Expanded viewpoint for broadband antireflection coating designs

Ronald R. Willey

Willey Optical Consultants, 13039 Cedar Street, Charlevoix, Michigan 49720, USA (ron@willeyoptical.com)

Received 6 August 2010; revised 22 September 2010; accepted 30 September 2010; posted 5 October 2010 (Doc. ID 132886); published 3 November 2010

Examining spectral regions outside of the band where an antireflection coating is specified can aid in finding optimal design solutions. The reflectance versus wavenumber plots at low frequencies indicate the overall thickness of the design. These plots also point to whether the design will provide the minimum possible average reflectance in the specified band. It has been discovered that these patterns are nearly replicated by the plot of a quarter-wave stack at peak frequency. It is also found that optimal solutions exist only at quantized intervals. © 2010 Optical Society of America

OCIS codes: 310.0310, 310.5696, 310.6805, 310.4165, 310.1210, 310.1620.

1. Introduction

It is thought that most antireflection (AR) coating designers have focused their attention only on the spectral region where the reflection is to be reduced. However, there is much to be learned by examining the reflection in the low-frequency or long-wavelength spectrum beyond the AR band. It is also helpful to start by setting up the initial design in the high-frequency or short-wavelength region beyond the AR band.

2. Reflectance beyond the Antireflection Band

Figure 1 shows a starting design where a quarter-wave optical thickness (QWOT) stack, $(1\,\mathrm{H}\,1\,\mathrm{L})^{19}$ at 308 nm, was used. Here 1 H represents one QWOT of high-index material at the design wavelength and 1 L is one QWOT of low-index material. This layer-pair combination is taken 19 times, as indicated by the superscript 19. This generates the approximate number of layers and the approximate overall thickness needed for the design. After some optimization over the 385 to 1540 nm band (4:1 bandwidth, which is the longest wavelength in the band divided by the shortest wavelength), the AR band is seen in Fig. 2. Details of the procedure used can be found in Ref. [1].

0003-6935/11/090C86-04$15.00/0
© 2011 Optical Society of America

Figure 3 results when the scale is changed from wavelength in nanometers to frequency in wavenumbers (cm^{-1}), and the range is extended from near 0 to $30,000\,\mathrm{cm}^{-1}$ (a wavelength of 333.3 nm). This then shows the low- and high-frequency spectral regions outside of the AR "box" from 6500 to $26,000\,\mathrm{cm}^{-1}$ (385 to 1540 nm). The three peaks in the low-frequency region indicate that the overall thickness of the design is three times that required by the minimum thickness for an optimal design [2]. The shape of the low-frequency spectrum can also be an indication of whether the design is near optimal [2].

Figure 4 shows the interesting discovery that a QWOT stack at a long wavelength can generate a spectral curve in the low-frequency region, which is similar to that of broadband AR (BBAR). However, the QWOT stack has higher harmonic reflection bands at 3 and 5 times the frequency of the first band; the second and fourth harmonics are missing. The AR design is acting like a "rugate" design to suppress all the harmonics up through the fifth.

Figures 5 and 6 compare these rugate and QWOT designs in reflection versus thickness. This is another viewpoint of the design that shows the reflection at the longest wavelength in the AR band that would be seen as the coating builds from the substrate. This plot format is useful in following the progress of a design for layers that are too thin and can also show by its shape whether the design is likely to be near optimum (as also does the format of Fig. 3).

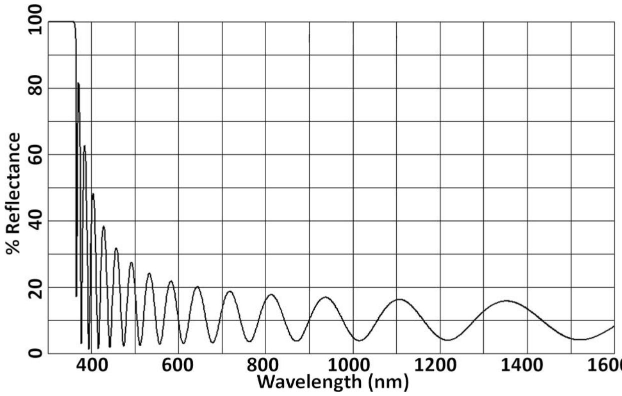

Fig. 1. QWOT stack at 308 nm as a starting design for the AR band.

