Another viewpoint on antireflection coating design

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ABSTRACT

Most antireflection coatings in use today are derived from concepts based on the use of quarter-wave (Q) and half-wave (H) optical thickness layers. We show an alternative and more general way of viewing the concepts and how special cases reduce to the commonly used forms. The monotonically graded inhomogeneous index layer from the substrate to the medium has been extensively reported by Jacobsson and Martensson(1), Dobrowolski and Ho(2), and others. Various oscillating index profiles between the substrate and the medium show promise in producing superior broadband AR coatings. These concepts have evolved from observation of broadband designs using multiple homogeneous quarter- and half-wave optical thickness layers as described by DeBell(3). The viewpoint leads to some further understanding of the possibilities and limitations of AR coatings in general.

1. INTRODUCTION

The goal of our investigations has been to understand the principles and limitations of practical broadband antireflection coatings as might be applied to reduce uncoated reflections on glass by an order of magnitude in the visible through the 1064nm spectral band. In a recent paper(4), we showed that there is a family of inhomogeneous index of refraction functions (Rugate films) which can produce very broadband AR coatings on substrates of any index. We showed that the more cycles there are in the function, the narrower the AR band will be. This disadvantage appears to be offset by the possibility that the designs with more cycles can be reduced to practical coatings with available real coating materials. We have carried this previous conceptual work further to show that a practical AR can be designed to cover the region from 450 to 1064nm for substrates in the index of refraction range from at least 1.46 to 2.5.

2. BACKGROUND

Jacobsson and Martensson(1) investigated the use of a single inhomogeneous layer which had a monotonic decrease in index of refraction from the substrate to the medium of vacuum or air. We approximated this by a stack of very thin homogeneous layers of various indices. We allowed these indices to be varied in an optimization program where the target was to produce as broad an AR band as practical. Figure 1 shows the resulting index profiles of these inhomogeneous coatings for various substrate indices. Curve A in Figure 2 shows the admittance diagram of such a layer on a 1.52 index substrate for the longest wavelength in the band. Curve A in Figure 3 shows the broad antireflection band that such a coating would produce. Curve B in Figures 2 and 3 illustrates what would result from a homogeneous layer whose index was the geometric mean of the indices of the substrate and the medium. A perfect AR results at the wavelength at which the layer has an optical thickness of one quarter-wavelength, but the band is relatively narrow. Curve C in Figures 2 and 3 shows, for comparison, the properties of the usual magnesium fluoride single layer coating on a 1.52 index substrate.

3. NEW DEVELOPMENTS

Most AR coatings have been based on stacks of quarter- and half- wave layers. DeBell(3) reported on the use of multiple half-wave layers to produce good AR coatings. The dotted lines in Figures 4, 7, and 9 plot the index profiles of a QHQ, QHHHQ, and QHHHHHQ design of homogeneous layers by DeBell. He also constrained the optical thicknesses of the layers and varied the index of each layer in the optimizations. Upon examining DeBell's results, we were impressed by the cyclic or undulatory nature of the index profiles. This led us to use the above mentioned very thin layer optimization to find inhomogeneous layer systems of one, two, and three cycles which produced broad band AR coatings. The smooth and continuous curves in Figures 4, 7, and 9 are the results of these optimizations for various index substrates. Figure 4 shows that the classical QHQ homogenous layer design is an approximation of the ideal inhomogeneous index function. Figure 5 compares the admittance paths of the two coatings. In a paper about to be published(5), we show that the closer the admittance loci of two coatings match, the closer the spectral performance will match. Figure 6 shows how the ideal AR and the 3 layer approximation compare in spectral performance. Figures 8 and 10 show the admittance loci for the 2, 2-1/2, and 3 cycle index profile functions.

