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Rugate broadband antireflection coating design

R. R. Willey

Opto Mechanik, Inc.
P.O. Box 361907, Melbourne, Florida 32935

ABSTRACT

The use of an antireflection (AR) coating which is a series of homogeneous layers whose index steps down from the substrate index to the index of air or a vacuum has been well described in the literature (1,2). These are particularly attractive for high index substrates such as germanium, but are limited by the availability of appropriate real coating materials. The limiting factor is a lack of practical materials whose index is less than about 1.35. Another family of AR coatings which include one or more half wave layers is also known. The most common of these is the classical QHQ design. DeBell(3) reported on designs such as QHHHQ and QHHHHHQ where the H's are alternating high and low index layers. We have found that there is a family of inhomogeneous or "Rugate" index functions which can produce broadband AR coatings. These point to some general principles of AR coating design which have not been previously obvious from the literature. We describe these investigations and findings in graphical form. We discuss the concepts and understanding gained and examine the possibilities and limitations of the approach.

1. INTRODUCTION

We have long been motivated to understand the basic principles and limitations which apply to developing an AR coating with a very broad band of very low reflectance. For example, we would like to produce an AR from 400 to 1100 nanometers that had less than 0.5% reflectance in that band. The work of DeBell(3) provided the basis for the start of this particular investigation. He optimized the indices of various homogeneous layer designs such as QHQ, QHHHQ, QHHHHHQ, etc. to give broadband AR's. We carried this further by finely dividing each of the layers into small sublayers after the fashion of Southwell(4) and optimizing the index of each sublayer. The resulting index profiles approximate smooth inhomogeneous index functions and lead to a better understanding of what might be accomplished in the area of broadband AR coatings. We have not constrained the index values allowed in the optimizations in either high or low index. This has permitted us to see where the ideal index profile might be if there were no limitation on available materials. From this, we can glean insight as to what can be done within the limitations of real materials. There were three main variables in our study: 1. the number of maxima and minima or cycles in the index profile from substrate to vacuum (or air); 2. the substrate indices; and 3. the overall thickness of the layer system. We will describe our findings in each of these areas.

2. PROCEDURES

We chose to divide the total coating thickness into 24 layers. We arbitrarily used quarter-wave optical thickness layers (QWOT's) at 1000 wavenumbers (or 10 micrometers) for the common base of comparison. We took a homogeneous design such as one of DeBell's and hand sketched an approximately fitting smooth inhomogeneous function for it. We then divided the total coating into 24 equal parts and picked off the approximate index values to represent each thin layer. These values were inserted in the optimization program as starting design values. Target reflection values of 0.1% were set over a broad wavenumber band such as 400 to 1600 wavenumbers (25 to 6.25 micrometers). All 24 indices were allowed to vary freely in the optimization while the layer thicknesses were kept fixed at a QWOT. In the optimization process, the main designer interaction was to broaden or narrow the target range and number of points in the range to force a smooth and low reflection over as wide a band as practical. As will be seen below, the more cycles in the function, the narrower the band which can be achieved. We actually found that by targeting too wide a band for a two cycle function, the optimization led to a one cycle function! The starting values, for example, in the case of the 1/2 cycle functions were taken as equally divided index decrements from the substrate index to 1.0. In the case of all but the highest index substrate investigated (4.0), the resulting optimized profile for 1/2 cycle was imperceptibly different from a straight line function. Figure 1 shows the breadth of the AR bands for coating of 1/2, 1, 2, and 3 cycles on a substrate of 1.52. Figure 2 shows the 1/2 cycle or "step down" profiles mentioned above.

3. RESULTS AND OBSERVATIONS

The resulting inhomogeneous index profiles are shown in Figures 2-5 for functions of various numbers of cycles. Figure 1 shows how broadband these AR's can be. It can be seen that the broadest is the 1/2 cycle design with the designs getting narrower with increased number of cycles. We did not expect this result. It can be observed in Figures 2-5 that all of the functions appear to be of a similar family. The termination at the vacuum end of the functions seem to all be of similar form. The termination at the substrate end must be at the substrate index, but can be in a range from positive to negative slope. There is a trend for the functions of a given number of cycles starting at different substrates to become very similar as they approach the vacuum end. It is interesting that the maxima and minima in the various functions seem to stay near achievable real indices of 2.5 and 1.5. It further appears that designs of about 1-1/2, 2-1/2, and 3-1/2 cycles might be found for substrates of index 2.5 or more which did not require film indices higher than 2.5 for good results. This is because the profile in these cases drops from the substrate to the first minimum rather than rising above 2.5 to a first maximum.

