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Designs of Broadband Normal-Incidence Visible Antireflection Coating

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Abstract

A design algorithm based on an additional iteration of a modified minimizing search technique is applied to design a broadband normal-incidence antireflection coating over the visible spectral region. The minimizing search design approach consisting of tuning and minimizing operations is effective in improving the antireflective performance and simplifying the design structure. An additional iteration of the minimizing search is utilized to further refine the visible antireflective performance of the desired solution. It is shown that the average visible spectral reflectivities for two-material 50-layer AR coating designs, obtained by different types of the 2-iteration minimizing search technique, are very good and comparable to each other, which are reduced to approximately 0.026-0.030%, and the final designs are reduced to 22-28-layered structures.

Keywords：minimizing search, iteration exchanging search, broadband antireflection coating, design algorithm, visible spectral region

廣波域之正射可見抗反射蒸鍍設計

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摘要

一個以額外循環之簡化搜尋技巧為基礎的設計演算法，被應用來設計可見光區之廣波域的正射抗反射。此簡化搜尋設計方法包含了調整操作及簡化操作能夠有效地改善抗反射成效及簡化設計結構，而額外循環之簡化搜尋則可進一步用以精煉可見抗反射成效。結果顯示，以不同搜尋方式之 2-循環簡化搜尋技巧來設計兩種-物質、50-層之抗反射蒸鍍，其抗反射成效非常良好，而彼此間的成效亦相當，可使得平均可見反射率約降低至 0.026-0.030%，且最終設計減少至 22-28 層結構。

關鍵字：簡化搜尋、循環交換搜尋、廣波域抗反射蒸鍍、設計演算法、可見光區域

1. Introduction

Antireflection (AR) coating plays an important role in thin-film technique for reducing the undesirable reflection loss from the surface of optical devices and/or increasing the transmittance of the optical systems. The

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reflection loss is mainly due to the sharp change of the refractive index at the air-substrate interface; for instance, the reflecting component of an uncoated glass substrate is approximately 4.2% with a refraction index of 1.52 of the glass. Another important reason for using AR coatings in modern optical systems is to improve the image contrast by eliminating the ghost images caused by the multiple reflections of the surfaces of optical devices in the system.

Many numerical design techniques[1-9)] have been applied for normal-incidence AR coatings, where refinement method[1-3)] and synthesis method[4-9)] are the two fundamental digital approaches. In general, the refinement method requires a starting point with a performance close to the desired solution, and the construction parameters are gradually adjusted to refine the performance to obtain the final solution. However, the performance of final design is heavily dependent on the starting point, and a suitable starting point is not easy to select in some complex cases. Contrary to the refinement method, the synthesis method can generate its own starting points, and tune the construction parameters subsequently to improve the performance and then yield the final solution.

In this research, a design algorithm based upon an additional iteration process of a minimizing search technique[6)] is applied to achieve a very low loss normal-incidence AR coating design for visible spectral region. The method first makes use of a tuning operation of layer thickness of a multilayer system, and second, unties a minimizing operation for reducing layer number to simplify the design structure and also to improve the AR performance of the system. An additional iteration process consisting of tuning and minimizing operations is afterward applied for the further refinement of the AR performance. It is shown that the average visible spectral reflectivities for different types of iteration minimizing search AR coating designs of a two-material 50-layer system are reduced to lie in the range of 0.026-0.030% and final designs are reduced to 22-28-layered structures.

2. Design Method

To design a very low loss normal-incidence AR coating over the visible spectral region, a two-material *N*-layer thin-film assembly with a binary code of high and low refractive indices as n_H-n_L-n_H-n_L-…is assumed to be designed for a glass substrate with index n_s=1.52, and the incident medium is air with refractive index n_o=1. To simplify the calculation in the searching process of the optimal construction parameters of the multilayer system, the refractive indices of the coating materials, incident medium and substrate are assumed non-dispersive.

The design process for searching the optimal construction parameters of visible AR coating includes the reduction of the visible spectral reflectivity over 400-750 nm region and the simplification of the design structure. The design algorithm consists of a 2-iteration of a modified minimizing search procedure and is described as follows.

A) Select a total physical thickness *D* of the *N*-layer assembly and set all layers initially with an equal thickness *d=D/N*.

B) Tune the physical thickness of all layers one by one from the substrate to the incident medium to yield a lower minimum mean reflectivity (*MR*) of the visible spectral region. The layer thickness is replaced by a value that results in a lower minimum *MR*; otherwise, restore the original layer thickness and tune the next layer. The tuning operation of layer thickness is completed if *MR* stabilizes in a pass in all layers.

During each tuning operation of layer thickness, the merit function *MR* defining the average visible spectral reflectivity over 351 wavelengths of 400-750 nm regions is calculated by

$$MR = \frac{1}{351}\sum_{\lambda=400}^{750} R(\lambda), \tag{1}$$

where the reflectivity $R(\lambda)$ at wavelength λ is obtained by[10)]

$$R(\lambda) = \left|\frac{Y_0 - Y_E}{Y_0 + Y_E}\right|^2 = \left|\frac{BY_0 - C}{BY_0 + C}\right|^2, \tag{2}$$

in which $Y_0 = 1/377$ S is the optical admittance of free space and $Y_E = C/B$ is the input optical admittance of the multilayer system, respectively, and *B* and *C* are determined from the matrix theory of the product as

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left(\prod_{j=1}^{N} M_j\right) \begin{pmatrix} 1 \\ n_s Y_0 \end{pmatrix}, \tag{3}$$

where

$$M_j = \begin{pmatrix} \cos\theta_j & \frac{i}{n_j Y_0}\sin\theta_j \\ i n_j Y_0 \sin\theta_j & \cos\theta_j \end{pmatrix}, \tag{4}$$

is the characteristic matrix of the *j*th sublayer and $\theta_j = 2\pi n_j d_j / \lambda$ is its optical thickness with the refractive index n_j and the physical thickness d_j, respectively, and $i = \sqrt{-1}$ is the imaginary unit.

