Design and production of three line antireflection coating for visible – far infrared spectral regions

Valeriy Zhupanov[a], Viktor Fedoseev[a], Michael Trubetskov[b,c], Tatiana Amotchkina[c], Alexander Tikhonravov*[,c]

[a]Scientific Research Institution "Luch", Zeleznodorozhnaya 24, Podolsk, Moscow, Russia; [b]Max-Planck Institute of Quantum Optics, Hans-Kopfermann str. 1, 85748 Garching, Germany; [c]Research Computing Center, Moscow State University, Leninskie Gory, 119992 Moscow, Russia

ABSTRACT

We discuss the production of antireflection coating with low reflection zones in the spectral regions around the wavelengths of 546nm, 1060 nm and 11000 nm and additional demands for the reflectance maxima in the visible spectral region. For the coating production we use ZnSe as a substrate material and ZnS/YbF_3 as layer materials. Their optical parameters are accurately determined in a wide spectral region using modern characterization and reverse engineering software tools. For the coating production we apply broad band monitoring in the spectral region from 1200 to 2300 nm that does not overlap with the regions where target requirements are specified. In order to select the most practical design that can be reliably manufactured we apply a combination of various modern design approaches and computational manufacturing experiments simulating production runs. Application of the most up-to-date software tools allows us to obtain excellent manufacturing results even from the first production run.

Keywords: antireflection coatings, multilayer design, deposition and fabrication, broadband monitoring

1. INTRODUCTION

Antireflection (AR) coatings are historically the first[1] and the most widely used thin film optical coatings. Their properties are well-known[2-4] and they are successfully produced by many companies all over the world. Nevertheless, the design and production of some types of AR coatings is still a big challenge. In particular, this relates to the design and production of AR coatings that must provide low reflectance in several far located spectral regions. In the present work we consider AR coating with three narrow low reflection zones in the vicinities of the wavelengths of 546 nm, 1060 nm and 11000 nm. Along with these main requirements there are also additional demands for the reflectance maxima in the visible spectral region.

One of the main challenges in the production of coatings with distant target spectral regions is reliable monitoring of thicknesses of coating layers. In this work we apply a version of broad band monitoring (BBM) that we refer to as *quasi-direct BBM*. Actually, this is a direct BBM in the sense that monitoring is performed directly on the coating to be deposited[3]. At the same time our monitoring spectral region of 1200-2300 nm is noticeably different from the spectral regions where target requirements are specified. This causes additional demands for the successful application of the quasi-direct monitoring system. In the first turn, this is the demand for very accurate determination of wavelength dependencies of refractive indices in wide spectral regions.

For the production of discussed AR coating we use zinc selenide (ZnSe) as a substrate material and zinc sulfide (ZnS) and ytterbium fluoride (YbF_3) as layer materials. There are no much data related to the refractive index of ZnSe. Usually cited references[5,6] contain ZnSe refractive index data starting from 540 nm which is close to our first target low reflection region. For our purposes it is desirable to know ZnSe index starting from the wavelength that is at least several tens of nanometers smaller than this value. It is also possible that substrates supplied by different vendors have somewhat different refractive indices. Thus careful characterization of the substrate refractive index is required. The same relates to the layer refractive indices because they are usually dependent on deposition conditions.

Optical characterization of thin films is usually performed based on spectrophotometric measurements of single layers with thicknesses that are several times more than thicknesses of respective layers in multilayer stacks. It is therefore possible that refractive indices of thin films in multilayer stacks will be somewhat different from those obtained by

Optical Systems Design 2015: Advances in Optical Thin Films V, edited by Michel Lequime, H. Angus Macleod, Detlev Ristau, Proc. of SPIE Vol. 9627, 962706 · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2191161

characterization of single thin films. In this paper we propose to verify thin film refractive indices based on reverse engineering of special test quarter wave mirrors.