The observation that the bandwidth seems to get less broad with increasing numbers of cycles is at first disappointing. However, it appears that there may be an advantage to the higher number of cycles in that the rate of decrease in index with thickness is greater in the last layer. This may lead to the possibility of achieving better homogeneous approximations with real indices such as 1.38 in the last layer.

The effect of overall thickness on a given profile was verified and is somewhat obvious. The wavelength of the center of the band increases directly with increasing film thickness. The ratio of the wavelengths at the longwave end to the shortwave end of the band remains constant and is independent of the center wavelength. These effects are somewhat easier to observe when the designs are plotted on the frequency (wavenumber) scale.

Figure 6 shows in curve A the admittance path followed by the 1/2 cycle Rugate layer from the substrate to a vacuum at admittance 1.0. This creates the broadband AR seen as curve A in Figure 7. Curve B in Figure 6 is an ideal single homogeneous layer whose index is the square root of the substrate index, and curve B in Figure 7 shows the narrow bandwidth of AR which this gives. Similarly, the C curves in Figures 6 and 7 show the results for the usual 1.38 MgF_2 AR on 1.52 glass. It can be seen that the single inhomogeneous layer has great potential with respect to the single homogeneous layer if the index profile could actually be achieved. This has been approximated with good spectral performance in practice by selective etching of some substrates.

Curve A in Figure 8 is the admittance locus of the one cycle inhomogeneous index profile on 1.52 glass. We optimized the homogeneous index values of a QHQ design which resulted in the usual solution of 1.65, 2.1, and 1.38 layers. This index profile is seen as a dotted line in Figure 3. Note that it is the closest three layer approximation of the ideal one cycle inhomogeneous layer. Curve B in Figures 8 and 9 show the admittance locus and reflectance plot of this classical three layer AR as compared with the ideal one cycle Rugate AR. We reported (5) the observation that the approximation which comes the closest to following the ideal admittance locus will also come the closest to reproducing the reflectance curve of the system approximated. We plan to expand on these approximations of Rugate AR's by homogeneous layers in a subsequent paper (6). The effects of different substrate indices on the admittance loci of a one cycle Rugate AR are shown in Figure 10.

Figure 11 shows the admittance locus for the two cycle Rugate AR on a 1.52 substrate in the solid curve and on a 2.5 substrate in the dotted curve. Figure 12 shows the locus for a three cycle Rugate on 1.52 glass. Note that all of the inhomogeneous layer admittance loci are plotted at the long wavelength or low frequency end of the AR band. As shorter wavelengths are plotted, the locus collapses to nearly straight lines near the real axis, and then it starts to expand in a spiral until each quarter wave has become a half wave at the shortwave cutoff end of the band.

4. CONCLUSIONS

We conclude that there are a family of functions of index of refraction versus thickness that produce very broadband antireflection coating designs on substrates of any index. These are in effect single inhomogeneous layers or Rugate layers. These can be of any reasonable number of cycles from less than 1/2 to 3 or more. More cycles in the same overall layer thickness produce a narrower AR bandwidth. Thicker overall layers will produce an AR for longer wavelengths, but the ratio of the longest to shortest wavelength in the AR band will remain constant for a given design. We have illustrated how these functions vary with substrate index of refraction and the number of cycles in the layer. We have also illustrated how the classical single and three layer AR designs are approximations of these ideal profiles.

5. REFERENCES

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3. G.W. DeBell, "Antireflection coatings utilizing multiple half waves," Thin Film Technologies, J. Roland Jacobsson, Ed., Vol. 401, pp. 127-137, SPIE, Geneva, 1983.
4. W.H. Southwell, "Coating design using very thin high- and low-index layers," Appl. Opt. 24, 457 (1985).
5. R.R. Willey, "Graphic description of equivalent index approximations and limitations," Appl. Opt. 28, #20, PP. ???, October 15, 1989 (accepted for publication).
6. R.R. Willey, "Another viewpoint on antireflection coating design," Design and Evaluation of Optical Systems, SPIE, Vol 1191-19, London, September 1989.

