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Full Length Research Paper

Non-polarizing beam splitter and antireflection coating design

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The optical coating design of beam splitters and antireflection coatings that are non-polarizing, those that have the same reflection for both "s- and p-polarizations" at specified angles, is a challenge. This is because the effective indices of refraction for the media and coating layer materials have a different function of the angle of incidence for each polarization. This limits what can be achieved. Specific materials can be used to design reasonable non-polarizing coatings at only certain angles, whereas other materials can be made to serve for other angles. The choice of materials seems to be critical to the success of any particular requirement. Since the range of practical coating materials and substrates is limited for most applications, non-polarizing solutions seem to be quantized in reflectance and angle. This is illustrated with the aid of reflectance amplitude (circle) diagrams, and some design "rules-of-thumb" are provided.

Key words: Beam splitter, antireflection coating, reflectance amplitude diagrams.

INTRODUCTION AND BASIC THEORY

Beam splitters are used to divide incident light into transmitted and reflected beams in a certain ratio over a broad range of wavelengths. To physically separate the three beams, these beam splitters are often required to operate at oblique angles of incidence. At oblique angles, unfortunately, the optical admittances for "s- and p-polarized" light are different according to LiLi (2003). When light travels from the first medium with a refractive index n_0 to the second medium with a refractive index n_1, the reflected and transmitted electric field amplitudes of the electromagnetic wave at the interface are governed by the Fresnel equations and given in Equations (1) and (2):

$$\begin{cases} r = \dfrac{\eta_o - \eta_1}{\eta_o + \eta} = |r| e^{i\varphi} \\ t = \dfrac{2\eta_o}{\eta_o + \eta} = |t| e^{i\varphi_t} \end{cases} \tag{1}$$

$$\begin{cases} \eta_o = n_o \cos\theta_o \\ \eta_1 = n_1 \cos\theta_1 \end{cases} (s - pol.) \quad \begin{cases} \eta_o = n_o / \cos\theta_o \\ \eta_1 = n_1 / \cos\theta_1 \end{cases} (p - pol.) \tag{2}$$

$$n_o \sin\theta_o = n_1 \sin\theta_1 \tag{3}$$

where r and t are also called the amplitude reflection and transmission coefficients, respectively. φ and φ_t are the phase changes on reflection and transmission. η_o and η_1 are the optical admittances for the two media and are different for s- and p-polarized light. θ_o is the incident angle and θ_1 is the refracted angle inside the second medium, and they are related to each other by Snell's law (Equation 3), and thus reflectance or transmittance of s- and p-polarized light tends to be different; it is rather difficult to design non-polarizing beam splitters that have the same reflectance and transmittance for both s- and p-polarized light. However, it has been mentioned above that a conventional thin film polarizing beam splitter (PBS) operating at angles smaller than the critical angle always reflects s-polarized light and transmits

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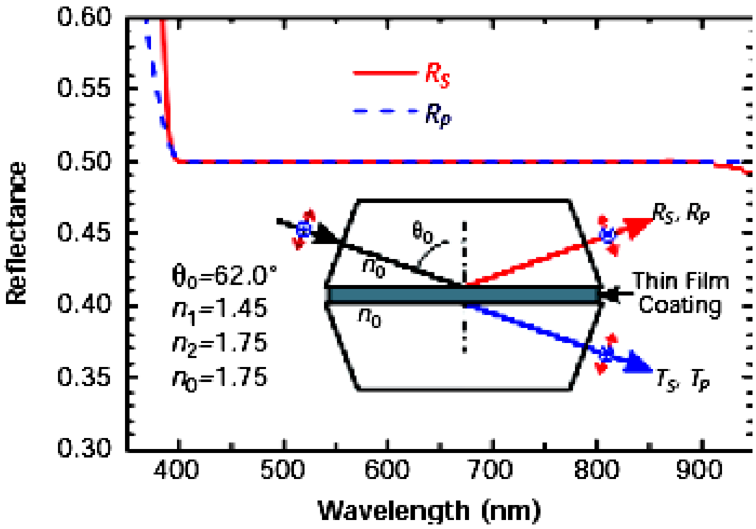

Figure 1. Calculated performance of a non-polarizing beam splitter operating beyond the critical angle (Macleod, 2001).

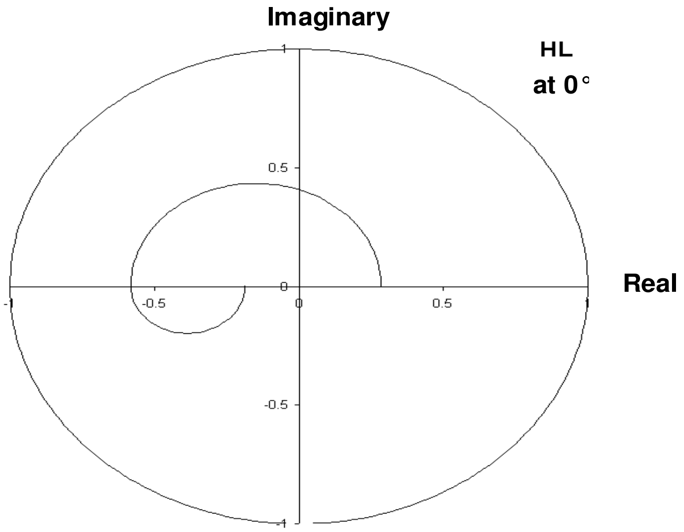

Figure 2. Reflectance amplitude diagram of a two QWOT layer coating at normal incidence of design: SHLA.

p–polarized light, while a PBS operating at angles greater than the critical angle always transmits s-polarized light and reflects p-polarized light. A transition angle must therefore exist at which the reflectance's for s- and p-polarized light are both equal to 50%. And indeed, this angle is above "but close to" the critical angle for the low refractive index layer. Macleod (2001) has described the design of such non-polarizing beam splitters based on admittance diagrams of frustrated total internal reflection (FTIR) layers. Figure 1 shows a design for a visible/near infrared beam splitter that operates from 400 to 900 nm.

The optical coating design of beam splitters and antireflection coatings that are non-polarizing at a specific wavelength and angle of incidence are addressed here. This work is further confined to “non-immersed” designs as opposed to coatings surrounded by glass such as cube beam splitters which offer broader possibilities when they can be employed. Macleod (2001) comments that “The techniques which are currently available operate only over very restricted ranges of wavelength and angle of incidence (effectively over a very narrow range of angles).” The current results support this conclusion. The results of the techniques of Thelen (1988) show examples which are also of this nature and Baumeister (2004) shows another variety of examples along the same lines.

These limitations on angle and bandwidth occur because the effective indices of refraction for the media and coating layer materials have different functions of the angle of incidence for each polarization.

