Building blocks for nonpolarizing optical coatings

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The problem of designing nonpolarizing beam splitters with as broad a spectral band as practical has not been clearly understood. The effort of the work reported here has been to glean understanding from the various results of a contest for such designs and further studies of what might be the underlying principles and behaviors that are involved in such designs. A few key layer patterns have been observed, and the importance of symmetry in these patterns has been discovered. Four-layer building blocks have been found that relate to the two quarter-wave optical thickness pairs used as building blocks in normal-incidence designs. © 2008 Optical Society of America

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1. Introduction

The principles of design for nonpolarizing beam splitters have been elusive. Macleod [1] stated: “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).” Macleod also discussed some beam splitter design cases in Sect. 4.2.2 of Ref. [1]. The problem of designing a nonpolarizing beam splitter with as broad a spectral band as practical was presented to the optical coating field by the 2007 Optical Interference Coatings conference held in Tucson, Arizona, in June 2007. The results of the contest were to be an all-dielectric nonpolarizing beam splitter on a plate of glass tilted at 45°, not immersed within prisms. The polarization phases were to be within 1° for s and p polarization, and the reflections in s and p polarization were to be the same to within 2% and within a band from 40–60%. Twenty-three designs were submitted by eight designers. A study of the results of this contest has led to some insight as to the patterns of thin film layers that can contribute to a nonpolarizing beam splitter and other coatings. One of the key patterns behaves somewhat like the typical pair of quarter-wave optical thickness (QWOT) layers at the design wavelength as used for normal-incidence designs. This pattern is approximately four QWOTs of optical thickness instead of two and uses three materials instead of the normal pair of two materials. These patterns can be used in much the same way as QWOT stacks are used at normal incidence, except that the designs are at high angles of incidence (such as 45°), which causes percent reflectance, percent transmittance, reflectance phase, and transmittance phase all to be near the same in s and p polarization. Baumeister [2] reported on such structures of medium-high–medium-low (MHML) indices. Thelen [3] touched on the use of these also, and Costich [4] had also reported some pioneering work on nonpolarizing designs. However, broadband results were not achieved in the earlier work, and phase matching was not included.

Tilsch and Hendrix [5] coordinated the thin film design contest. The problem was to design as broadband a nonpolarizing, nonimmersed beam splitter as possible at 45° on a slab of 1.52 index glass centered about 550 nm. The designs could use a maximum of three materials that were nonabsorptive and nondispersive and chosen from the indices 1.38, 1.45, 1.65, 1.8, 2.05, 2.2, and 2.35. The three best submissions had a bandwidth of approximately 520–580 nm. All designers used 1.38 and 2.35 for the low- and high-index materials, respectively, and all but one designer used either 1.65 or 1.8 for the third material.
Since all the designs submitted were by eight experienced and independent thin film designers from around the world who used various different automatic thin film design computer programs and different approaches to put forth their best efforts, it is believed that the general similarities in the patterns of the designs illustrate the natural design structures needed to solve such design problems.

The root of the problem for such designs is that the indices of the substrate and coating materials change differently with angle of incidence for the $p$ and $s$ polarizations, and thereby the reflectances will differ with polarizations \cite{6}. Figure 1 shows the reflectance amplitude (RA) plot for the $p$ and $s$ polarizations of the first two thin layers on a 1.52 index substrate of one such design. It can be seen that the $p$ reflection for the substrate and layers appears to the right of the $s$ reflection at 45°, whereas both $s$ and $p$ polarizations would be coincident at point Z on this plot for a 0° angle of incidence. Subsequent layers must bring the $p$- and $s$-polarization reflectances to the same point in amplitude and reflected and transmitted phases and must remain within the bounds of the two circles for 40% and 60% reflectance intensity (or 0.632 to 0.775 reflectance amplitude) for all wavelengths in the band. This would produce the required “same” reflected and transmitted phases for $p$ and $s$ polarizations, and the reflected intensity (reflectance amplitude squared) would be between 40% and 60%.