C) Simplify the design structure and further refine the AR performance with a minimizing operation by eliminating the layers one by one. Once a layer is eliminated, restart the tuning operation of layer thickness to yield a lower minimum *MR*. If the *MR* is not refined in a minimizing operation, restore the original eliminated layer, and eliminate the next layer. The minimizing operation is carried out in the following different manners:

(a) First, from the high-index layers in the direction from the substrate to the incident medium, and then from the low-index layers.

(b) First, from the low-index layers in the direction from the substrate to the incident medium, and then from the high-index layers.

(c) First, from the high-index layers in the direction from the incident medium to the substrate, and then from the low-index layers.

(d) First, from the low-index layers in the direction from the incident medium to the substrate, and then from the high-index layers.

If the *MR* stabilizes in one pass in all layers, then finish the minimizing operation.

D) An additional iteration process consisting of the tuning and minimizing operations is reused to further refine the visible AR performance. Add a period of the design in the last step of the minimizing operation, and restart the tuning and minimizing operations to obtain a superior visible AR performance. The desired solution is considered to be achieved when the iteration process is finished.

3. Results and Discussion

To exhibit the design algorithm of the iteration minimizing search method, we first design a broadband visible AR coating for a glass substrate with a two-material 50-layer system at a starting total physical thickness of 700 nm. The layers are binary coded of alternating of high and low refractive indices as n_H-n_L-n_H-n_L-…, where the coating materials are ZnS and MgF_2 with indices n_H=2.35 and n_L=1.38, respectively. The tuning thickness for the tuning operation is 0.1 nm. After a 2-iteration minimizing search, the results are shown in Figs. 1-4.

In Figs. 1(a)-4(a), the broadband visible AR coating designs, obtained by different types of minimizing operation, are reduced to 22-, 26-, 26- and 28-layered structures with the total physical thicknesses of 1481.3 nm, 1483.8 nm, 1571.6 nm and 1515.2 nm, respectively, and their corresponding average visible reflectivities, shown in Figs. 1(b)-4(b), are reduced to less than 0.030%, 0.026%, 0.029% and 0.026%. It is shown that even if start with the same initial points, different types of minimizing search method lead to different final designs. However, the visible AR performances of the final designs are very good, comparable and similar to each other. During the tuning operation, the thickness of a layer may be tuned increase (or decrease) in one pass and may be tuned decrease (or increase) in the other pass. Some layers may vanish when their thicknesses are decreased to zero by the tuning operation or layers may be eliminated by the minimizing operation, and then some layers with same index are merged to a new layer; as a result, the layer number is reduced. Not only the design structure is simplified during the tuning and minimizing operations, but also the visible AR performance is refined with the *MR* moving from a minimum to a lower minimum in each pass of tuning and minimizing operations. It is shown that the visible AR performance is much improved by the tuning operation and the design structure is obviously simplified by the minimizing operation. Furthermore, an additional iteration of the minimizing search can be effective applied to further improve the AR performance. It is found that the *MR*s obtained by different types of the 1-iteration minimizing search designs are reduced to 0.033%, 0.033%, 0.032% and 0.033%, respectively. The improved percentage of visible AR performance for the 2-iteration minimizing search design with respect to the 1-iteration minimizing search design is approximately 9.1-21.2% as compared to the *MR*s, 0.030%, 0.026%, 0.029% and 0.026%, obtained by the 2-iteration minimizing search. Thus, it is worthwhile to apply an additional iteration minimizing search to achieve a superior visible AR performance, even if it needs some more treatments to obtain the final design.

To compare the visible AR performance yielded by the iteration exchanging search technique,[7)] a second attempt of the visible AR coating is designed by the iteration exchanging search method with the same starting point mentioned above that using a two-material 50-layer system of 700 nm total physical thickness. The layers indices are coded with high and low refractive indices as n_H-n_L-n_H-n_L-…, where the refractive indices are n_H=2.35 and n_L=1.38, respectively. After a 2-iteration exchanging search, the results obtained by different manners of the exchanging operation are shown in Figs. 5-8.

The two-material 50-layer iteration exchanging search universal AR coating designs by exchanging layers from the thin layer to the thick layer, from the thick layer to the thin layer, in the direction from the substrate to the incident medium and from the incident medium to the substrate are shown in Figs. 5(a)-8(a). These designs were reduced to 38-, 36-, 28- and 26-layered structures with the total physical thicknesses of 1511.7 nm, 1655.2 nm, 1658.4 nm and 1456.1 nm, respectively, and the corresponding average visible reflectivities shown in Figs. 5(b)-8(b) are reduced to less than 0.026%, 0.030%, 0.031% and 0.027%. It is shown that the visible AR performances obtained by different types of the iteration exchanging search technique are quite comparable to those obtained by the iteration minimizing search method, but the design structure achieved by the former method is somewhat more complex than the latter method proposed in this study.

4. Conclusion

We have applied the iteration minimizing search method to design a very low-loss normal-incidence AR coating over the 400-750 nm spectral region. It is shown that the average visible spectral reflectivities for two-material 50-layer AR coating designs, obtained by the 2-iteration minimizing search technique, are comparable to each other and reduced to approximately 0.026-0.030%, and the final designs are reduced to 22-28-layered structures.