We use (filmstar free version) (http://www.ftgsoftware.com/design.htm) to draw the reflectance amplitude and phase diagram and for the comparison purpose with other experimental works. Figure 2 shows the reflectance amplitude and phase diagram (or “circle” diagram) (Willey, 2002) of a two quarter wave optical thickness QWOT layer coating at normal incidence of the following design: Substrate (S) HL Air (A), where L,M and H represent low, medium and high respectively. Such diagrams are closely related to admittance (Macleod, 2001; Willey, 2002) diagrams when rotated 180° about the origin.

Figure 2 shows how Figure 3 changes when the angle is 50° and the polarizations split. The s-polarization shifts to the left and the p to the right. The final reflectance of the coating at the end point to the right is greater for the p than for the s. Figure 4 shows the case at 89° as the

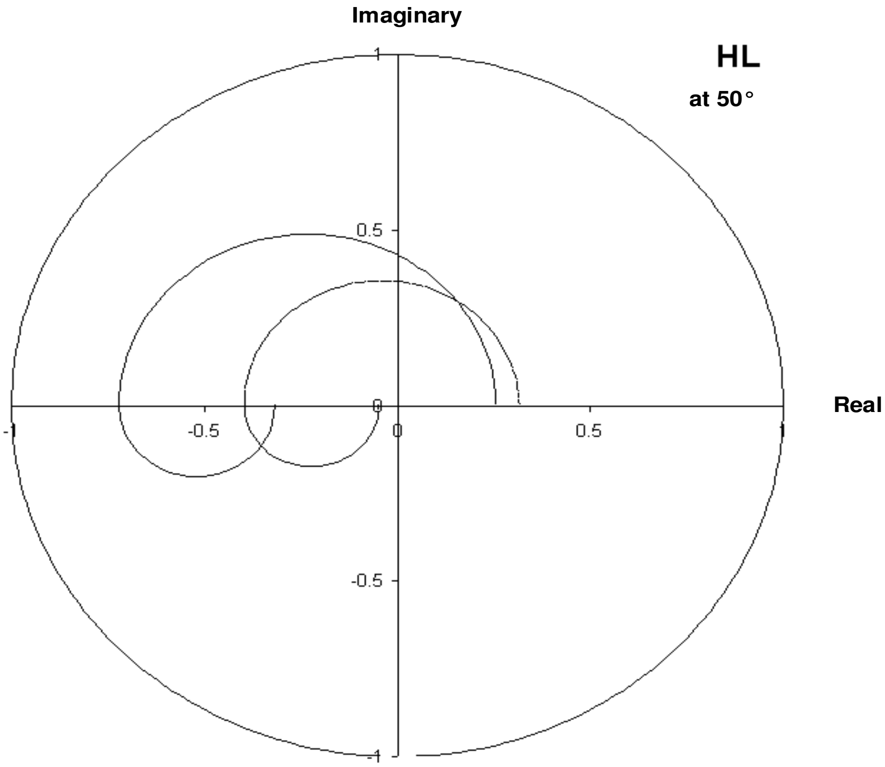

Figure 3. Change from Figure 2 when the angle is 50° and the polarizations split.

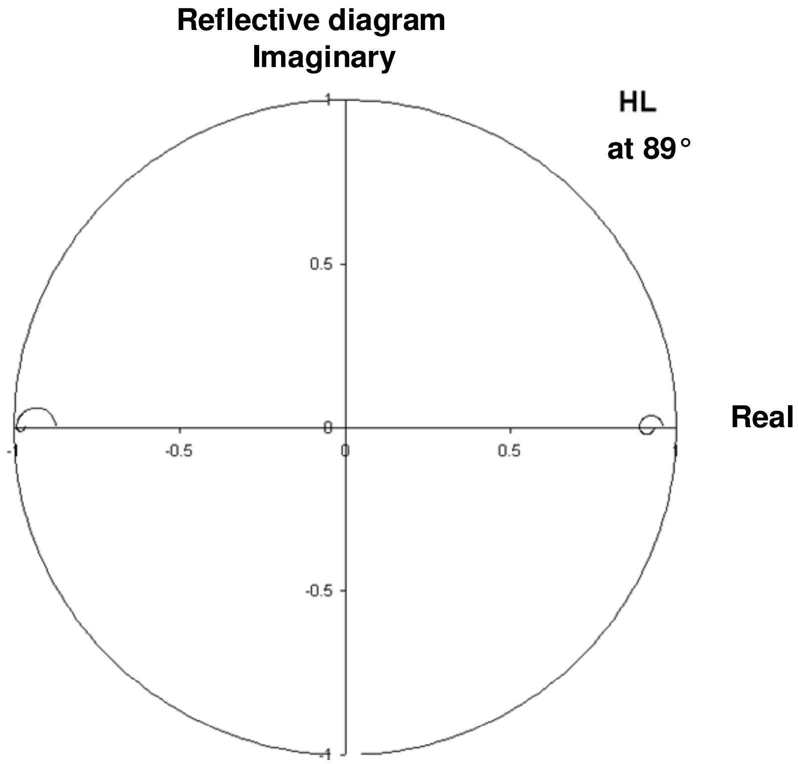

Figure 4. Same case as Figure 1 at 89° as 90° is approached. The s-polarization shifts to the left and the p to the right.

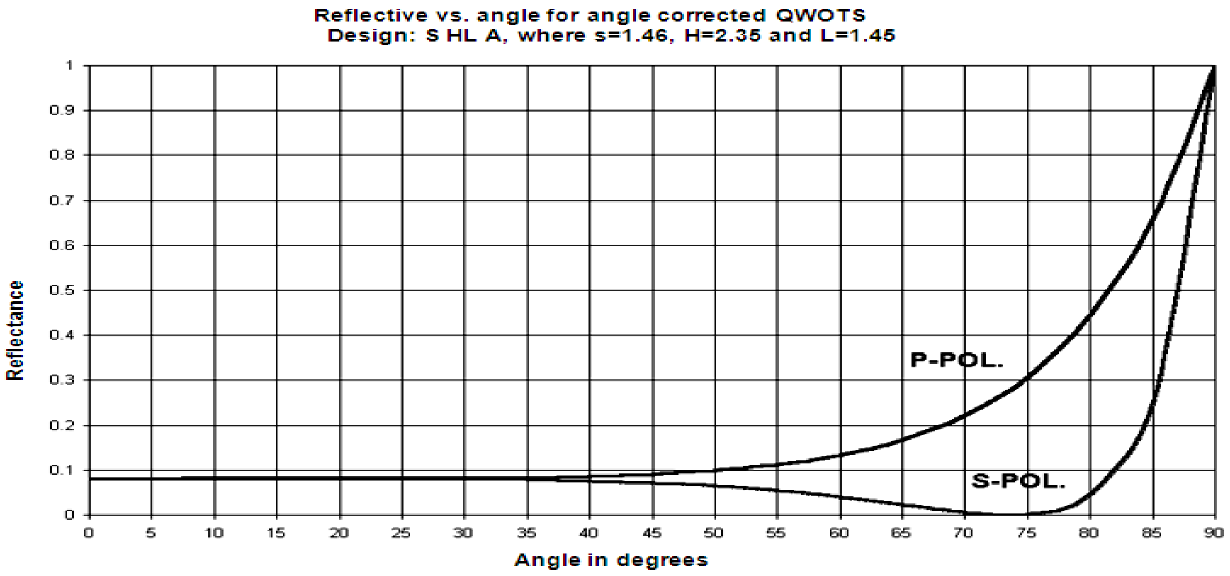

Figure 5. Reflectance of the SHLA design in s- and p-polarizations over 0 to 90°.

extreme angle is approached; both s and p approach 100% reflectance, but are 180° apart in phase. Figure 5 shows the reflectance of this coating configuration as a function of all angles of incidence from 0 to 90°.