2. Results from the Competition

Figure 2 shows the index versus thickness profile of the best of the submissions to the contest. This has a bandwidth of 61.7 nm, 214 layers, and a total thickness of 15,148 nm. The second best, shown in Fig. 3, has a bandwidth of 58.7 nm, 132 layers, and a total thickness of 9710 nm. The third design, seen in Fig. 4, has a bandwidth of 58.0 nm, 226 layers, and a total thickness of 15,230 nm.

It is often found that there are thin layers in a design that can be removed from the design without effect or even with improvement of the design (Ref. \cite{6}, p. 143). The procedure used to check for that in these cases was to change the index of the thin layer to that of the layer next to it, reoptimize all the remaining layers, and use the new reduced design if the merit improved or returned to the same value as before the layer was removed. Several layers could be removed without loss from each of the above three designs.

3. Observations

At first examination, these three designs seem quite different, but after some study, several similarities are seen. Five types of layer configuration have been identified in the three designs that seem representative of necessary or useful elements of the designs. The automated design optimization...
programs seemed to have settled in on these five index profile patterns independent of the designers or the programs that they used. This is interpreted as being natural to the design of this type of coating, and that is what is being sought in this work and reported here.

The five layer patterns will be identified as A, B, C, D, and F; and they are underlined in Figs. 2–4. A will be referred to as the “traveling” pattern, B as “symmetric,” C as “Herpin,” D as “wide” symmetric, and F as the “final” pattern. The observation of these five similar patterns in three of the best designs has been reported [7]. Two of these patterns are the subject of this report. The first and key pattern (A) has the ability to move the current reflection to a higher level where the p and s polarizations are closer to each other in reflection (and phase). This type of pattern advances the reflection of the p polarization at the peak reflectance wavelength of the stack more rapidly than the s polarization (as opposed to the QWOT stack, which does the opposite) while keeping the reflected and transmitted phases together.

Figure 5 shows the RA plot of such a pattern, which was repeated many times in the index profiles of the three best designs. When such a pattern is used many times in succession, it can bring the p and s polarizations to higher reflectances and a point where they are the same or even reversed in reflectance difference. Figure 6 shows an example of the reflectance of increasing numbers of four-layer sets (FLSs) in p and s polarizations. The peaks of the p- and s-polarization curves are linked by an arrow so that it can be observed how the p reflection overtakes the s reflection at about 60% and at 10 FLSs. The design prescription of the highest reflecting design of 10 FLSs is (0.89627 M 1.55613 H 0.89627 M 1.06596 L)10, where L = 1.38, M = 1.65, H = 2.35, and the substrate is of index 1.52. It can be noted that the repeating pattern (in parenthesis) is four quarter-waves at the design wavelength of 539 nm, whereas the peak reflectance is at 595 nm. The usual two QWOTs in common stacks would be at the peak

Fig. 5. Locus in s and p polarizations of four layers in the A type of pattern.

Fig. 6. Reflectance of an A type of pattern with 2, 4, 6, 8, 10, and 12 sets of four layers showing how (see arrows) the percent reflectance (%R) for s and p polarizations converges at about 10 sets.

Fig. 7. Index versus thickness profile of the A type of pattern that produces the results in Fig. 6.

Fig. 8. Reflectance amplitudes for s and p polarizations for a symmetric layer pattern at the wavelength of symmetry (498 nm). The phases at the end of the pattern return to essentially the same points as they started with no net effect at that wavelength and angle.
wavelength of 595 nm. These patterns cause the reflectance to increase from inequality of reflection to equality in the p and s polarizations. The index profile versus thickness of this group of 12 FLSs is shown in Fig. 7. These FLSs or patterns are similar in behavior to a two-layer pair in QWOT stacks used as the building blocks for many types of normal-incidence coating design (Ref. [6], p. 22). However, the FLSs have the ability to ameliorate the polarization divergence that is aggravated by QWOT stacks when used at nonnormal incidence.

Symmetry of the patterns seems to be a key factor in all the examples studied. At some short wavelength, a given pattern might look like Fig. 8 on an RA plot. Here the reflectance amplitudes and phases at the end of the pattern return to the same points as they started (180°) with no net effect at that wavelength and angle, just as it does in half-wave layers (absentee layers) in more conventional designs. However, at longer wavelengths, these are no longer like multiples of half-waves and can build the reflection as seen in Fig. 9. Figure 10 shows one period versus physical thickness of such a pattern, Fig. 11 shows how the reflectance of s and p polarizations builds with increasing thickness and periods up to six, and Fig. 12 shows the reflection versus wavelength in s and p polarization of the stack in Fig. 11.