Note also that the number of peaks is the same as in Fig. 3. This number of peaks would be one for a design of minimal overall thickness (on low-index substrates) and two for a design that is two times the minimum thickness. For high-index substrates, it can be seen that the minimum thickness has its peak starting at the substrate (or one-half a cycle), and thicker "optimal" designs will be found with 1 – 1/2, 2 – 1/2, 3 – 1/2 peaks or cycles, as is seen in Figs. 8 and 9. The QWOT design has a related low-frequency spectrum and a reflectance versus thickness shape similar to that of the rugate, but it does not cause the reflectance to move as smoothly through the thickness growth.

3. Quantization

AR designs of various overall thicknesses were optimized using the constrained optimization feature of FilmStar [3] to restrain the overall physical thickness of the design to specific values. The optimization procedure that was used here in FilmStar was the NOL [4] Gradient Method, which allows the use of constrained parameters, such as a target thickness and other functions, that can be calculated from the design results in a spreadsheet. The optimization engine used in FilmStar is the DSNL Library [4], which maximizes (or minimizes) a function (such as the average reflectance over a band of wavelengths) and constrains some parameter(s) to be either equal to some specified value or some other parameter(s) to be greater than or less than some specified value. The detailed internal workings of this software module are proprietary, but its behavior is well defined.

A design of the type in Figs. 1–3 was used as the starting configuration, and progressively larger overall thickness targets were used for the optimization, with reflection targets of near zero for the AR band from the 385 to 1540 nm band (4:1 bandwidth). Figure 7 shows the results where the dots show individual optimal results with the thickness restraint, and the triangles show the best designs in the local thickness range. Figure 8 shows the low-frequency spectra of the best (triangle) designs, which are 1, 2, and 3 times the minimum optimal thickness.

As the target thickness was reduced from some higher value that was greater than optimal, the R_{ave} decreased and then increased as a minimum was approached and passed from a higher thickness. The design would change in nature at these points where various layers reduce to near zero thickness, indicating that fewer layers were needed for an optimal design of that thickness. When a local minimum thickness was reached, attempts to again add thickness resulted in the same R_{ave}; the R_{ave} did not increase to the previous higher values. This seems to have a hysteretic nature.

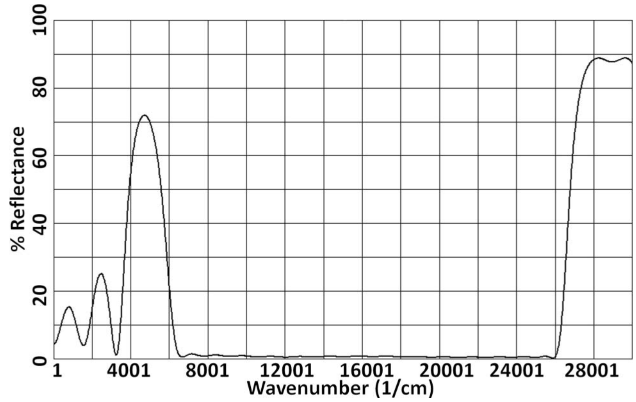

Fig. 3. AR band plus the extended range.

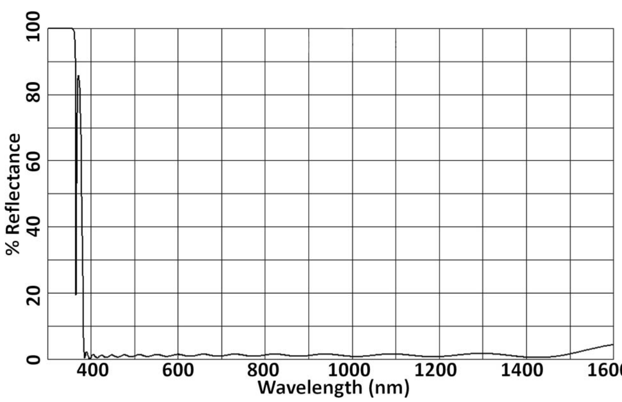

Fig. 2. Optimized design for the AR band from the start in Fig. 1.