At the modern state-of-the-art in optical coating design techniques[7] synthesis of AR coatings is not a problem. Various AR design solutions can be easily obtained and the main challenge here is choosing the most feasible design that can be successfully manufactured using specific monitoring approach. In this respect computational manufacturing experiments are especially useful[8-9].

In the course of AR coating production with BBM monitoring in the infrared (IR) spectral regions, noticeable deviations of broadband monitoring signals from the theoretically predicted spectra at the end of the deposition of each layer may be observed[10]. It was previously shown[10-11] that accuracy of BBM monitoring can be essentially improved by taking into account correspondence between wavelength positions of the monitoring signal extreme values and theoretically predicted transmittance extreme values at the end of the deposition of each layer. In the present work we also apply this approach.

In Section 2 of this paper we discuss optical characterization of our substrate and thin film materials. In Section 3 the verification of found refractive indices with the help of reverse engineering is performed. Section 4 is devoted to choosing AR design solution. In Section 5 we discuss monitoring issues and consider manufacturing results. Final conclusions are provided in Section 6.

2. DETERMINATION OF THE SUBSTRATE AND THIN FILM REFRACTIVE INDICES

The substrate material is strongly absorbing below 480 nm and the accurate determination of its optical parameters requires using various combinations of reflectance and transmittance measurements and applying sophisticated thin film models that are available in OptiLayer thin film software[12]. Figure 1 shows one-side reflectance (*R*) data for the wedged ZnSe substrate and transmittance (*T*) data for the plane-parallel substrate in the 400-800 nm spectral region. Along with this data we had in our disposal also reflectance data for the plane parallel substrate and *T*, *R* data measured in other spectral regions. Substrate thickness is 1 mm.

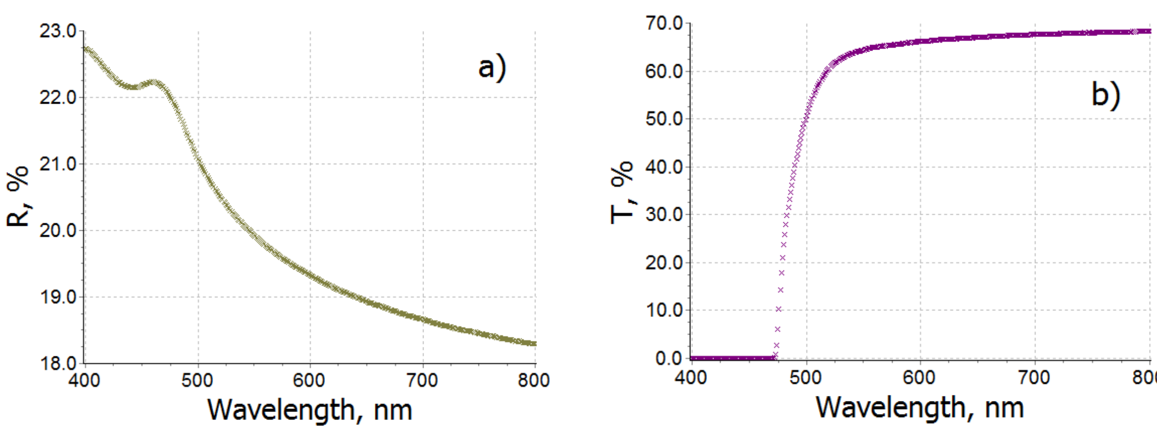

Figure 1. a) One-side reflectance data for the wedged ZnSe substrate. b) Transmittance data for the plane-parallel ZnSe substrate.

First we characterize the ZnSe substrate in the spectral region from 400 nm to 800 nm. The wavelength dependence of the refractive index of ZnSe can be found using one-side reflectance data for the wedged substrate. For its determination we use a nonparametric refractive index model with an additional demand for smoothness of the refractive index wavelength dependence[13]. Then, reflectance and transmittance data for the plane parallel substrate are to be used to determine extinction coefficient wavelength dependence in the 480-800 nm spectral region. For the extinction coefficient the non-parametric model with an additional smoothness demand[13] is to be used as well.