The point to notice in Figures 5, 8, and 10 is that the slope of the admittance locus, as it terminates at the admittance equal to one(1.0) point (AR), is greater with increasing numbers of cycles. The basic problem preventing the realization of a broadband coating of the type in Figure 1 (1/2 cycle or "step-down") is that very low indices approaching 1.0 are required but not available. The lowest index that we consider using when durability is an issue is 1.38 (MgF_2). This implies that coating of the type in Figure 1 will not be practical on most glasses and have only limited bandwidths on high index substrates such as germanium. It is shown in Reference 5 and many other places that any index layer can be simulated by a combination of higher and lower index layers, but no technique has been discovered to generally simulate a layer of index lower than the parent materials over an extended spectral range. This limitation has a major effect on what can be achieved with the 1/2 cycle and one cycle function AR's. Figure 11 illustrates the problem. A twelve layer approximation of curve A from Figure 5 was optimized with 1.19 as the lowest index of the last layer and the resulting low reflectance which averages less than 0.3% is seen in Figure 11. The system was again optimized with the lowest index set to 1.38 and the average reflectance was greater than 1.5%. The fact that the slope of the admittance curve at its termination increases with number of cycles starts to make the possibilities more interesting with two and three cycle function AR's. Figure 12 shows what can be done with a last layer of 1.38 index in a 24 layer approximation of the three cycle function of index profile. The AR is broader and lower than most reported, but still does not meet our goal of 450 to 1064nm. Figure 13 shows the admittance diagram to be compared with the ideal in Figure 10. The bandwidth, as mentioned above, is narrower with increasing number of cycles. This then suggests that two cycles might be a better compromise; and this is in fact the case. Figure 14 shows the result which averages less than 0.3% from 450 to 1064nm. Figure 15 shows the admittance diagram for comparison with Figure 8. These last two designs are actually the result of further reduction to practicality. The ideal index profiles were approximated by 12 pairs of layers made up of appropriate proportions of index 2.35 and 1.46 (TiO_2 and SiO_2). The systems were optimized with 1.38 (MgF_2) as the index of the last layer. The admittance of this last layer comes in to the 1.0 point more steeply than desired, but it is a better approximation for the termination of the two and three cycle functions than for the one cycle.

We took the design of Figure 15 and progressively reduced the number of layers to make the simplest design that still meets our requirements. We were able to get a good solution with twelve layers which is seen as curve A in Figure 16. It has been mentioned by Aguilera, et al.(6) that the ripples in the AR band increase as the design is pushed for greater width. Conversely, a narrower band for a given design can yield a design with less amplitude in the residual ripples. Figure 16 illustrates this fact with designs that have been reoptimized with respect to progressively narrower targets for the AR bandwidth.

There are common requirements for an AR which covers the visible spectrum and the YAG laser line at 1064nm, but are not concerned with the reflectance between the two bands. We reoptimized the twelve layer very broadband AR with respect to this target and were able to achieve the result seen in Figures 17 and 18. This design, admittedly, might be difficult to produce so that the narrow AR at 1.064 was right on the desired wavelength.

4. PROCEDURES REVIEW

We will now review the procedures which we have found useful in the design of a new broadband AR coating. These apply the concepts described above to design an AR for any real index substrate using real materials. We assume the use of a computer program which can optimize a design with respect to a set of desired reflectance targets by varying either layer indices and/or thicknesses.

We use the following general steps:

1. Choose an approximate index profile on the basis of required bandwidth and substrate index. This can be done for example by hand drawing an index function from the substrate index to the index 1.0 with one or more cycles as in Figures 4, 7, or 9. Since there are practical coating materials for the visible and IR spectral regions in the range from 1.45 to 2.35 or more, it is practical to keep the oscillations in this range. If the substrate is of index 2.35 or higher, it is expected that the function should decrease in index from the substrate. If the substrate is of low index, it is advisable for the index to increase from the substrate. This can be inferred from observing Figures 7 and 9 where the solution for a high index substrate tends to go out of the real index bounds if it starts up rather than down. These profiles which decrease from the substrate are what we call half-cycle solutions or 1/2, 1-1/2, 2-1/2, etc. The freehand sketch of the function is an adequate starting point for the design.

2. Divide the inhomogeneous layer function generated in step #1 into a number of equal layers at least greater than two times the number of cycles in the function, preferably 10 to 20 or more. Assign a homogeneous index to each of these thin layers that is the arithmetic mean of the inhomogeneous index in that layer.

3. Enter the discrete homogeneous layer design into the optimization program and optimize the index of all the equal thickness layers with respect to the target function. This should generate a refined design which approximates the desired reflectance function. This function can then be redrawn as the continuous index profile that passes through the new index values found at the discrete layer points.

4. The new profile can then be redivided into sections of possibly fewer layers than

in step 2. Each of these steps would then be replaced by an approximating pair of layers of the desired construction materials (such as 1.46 and 2.35) which give an equivalent index to the replaced layer at the design (usually longest) wavelength. This approach is related to the work of Southwell(7). The last layer should usually be of the lowest practical index if an AR coating is desired.