The foregoing figures are cases where the thicknesses are adjusted to produce quarter wave optical thickness (QWOT) for each layer and index at the angle being evaluated. This are referred to as "angle matched" thicknesses and are discussed more in details in the referenced texts (Macleod, 2001; Thelen, 1988; Baumeister, 2004). It will be seen that two advantages accrue when only "matched" QWOT layers are used:

1. The change in reflectance with wavelength is minimum at the design wavelength because it goes through zero, and
2. The sensitivity to layer errors can be minimum.

PROCEDURE

A systematic search was done of all possible QWOT coating designs having from one to five layers, where the substrate index was 1.46 and the coating material indices were L = 1.45, M = 1.65, and H = 2.35. Each design was evaluated from 0 to 90° with the necessary adjustments of thickness with angle. If the reflectances of the s- and p-polarizations intersect at other than 0 or 90°, there is a non-polarizing design with all QWOT's at that angle and reflectance. Figure 6 is an example of such a case where, in the design S HMHM A, the s and p reflectances intersect near 45°. Twelve intersecting designs were found for five layers or less. An exhaustive search of all possible QWOT designs with 6 and 7 layers was beyond the scope of this work, but all of the 7-layer designs which start with MH layers on the substrate were evaluated. Fourteen additional non-polarizing designs were found. These 26 designs are plotted in Figure 7 for their %R versus non-polarizing angle.

Table 1 shows these designs and resulting non-polarizing angles, %R, and dR/dA (rate of change of the reflectance difference between s and p versus angle in degrees) for the 26 cases found. Table 2 groups the designs together where they have similar or identical results. There are only 14 unique cases found for angle and reflectance. The choice between designs of similar results might be based on the number of layers or other physical property considerations, but the optical performances are the same.

The results in Figure 7 point to the possibility of beam splitter designs at 45° which have a reflectance between 20 and 30%. If a 50/50% beam splitter is needed related to this group, it would apparently be at angles in the range of 59 to 69°. It is conjectured that 50/50% all QWOT dielectric designs might be achievable with more than seven layers of these materials at 45°, over a small wavelength and angle range. The popular compromise for a nearly non-polarizing 50/50% beam splitter at 45° which is available from various component suppliers is a cube beam splitter (immersed coating) with about 45/45% over the visible or similar bandwidth. This is done with a silver layer that has 5 to10% absorbance and additional dielectric layers.

Figure 8 plots the change of percentage reflectance difference in the s- and p-polarizations with change of angle in degrees for the various intersecting cases examined. It can be seen that there is a change with increasing angle of incidence which appears to be unavoidable. This can be seen to be close to a function of 1/cos^2(angle). For example, at 45°, one can expect at least 0.2% split in reflectance of s and p for each degree of departure from the non-polarizing angle of the design.

CHANGES WITH INDICES

The effects of varying indices were evaluated using DOE methodology (Schmidt and Launsby, 1994;DOE, 1997) over the ranges of 1.38 to 1.52 for L, 1.55 to 1.75 for M, and 2.2 to 2.5 for H for a representative design, S MHMHLHM A. Figures 9 and 10 show, in surface plot format, how the non-polarizing angles vary with L, M, and H, and Figures 11 and 12 show, in contour plot format, how the percentage reflectance (%R) at the non-polarizing angles vary with L, M and H.

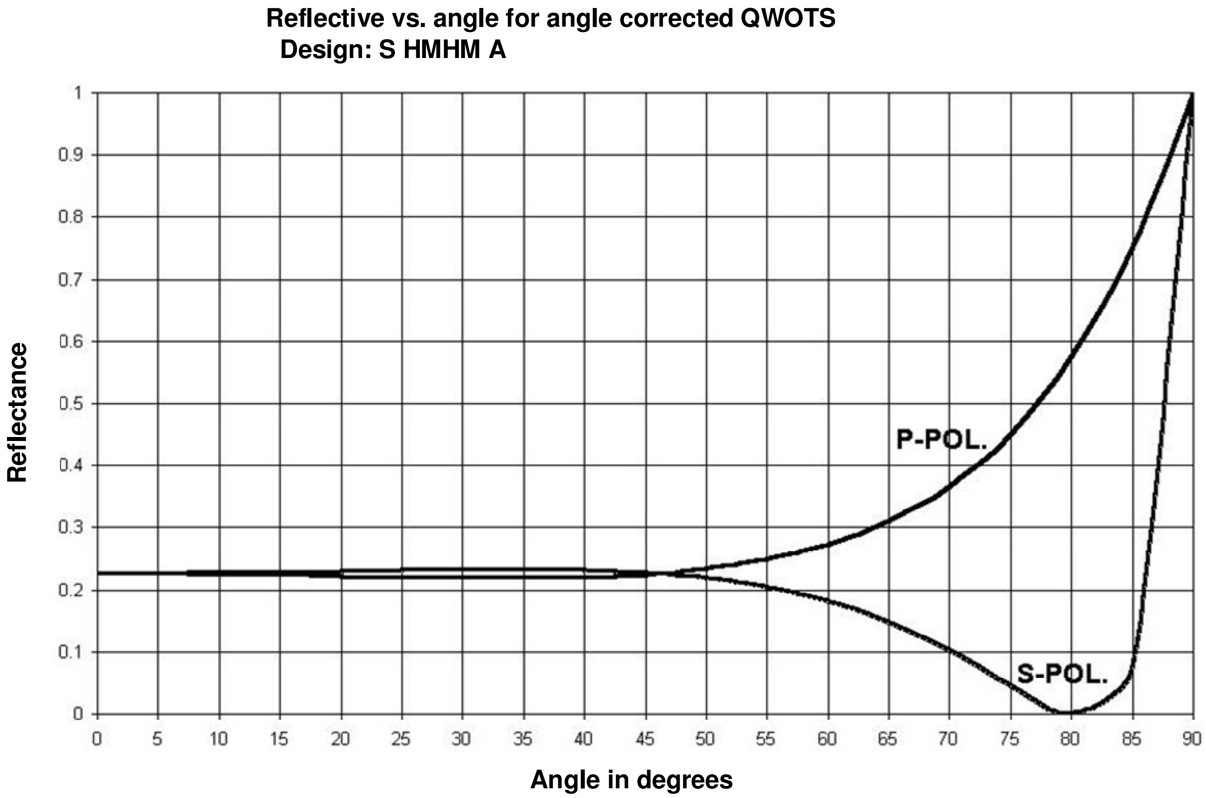

Figure 6. Reflectance versus angle where, in the design SHMHMA, the s and p reflectances intersect near 45°.