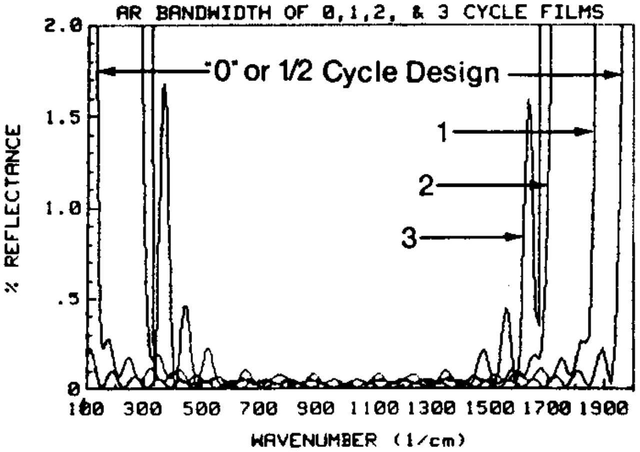

Fig. 1. Reflectance of Rugate AR coatings on 1.52 index substrates for designs of "0" (1/2) cycle, 1, 2, and 3 cycles.

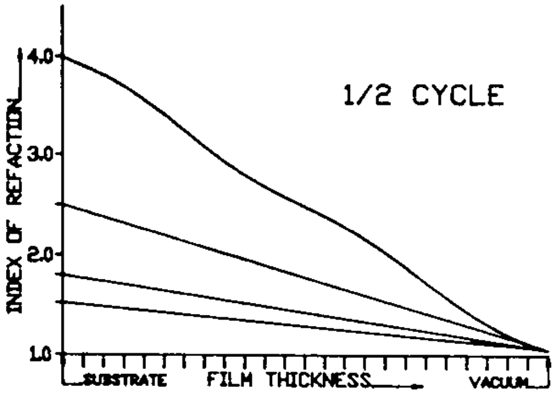

Fig. 2. Index of refraction versus thickness of inhomogeneous layers of less than one cycle, like step-down layers.

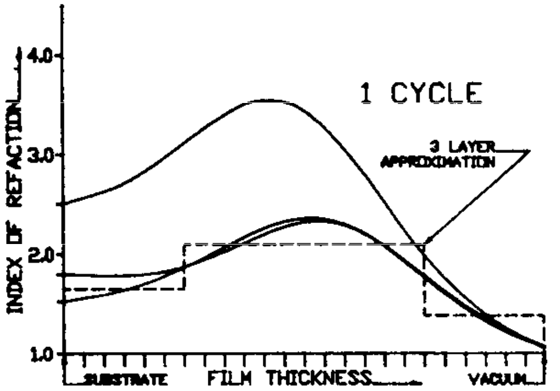

Fig. 3. Index profiles of one cycle on substrates of index 1.52, 1.8 and 2.5. Dotted line is ideal homogeneous 3 layer.

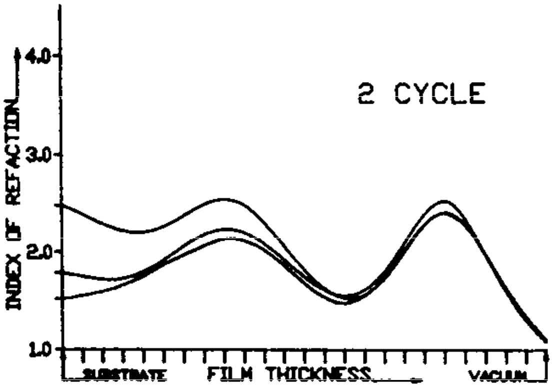

Fig. 4. Index profiles of two cycles on substrates of various indices.

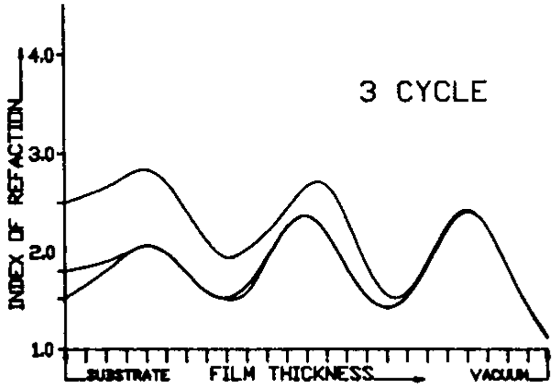

Fig. 5. Index profiles of three cycle Rugate AR's on various index substrates.