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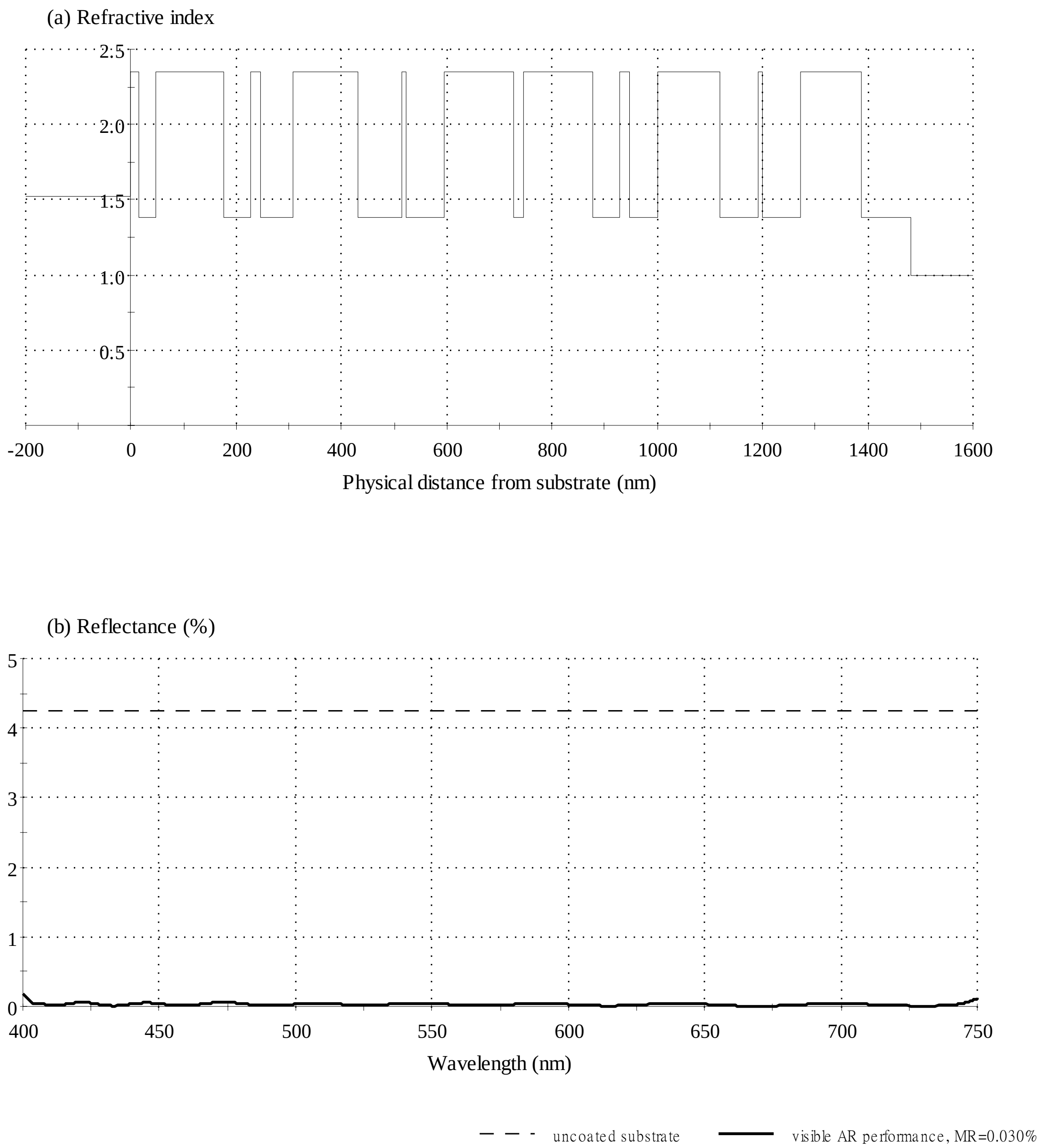


Fig. 1. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration minimizing search AR coating design with the minimizing operation proceeding first from the high-index layers in the direction of the substrate to the incident medium, and then from the low-index layers. The final design is a 22-layered structure with a physical thickness of 1481.3 nm and the average visible spectral reflectivity is reduced to less than 0.030%.

