Preliminary study on the broadband antireflection coatings for large aperture telescopes

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Received 2017 May 10; accepted 2017 August 29

Abstract A broadband anti-reflective (AR) coating design for astronomical large-aperture telescopes is proposed. we give simulations of the two-, three- and four-layer silica sol-gel on fused silica and finally get the optimal optical constants. As a comparison, we discuss the traditional dielectric material that applied to broadband AR coatings. To better guiding the following experiment, we also conduct error analysis and feasibility analysis, combining with the technological characteristics of sol-gel. The analytical method is suitable for other wavebands and substrates. It is also instructive for the large area AR coatings in the field of solar cell.

Key words: instrumentation: miscellaneous — methods: numerical — techniques: spectroscopic

1 INTRODUCTION

It is more and more difficult to apply appropriate AR coatings onto the transmission optical elements, the aperture of which are gradually increasing as large ground-based optical/infrared telescopes develop (Tokunaga 2014). In spite that most large-scale telescopes adopt the segmented mirror active optics and reflective optical structures, many large-aperture prisms, which could improve the light gathering power and collect more information from the observation objects, are used in the terminal equipment such as various spectrographs (Angeli et al. 2004). In addition, the hermetic windows of many telescopes need to be coated with AR coatings. Unlike AR coatings that used in solar cells and other devices which only focus on its transmission properties (Kanamori et al. 2002; Liu et al. 2012), rigorous surface precision is desired for optical lens in telescope, especially the correctors. Thus, we hope that the thickness of coating would be small as possible and the whole coating growth process could be carried out under lower temperature, which will make less influence on the surface precision. In addition, a good spectral reproduction ability is very important, which makes the subsequent spectrum analysis more precise and easier. In view of the fact that most dielectric materials have absorption in the ultraviolet wave region, the limitation of alternative materials in the coating design makes an unsatisfactory spectrum transmittance when applied to telescopes whose working waveband ranging from UV to the near IR.

At the beginning of this century, the sol-gel coatings was firstly applied in large-aperture telescopes and an encouraging ultra-broadband AR result was achieved (Phillips et al. 2008). The Atmospheric Dispersion Corrector (ADC) for the Keck-I Cassegrain focus with fused silica prisms is about 1022mm in diameter. A simple structure of silica sol-gel over MgF₂, layer which is conventionally obtained by the vacuum deposition, produces a well-formed coating from 310 nm to 1100 nm (Phillips et al. 2006). The relative-low refractive index (RI) of the silica sol-gel is perfectly matched with the fused prisms, and there is a fewer RI difference between the silica sol-gel and incident medium (i.e. air). The features above make it possible to achieve a good broadband transmittance in two layers only. On the contrary, much more layers should be conducted if the traditional dielectric materials are used. Therefore, we reduced the thickness and number of layers by employing the sol-gel coatings, and whats more, the transmittance results became even better. Moreover, the sol-gel process has its minor restriction in the substrate shape and size, a better homogeneity, and a lower temperature process, all of which give a perfect substitute for the traditional vacuum deposition while involving in the ultra-broadband AR coatings on large-aperture substrate, and, it features the simple technical process and high cost performance. There are many larger optics in the Thirty Meter Telescope (TMT) under construction and the Large Optical Infrared Telescope (LOT) planed in China (Zhang et al. 2016). If we replace the combination of dielectric materials and sol-gel layers in KECK with silica sol-gel only, then the difficulties in film uniformity, the limitation in the dielectric materials, safety and economy problems will be readily solved. An exciting prospect of sol-gel coatings application in the astronomical telescope could be predicted.

In this paper, this problem will be in-detail discussed. We firstly carried out numerical simulation for the sol-gel broadband AR coatings, focusing on the coating design, and we also hope to propose an ideal coating structure in theory and finally obtain some good results. These simulations are based on the existing experimental facts rather than the theoretical possibility. Then, we conducted the feasibility and error analyses combined with the specific processes, and finally canceled some solutions that are extremely difficult to implement. The results would give some basic guidelines for the subsequent experiments.