A second type of pattern (C) of layers observed is seen in Fig. 13 and has a pattern of approximately one QWOT of medium index plus a group of 3, 5, or 7 thinner layers of high and low index in a Herpin-like structure, apparently to change the effective index of the single layer being replaced. These 3, 5, or 7 layers are approximately equal to another QWOT. It can be seen in Fig. 14 that these patterns also increase the reflectance, and it has been observed that these patterns do not materially change the phase relationships from start to finish.

In one sense, the simplest pattern (as in Fig. 7) could be viewed as a Herpin stack of medium–high–medium index in a background of low index. The effective index of that triplet will depend on the relative thicknesses of the three layers. The thicknesses of the two medium index layers are essentially the same in each FLS found in all the various designs submitted to the contest.
4. Discussion

The FLS pattern A seems to be the basic building block as is the QWOT stack in normal-incidence designs. Symmetry appears to be key to controlling the phase differences. There is also a common non-symmetric pattern (F) to the last few layers of each design. The previously observed patterns B and D are not as universal to all the designs but seem to also follow the symmetry tendency. These types of pattern seem to serve to coordinate with the two types of building block shown here to bring the reflections and phases to the desired final values. These other patterns might be considered the “mortar” that holds the building blocks together to achieve the desired structure. There is some indication that only patterns A and F are essential to solving this class of problem.

The approach to designing a nonpolarizing beam splitter at 45° (or other angles) over a broadband and also narrow bandpass filters, edge filters, etc., using these FLS building blocks is the same as it would be using QWOT layer-pair building blocks at normal incidence. To design a broadband reflector or beam splitter, each block or “stack” of FLSs that achieves the needed reflectance might be repeated after scaling for a slightly shorter wavelength than the previous block in order to obtain smooth reflection versus wavelength over the band. The nature of the FLS would tend to allow the percent reflectance of the s and p polarizations to be the same and generally keep the phases close to each other. A rough design could then be refined by optimization with respect to the design goals.

The type of mirror stack shown in Fig. 6, where the FLS is used as a QWOT pair would be used in normal-incidence designs, can be redesigned to provide a nonpolarizing edge filter at 45° as seen in Fig. 15. This edge filter design is Sub 2.24113 L 2.03491 M 0.3964 H 1.50906 M 1.52029 L (1.16695 M 1.83698 H 1.12632 M 0.59714 L)38 1.76492 M 1.54489 H 0.16519 M 1.00658 L Air. Two mirrors (as in Fig. 6) can be separated by a spacer of several layers to form a narrow bandpass filter as seen in Fig. 16. This narrow bandpass filter design is Sub 1.97917 L (0.9840 M 1.68345 H 0.9588 M 1.15318 L)10 1.84348 M 0.81208 H 0.76513 L 0.10753 M 0.42371 H 0.26608 M 1.72373 L (0.9840 M 1.68345 H 0.9588 M 1.15318 L)10 Air. The reflected and transmitted phases are also matched at the edge and bandpass wavelengths of these filters and surrounding regions. It can be seen that the basic concept is applicable to

Fig. 13. Index versus thickness profile of the C type of pattern.

Fig. 14. Locus of RA for the second type of pattern (C) seen in Fig. 13 in p polarization at 45° and 550 nm.

Fig. 15. Nonpolarizing edge filter at 45° from the A type of pattern.

Fig. 16. Nonpolarizing narrow bandpass filter at 45° from the A type of pattern.
more general types of optical coating than just beam splitters. Both of these filter examples do, however, have significantly narrower blocking bands when compared with conventional mirror stacks.

5. Conclusions

Building-block patterns of thin film layers have been identified that can be used to design various nonimmersed optical coatings with nonpolarizing properties at angles such as 45°. It should be noted that these patterns and designs not only bring the s- and p-percent reflectance to the same values in the regions of interest but also bring the reflected and transmitted phases to the same values.

References