5. Reoptimize the new configuration for layer thicknesses with respect to the target function. This should yield a design with real materials that approximates the target reflectance curve.

6. Steps 4 and 5 can be repeated with fewer sections to see if an acceptable result can be achieved with fewer layers for ease of manufacture.

This procedure has worked very easily and quickly for us in preparing the results given here for a variety of substrates and number of cycles in the functions. It would appear to be practical to apply this procedure to coatings other than AR's, but the approximate starting function might not necessarily be known. This work has suggested that the Fourier techniques described by Dobrowolski and Lowe(8) should lead to the same functions as we have described here when applied to the same target requirements. The techniques described by Dobrowolski have been shown capable of solving the most general reflectance function design problems. We have collaborated with Dobrowolski and Verly to show that both techniques lead to the same solutions and that is the subject of a paper now in preparation(9).

5.CONCLUSIONS

We have clarified the understanding of the natural and ideal form of broadband antireflection coatings and found a practical application design superior to those previously published that should be achievable in practice with real materials. We have described the practical procedure which we used to achieve the results reported.

6.REFERENCES

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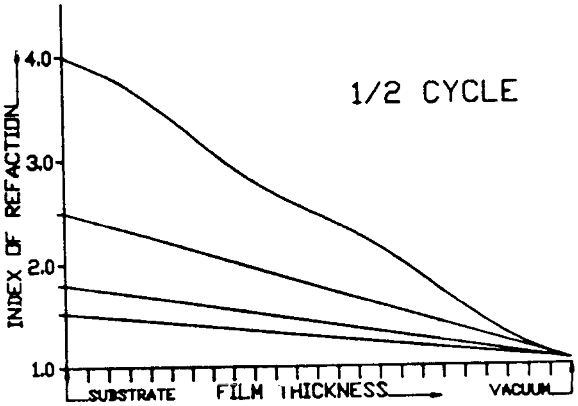

Fig. 1. Index of refraction versus thickness of monotonically decreasing inhomogeneous layers, like step-down layers.

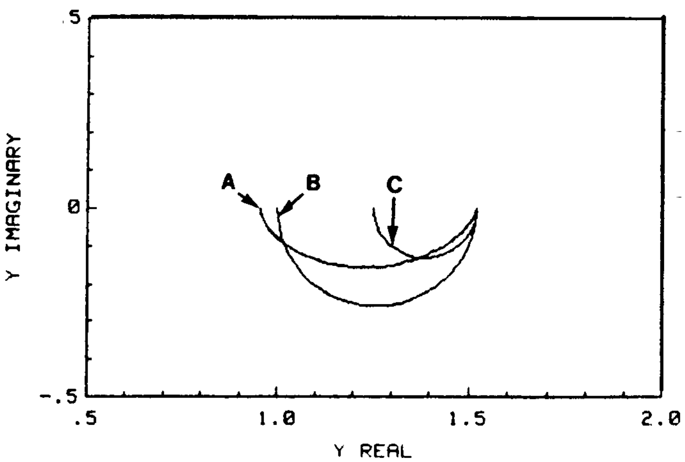

Fig. 2. Admittance diagram of ideal Rugate (Curve A) at longest wavelength. Curve B is SLAR of 1.233 index, C is a 1.38 QWOT.

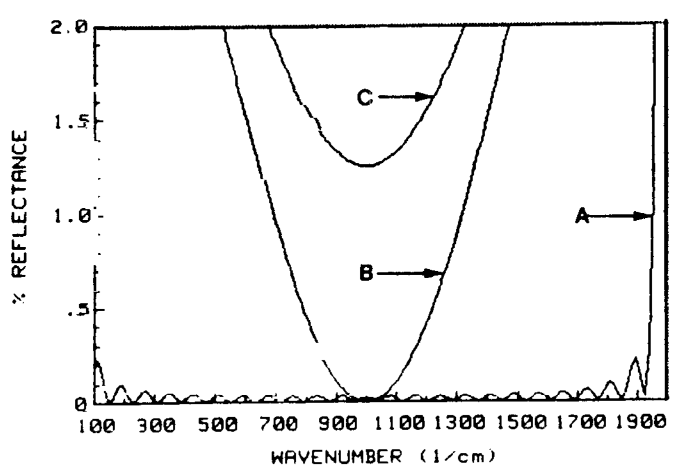

Fig. 3. Comparative reflectance of Rugate AR (A) with an ideal SLAR (B) and MgF2 SLAR (C) on a 1.52 index substrate.