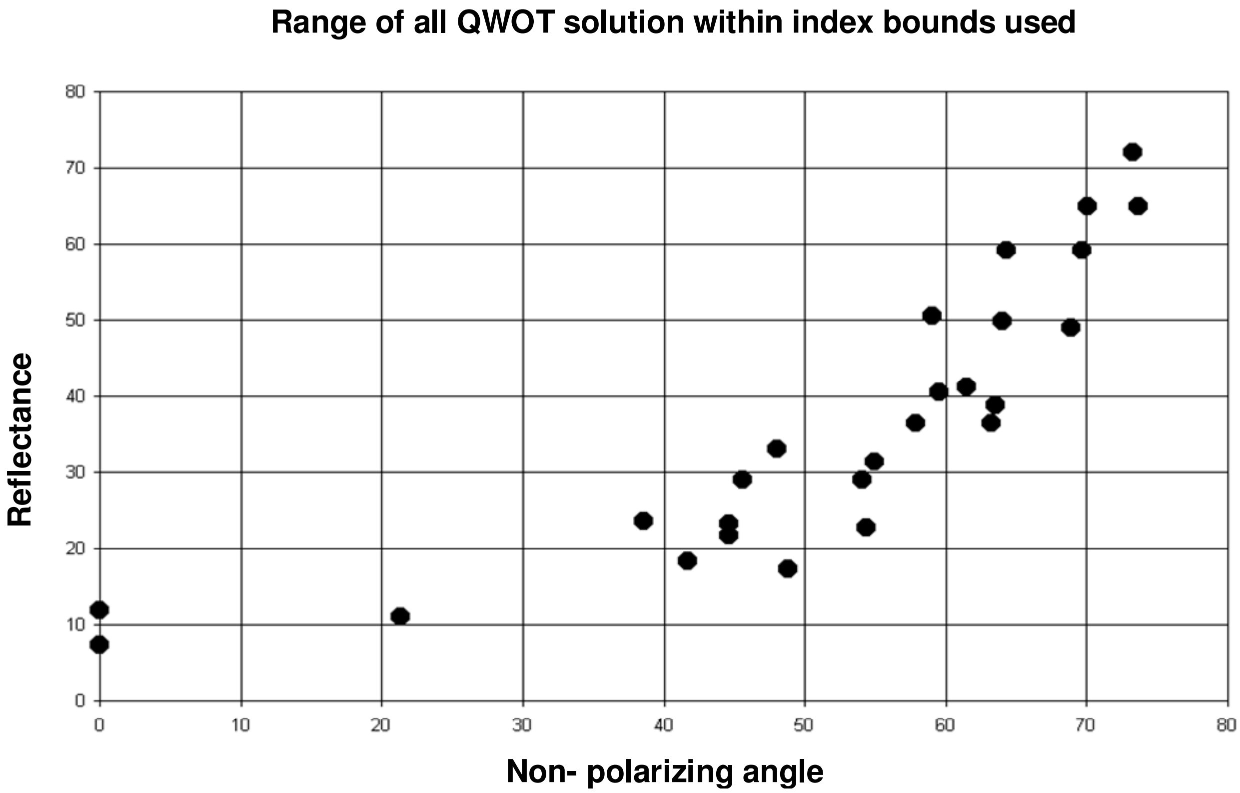

Figure 7. Reflectance versus non-polarizing angle of the 26 all-QWOT designs found.

Table 1. Designs, resulting non-polarizing angles, %R, and dR/ for the 26 all-QWOT designs found.

Design	Angle	%R	dR/dA
HL	27.57	8.15	0.026
MLHL	53.18	15.95	0.39
MLHM	27.57	8.15	0.026
HLML	53.18	15.95	0.39
HLHL	67.2	42.33	1.73
HLHM	59.48	32.47	0.712
HMHL	59.48	32.47	0.712
HMHM	45.67	22.68	0.342
MHLML	30.64	8.51	0.054
MHLHL	60.17	33	1.223
MHLHM	46.66	23.18	0.328
MHMHL	46.66	23.18	0.328
MHLMLML	54.5	16.5	0.53
MHLMLHL	68	42.9	1.13
MHLMLHM	60.3	32.9	0.96
MHLHLML	68	42.9	1.13
MHLHLMH	31	8.5	0.037
MHLHLHL	74.5	66.2	2.75
MHLHLHM	70.5	58.5	1.92
MHLHMHL	70.5	58.5	1.92
MHLHMHM	64	49.8	1.42
MHMHLML	60.3	32.9	0.96
MHMHLHL	70.5	58.5	1.92
MHMHLHM	64	49.8	1.42
MHMHMHL	64	49.8	1.42
MHMHMHM	55	40.4	0.68

This information can be used as guidance to adjust the indices of a design to achieve a specific reflectance at a given angle. For example, it was calculated that this S MHMHLHM A design with L = 1.52, M = 1.75 and H = 2.35 would have 33.06% R at 48.04°. It was found that adjusting this for 30%R at 45° caused the L and M to move toward each other in the region of 1.7. This then suggested that the one L-layer could be replaced by an M-layer to make a two-material only design. The S MHMHMHM A design could then be adjusted to 30%R at 45° when M = 1.6845 and H = 2.31. These might be achievable indices with the proper process parameters in a given wavelength region. Figures 13 and 14 show the reflectance versus wavelength and versus angle for this design. Figure 15 shows the reflectance amplitude diagram for this design at 45°.

OTHER ADJUSTMENTS

The choice of having only QWOT's in the cases shown above leads to the coating terminating with the s and p reflectance's on the 0° phase line of the circle diagram. This is the condition where the change in the difference between s and p reflectance with angle passes through zero and is minimal in that angular region. It is possible to sacrifice some of this minimal difference in s-p in exchange for less variation of the difference with wavelength. This then requires non-QWOT layers, and the final phase is not likely to be zero.

ANTIREFLECTION COATINGS

Some of the findings of the search procedure described above included cases where the reflectance was near zero over a broad angular range, such as 0 to 40°. When these were optimized from 0 to 45°, none proved to be better than the classic S MHHL A design (3-layer quarter-half-quarter wave (QHQ)) after it had been optimized for the broader angles. This, of course, results in a design with non-QWOT layers. Therefore, this present design approach has yet to add anything to the antireflection coating knowledge.

CONCLUSION

Specific materials can be used to design reasonable non-polarizing coatings at only certain angles, whereas other materials can be made to serve for somewhat different angles. The choice of materials seems to be critical to the success of any particular requirement. Since the range of practical coating materials and substrates is limited for most applications, non-polarizing solutions seem to be quantized in reflectance and angle to the same extent that the indices of the materials are

Table 2. Designs of Table 1 grouped together where they have similar or identical results.