In the spectral regions above 800 nm, ZnSe is non-absorbing and for the determination of its refractive index one-side reflectance data for the wedged substrate can be used. In the spectral region from 800 to 2500 nm the nonparametric refractive index model with an additional smoothness demand has been applied. Figure 2 shows combined results for the wavelength dependencies of the ZnSe refractive index and extinction coefficient in the 480-2500 nm spectral region. A small jump in the refractive index wavelength dependence is observed at 800 nm where characterization results were merged.

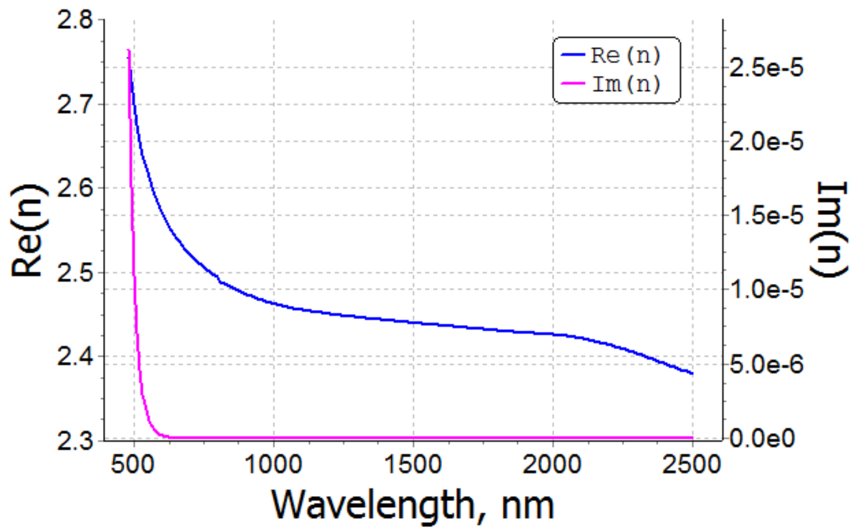

Figure 2. Refractive index and extinction coefficient of ZnSe substrate in the 480-2500 nm spectral region.

The found ZnSe refractive index wavelength dependence is a little bit lower than Connolly's dependence for the wavelength region above 540 nm. The relative difference in the refractive index values is less than 1% and can be connected with real difference in substrates supplied by different vendors.

For the characterization of ZnS and YbF_3 thin film materials we deposited several samples with ZnS layers of about 700-900 nm thicknesses and YbF_3 layers of about 1000-1400 nm thicknesses. Layers of the both thin film materials have been deposited on ZnSe substrates. Also, for the ZnS characterization we used additionally ZnS samples on calcium fluoride (CaF_2) and fused silica substrates. This has been done to increase a contrast between indices of the characterized thin film material and the substrate. For the determination of refractive index wavelength dependencies the Cauchy dispersion model can be used in all cases. For the determination of extinction coefficient wavelength dependencies a three-parametric exponential model can be used. This model is the most suitable one for the near ultraviolet and visible spectral ranges in the case of slightly absorbing dielectric thin films. This model is available in OptiLayer thin film software[12]. The ZnS layers has been found to be rather homogeneous while in the case of YbF_3 sample it is required to use thin film models taking into account bulk inhomogeneity of thin films[12].

In the case of ZnS samples all found refractive index wavelength dependencies differ from each other with the relative difference not exceeding 2%. The most essential fact is that the differences in determined indices are observed mainly as shifts of wavelength dependencies upwards or downwards. Such shifts may be attributed to slightly different packing densities of the films on different substrates as well as to some small systematic errors in measurement data[14-15]. This assures us in the correctness of the general pattern of the found wavelength dependencies. Analogous results have been obtained in the case of YbF_3 but shifts of the found wavelength dependencies upwards or downwards are even less than in the case of ZnS. On the whole, the average relative deviations of found refractive indices are less than 1%.