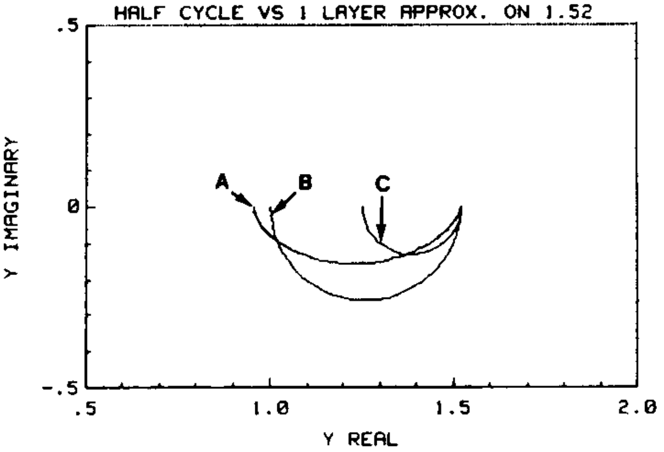

Fig. 6. Admittance diagram of ideal Rugate (curve A) at longest wavelength. Curve B is SLAR of 1.233 index, C is a 1.38 QWOT.

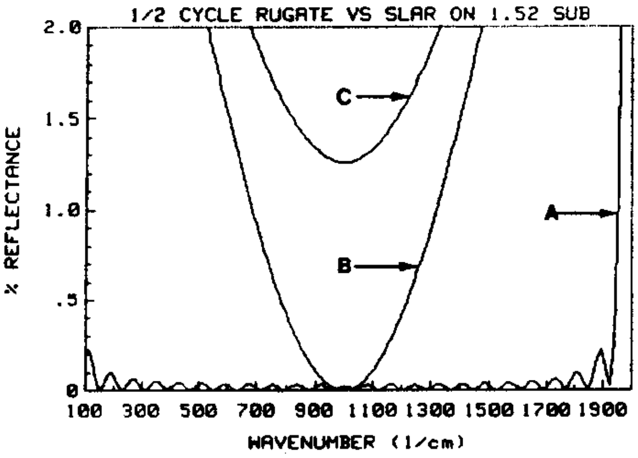

Fig. 7. Comparative reflectance of Rugate AR (A) with an ideal SLAR (B) and MgF2 SLAR (C) on a 1.52 index substrate.

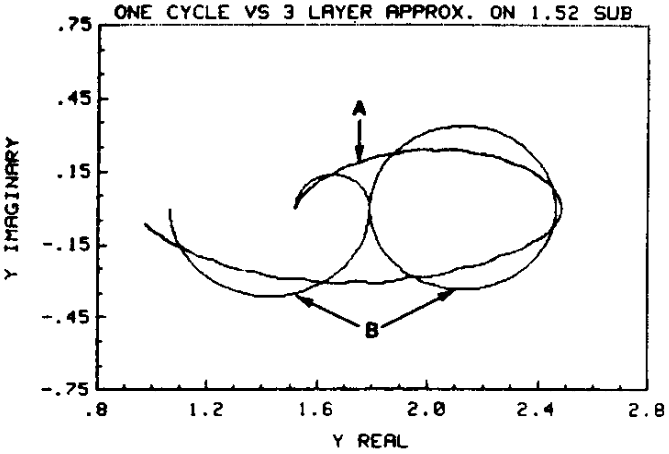

Fig. 8. Admittance of ideal one cycle Rugate AR (Curve A) and the classical three homogeneous layer AR (Curve B).