Design	Angle	%R	dR/dA
HL	27.57	8.15	0.026
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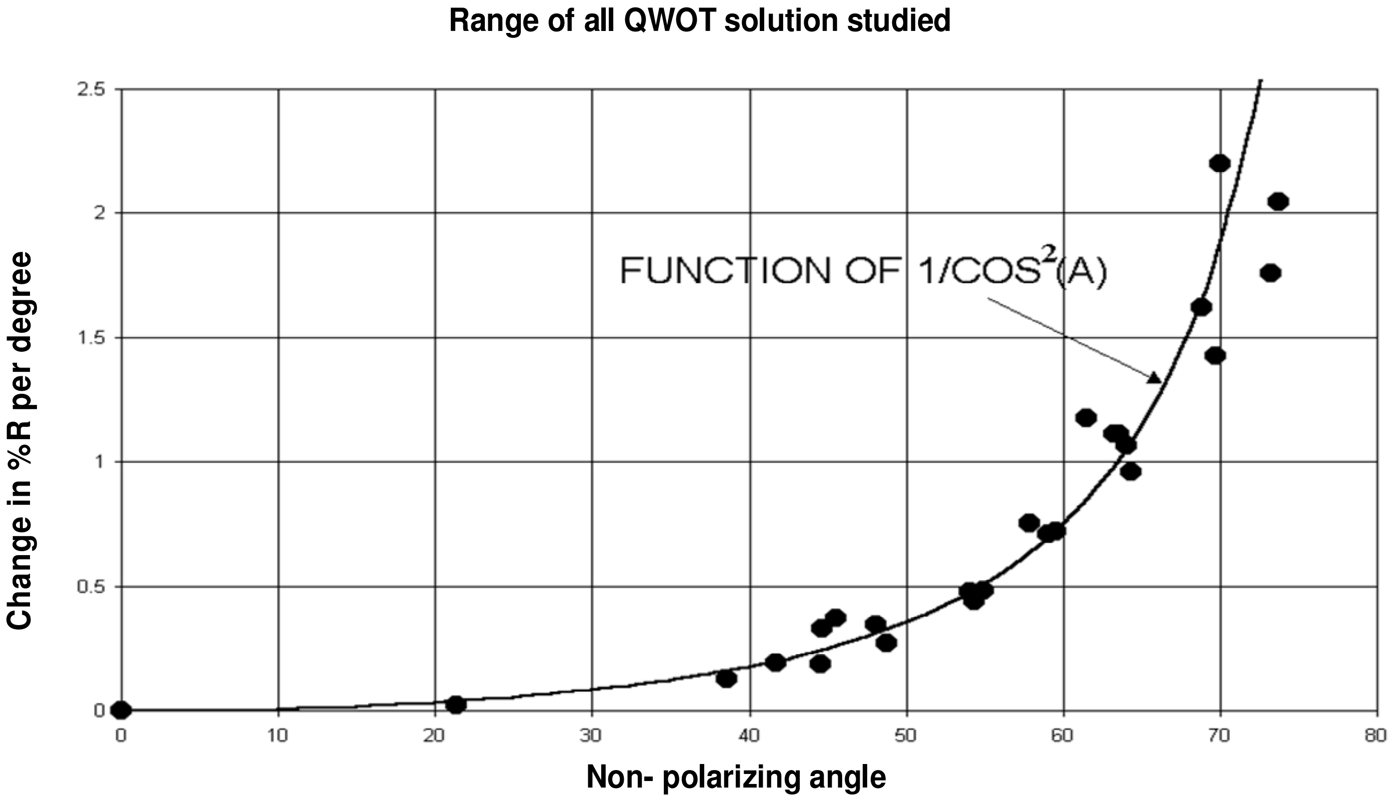

Figure 8. Percentage reflectance difference in the s and p-polarizations versus non-polarizing angle of the 26 designs.

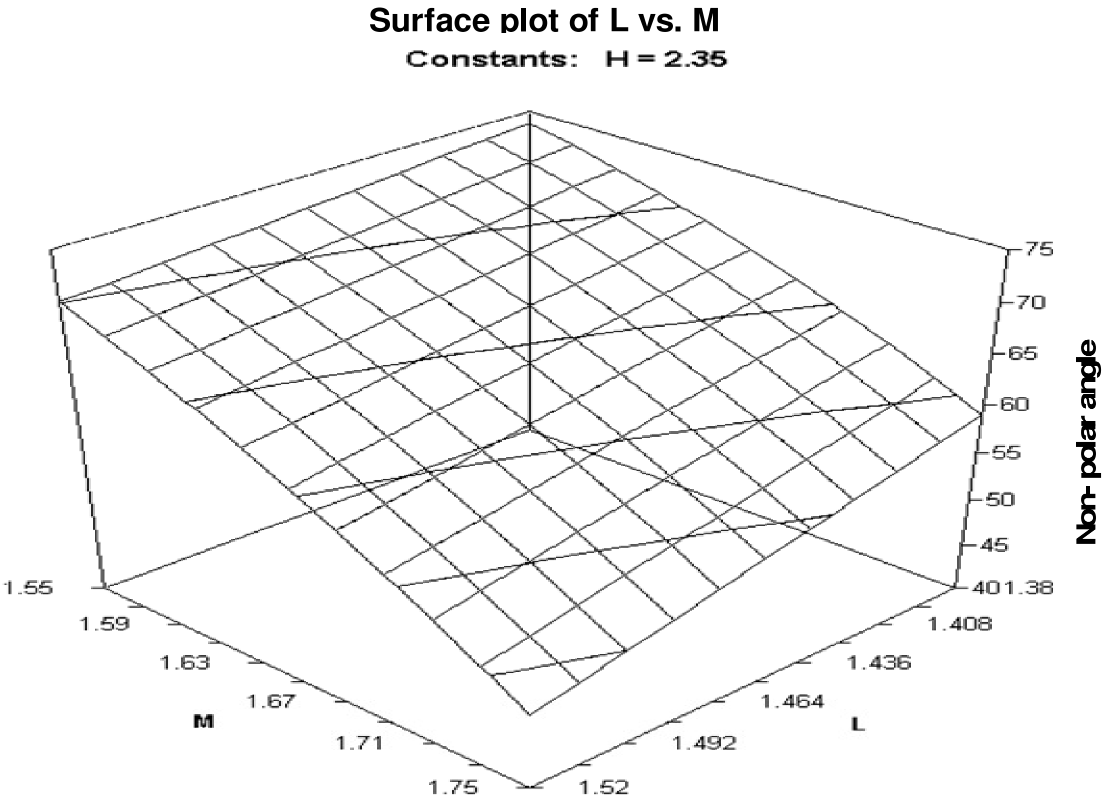

Figure 9. Surface plot of the variation of the non-polarizing angles with L and M.