2 THEORY AND HYPOTHESIS

Reflection and transmission occurs when a light arrives the interface of two different media, the refractive index are n_0 and n_1 , respectively (Born & Wolf 1959). The reflectivity of the normal angle incidence is $R = [(n_0 - n_1)/(n_0 - n_1)]^2$, supposing that the media is nonabsorbent. For the common BK-7 glass, of which the refractive index is about 1.52, the reflectivity is as high as 4% from one side, in other words, the transmittance is only about 92%. An ideal homogeneous single-layer AR coating could achieve zero reflection at the reference wavelength while satisfying the following conditions: the optical thickness of the coating should be $\lambda/4$, where λ is the reference wavelength; and $n_c = (n_a n_s)^{1/2}$, where n_a , n_c , n_s are the RIs of the air, coating, and substrate, respectively. For the dielectric material, in order to achieve near zero reflection of the monolayer, the refractive index of the substrate, which is calculated under the above conditions, is at least 1.9 or more, and it is clear that most of the substrates of low refractive index do not satisfy this condition. Due to its loose and porous characteristics, the refractive index of the silica sol-gel is very low, which perfectly matching with the low RI substrate, and thus the zero reflectance at a special wavelength can be achieved. However, an effective near-zero reflectance is achieved only for a narrow spectral width around the reference wavelength because of the uniform RI throughout the whole coating, and in the rest of waveband, the reflectance will increase rapidly until up to the bare substrate at half-wavelength.

Let's back to the reflectance formula concerning light travels between two media with different RI, $R = [(n_0 - n_1)/(n_0 - n_1)]^2$, we can draw a conclusion that the smaller the difference of RI between adjacent layers is, the fewer the reflection loss is. It is conceivable that there will be nearly no reflection loss when the RI of the coating changes slowly from the substrate to the air, that is to say, the sharp variation of refractive index between adjacent layers should be avoided. The ideal condition would be that the RI continuously decreases from the bottom to the top of the coating, which is the so-called gradient-index AR coating. Since the 1960s, a great many of papers have payed great attention to the design and application of the optical gradient-index coatings (Anders & Eichinger 1965; Southwell 1983, 1985; Dobrowolski et al. 2002). There are many advantages besides the perfect broadband and omnidirectional spectral performance, e.g. excellent mechanical properties (Rats et al. 1999), fewer scattering losses (Arnon 1977), the less residual stress (Tang et al. 2011), the enhanced laser damage resistance (Ristau et al. 2008), and the enhanced temperature stability (Tang et al. 2011). However, it is very difficult to manufacture gradient-index coatings in optical and infrared band. Although some special process may be used to produce materials with continuous changes in refractive index (Li et al. 2010; Huang et al. 2007), the production process is complicated, which is not suitable for large area of fabrication, and the scope of application is limited. The multilayer coating can be viewed as a discrete approximation of the gradient-index AR coating, which is described as quasi-gradient coating, so a more feasible method is to use several uniform sub-layers to approximate the inhomogeneous gradient-index coating. Until now, the oblique-angle deposition and chemical etch-leach process have successfully manufactured the quasi-gradient coating (Xi et al. 2007; Liu et al. 2012), but they are not suitable for astronomical lens. Through our analysis, three layers, or even two layers of sol-gel film achieve excellent broadband anti-reflective effect. This method has a marvelous application prospect in the field of broadband large-aperture telescopes due to its advantages in film uniformity, low-stress and suitability for large area plating. At the same time, the sol-gel practice can also be applied to the field of solar cells, so that the photoelectric conversion efficiency could be widely improved.