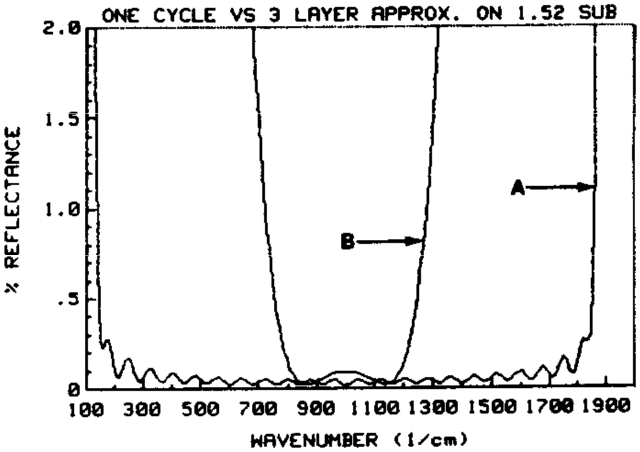

Fig. 9. Comparative reflectance of one cycle Rugate AR (Curve A) with classical 3 layer AR (Curve B, 1.65Q, 2.1H, 1.38Q).

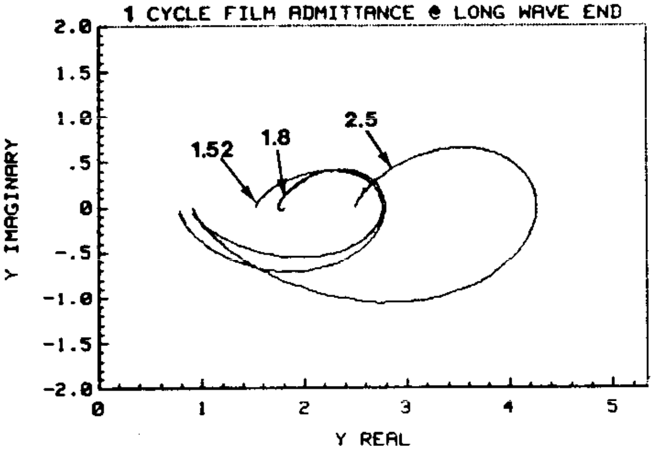

Fig. 10. Admittance of one cycle Rugate AR's on substrates of index 1.52, 1.8, and 2.5

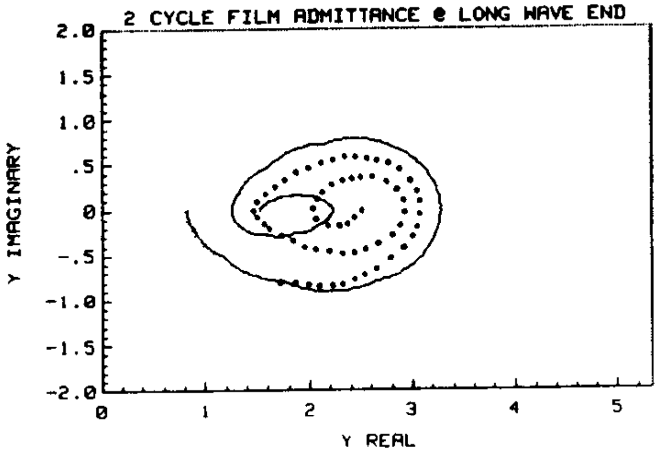

Fig. 11. Admittance of two cycle Rugate AR on 1.52 substrate (solid line) and 2-1/2 cycle on 2.5 sub. (dotted line).

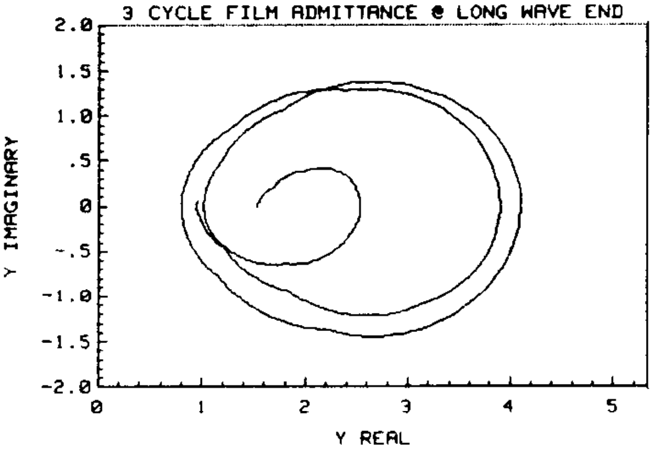

Fig. 12. Admittance diagram of three cycle inhomogeneous index layer AR (Rugate) on a 1.52 index substrate.