Design of Non-Polarizing Beamsplitters

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ABSTRACT

The principals of design for non-polarizing beamsplitters have been elusive to date. The problem of designing a non-polarizing beamsplitter 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 in June 2007; 23 designs were submitted by 8 designers. The spread of the results shows that overall design thickness is an important factor, as it is in broadband antireflection coating designs. The effort of the work reported here has been to glean from these contest results and further studies what underlying principles and behavior are involved in these designs. The results of the contest were an all dielectric non-polarizing beamsplitter from 520-580 nm which would be effective as a 50-50% beamsplitter in an interferometer and other applications. This appeared to be a practical limitation when the polarization phases are to be within 1 degree for s- and p-polarization and the reflections in s- and p-polarization are to be the same to within 2% and within a band from 40-60%. The interferometric efficiency, (R x P)/.25, for such a design would be at least 96% over the spectral range of 520-580 nm.

INTRODUCTION

Tilsch and Hendrix [1] coordinated a thin film design contest in conjunction with the OIC 2007 meeting in Tucson. Eight top thin film designers from around the world using various thin film design software and various approaches put forth their best efforts to design as broadband a non-polarizing beamsplitter as possible at 45° on a slab of 1.52 index glass centered about 550 nm. The requirements included that the reflection of the p- and s-polarizations were to be within 2% of each other and within the bounds of 40% to 60%. The reflected and transmitted phases of the p- and s-polarizations also were to be within 1° of each other. The three best submissions had a bandwidth of approximately 520-580 nm. The designs could use a maximum of three materials which were non-absorptive and non-dispersive and chosen from the indices 1.38, 1.45, 1.65, 1.8, 2.05, 2.2, 2.35. All designers used 1.38 and 2.35 for the low and high index materials, and all but one used either 1.65 or 1.8 for the third material.

The root of the problem for such designs is that the indices of the substrate and coating materials change differently for the p- and s-polarizations with angle of incidence, and thereby the reflectances will differ with polarizations [2]. 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 of the designs to be discussed. It can be seen that the p-reflection for the substrate and layers plot to the right of the s- reflection at 45°, whereas both would overlap at point "A" on the plot for 0° angle of incidence. Subsequent layers must bring the p- and s-polarization reflectances to the same point in amplitude and phase, 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%.

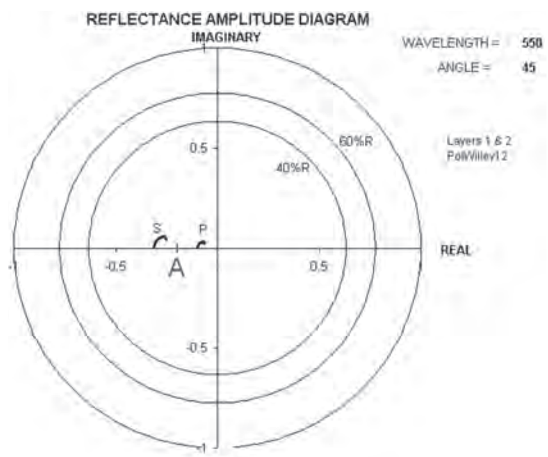

Figure 1: First two layers of a design showing the split of s- and p-pol at 45°.

RESULTS FROM THE OIC07 COMPETITION

Figure 2 shows the index versus thickness profile of the best of the submissions to the contest by Fabian Lemarchand of Institut Fresnel, Marseille, France. This has a bandwidth of 61.7 nm, 214 layers, and a total thickness of 15148 nm. The second best, shown in Figure 3, was submitted by Michael Trubetskov of the Moscow State University, Moscow, Russia. It has a bandwidth of 58.7 nm, 132 layers, and a total thickness of 9107 nm. The third design, seen in Figure 4,

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was submitted by Vladimir Pervak at Ludwig Maximilian University, Garching, Germany. It has a bandwidth of 58.0 nm, 226 layers, and a total thickness of 15230 nm.

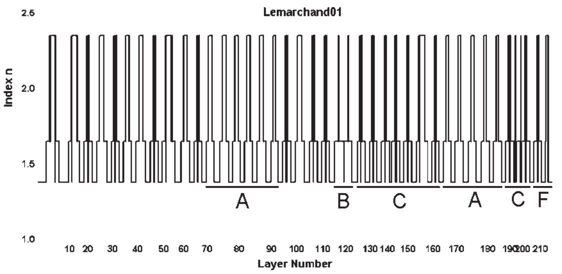

Figure 2: Index versus thickness profile of the winning design by Lemarchand.