3. VERIFICATION OF REFRACTIVE INDICES WITH THE HELP OF POST-PRODUCTION CHARACTERIZATION

Verification of thin film material refractive indices has been performed using post-production measurements of reflectance and transmittance for several test quarter wave mirrors with the central wavelength of 1400 nm. This value has been chosen in accordance with our intended BBM spectral region of 1200-2300 nm. Another consideration for choosing this value is to have thicknesses of mirrors' layers closer to the thicknesses of AR coating layers than thicknesses of layers used for preliminary determination of refractive indices. Physical thickness of the YbF_3 layers are about 223 nm and thicknesses of the ZnS layers are about 154 nm, i.e., these layers are several times thinner than the single layers characterized in the previous section. Deposited mirrors have 4, 6, and 8 layers with the YbF_3 layers as first layers starting from the substrate.

Figure 3 compares measured and theoretical reflectance of the 6-layer quarter wave mirror. One can see that the width of the high reflection zone of the measured reflectance is greater than that one of the theoretical reflectance. For calculating the theoretical reflectance curve the refractive indices of ZnS and YbF_3 found by optical characterization of single layers (Section 2) have been used. Among our characterization results we chose those that we considered as the most reliable ones. The chosen ZnS and YbF_3 refractive index wavelength dependencies are shown by the blue curves in Fig.4.

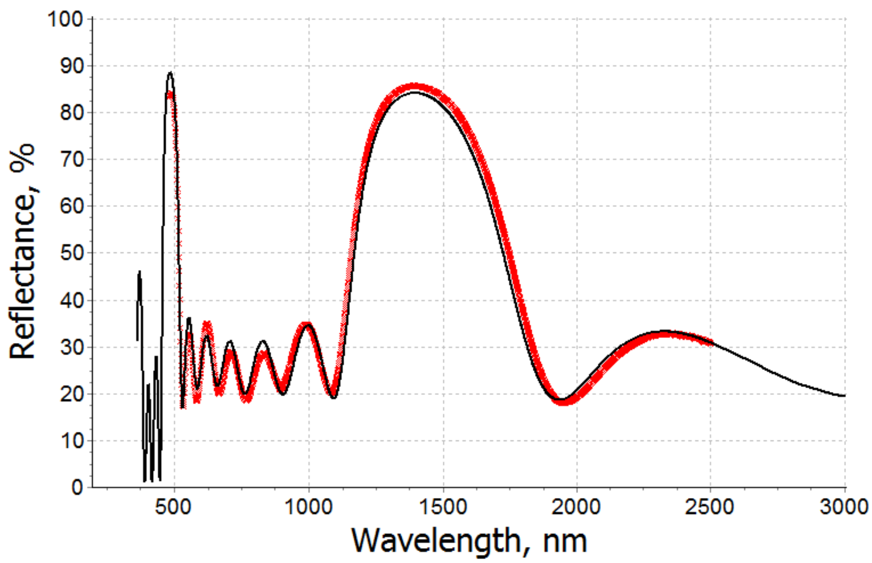

Figure 3. Measured (red crosses) and theoretical (black solid curve) reflectances of the 6-layer quarter wave mirror.

It is known that the width of the high reflection zone of a quarter wave mirror depends on the ratio of refractive indices of high and low index materials[16]. The higher ratios provide the wider higher reflection zones. Thus, actual refractive indices of ZnS and YbF_3 are somewhat different from the specified dependencies and their ratio is higher than the ratio of the indices found in the course of the characterization. It has been discussed in Section 2 that general patterns of ZnS and YbF_3 refractive indices' wavelength dependencies have been determined reliably but some shifts of these dependencies upwards or downwards are still possible. These shifts are obviously the main reason for the discrepancy between measured and theoretical reflectance values observed in Fig. 3.

