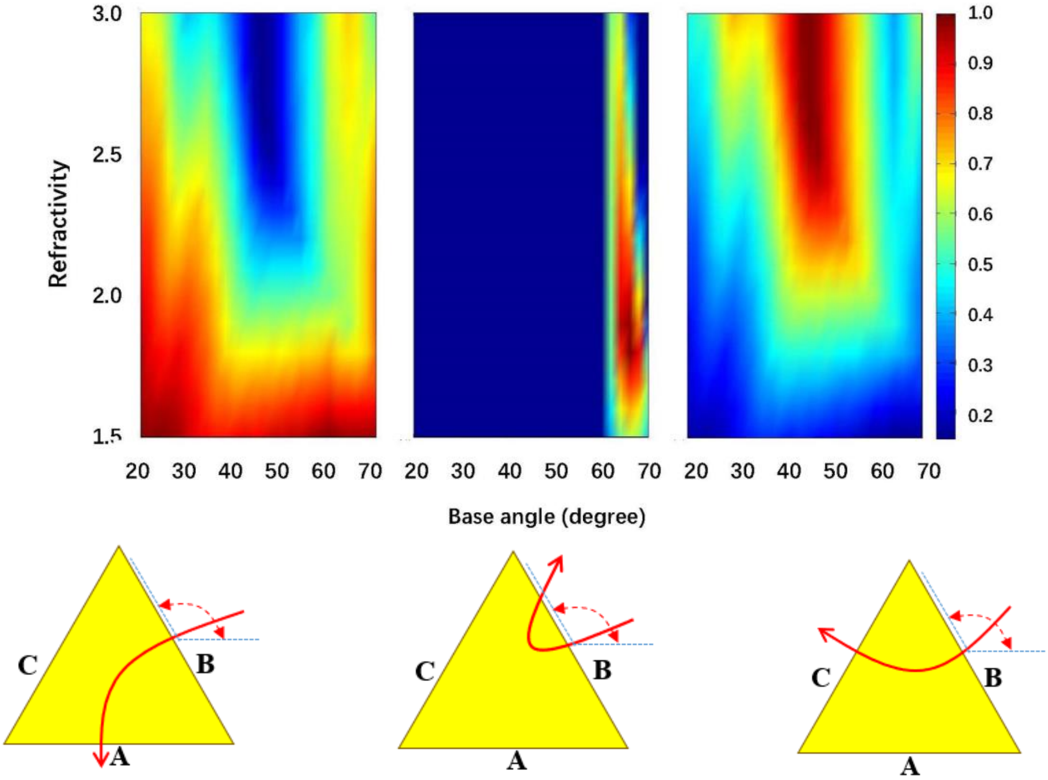
To deal with the light transmission, as Fig. 2(b) shows, the definition of incident angle symbol is as follows: 1) Right-handed helix rule: Four fingers straighten along the direction of light transmission, and then bend towards the normal direction of the interface (less than 180 degrees). When the thumb points out of the paper, the angle sign is positive, and vice versa. Therefore, when the light is reflected at the interface, the symbol remains unchanged, and when the light is refracted, the symbol changes. 2) The incident angle of light emitted from one side to the other side: for example, when a light emits from A side, if counter-clockwise incidence occurs (A→B→C), the incident angle on B side is $+\varphi-\theta$, φ is the angle between A side and B side (positive value). When clockwise incidence occurs (A→C→B), the incident angle on C side is $-\varphi-\theta$.

Ray tracing method is used to track the final reflection or transmission of the incident energy. At the interface, Fresnel reflection is considered. For a total reflection on a prim side, the light energy will redistribution on the other two sides of the prism. The energy redistribution ratio are: Lf=Li0-Lr and Lr=min{Lmax,Li0}-Ls. Here, Lmax=0.5*∧*sin(2φ-90º-θ)/sin(90º+θ)/cos(φ). The reflection and transmission of light in the prism will be calculated until the remaining energy in prism is less than 0.1% of the incident light.

3. Results and discussions

In the case that two flat radiators are placed on both sides of the film, the energy transmission has been evaluated.