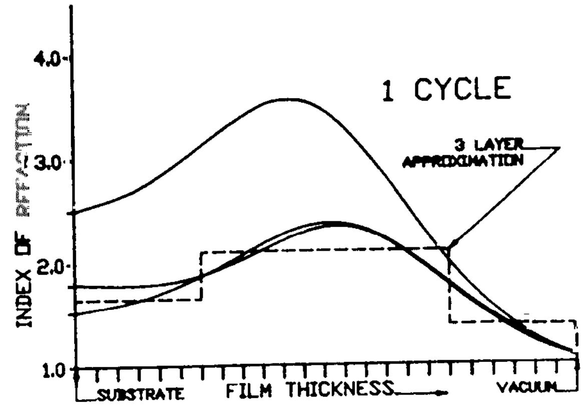

Fig. 4 Index profiles of one cycle on substrates of index 1.52, 1.8, and 2.5. Dotted line is ideal homogeneous 3 layer.

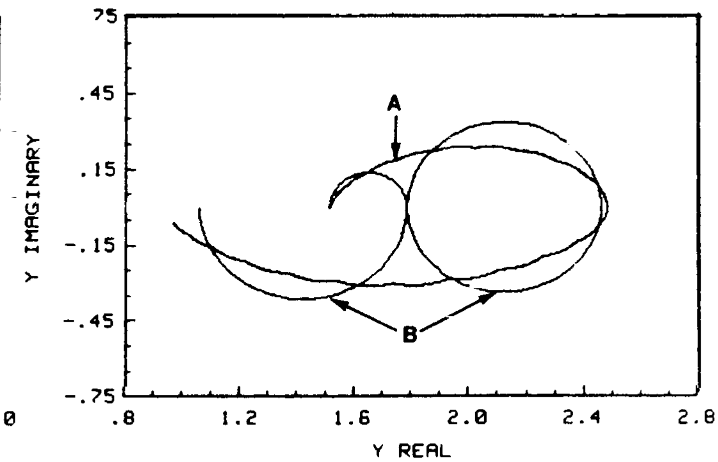

Fig. 5. Admittance of ideal one cycle Rugate AR (Curve A) and the classical QHQ homogeneous layer AR (Curve B).

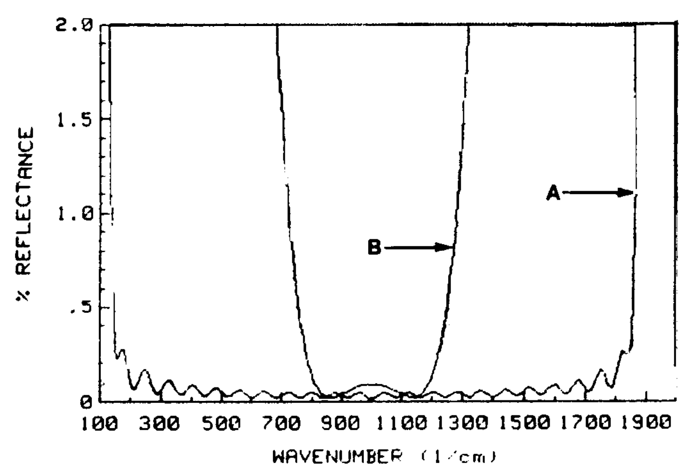

Fig. 6. Comparative reflectance of one cycle Rugate AR (Curve A) with classical 3 layer AR (Curve B, 1.65Q, 2.1H, 1.38Q).

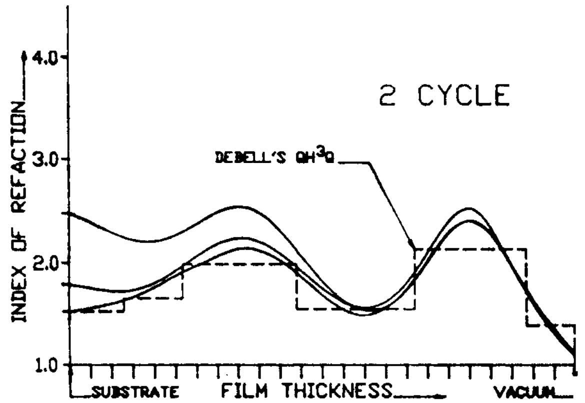

Fig. 7. Index profiles of two cycle functions on substrates of various indices. Dotted line is QHHHQ from DeBell(3).