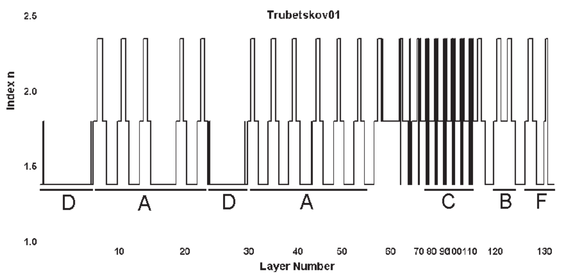

Figure 3: Index versus thickness profile of the second design by Trubetskov.

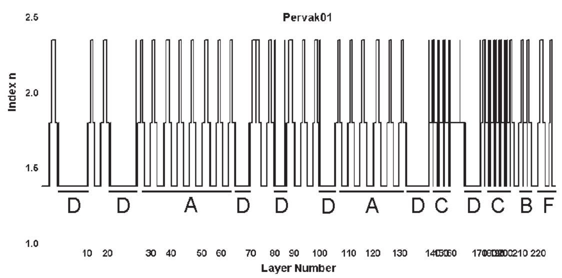

Figure 4: Index versus thickness profile of the third design by Pervak.

It is often found that there are thin layers in a design that can be removed from the design without effect or even with an improvement of the design [Ref. 2, 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 of the remaining layers, and use the new reduced design if the merit improved or at least 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.

STUDY OF THE RESULTS

At first examination, these three designs seem quite different; but after some study, several similarities are seen. Five types of layer configurations have been identified in the three designs which 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 which 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 Figures 2, 3, and 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.

Pattern A has the ability to move the current reflection to a higher reflection where the p- and s-polarizations are closer to each other in reflection (and phase). Figure 5 shows the RA plot of such a pattern which is repeated many times in the index profiles of Figures 2, 3, and 4. When such a pattern is used successively many times, 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. These four-layer sets (FLS) or patterns are similar in behavior to a two-layer pair in quarter wave optical thickness (QWOT) stacks used as the building blocks for many types of normal-incidence coating designs [Ref. 2, p. 22]. However, the FLS have the ability to ameliorate the polarization divergence that is aggravated by QWOT stacks when used at non-normal-incidence. Figure 6 shows the reflectance of increasing numbers of FLS in p- and s-polarizations. The peaks of the p- and s-polarizations curves are linked by a bold line so that it can be observed how the p-reflection overtakes the s-reflection between 50% and 60% at 9 and 10 FLS. The design prescription of the highest reflecting design of 10 FLS is 1.82949L (.90625M 1.55613H .88629M 1.06596L)10, where L = 1.38, M = 1.65, H = 2.35, and the substrate is 1.52. It can be noted that the repeating pattern (in parenthesis) is nearly four quarter waves at the design wavelength of 595 nm rather than the usual two QWOTs in common stacks. The A patterns therefore cause the reflectance to “travel” from inequality of reflection to equality in the p- and s-polarizations. This also seems to relate to the need for a certain minimum reflection to get a good design at a given reflectance level like 50%.

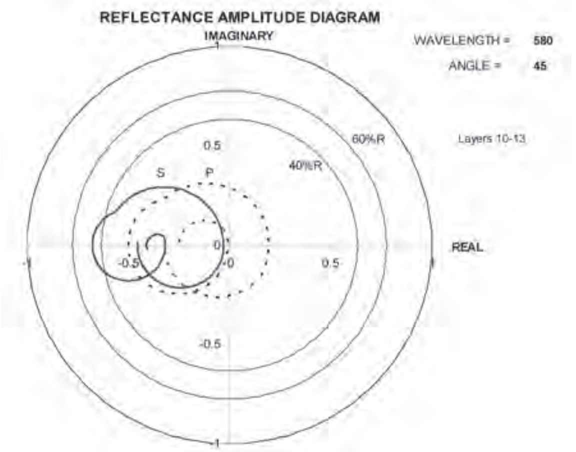

Figure 5: Locus in s- and p-pol of four layers in an A-type Pattern.