Sol-gel process is a kind of chemical coating method. The usual practice is to have organic metal alkoxide dissolved in ethanol or methanol and then to add water as hydrolytic reagent, which is accelerated by catalysts. Here we use tetraethyl orthosilicate as reactant and the overall reaction is shown as follows (Thomas 1985, 1992)

 $Si(OC_2H_5)_4 + 2H_2O \longrightarrow SiO_2 + 4C_2H_5OH$

We often use concentrated hydrochloric acid or concentrated ammonia as catalyst, which also supplies the water. According to the various catalyst being added, this reaction will produce products different in their microstructure, which would affects coating properties. With acid catalyzing, a siloxane chain structure with an alkoxy and hydroxyl group is firstly formed, it will be in continuous polycondensation as the solvent evaporating after its being coated until a cross-linking, dense SiO₂ coating is formed, the characters of which is low porosity and high RI (approximately 1.43). Under alkalinious catalyst condition, the sol tends to form monodisperse silica colloidal suspension. By adjusting the process parameters, the silica colloid can be maintained in a size and morphology (~20nm) suitable for coating, as a result, the coating is made up of disordered accumulational silica particles with high porosity and low refractive index. Considering two different RIs of acid and base catalyzed suspension, we add the acid catalyzed sol to the base catalyzed sol in a certain proportion, which is the so-called two-step method, the siloxane chain structure acts as a linking medium for the alkali-catalyzed sol suspended particles, then a material with a refractive index between them is prepared. The refractive index adjustment range depends on the two mixtured sol (Thomas 1992).

The simplified quasi-gradient form usually follows the theoretical numerical solutions. Considering that the particular coating design depends on the available coating technology, we give the quasi-gradient coating design directly, combined with experimental facts and practical experience. We also give the error and feasibility analysis. To better guide our experiments in the future, we exclude the results either impossible or difficult to achieve. So, several notes are proposed for better simulation as follows.

- 1. Considering that the operating band of the ADC of KECK and TMT telescope are about 300nm-1100nm, our optimization is also within this range.
- 2. The alkali-catalyzed thin film silica particles are about 20nm. Taking the film thickness uniformity into account, we set the optimized film thickness of a single layer to be at least 50 nm.
- 3. Due to the limitation of the refractive index and thickness controlling accuracy, we will give the tolerance range of the optical constants and its influence on the transmittance and examine the feasibility of the designed film structure.



Fig. 1 The red line is composed of measured date by ellipsometer, and the black one is the fitted result.

- 4. Fused silica is chosen as the substrate, which is commonly used and has no absorption in ultraviolet band.
- 5. In the optimized band, the silica sol-gel film is in normal dispersion. In order to better fit its true dispersion curve, the simulation value is set to a linear relationship, as showed in Figure 1. There is a different value of 0.01 in refractive index between the center wavelength and the edge of the band, which is

$$y = -2.5 \times 10^{-5} x + 0.0175 + n_{mid} \tag{1}$$

 n_{mid} is the refractive index value at the center of the band (i.e. 700nm). We name the material with the refractive index at 700 nm. Of course, you can also ignore the dispersion, which have few effect on spectrum performance.

With the assistance of Essential Macleod, we will start our simulations from the simplest two-layer film, to find the best combination of RI and film thickness and finally give the optimum solution. The analysis method can be applied to more layers and the target band can also be changed as needed with analysis method remains unchanged.

3 NUMERICAL SIMULATION AND ANALYSIS

By means of the acid-base two-step method, the refractive index can be continuously adjusted from the alkali-catalyzed film (about 1.18) to the acid-catalyzed film (1.42 or so). Our basic idea is to discretize the refractive index with the sample interval $\Delta n = 0.03$ and the results are as follows:

$$n = 1.43, 1.40, 1.37, 1.34, 1.31,$$

 $1.28, 1.25, 1.22, 1.19, 1.16.$

For multilayer coatings, different refractive index values are assigned to each layer, and then we optimize thickness for each combination, the aim of which is to make the transmittance in each point as higher as possible in the target band. The best coating structure would be sought out after comparing the optimal solutions of the whole RI combinations. Since the transmittance varies continuously with the refractive index and thickness, i.e., there is no occurrence of mutation, our results could be accordingly considered as the optimal solution under the certain number of layers.