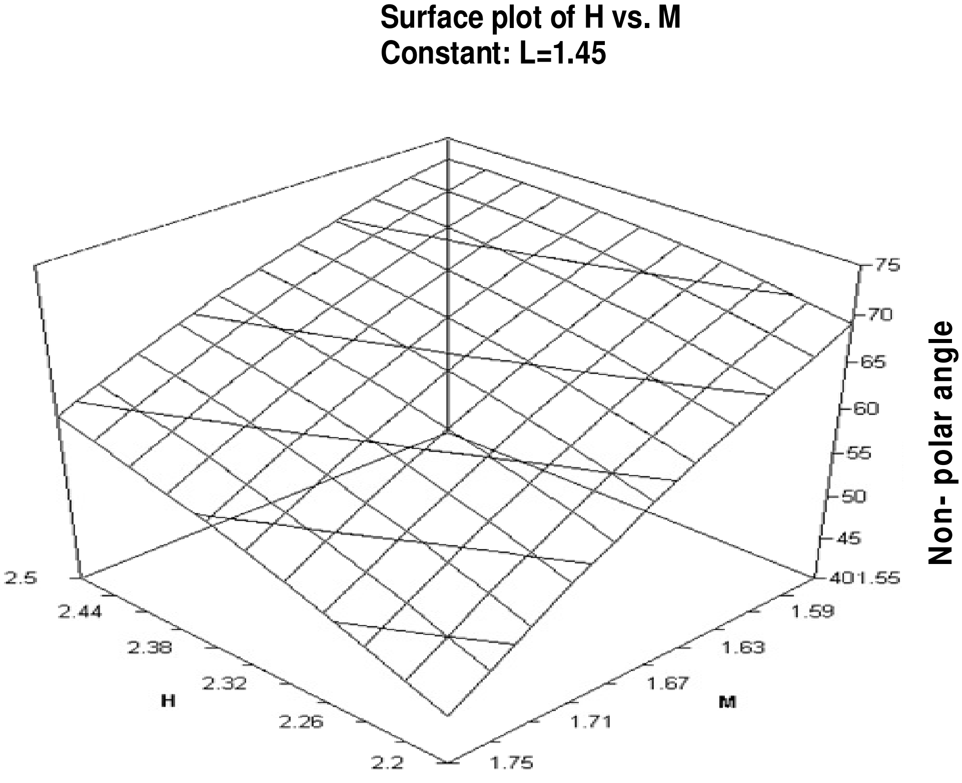

Figure 10. Surface plot of the variation of the non-polarizing angles with M and H.

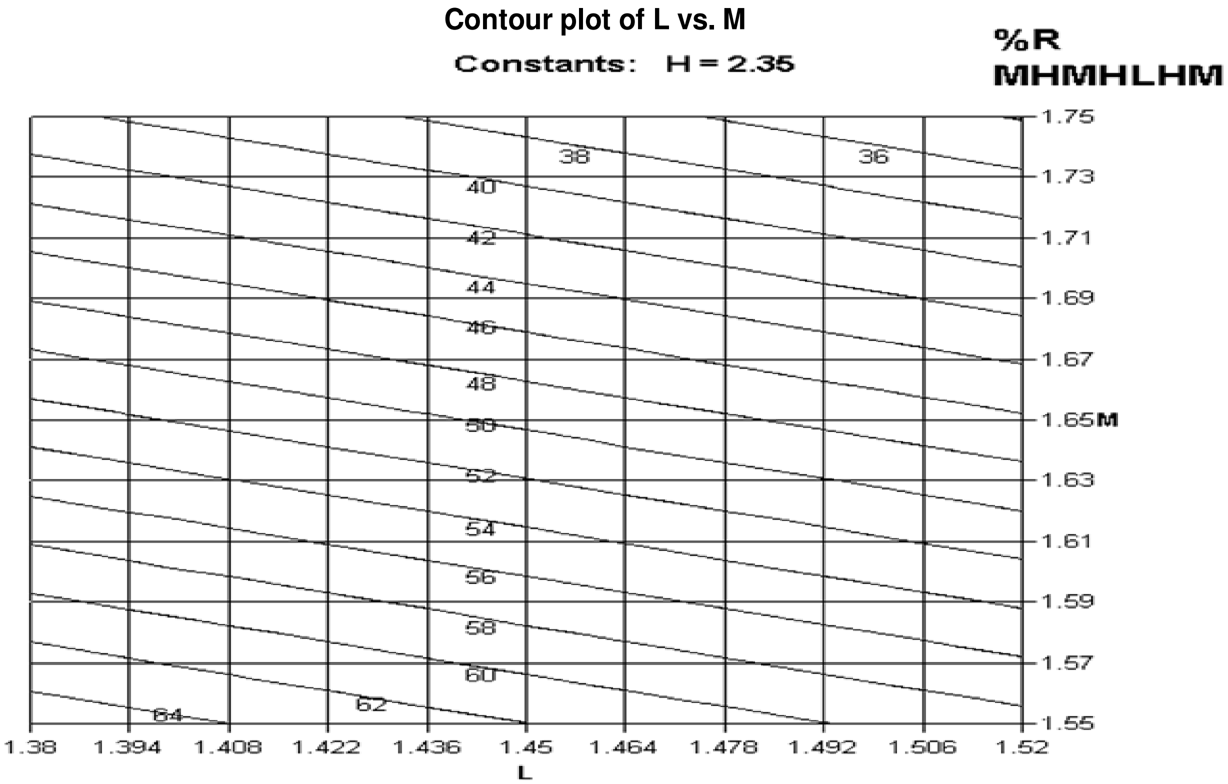

Figure 11. Contour plot of the variation of the percent reflectance (%R) at the non-polarizing angles with L and M.