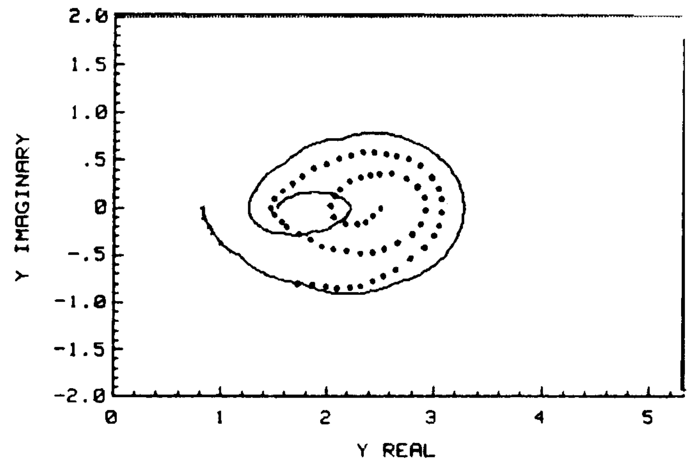

Fig. 8. Admittance of two cycle Rugate AR on 1.52 substrate (solid line) and 2-1/2 cycle on 2.5 sub. (dotted line).

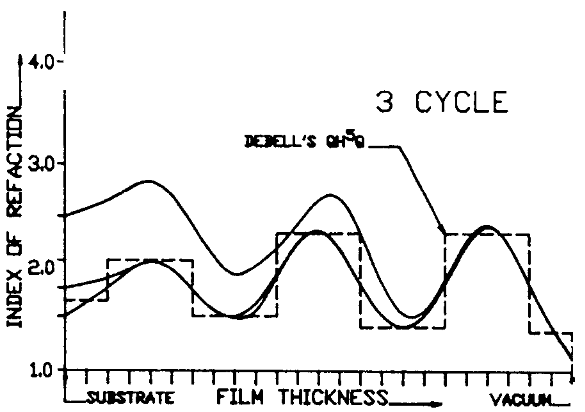

Fig. 9. Index profiles of three cycle Rugate AR's on various index substrates. Dotted line is QHHHHHQ from DeBell(3).

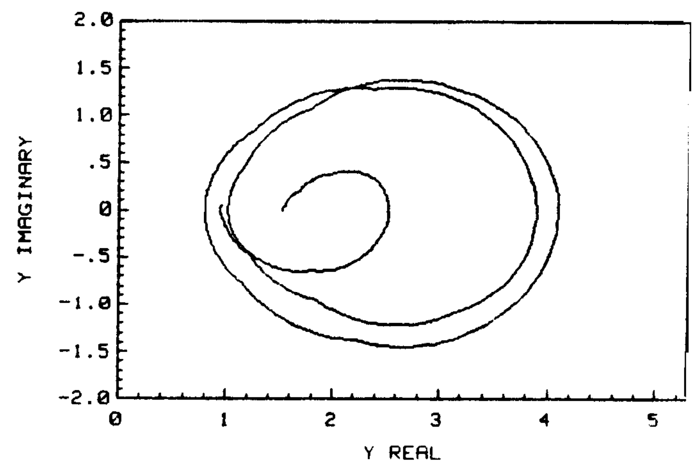

Fig. 10. Admittance diagram of three cycle inhomogeneous index layer AR (Rugate) on a 1.52 index substrate.

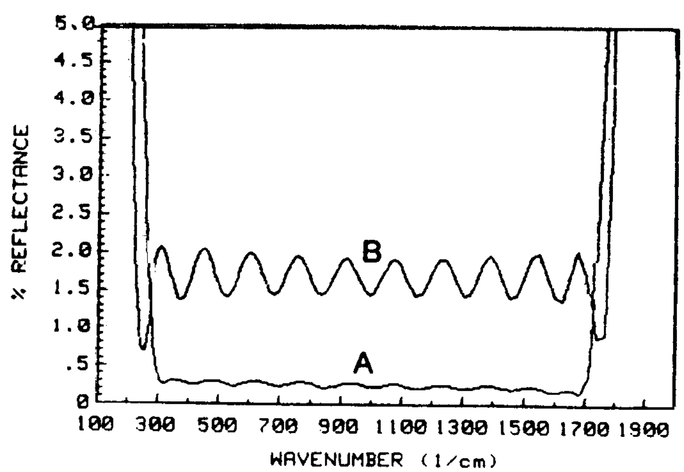

Fig. 11. Twelve layer AR optimized with 1.19 as lowest last layer index in Curve A and 1.38 as last index in Curve B.