Fig. 2 Transmittance that change with n_1 when n_2 were fixed. The curves go down with the increase of n_1 in the visible region, and the red lines denote conditions which $n_1 > n_2$.

3.1 Two-layer System

Assume that the RI of the outer layer is n_1 , and the film thickness is d_1 , similarly, n_2 and d_2 are the optical constants of the inner layer. By means of control variable method, n_1 , n_2 are fixed respectively to discuss the impact of RI variation of the other layer on the transmittance. The following results, unless particularly stated, are of the single-sided transmittance.

Firstly, the RI of the inner layer is fixed, the structure of which is Sub $/ n_2 / \cdots /$ Air, the transmittance curves are shown in Figure 2. In general, the curves decline with the increase of RI of the outer layer in the visible region, whereas, in the ultraviolet and near infrared regions, the condition is complicated that the curve is crossed which is not serious. Therefore, it can be approximated that the smaller the outer layer RI is, the higher the transmittance is. Except the Figure 2a,each figure has a unimodal curve (red lines) that appears to be different from others, which are the results when the outer layer RI is greater than that of the inner layer. The simulation results show that the outer layer thickness is zero, that is, the two-layer system degenerates into a single layer, so the inequation of $n_1 < n_2$ must be fit when applying two-layer AR coatings.

Then we fix the n_1 , that is, Sub / \cdots / n_1 / Air. In view of the above conclusions drew when n_2 was fixed, several RI combinations that have a small value of n_1 were chosen to be discussed, with the restricted condition $n_1 < n_2$, which is illustrated in Figure 3.It is obvious that the transmittance curves



Fig. 3 Transmittance that change with n_2 when n_1 were fixed. The curves go up with the increase of n_2 in the visible region, and the red lines denote the best result, respectively.

rise with the increase of RI of the inner layer in the visible region, whereas, a converse variation in the ultraviolet and near infrared regions.

In these different curves, we should choose the optimal one, which is related to the specific transmittance spectral requirements, e.g., the requirement that a high transmittance in a relative narrow band, or that an average transmittance as high as possible in the whole band, and there would be different optimization results with regard to various spectral performance requirements. Here, our optimization target is, maximizing the lowest transmittance in the region from 300nm to 1100nm, that is,

$$MAX(T_{min}(\lambda))$$

According to the optimization target, we choose three best results from Figure 3 b, c, d, respectively, namely, 1.34/1.22, 1.31/1.19, and 1.28/1.16 (Fig. 4). Apparently, combination of 1.28/1.16 gets the best consequence. In order to make the results more accurate, we have the RIs in the range of 1.25-1.31 discretized by $\Delta n = 0.01$, in view of practical feasibility, the lowest RI be set as 1.16. With the same optimization method, we get the best result, 1.29 / 1.16, as shown in Figure 5, the minimum transmittance is $T_{min} = 99.175\%$, which is the highest value we believe that could achieve theoretical.

Figure 4 and 5 shows a shape of "M" curves in the target waveband, which has a minimal value in visible region, two maximal values in ultraviolet and near infrared region. In visible region, the curves meet the conditions $T \propto 1/n_1$ and $T \propto n_2$, but an opposite variation trend in the rest wavebands, bounded by wavelengths at two maximal transmittance. In other words, the trend of the middle part of the "M" curve is opposite to that of the two sides. So the process of seeking the optimal solution could be intuitively expressed as finding a curve that makes the minimum point equal to the edge transmittance on both sides of the band, that is, A, B, C three points in the same line as far as possible (Fig. 5).



Fig. 4 Three best results from Figure 3

Since the sol-gel method is affected by many process conditions, it is impossible to precisely adjust the refractive index and film thickness during the actual fabrication. In the following part of this section, we will discuss the effect of the small changes in the optical constant on the transmittance curve.