In order to determine ZnS and YbF_3 refractive indices more accurately, we apply a reverse engineering model with possible drifts of layer refractive indices upwards or downwards. This model is available in the OptiRE module of OptiLayer thin film software[12]. The black curves in Fig. 3 represent the refractive indices of ZnS and YbF_3 found by the reverse engineering procedure. Refractive index of ZnS is approximately 1% higher and refractive index of YbF_3 is approximately 1.4% lower than the indices determined in the course of the characterization process. Reverse engineering of other test mirrors gives similar results. Thin film refractive indices shown by black curves in Fig.4 are used in all our further investigations.

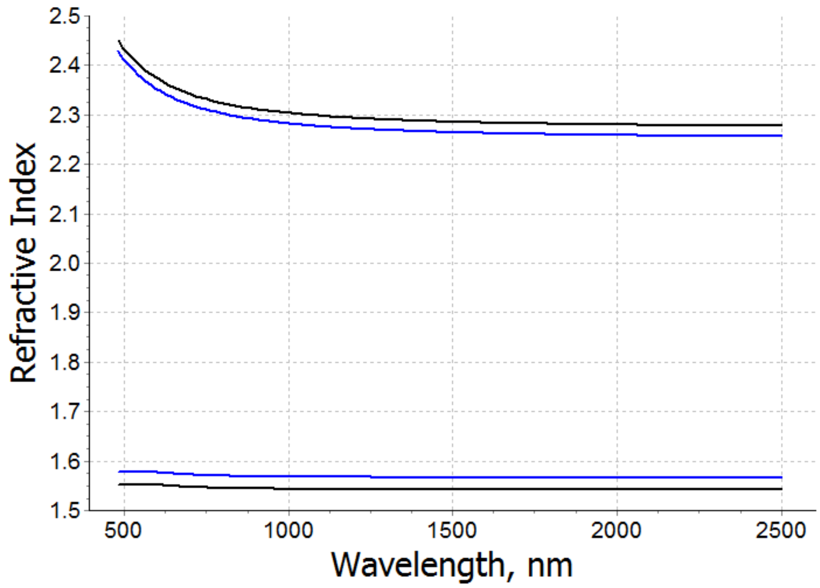

Figure 4. Refractive indices of ZnS and YbF_3 found by optical characterization of single thin films (blue curves) and refined refractive indices found by the reverse engineering procedure (black curves).

4. DESIGN OF ANTIREFLECTION COATING

Our goal is to design the AR coating with low reflectance at the wavelengths of 546 nm, 1060 nm and 11000 nm. In order to account for possible thickness errors we specified zero target reflectance in three spectral zones around these wavelength values: 522-570 nm, 1020-1100 nm, and 10900-11100 nm. Target reflectance values are shown by crosses in Fig.5. Along with these demands, an additional requirement has been specified: the design reflectance in the visible spectral range from 400 to 700 nm may not exceed 30%. This requirement can be taken into account with the help of so-called bypass targets available in the OptiLayer thin film software[12]. In the case of "bypass bellow" target with reflectance level of 30% this target value is taken into account by the design procedure if reflectance values exceed 30% only. The bypass target is shown in Fig. 5 by the straight line consisting of small crosses.

To design AR coatings, we apply several modern design approaches including needle optimization technique and random optimization technique with constraints for design layer thicknesses[7]. The latter technique is to be used in order to obtain designs with upper constraints for layer thicknesses because AR designs with too thick layers may cause problems connected with exfoliation of deposited coatings[10]. As a result, a series of AR designs with the numbers of layers ranging between 8 and 11 have been obtained. In order to select the most practical design that can be reliably manufactured using planned quasi-direct BBM, we used computational manufacturing experiments simulating production runs[12].

Finally, the 9-layer design with the reflectance shown in Fig.5 by the solid curve was chosen as the most promising one. Layer optical thicknesses of this design are depicted in Fig.6.