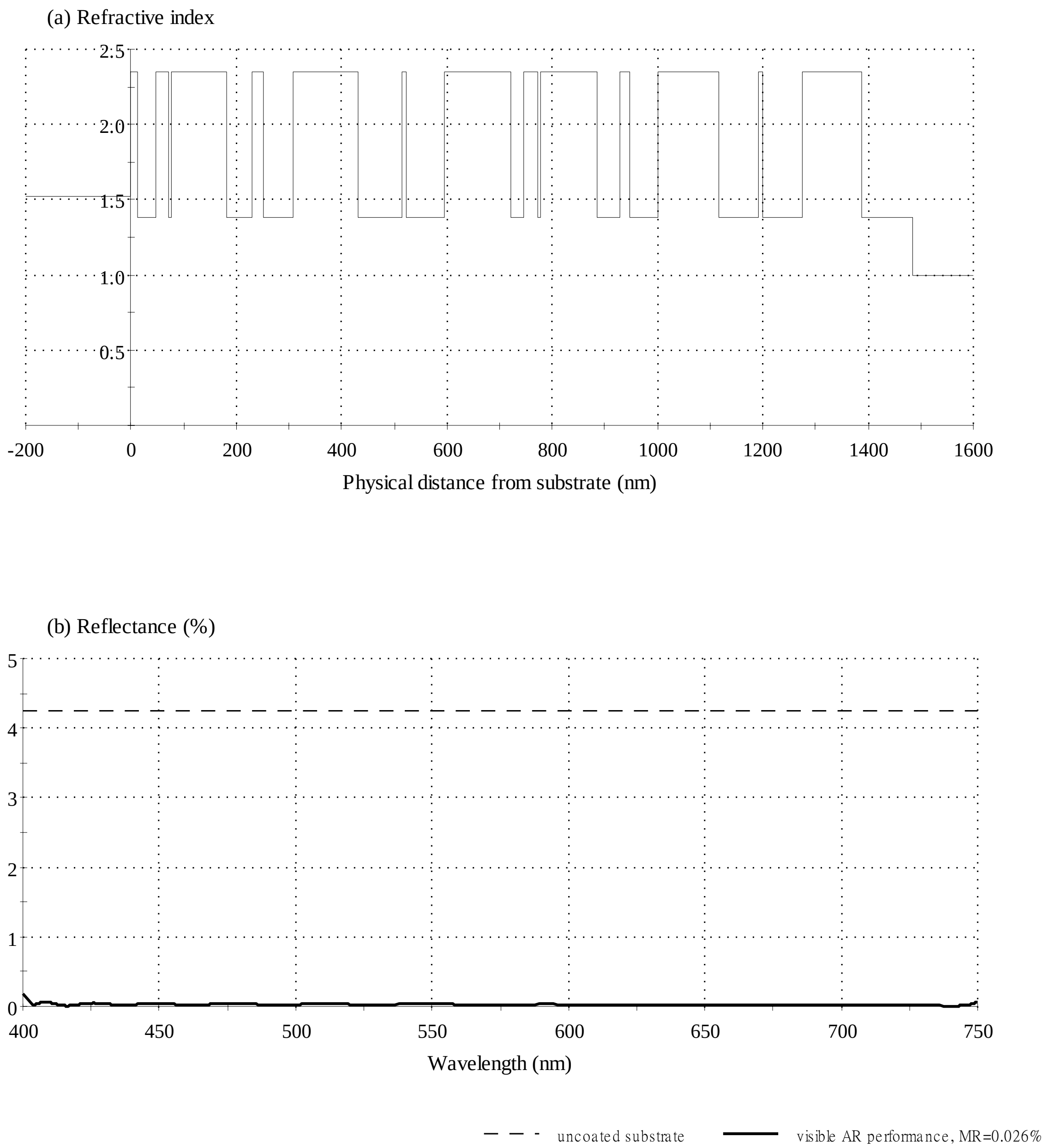


Fig. 2. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration minimizing search AR coating design with the minimizing operation proceeding first from the low-index layers in the direction of the substrate to the incident medium, and then from the high-index layers. The final design is a 26-layered structure with a physical thickness of 1483.8 nm and the average visible spectral reflectivity is reduced to less than 0.026%.