We take the best coating structure 1.29 / 1.16 for example, several cases with $\Delta n = 0.01$ are shown in Figure 6, the small error of the RI makes a transmittance variation of about 0.1% in the short wave region, and 0.05% in the infrared region ,which are acceptable.

We all know that the changes in the thickness of optical coating could lead to the horizontal movement of the transmittance curve. We still choose the combination 1.29/1.16 to do our analysis, the designed value of the physical thickness is $d_1 = 102$ nm, $d_2 = 91$ nm. Figure 7 shows variation of transmittance with the physical thickness error, $\Delta d_1 = \pm 5$ nm. The average transmittance of the whole band remains unchanged, but the curve shifts to the infrared region as the thickness increase, as a result, the main variation of T_{min} occurs at the edge of band, i.e., 300nm and 1100nm. There is a transmittance decline of 0.3% at 300nm when $\Delta d_1 = +5$ nm, yet, only a decline of 0.1% at 1100nm when $\Delta d_1 = -5$ nm, that's because the slope of the curve near 300nm is larger than that near 1100nm, as a consequence, greater influence occurred in ultraviolet region, so we prefer the positive physical thickness errors supposing that the error exists. The inner layer shares a similar error rule with the outer layer. Another significant practical guiding conclusion is that the single layer thickness error (as small as possible) does not affect the transmission curve if we keep the total thickness of the two layers as a constant. In the actual coating forming process, we can have a thickness test after one layer, and make up the error by the subsequent layers.



Fig. 5 The best result of two-layer system, i.e. sub/1.29/1.16/air. A, B, C are three minimum points

Let's back to Figure 6 above, the two clusters of curves on both sides of the optimal curve are almost respectively coincident with no cross, and similar features are also found in Figure 4, these three clusters of curves are characterized by a fixed refractive index difference between two layers. Then we list a series of curves with the RI difference of 0.13, as shown in Figure 8, when n_1 and n_2 change 0.03 simultaneously at a time, $\Delta T \approx 0.1$. Comparing with the results in Figure 6, we believe that the optimal RI difference between two layers is 0.13, the more deviation from this value, the far the transmittance deviates from the optimal solution. While the synchronous RI errors of two layers will introduce less transmittance variation than individual error of one layer. Under the premise of maintaining Δn , the lower the RI of the outer layer, the higher the transmittance. This conclusion is of great significance in guiding the actual process.

3.2 Comparison with the vacuum dielectric film

Due to the good performance of the two-layer sol-gel coatings, we believe a better result with the increasing number of layers with different RIs. However, before introducing the three-layer structure, we will make a comparison between the vacuum dielectric coating and the sol-gel coating.

A typical 8-layer structure with the substrate of fused silica is shown in Table 1, and the transmittance curve is shown in Figure 9. As we can see, the curve decreases much near 400 nm, which is caused by absorption of the TiO_2 layer. If we extend the band to 300 nm, the absorption will be more severe (Fig. 9 inset). A number of conventional dielectric materials have an absorption in the ultraviolet region, which makes the vacuum dielectric film a great disadvantage when apply to wideband AR coatings.



Fig. 6 Influence of minor error of refractive index on transmittance. The black line in the middle denotes 1.19/1.16, the two red lines above shares the same RI difference 0.14, and the two blue lines are 0.12.