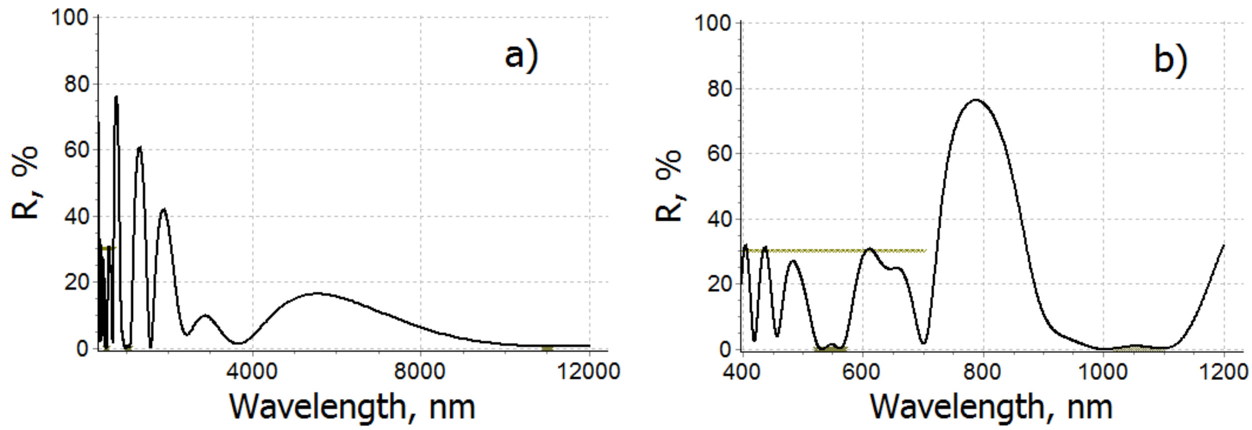

Figure 5. Target reflectance (crosses) and reflectance of the theoretical AR design: a) in the 400 - 12000 nm spectral region, b) in the 400-1200 nm spectral region.

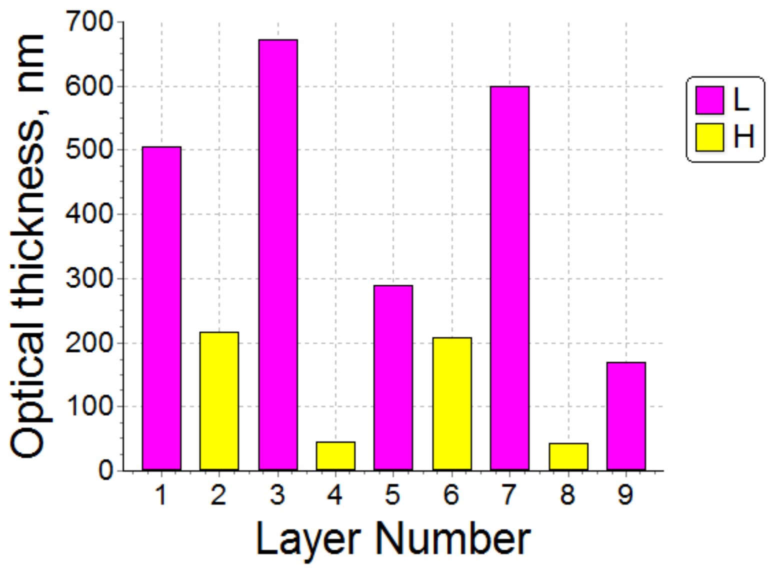

Figure 6. Layer optical thicknesses of the 9-layer AR design.

5. QUASI-DIRECT MONITORING AND MANUFACTURING RESULTS

For the coating production we apply the BBM in the spectral region from 1200 to 2300 nm that does not overlap with the regions where target requirements are specified. In the course of the coating production we apply a special stabilization procedure aimed at raising accuracy of BBM layer thickness control. This procedure has been successfully applied in our previous works related to coating production with BBM thickness control[10-11]. It is based on taking into account wavelength positions of monitoring signal extrema. Thickness control with taking into account correspondence of these positions to theoretically predicted extrema positions at the end of the deposition of each layer is especially important for the first several coating layers when the monitoring signal in BBM spectral region exhibits a very simple interference pattern without essential interference oscillations. Figure 7 a-c shows the correspondence between measured BBM signals and theoretically predicted transmittance signals at the end of the depositions of the first, second and third layer.