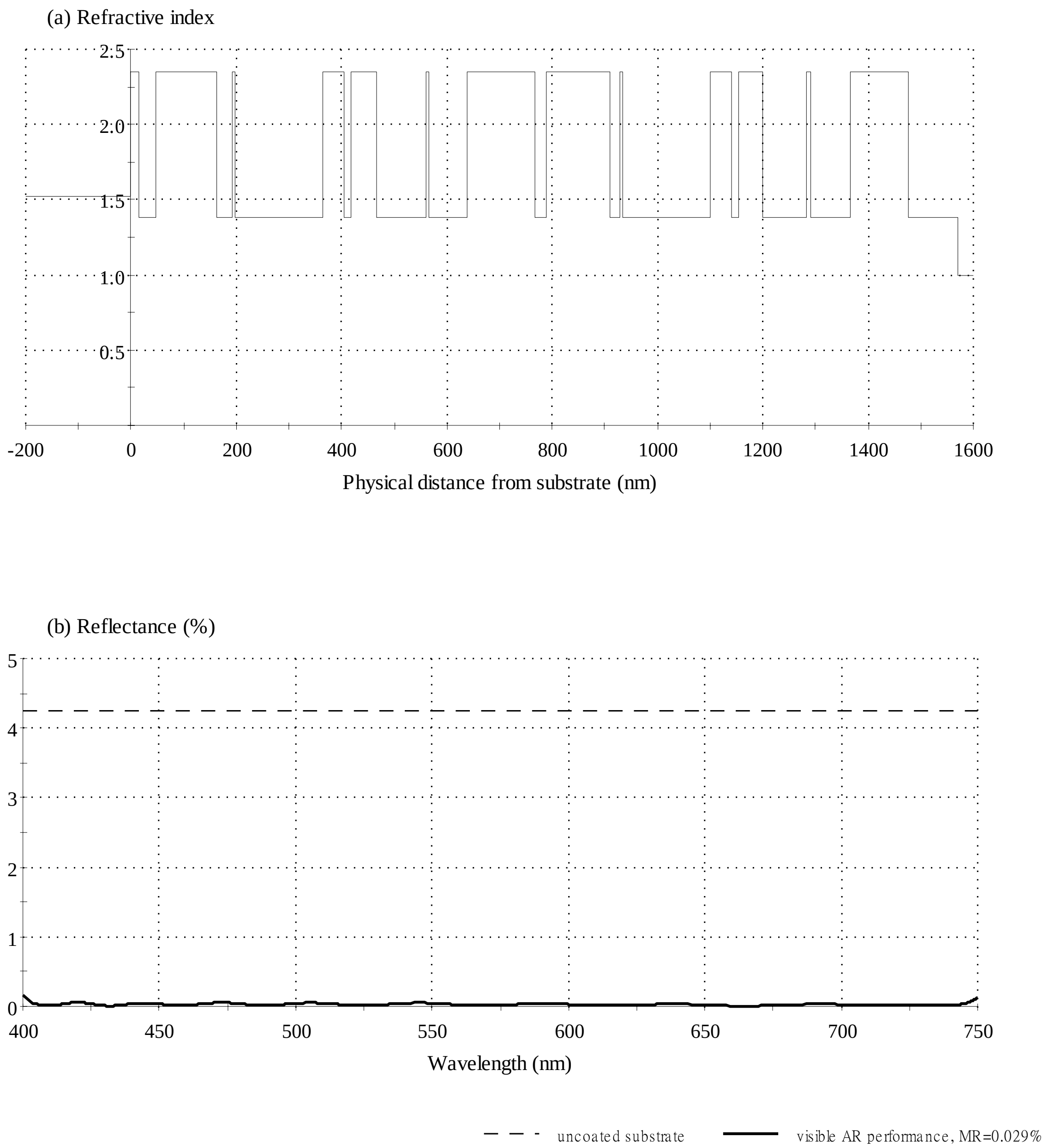


Fig. 3. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration minimizing search AR coating design with the minimizing operation proceeding first from the high-index layers in the direction of the incident medium to the substrate, and then from the low-index layers. The final design is a 26-layered structure with a physical thickness of 1571.6 nm and the average visible spectral reflectivity is reduced to less than 0.029%.

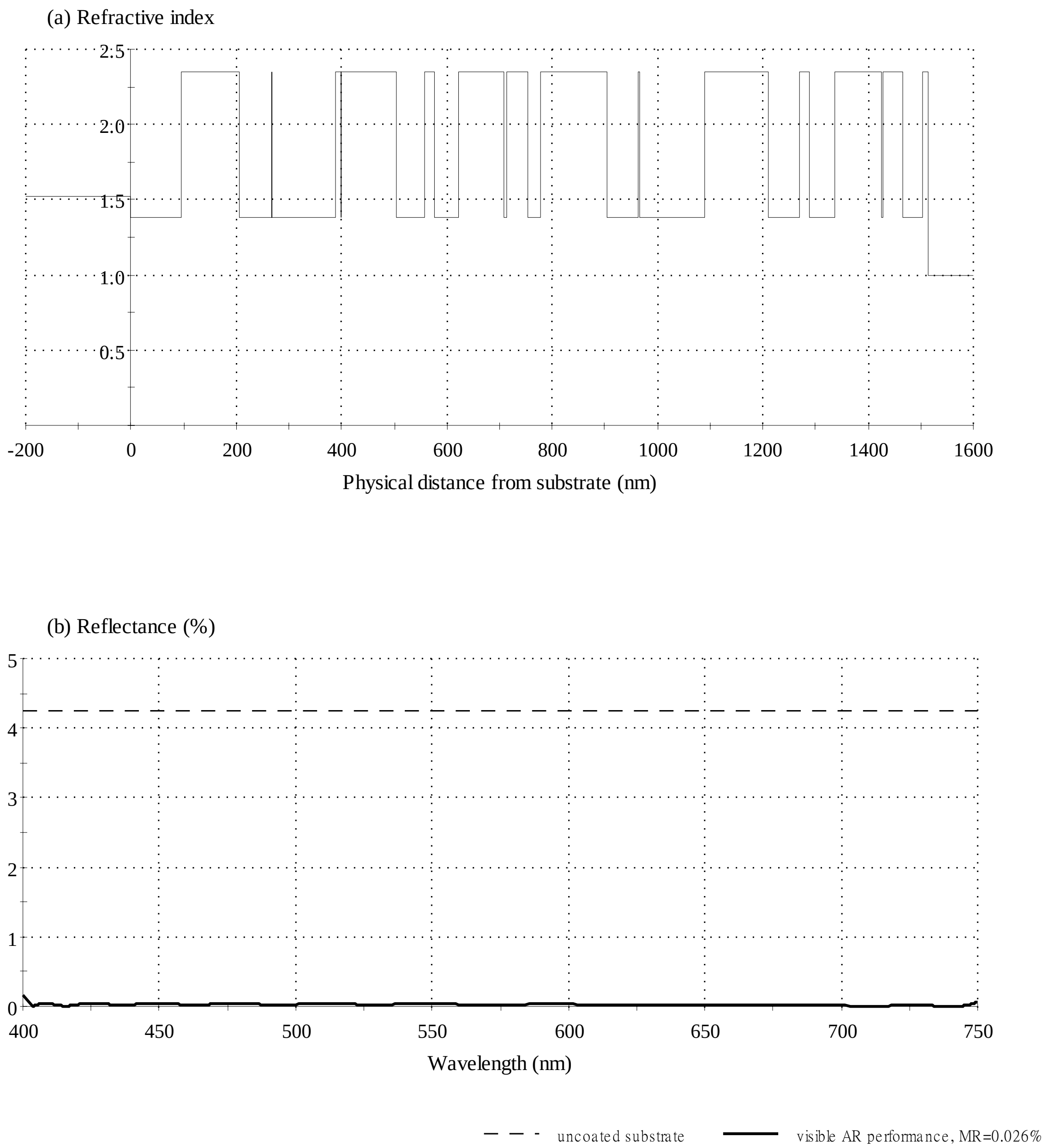
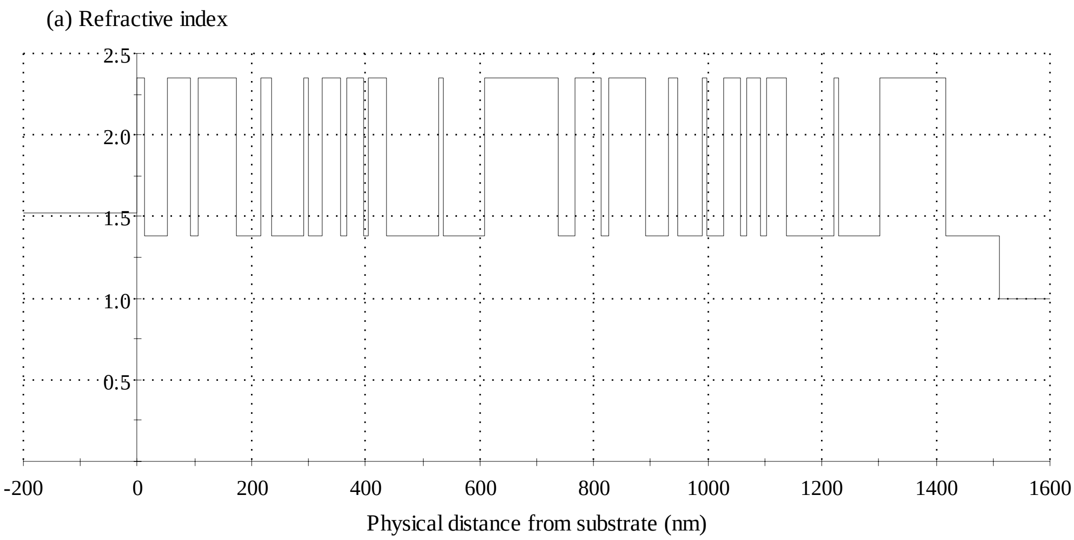