Here, the TiO_2 layers are replaced with HfO_2 that have no absorption in the ultraviolet region, and we get a better result (Fig. 10). However, there are big challenges in coating homogeneity, coating stress and process controlling as the increasing layers. Therefore, it is almost the best result for the vacuum dielectric coating. While in the KECK telescope, a combination of silica sol-gel over dielectric

| Table 1 | The construction | n parameters | of a typical | 8-layer (| dielectric | film sta | ck with | the su | ıb- |
|-----------|-------------------|---------------|--------------|-----------|------------|----------|---------|--------|-----|
| strate of | fused silica, the | reference way | elength is a | t 510nm. | | | | | |

| Layer | Material | Refractive Index | Extinction Coefficient | Optical Thickness (FWOT) | Physical Thickness (nm) |
|-----------|----------|------------------|------------------------|--------------------------|-------------------------|
| Medium | Air | 1 | 0 | | |
| 1 | MgF_2 | 1.38542 | 0 | 0.28857433 | 106.23 |
| 2 | TiO_2 | 2.34867 | 0.00037 | 0.09577107 | 20.8 |
| 3 | SiO_2 | 1.4618 | 0 | 0.0612797 | 21.38 |
| 4 | TiO_2 | 2.34867 | 0.00037 | 0.51796575 | 112.47 |
| 5 | SiO_2 | 1.4618 | 0 | 0.04651835 | 16.23 |
| 6 | TiO_2 | 2.34867 | 0.00037 | 0.1164711 | 25.29 |
| 7 | SiO_2 | 1.4618 | 0 | 0.12799445 | 44.66 |
| 8 | TiO_2 | 2.34867 | 0.00037 | 0.04589671 | 9.97 |
| Substrate | SiO_2 | 1.4618 | 0 | | |
| Total | | | | 1.30047145 | 357.02 |



Fig.7 Influence of film thickness error on transmittance. $\Delta d_1 = +5$ nm (red line), $\Delta d_1 = -5$ nm (blue line)

 MgF_2 was used, and makes a better result than the traditional vacuum dielectric multilayer coatings. Figure 10shows the double-sided transmittance of vacuum 8-layer coating, KECK coating and sol-gel coating from 300nm to 1100nm, and the statistical data are shown in the insert of Figure 10. The Sol-gel coating has the highest average and minimum transmittance in the whole band, followed by KECK, and the worst is the dielectric coating, but there is a certain advantage in the visible waveband of the KECK coating. The reason why the KECK AR coatings have a somewhat poor result is that the MgF₂ layer has a RI of 1.37, far from the best n_2 (1.29). Therefore, it is possible to get a better result using the sol-gel two-layer structure than using the vacuum 8-layer or KECK coatings. The difficulty lies in the precise regulation of RI and thickness, so as to achieve the theoretical value, which is the focus of the following experiment.

3.3 Three-layer System

The optimization methods are also applicable to three-layer structures. Firstly, we list several curves to understand how transmittance changes along with the RI of the three layers respectively (Fig. 11), and then do a simple partition of it and give the summary of the variations in Table 2.From this rule, we can gradually adjust the curve for any combination of RIs until to the target requirements, that is, the minimum points on the same horizontal line as much as possible. Figure 12 shows the optimized curve, which is 1.40/1.29/1.16, and $\Delta n \approx 0.12$. We also make a comparison between the two-layer and three-layer system in Figure 13b, the two have an approximate average transmittance (two-layer, three-layer



Fig. 8 A cluster of curves with the refractive index difference of 0.13, n_1 and n_2 change 0.03 simultaneously at a time.

Table 2 Variation rules of partition in Figure 12

| | A B | C | D E |
|--------------------------|-------------------------|----------------|--------------------------|
| $ n_1\uparrow $ | ↑ | \downarrow | ↑ |
| $\mid n_2 \uparrow \mid$ | \downarrow | $ \uparrow $ | \downarrow |
| $\mid n_3 \uparrow \mid$ | $\downarrow \uparrow$ | $ \downarrow $ | $\uparrow ~ ~\downarrow$ |

are 99.68%, 99.76%, respectively), but the three-layer system possesses a better spectral reproduction ability and a smaller fluctuations, with single-sided transmittance is more than 99.6% in the whole band.



Fig. 9 The transmittance of single-side coated films in table 1. The absorptance of quarterwave TiO_2 coatings from 300nm to 500nm is shown in the insert.