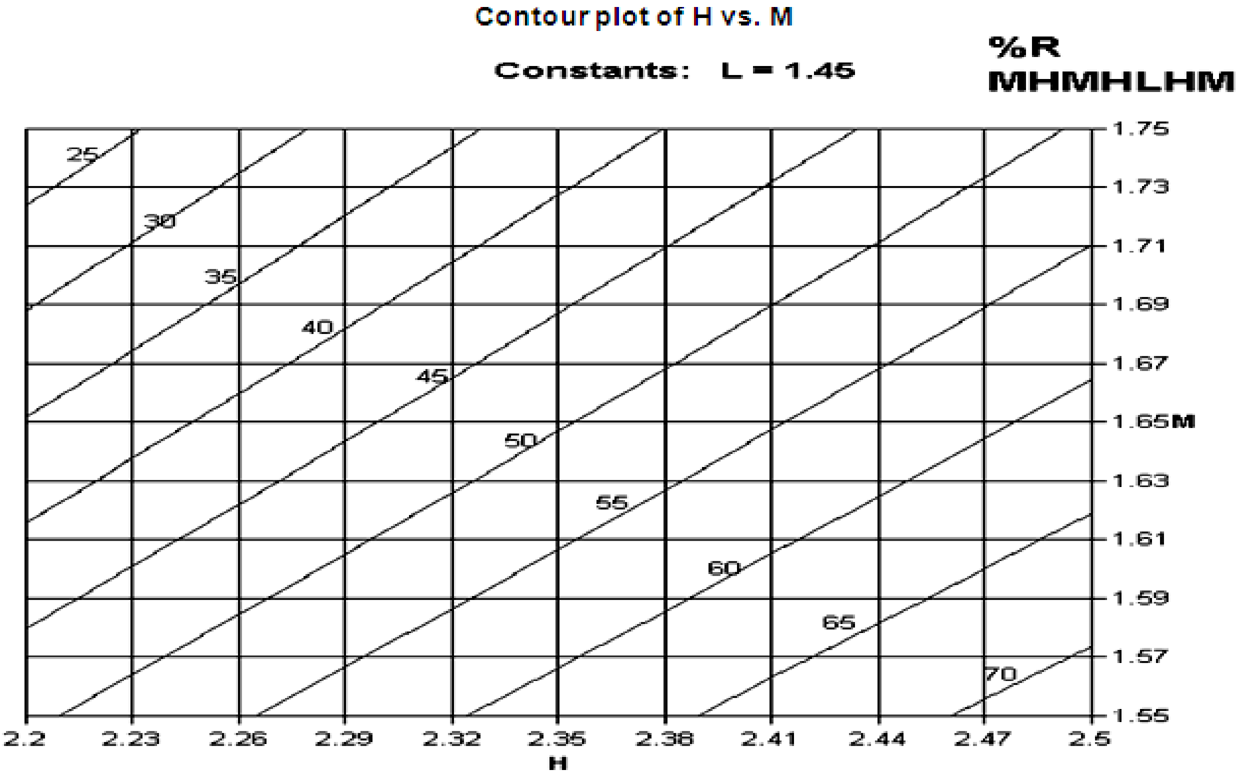

Figure 12. Contour plot of the variation of the percent reflectance (%R) at the non-polarizing angles with H and M.

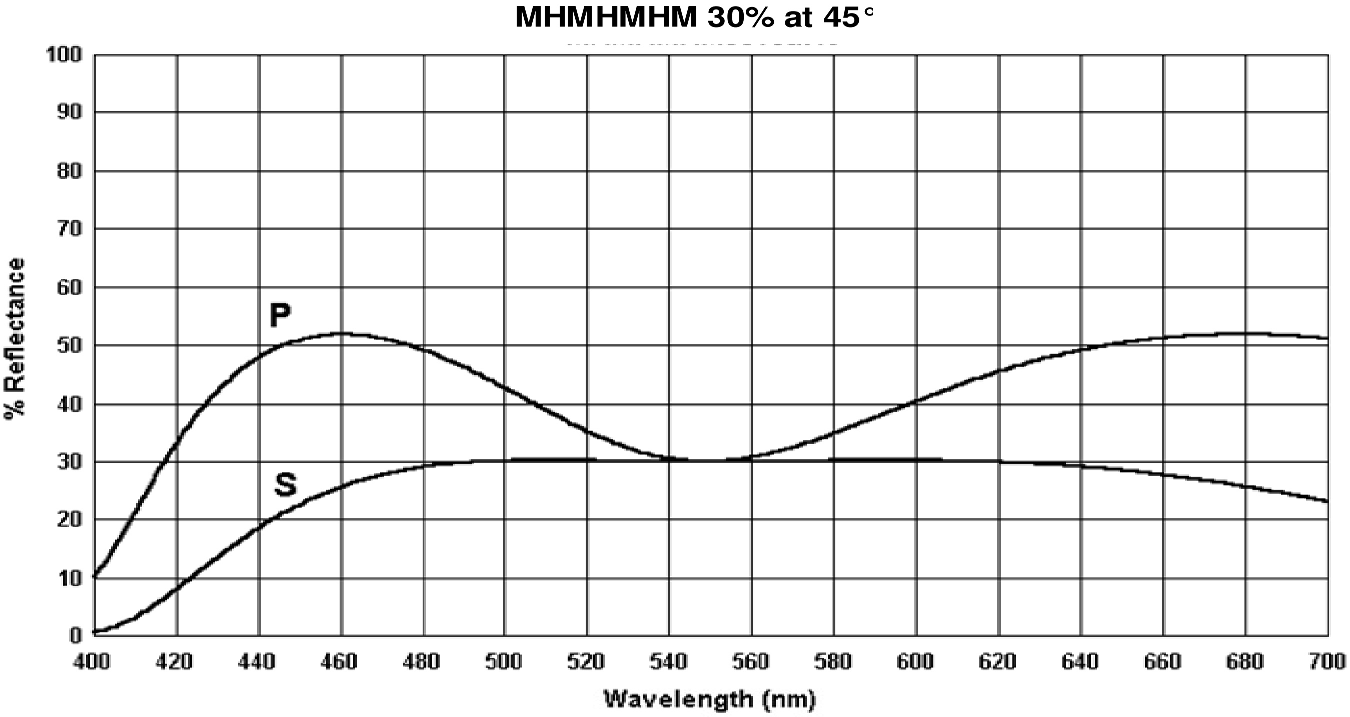

Figure 13. Reflectance versus wavelength for the design SMHMHMHMA.