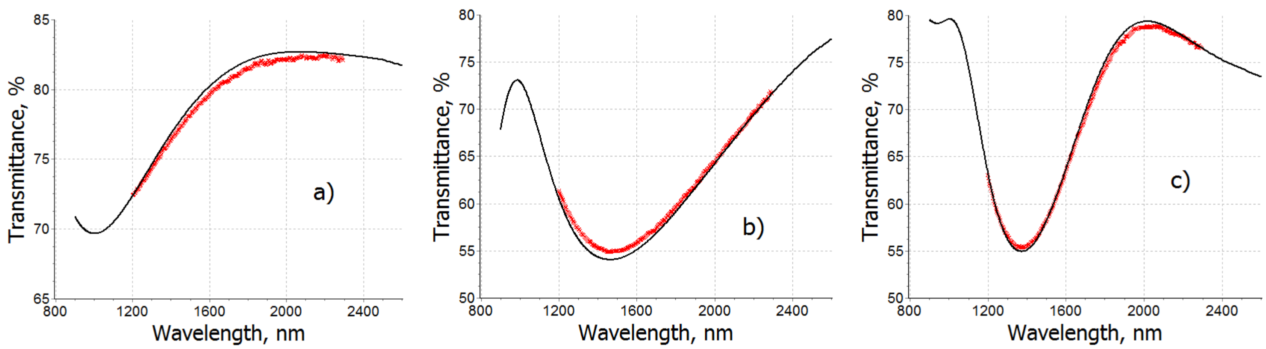

Figure 7. Correspondence between measured (red crosses) and theoretical monitoring signals (black solid curves) at the ends of layer depositions: a) first layer, b) second layer, c) third layer.

Due to the careful determination of thin film refractive indices wavelength dependencies in a wide spectral region, the production of our AR coating has been successful at the very first deposition run. Figure 8 shows the correspondence between measured and theoretical reflectancies of the produced coating in the spectral region from 500 to 2500 nm. One can see an excellent correspondence in the intended AR regions of 522-570 nm and of 1020-1100 nm. The residual reflection in these regions is connected with the reflectance from the substrate back side. The correspondence between measured and theoretical reflectancies in the spectral region around 11000 nm is also excellent.

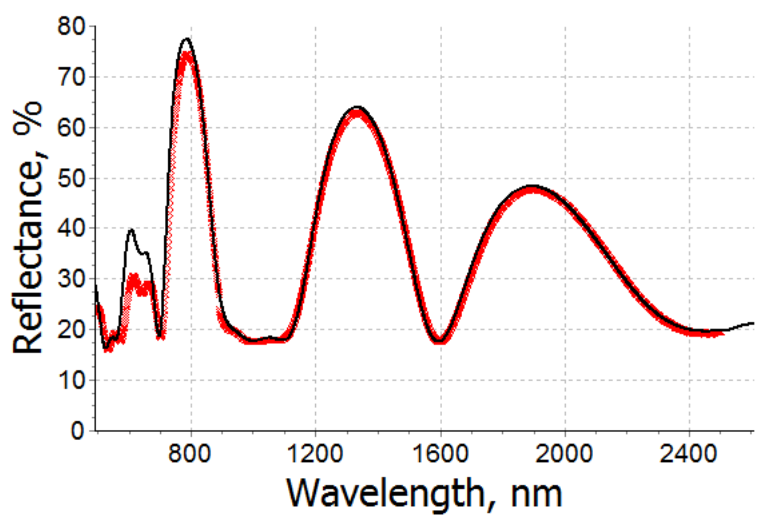

Figure 8. Comparison of measured (red crosses) and theoretical reflectance (black solid curve) in the 500-2500 nm spectral region.