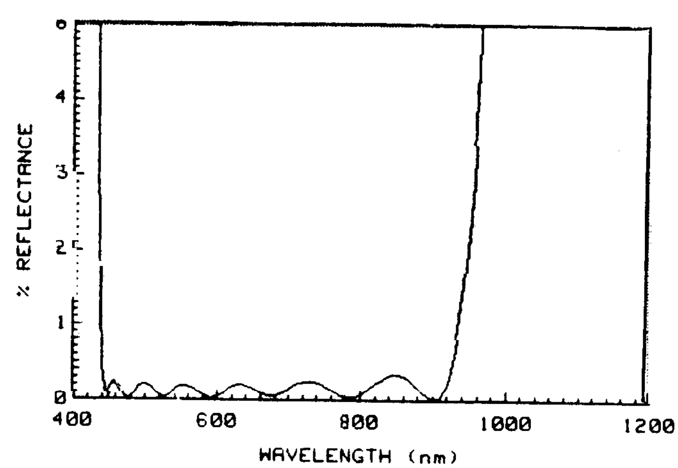

Fig. 12. 24 layer three cycle Rugate AR of 1.46 and 2.35 with 1.38 for the last layer after Southwell's(7) technique.

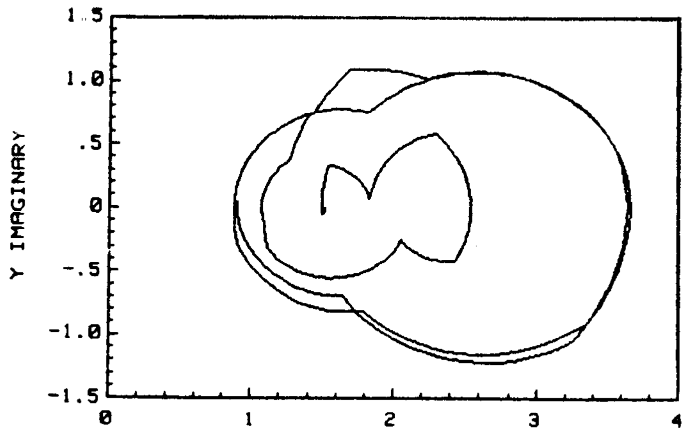

Fig. 13. Admittance diagram of design in Figure 12 for comparison with that of Fig. 10 for a three cycle Rugate AR on 1.52 sub.

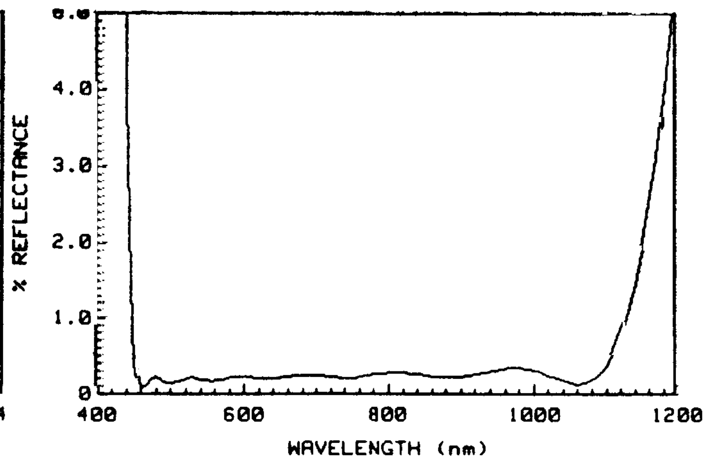

Fig. 14. Reflectance of a two cycle Rugate AR of 24 layers of 1.46 & 2.35 with a last layer of 1.38 on a 1.52 sub.