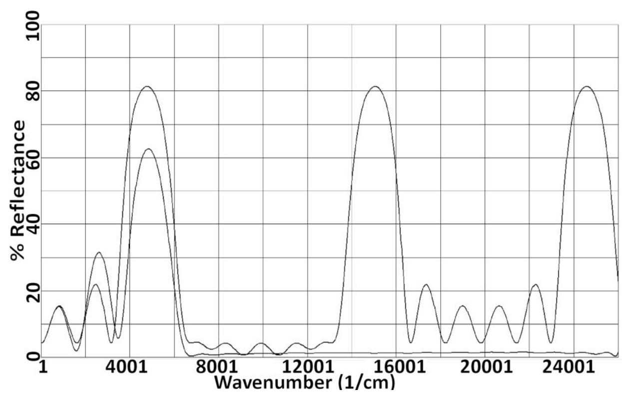

Fig. 4. QWOT stack $(0.5\,\mathrm{L}\,1\,\mathrm{H}\,0.5\,\mathrm{L})^3$ at $4953\,\mathrm{cm}-1$ (upper curve) and design similar to Fig. 3 (lower curve).

It has been observed that, with higher index substrates (such as 2.35 as opposed to 1.52), the low-frequency spectra start at a higher reflectance and initially decrease with thickness rather than increase, as seen in Fig. 9. This first portion behaves like a “step-down” AR, which simulates a gradually decreasing index from the substrate to the medium. Because the high-index coating material is equal to the substrate index in this case, layer pairs can be constructed whose effective index decreases gradually from the substrate index to that of the low-index coating material at the last layer. Figure 9 shows the

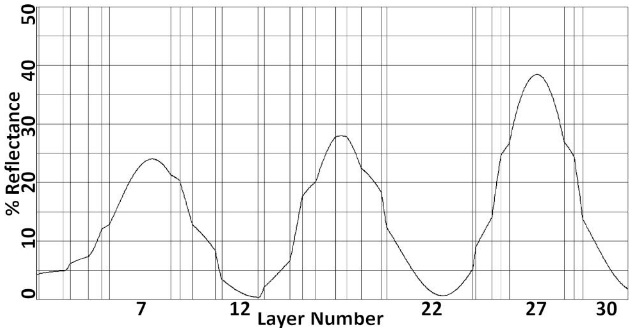

Fig. 5. Reflectance versus thickness at the longest wavelength of the AR band (1540 nm or 6500 cm^{-1}) for the rugate design.

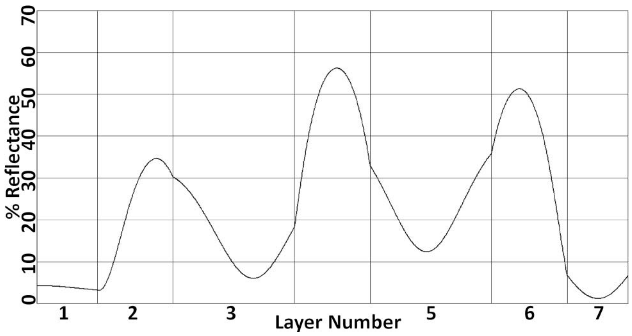

Fig. 6. Reflectance versus thickness of the QWOT design of Fig. 4 related to the rugate design.