6. CONCLUSIONS

The design and production of AR coatings with low reflectance in several distinct spectral regions present a big challenge even at the modern state-of-the-art of optical coating technology. To meet this challenge, the application of all modern software tools supporting characterization, reverse engineering, design, computational manufacturing, and monitoring of optical coatings is required. One of the key issues is the careful determination of layer refractive indices with the help of modern characterization and reverse engineering software. Combination of modern design techniques and computational manufacturing experiments enables choosing the most practical design so that its successful manufacturing can be accomplished even without test production runs.

FUNDING

This work was financially supported by the Russian Foundation for Basic Research (RFBR), research project No. 13-07-00846 A "Mathematical modeling and simulation of optical nano-coatings deposition."

REFERENCES

[1] Schumacher, P., [Die ZEISS Punktal Story], BoD – Books on Demand, (2013).
[2] Thelen, A., [Design of Optical Interference Coatings], McGraw-Hill Optical and Electro-Optical Engineering Series (1989).
[3] Macleod, H. A., [Thin-Film Optical Filters, 4th ed.], Taylor & Francis (2010).
[4] Dobrowolski, J. A., [Optical properties of films and coatings, in Handbook of Optics, 3d ed.], McGraw Hill Professional, Access Engineering, Vol. IV, pp. 7.1–7.136 (2010).
[5] "Zinc Selenide ZnSe," < http://www.iiviinfrared.com/Optical-Materials/znse.html>.
[6] Connolly, J., diBenedetto, B. and Donadio, R., "Specifications of Raytran material," Proc. SPIE, 181, 141-144 (1979).
[7] Tikhonravov, A. and Trubetskov, M., "Modern design tools and a new paradigm in optical coating design," Appl. Opt. *51*, 7319–7332 (2012)
[8] Tikhonravov, A. and Trubetskov, M., "Computational manufacturing as a bridge between design and production," Appl. Opt. 44, 6877-6884 (2005).
[9] Amotchkina, T., Schlichting, S., Ehlers, H., Trubetskov, M., Tikhonravov, A. and Ristau, D., "Computational manufacturing as a tool for the selection of the most manufacturable design," Appl. Opt. 51, 8677-8686 (2012).
[10] Tikhonravov, A., Zhupanov, V., Fedoseev, V., and Trubetskov, M.," Design and production of antireflection coating for the 8–10 µm spectral region," Optics Express 22, 32174–32179 (2014).
[11] Zhupanov, V., Klyuev, E., Alekseev, S., Kozlov, I., Trubetskov, M., Kokarev, M. and Tikhonravov, A., "Indirect broadband optical monitoring with multiple witness substrates," Appl. Opt 48, 2315–2320 (2009).
[12] Tikhonravov, A. and Trubetskov, M., "OptiLayer software," <http://www.optilayer.com>
[13] Amotchkina, T., Janicki, V., Sancho-Parramon, J., Tikhonravov, A., Trubetskov, M. and Zorc, H., "General approach to reliable characterization of thin metal films," Appl. Opt. 50, 1453-1464 (2011).
[14] Tikhonravov, A., Trubetskov, M., M., Kokarev, M., Amotchkina, T., Duparre, A., Quesnel, E., Ristau, D. and Gunster, S., "Effect of systematic errors in spectral photometric data on the accuracy of determination of optical parameters of dielectric thin films," Appl. Optics 41, 2555-2560 (2002).
[15] Tikhonravov, A., Trubetskov, and DeBell, G., "On the accuracy of optical thin film parameter determination based on spectrophotometric data", Proc. SPIE 5188, 190-199 (2003).
[16] Furman, Sh. and Tikhonravov, A., [Basics of optics of multilayer systems], Editions Frontiers, Gif-sur Yvette, 76-78 (1992).