Fig. 4. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration minimizing search AR coating design with the minimizing operation proceeding first from the low-index layers in the direction of the incident medium to the substrate, and then from the high-index layers. The final design is a 28-layered structure with a physical thickness of 1515.2 nm and the average visible spectral reflectivity is reduced to less than 0.026%.



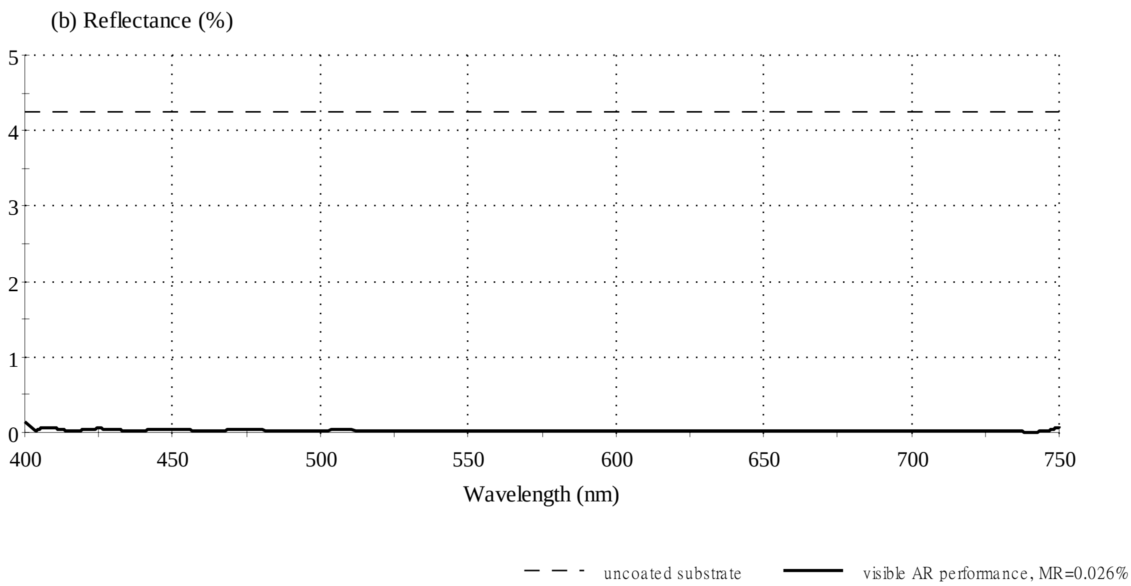


Fig. 5. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration exchanging search AR coating design with the exchanging operation of layers from the thick layer to the thin layer. The final design is a 38-layered structure with a physical thickness of 1511.7 nm and the average visible spectral reflectivity is reduced to less than 0.026%.