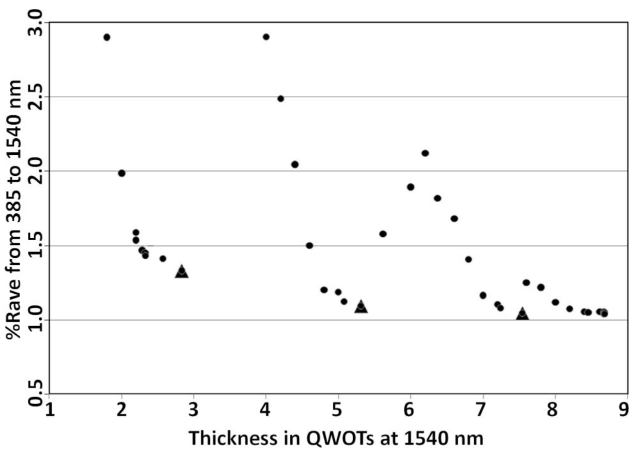

Fig. 7. $R_{ave}\%$ for the best designs at controlled overall thicknesses for AR band 385–1540 nm ($n_{sub} = 1.52$, $n_H = 2.35$, and $n_{L=1.46}$).

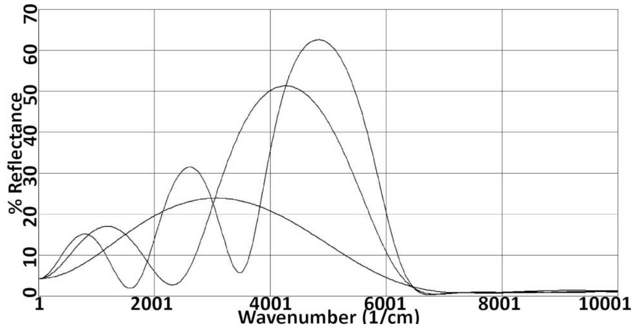

Fig. 8. Low-frequency spectra of the best 1, 2, and 3× minimum thickness designs, shown as triangles in Fig. 7.

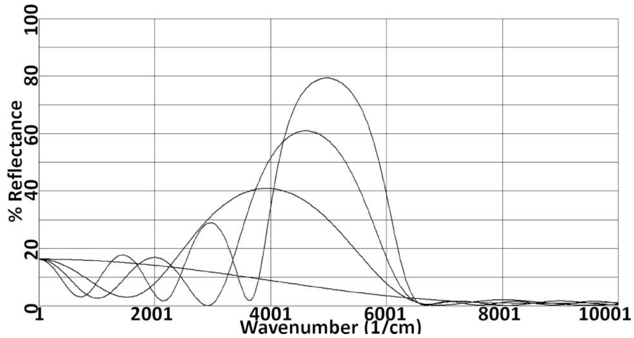

Fig. 9. Low-frequency spectra of the best four designs on high-index (2.35) substrate for AR band of 385 to 1540 nm ($n_{sub} = 1.52$, $n_H = 2.35$, and $n_{L=1.46}$).

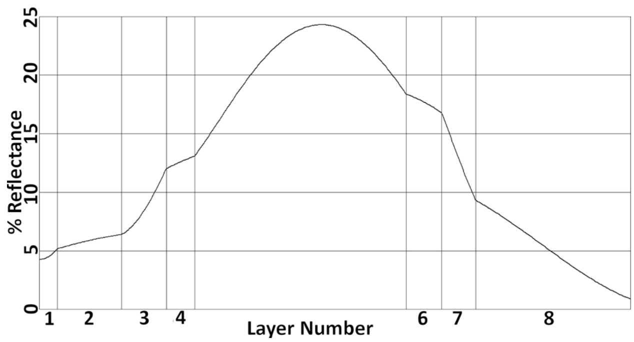

Fig. 10. Reflectance versus thickness at the longest wavelength of the AR band for a one-cycle design on a low-index (1.52) substrate.

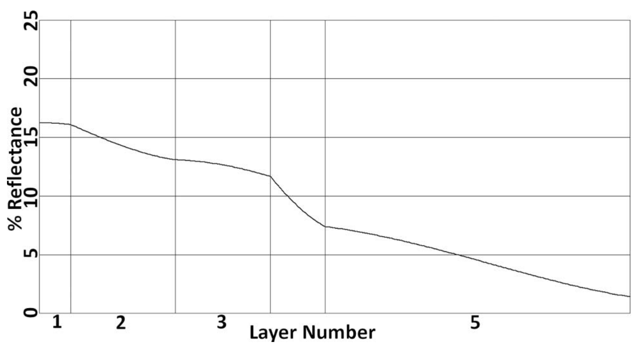

Fig. 11. Reflectance versus thickness at the longest wavelength of the AR band for a half-cycle (step-down) design on a high-index (2.35) substrate.