As Fig. 3 shows, when the light is incident from the B side and the base angle of the prism is less than 60 degrees, little energy will emitted out from the B side. When the base angle is between 35-60 degrees and the refractive index is greater than 2.0, the energy is mainly transmitted out from the C side, and little from the A side. For the film, the energy is mainly reflected and the transmission is very small. Outside this region, the incident energy will transmit out from the A side. For the film, the energy is mainly transmitted and the reflection is very small. When the base angle of the prism is larger than 60 degrees and the refractive index is about 2.0 or a little smaller, and the incident energy will mainly reflect from the B side. For the film, the energy is mainly reflected and the transmission is very small.

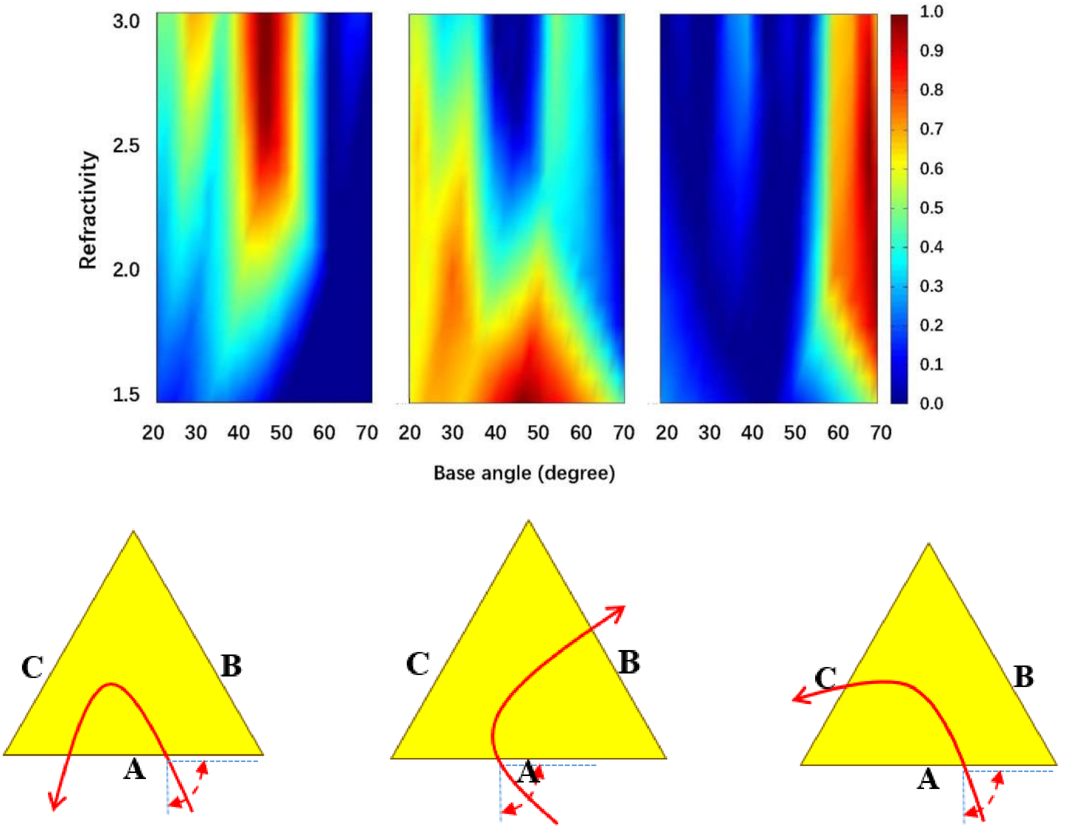


(a) A side *(b) B* side* *(c) C side*

Fig. 3. When the light is incident from the B side, the light energy ratios transmit out from the A(a), B(b), C(c) sides (color online)

As Fig. 4 shows, when the light is incident from the A side and the base angle of the prism is greater than 55 degrees, the incident energy on the A side is almost not reflected, and the energy is mainly transmitted out from the C side. When the refractive index decreases, this range expands to the direction of small base angle. For the film, the energy is mainly transmitted and the reflection is very small. In this region, the refractive index of the material is less than 2.0, and the energy is mainly transmitted out from the B side, especially when the bottom angle is between 40-60 degrees. When the base angle is larger than 60 degrees, the energy is mainly transmitted out from the C side, especially when the bottom angle is larger than 65 degrees. When the base angle is between 35-60 degrees and the refractive index is greater than 2.0, the energy is mainly transmitted out from the A side. For the film, the energy is mainly reflected and the transmission is very small.