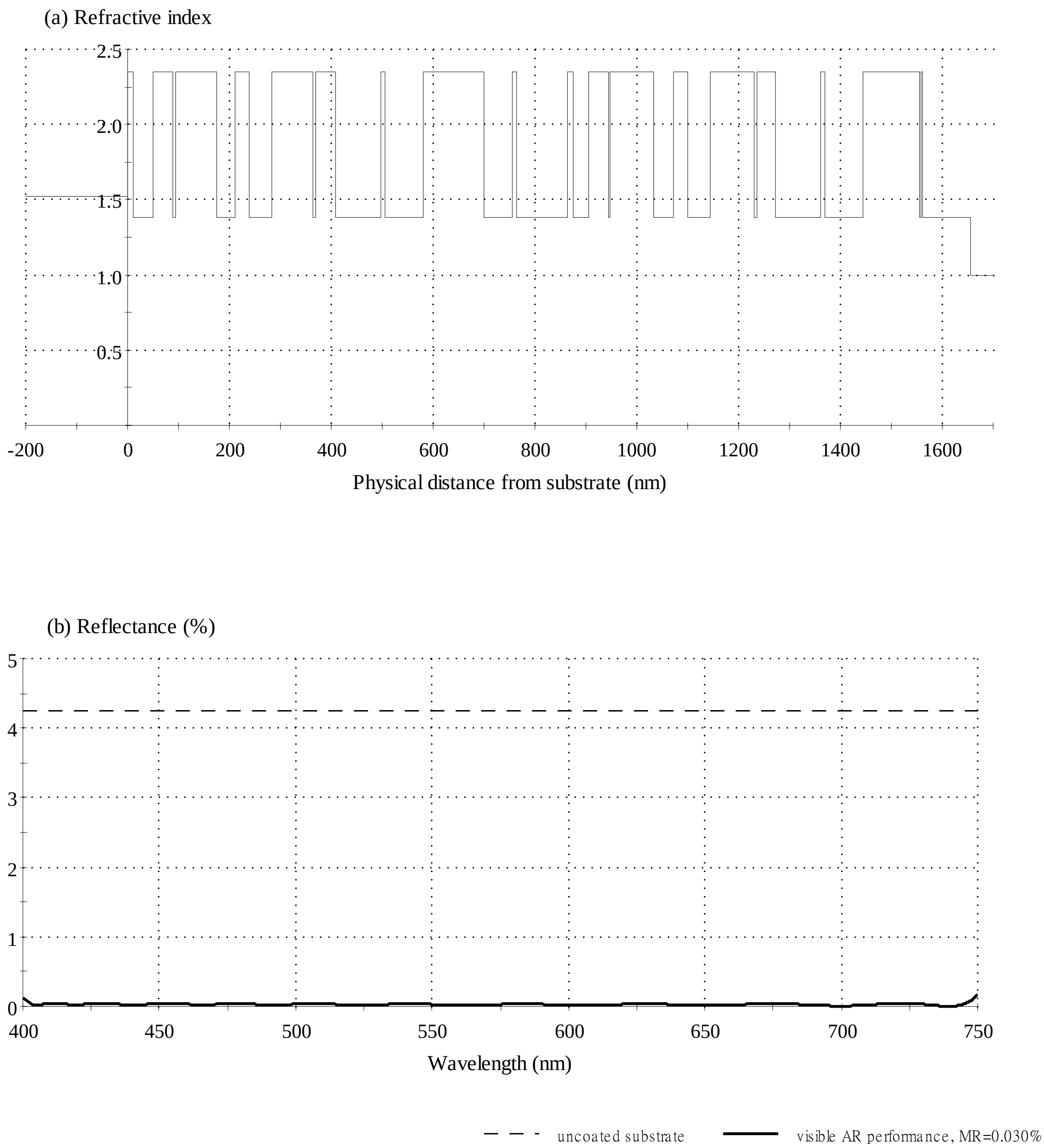


Fig. 6. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration exchanging search AR coating design with the exchanging operation of layers from the thin layer to the thick layer. The final design is a 36-layered structure with a physical thickness of 1655.2 nm and the average visible spectral reflectivity is reduced to less than 0.030%.

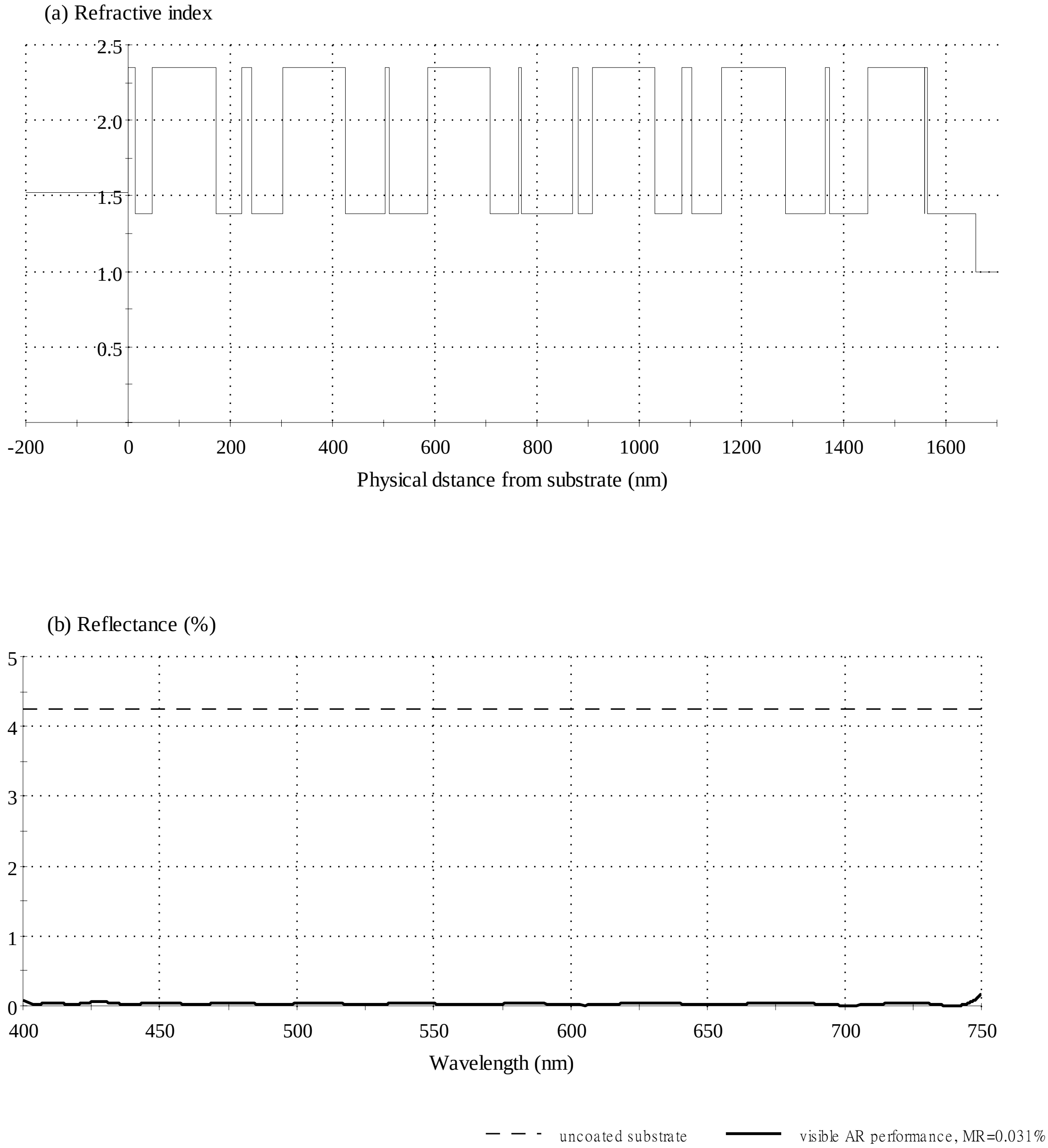
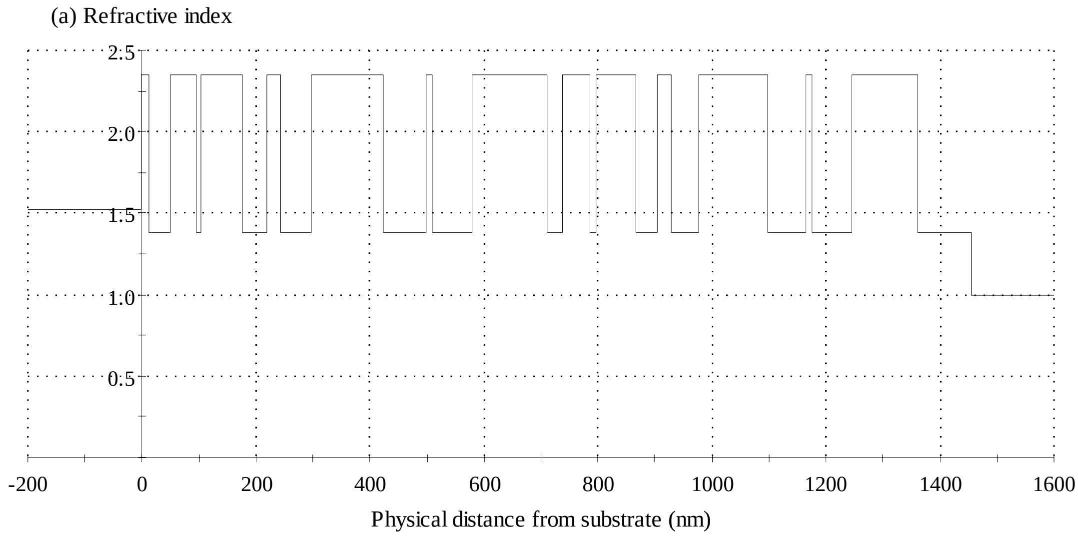