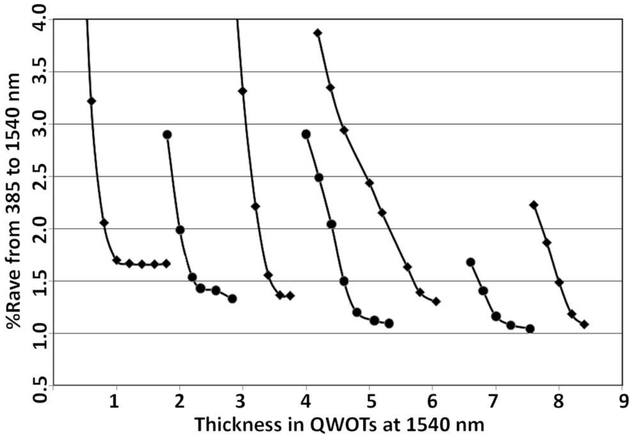

Fig. 12. R_{ave}% for the best designs at controlled thicknesses designs on 1.52 (dots) and 2.35 (diamonds) substrates.

low-frequency spectrum of designs of the step-down and 3, 5, and 7 times that overall thickness; or 0.5, 1.5, 2.5, and 3.5 times the minimum thickness seen in Fig. 7. For further illustration of this, Figs. 10 and 11 compare the reflectance versus thickness of the one-cycle design on a low-index (1.52) substrate with the half-cycle (step-down) design on a high-index (2.35) substrate.

Figure 12 shows the R_{ave}% with thickness for optimized designs on 1.52 (dots) and 2.35 (diamonds) index substrates. This illustrates that the optimal thicknesses are quantized and confirms earlier [2] conclusions that the quantum thickness is approximately 2.5 QWOT at the longest wavelength in the AR band. Quantization effects had been observed some time ago by Verly *et al.* [5], but they are becoming more defined with these further investigations.

This work incidentally shows that, if the substrate is near the highest index of the layer structure, a step-down design (lowest curve in Fig. 9) is practical where the layer pairs are of the nature of Herpin equivalent layers. With lower index substrates, it appears that the early layers increase the reflectance to a point where the last layers of the coating are similar to a step-down design.

4. Conclusions

A useful starting design for a BBAR coating is a QWOT stack outside the short wavelength end of the desired AR band, which will give more than enough layers and overall optical thickness to be brought to an optimum design for the overall thickness desired.

The low-frequency reflectance spectrum from a near zero frequency (near infinite wavelength) to the AR band (accessed by viewing on a wavenumber scale), which may have often been previously overlooked, yields useful information on the overall thickness of the coating design and some indication of whether the design is at or near an optimum design.

The optimum designs are shown to be found only at specific overall optical thicknesses that seem to be found at intervals of approximately 2.5 QWOTs of the longest wavelength (or lowest frequency) in the AR passband. There seem to be two different classes of solutions, which depend on whether the substrate is of high or low index with respect to the high-index coating material used in the design.

References

1. R. R. Willey, *Practical Design of Optical Thin Films*, 2nd ed. (Willey Optical Consultants, 2007), App. C.
2. R. R. Willey, *Practical Design of Optical Thin Films*, 2nd ed. (Willey Optical Consultants, 2007), Sec. 2.2.4.
3. F. T. Goldstein, "FilmStar," FTG Software Associates, P.O. Box 579, Princeton, N.J. 08542.
4. Numerical Optimization Library (NOL), DSNL Version 2.0, Technologix Corporation, 12020 113th Avenue NE, Kirkland, Wash. 98034-6938.
5. P. G. Verly, J. A. Dobrowolski, and R. R. Willey, "Fourier-transform method for the design of wideband antireflection coatings," Appl. Opt. **31**, 3836–3846 (1992).