Fig.13 (a) Comparison of three-layer coating with different n_1 which is available. (b) Optimum transmittance of 2-layer, 3-layer and 4-layer coatings.



Fig. 10 The double-sided transmittance of dielectric 8-layer, KECK and sol-gel coatings as a function of wavelength from 300nm to 1100nm, the inserted table gives the statistical data in average and minimum transmittance.

In consideration of the experiences above, we may expect a better spectrum performance with the ever-increasing layers, however, the results are not notably better than the three-layer system after a large number of simulation tests, what's more, manufacture difficulties rise rapidly with the increasing layer number, so it is not practical. Let's back to the simulations about the two-layer and three-layer systems, the lowest refractive index is 1.16, a big gap from the air, which limits the ultimate performance. In fact, the degree what transmittance performance might achieve is mainly determined by the outermost film, so we would expect a better result as the n_1 is decreasing, as shown in Figure 13a.

Comparing the results of two-layer and three-layer structures, we found that the RI difference of the adjacent layers is about 0.11-0.13. Without considering the actual feasibility, the silica sol-gel on fused silica substrate is no more than four layers. Figure 13b shows one of the results, with a minimum transmittance 99.93%, and an average transmittance 99.98%, indicating an approximate ideal zero reflectance of no more than 0.07% in the whole band, a big gain in transmittance than the three-layer system. However, the encouraging results stay in theory by now since the sol-gel film with a refractive index less than 1.1 is difficult to achieve, and of course, by reducing the outermost refractive index, a three-layer film could also yield a perfect acceptable result. There is a comparison of the two, three and four-layer coating single-sided transmittance as shown in Figure 13b.

Besides the perfect broadband AR performance, the graded-index multilayer coatings also own a great potential in suppressing reflection for a wide range of angles of incidence. The relationship between the transmittance and the incident angle of the sol-gel two-layer, three-layer and four-layer are



Fig. 11 Transmittance variation of different fixed refractive index of three-layer AR coatings.



Fig. 12 The optimized curve of three-layer coating, which is 1.40/1.29/1.16.

shown in Figure 14. The curves of the two and three layers are close to each other, and $T_{0-55} \ge 99\%$, $T_{0-72} \ge 90\%$. For four-layer structure, $T_{0-62} \ge 99\%$, $T_{0-76} \ge 90\%$.

4 CONCLUSION

In this paper, we give the structure designs for ultra-wideband AR coatings used in large aperture astronomical telescope, and obtain the optimal solution by numerical simulation. The error analysis and feasibility analysis are carried out according to the actual process characteristics of sol-gel method which will provide abundant data support for the following experiments. In the end, we list several notes for the broadband multilayer coatings based on fused silica, the target band is 300nm-1100nm.

- 1. The RI of the coating gradually decreases from the substrate to the air, that is, $n_{sub} > n_k > \cdots > n_1 > n_{air}$, where k is the number of sublayers.
- 2. The RI difference between adjacent layers is about 0.11-1.13.
- 3. On the premise of note 2, the lower the RI of outmost layer, the better.

Satisfying the above conditions, silica sol-gel coatings are applied with a maximum of four layers, and the optical thickness of each layer is about one quarter of the reference wavelength. More layers



Fig. 14 Transmittance of bare substrate, 2-layer, 3-layer and 4-layer as a function of incident angle.

cannot achieve remarkably better results. Taking into account the practical feasibility, two or three layers could achieve a perfect result with the average transmittance of 99.7% in the region from 300nm to 1100nm.

The analytical suitable for other bands and substrates. It is also inmethod is structive for the large area AR coatings in the field of solar cells. The solgel films, due to their good broadband antireflection (especially in the ultraviolet bandZhang2016PreliminaryZhang2016PreliminaryXi2007OpticalZhang2016Preliminary), simple manufacturing process, suitability for large area coating and high cost-performance ratio, etc, are believed to have a wide application prospect in the field of astronomical telescope whose aperture is enlarging.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 11603055)

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