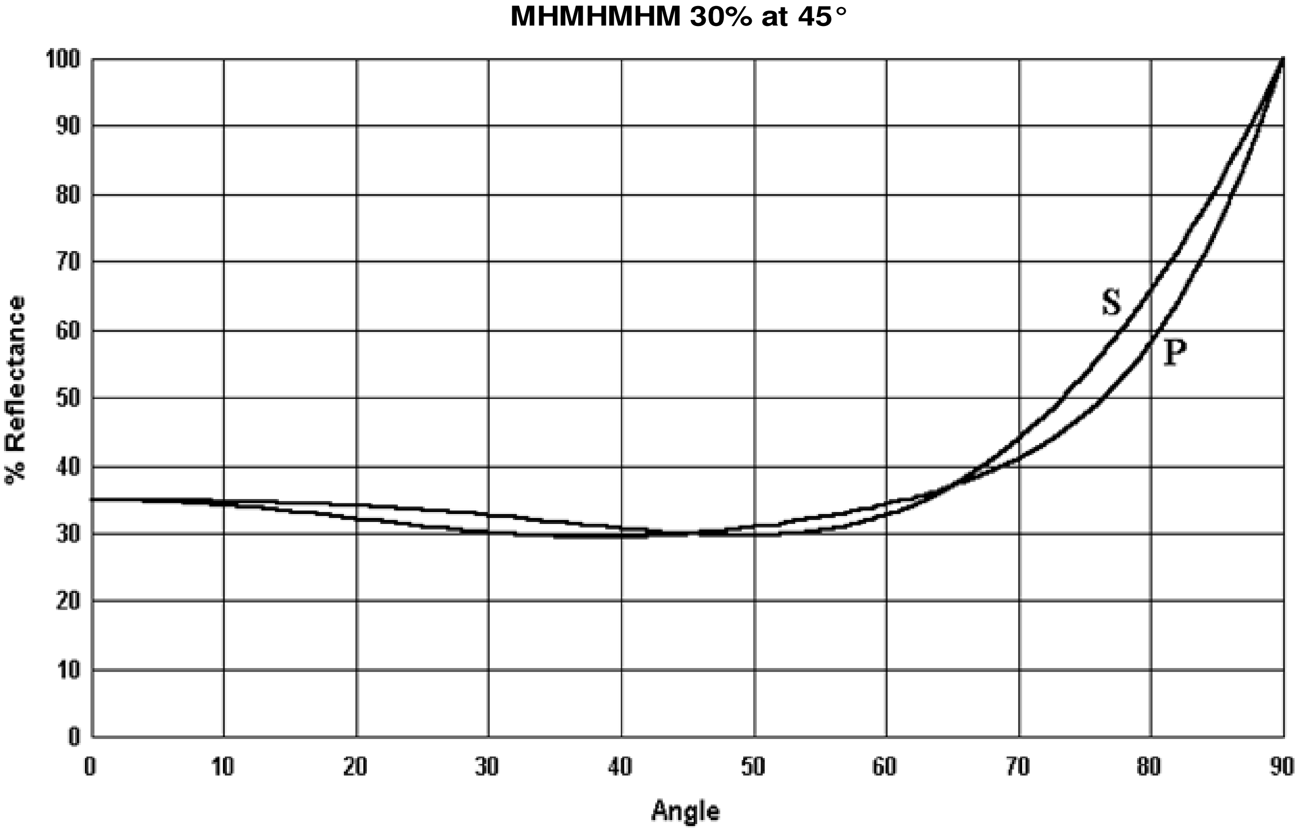

Figure 14. Reflectance versus angle for the design SMHMHMHMA.

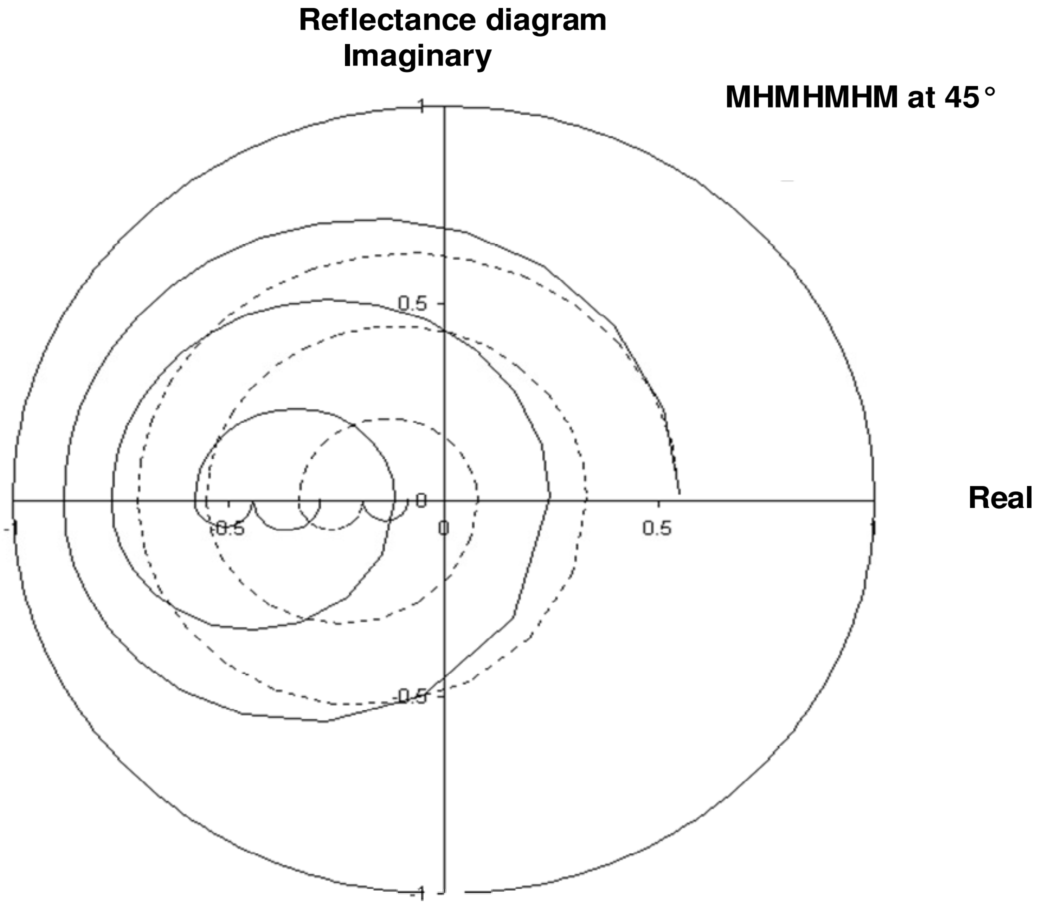

Figure 15. Reflectance amplitude diagram for this design at 45°. The sold line for s-polarization and the dotted line for the p- polarization.

quantized into narrow bands of index. This has been illustrated with the aid of reflectance amplitude (circle) diagrams and other plots. We use (filmstar free version) (http://www.ftgsoftware.com/design.htm) to draw the reflectance amplitude and phase diagram and for the comparison purpose with other experimental works.

Design rules-of-thumb for this family of coatings might be:

1. Determine the low, medium and high indices which your facility can reliably produce at the wavelength needed.
2. Search for the possible combinations of layers using these materials with QWOT solutions (intersections) near the desired angle and reflectance (be sure to include the proper “angle matched” thicknesses).
3. Adjustment the indices to gain the angle and reflectance as needed (within the ranges that can be produced.
4. Adjust the design with optimization as necessary, using non-QWOT layers to achieve the most acceptable compromise for the application.

REFERENCES

Angus Macleod H (2001). Thin-Film Optical Filters, 368, 3rd Ed., Inst. of Phys. Pub.

Baumeister PW (2004). Optical Coating Technology, 6-29 to 6-39, SPIE Press, Advanced Optical Thin Film Technology from: FTG Software Associates http://www.ftgsoftware.com/design.htm

DOE KISS, Ver. 97 for Windows, Air Academy Associates (and Digital Computations, Inc.), Colorado Springs, 1997.

http://www.optics.arizona.edu/opti380a/Opti380A/Lab2/Papers/OPNpaper.pdf.

Li Li (2003). The Design of Optical Thin Film Coatings With Total and Frustrated Total Internal Reflection, Optics and Photonics News, Optical Society of America, September 2003.

Schmidt SR, Launsby RG (1994). Understanding Industrial Designed Experiments, Air Academy Press, Colorado Springs.

Thelen A (1988). Design of Optical Interference Coatings, 114, McGraw-Hill.

Willey RR (2002). Practical Design and Production of Optical Thin Films, 2nd Ed., 8, Marcel Dekker.