For the film, the transmittance difference of the incident energies on both sides can be obtained by calculating the transmittance of the incident energy on the A side of the prism and transmit out from the B and C sides, as well as the transmittance of the incident energy on the B and C sides and trasnmit out from the A side. As Fig. 5 shows, when the prism base angle is less than 53 degrees and the refractive index is between 1.5 and 3.0, the unidirectional energy flow difference of the film is less than 30%. When the refractive index is about 2.0 and the bottom angle is between 58-65 degrees, the unidirectional energy flow difference of the film is about 55%. In this range, the smaller the base angle is, the larger the refractive index range is.



(a) A side* *(b) B side* *(c) C side*

Fig. 4. When the light is incident from the A side, the light energy ratios transmit out from the A(a), B(b), C(c) sides (color online)

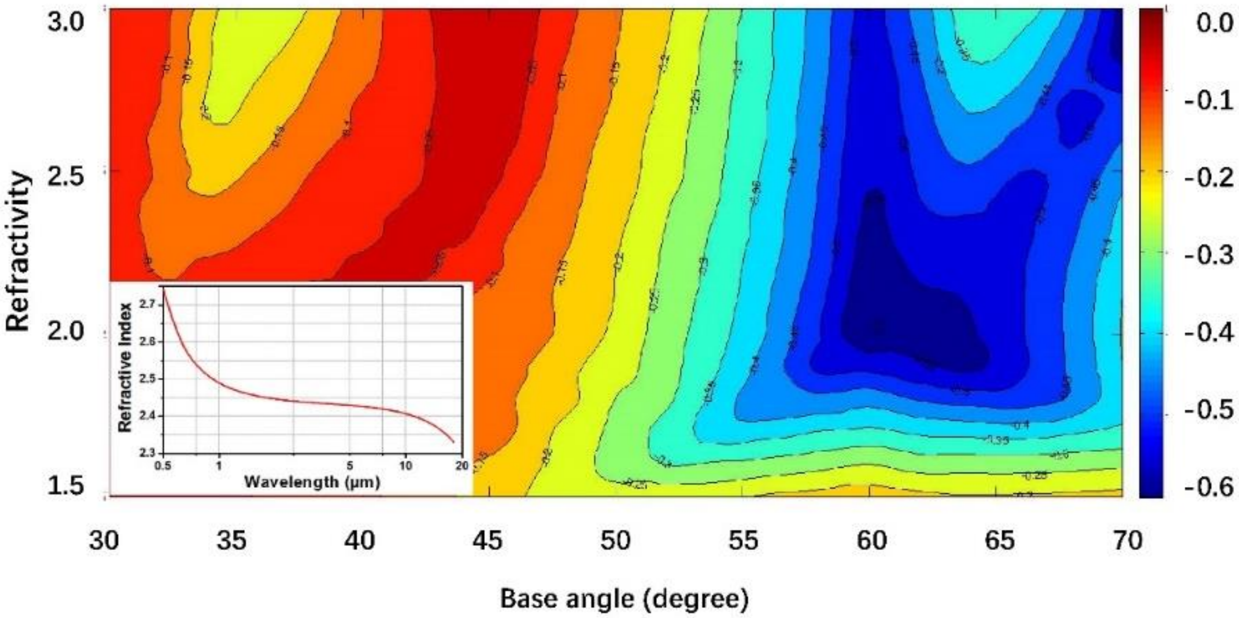
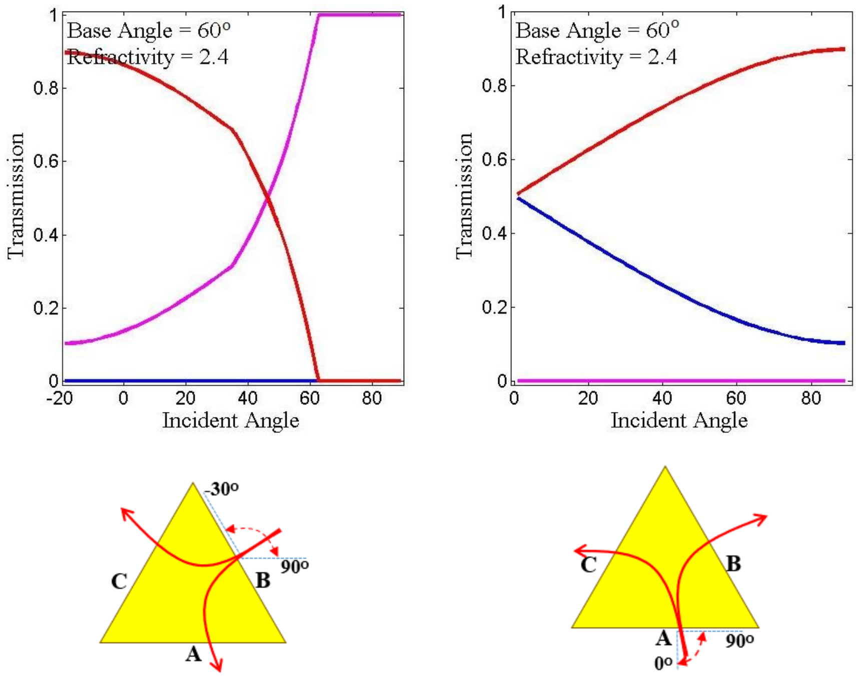