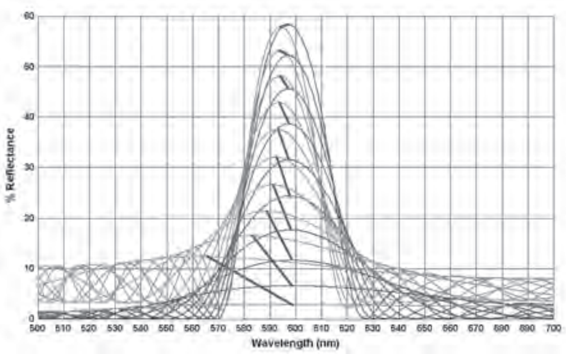

Figure 6: Reflectance of A Patterns with 1 to 10 sets of four layers.

Figure 7 shows the index profile of another design having good performance where all of the A patterns are together, similar to the designs of Figure 6. The spectral performance of the design in Figure 7 is shown in Figure 8 wherein all of the other patterns are also used.

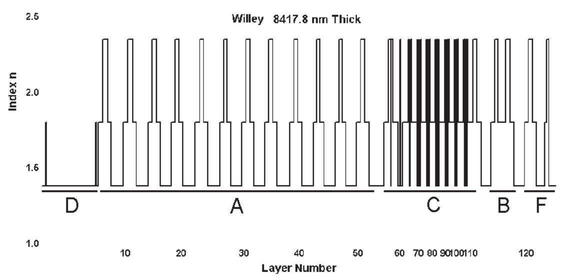

Figure 7: Index versus thickness profile of another design showing patterns separated.

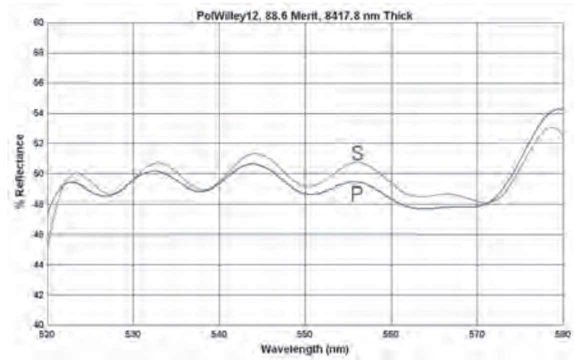

Figure 8: Reflectance spectrum of design in Figure 7.

In order to achieve a broad bandwidth, achromatizing layers as used in antireflection coatings are needed in these cases also. It appears that all of the patterns other than A may contribute to this effect. On RA plots, these patterns appear to be like clock springs which wind tighter or unwind with changing wavelength to compensate for reflectance changes with wavelength.

Pattern B occurs only once in the design of Figure 7; its RA plot at 580 nm is seen in Figure 9. The round dots are the start of the layers pattern, and the triangles are the end of the pattern. The s-locus is solid, and the p-locus is dashed. This pattern appears to serve the functions of both changing the reflectance amplitude of the p- and s- polarizations and their relative phases.

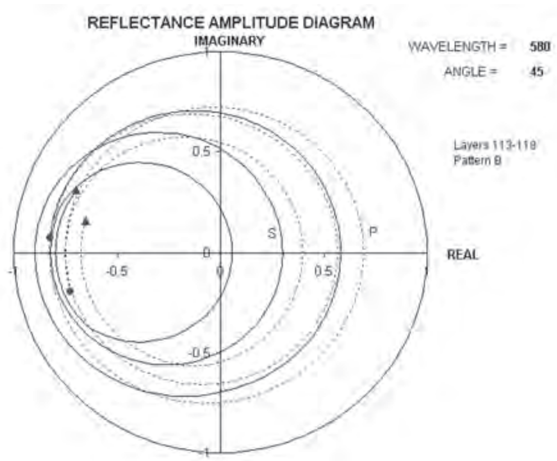

Figure 9: Locus in s- and p-pol of six layers in the B-type Pattern.

Pattern C however seems to primarily function as a phase shifting mechanism of p- relative to s-polarization. In that sense, its function is orthogonal to that of the A patterns. There are various detailed forms of the C pattern found in Figure 7 as seen in its expansion in Figure 10. The basic pattern is a broad layer of medium index with a group of thin high and low index layers forming what amounts to a Herpin equivalent index layer very near in index to that of the broad layer. As seen in Figure 11, this would not change the reflectance amplitude by much, but primarily advances the relative phase of the s- with respect to p- polarization. The Herpin layers are more obvious in Figure 12. It becomes apparent that the Herpin equivalent layer can be made to match a single layer index, but the phase effects are different from a homogeneous single layer to the Herpin equivalent layer. The "average" index of the layers in Figure 10 would appear to be approximately 1.8.