Fig. 7. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration exchanging search AR coating design with the exchanging operation of layers in the direction from the substrate to the incident medium. The final design is a 28-layered structure with a physical thickness of 1658.4 nm and the average visible spectral reflectivity is reduced to less than 0.031%.



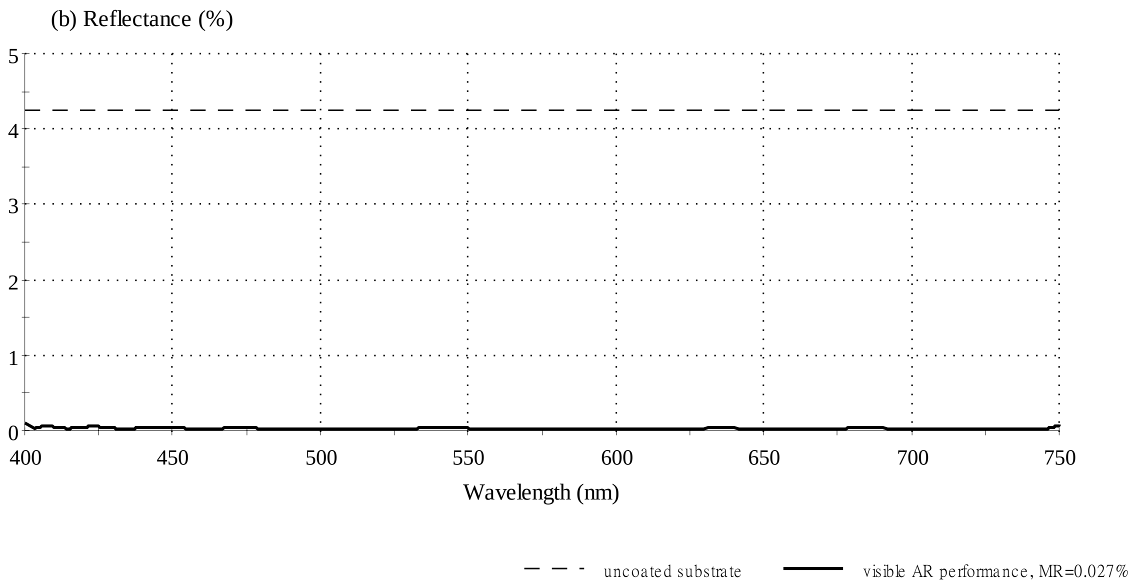


Fig. 8. (a) Refractive index profile and (b) broadband visible spectral reflectance of a two-material 50-layer iteration exchanging search AR coating design with the exchanging operation of layers in the direction from the incident medium to the substrate. The final design is a 26-layered structure with a physical thickness of 1456.1 nm and the average visible spectral reflectivity is reduced to less than 0.027%.