Fig. 5 Variation of energy flow difference with refractive index and base angle. The illustration shows the refractive index dispersion curve of ZnSe, which is derived from the website of: https://en.wikipedia.org/wiki/Sellmeier_equation (color online)



(a) Energy inflow from B sides *(b) energy inflow from A sides*

Fig. 6. When the refractive index is 2.4 and the base angle is 60 degrees, the energy flow difference changes with the incident angle. Magenta-A edge, blue-B edge, red-Cedge (no energy return from the incident edge) (color online)

The energy transmittance of the unidirectional film with micro prism structure is determined by the refractive index, while the broadband unidirectional transmittance is determined by the dispersion of the refractive index. For most dielectric materials, the fluctuation of refractive index dispersion curve is not too large in the non absorption region. For example, the refractive index of ZnSe is greater than 2.4 in the solar radiation band, and increases with the decrease of wavelength and approaches 3.0. In this refractive index range, when the base angle of prism is 60 degrees, 50% energy flow difference can be obtained. In the thermal infrared radiation band, the refractive index of ZnSe is about 2.4, and decreases with the increase of wavelength, but it remains larger than 2.3 up to the wavelength of 20 μm. Therefore, when the base angle of zinc selenide micro prism is 60 degrees, about 55% energy margin can be obtained.

For a specific unidirectional films, when the base angle of the micro prism is 60 degrees and the refractive index is 2.4, the transmittance difference changes with the incident angle is shown in the Fig. 6. When the incident angle on the B side of the micro prism increases from - 30 to 90 degrees, there is no output energy on the B side. The output energy on the A side increases from 10% to 100%. Correspondingly, the energy transmits out from the C side decreases from 90% to 0%. When the incident angle on the A side of the micro prism increases from 0 to 90 degrees, there is no output energy on the A side, and the output energy on the B side decreases from 50% to 10%. Correspondingly, the energy transmits out from the C side increases from 50% to 90%.

4. Conclusions

Based on the ray tracing method, the transmittance and reflectivity of the designed micro-prism structure film were calculated. When the refractive index is about 2.0 and the bottom angle of the micro-prism is between 58-65 degrees, the unidirectional energy flow difference of the film is about 55%. When the refractive index of the used material changes little with the wavelength, the film performance changes little with the wavelength. This film is expected to be used in the field of light transmission energy adjustment, and it can be applied in the case of a wide range reqiument of wavelengths and incident angles. Used in solar cell or passive radiation cooling, this film can greatly improve the device performance.

In this paper, the performance of the films is analyzed based on geometrical optics. Geometrical optics is suitable for the case of small wavelength or large structure size. For instance, in the case of the radiation cooling application, the electromagnetic wavelength is about 10 microns. Therefore, the micro prism structure size needs to be in the order of 100 microns or more.

Acknowledgements

This research was supported by the Zibo Key Research and Development Project (grant 2020XCCG0106).

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