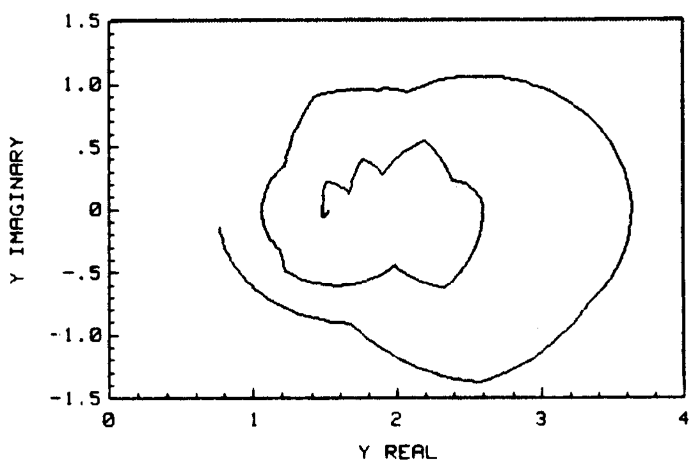

Fig. 15. Admittance diagram of design in Figure 14 for comparison with that of Fig. 8 for a two cycle Rugate AR on 1.52 sub.

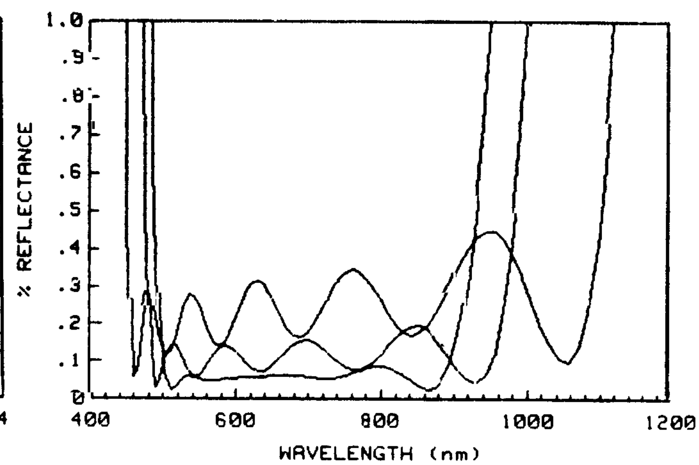

Fig. 16. Residual ripple in AR of 12 layers which have been optimized for various bandwidths.

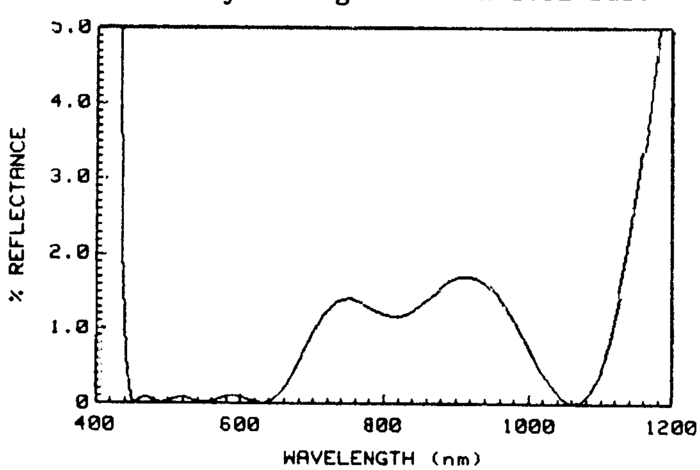

Fig. 17. Twelve layer AR optimized for 450-650nm and 1064 with SiO2, TiO2, and a last layer of MgF2.

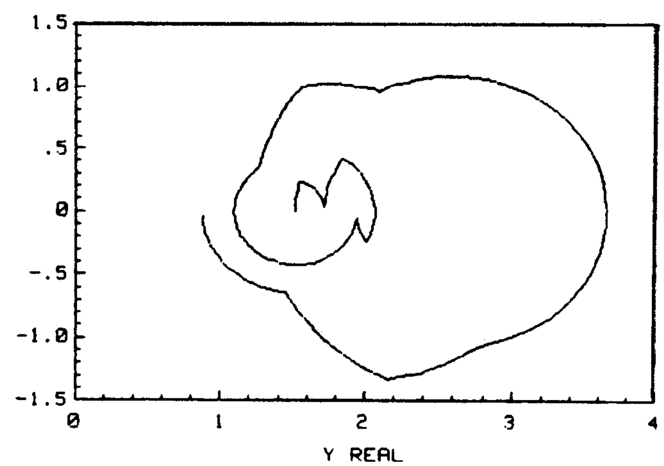

Fig. 18. Admittance diagram of design in Figure 17 for comparison with the two cycle Rugate in Figure 8