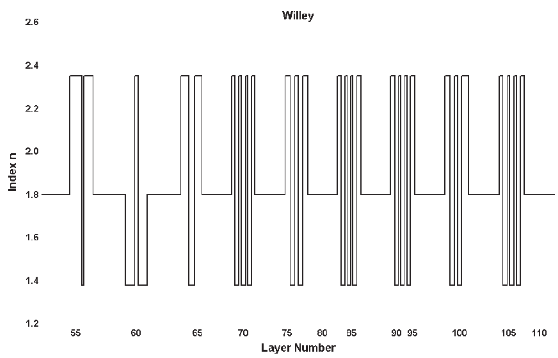

Figure 10: Index versus thickness profile of C Patterns seen in Figure 7.

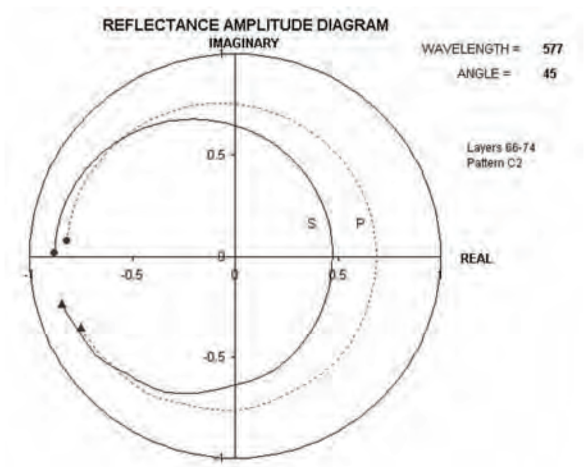

Figure 11: Loci of a 9-layer C-type Pattern.

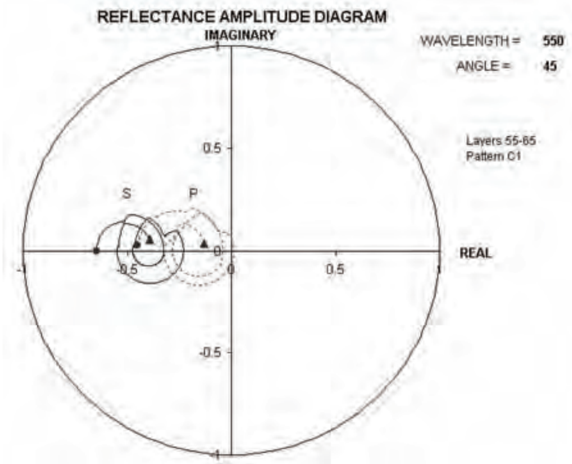

Figure 12: Loci of a C-type Pattern which makes Herpin layers more obvious.

Pattern D acts as a long achromatizing "spring" in its thick third layer which includes several half waves of thickness at the center wavelength of the band. Its RA is shown in Figure 13. It was attempted to remove this pattern, but found that it provided sufficient benefit to the particular design to be retained. It seems to serve multiple functions in the overall design.

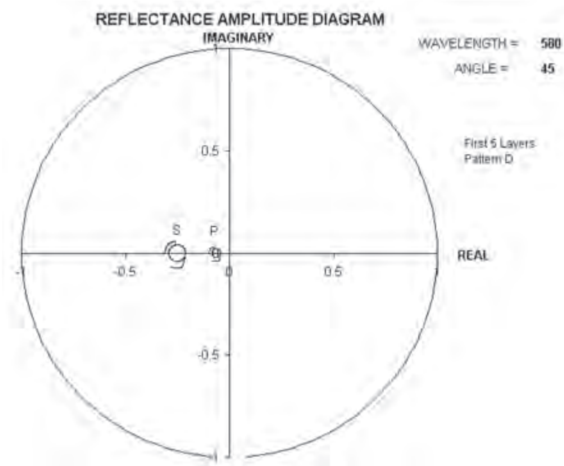

Figure 13: Loci of the D Pattern in Figure 7.

A common pattern, F, is found in all of the designs shown; it is the eight layers at the finish of the stack. Figure 14 is the RA plot for the last eight layers of the design of Figure 7, and this would be quite similar for all of the designs shown. All of the layers up to the last eight layers have brought the s- and p-reflectances to the points marked by the round dots. The last eight layers bring those to the same point at the triangle(s), the end of the coating stack. This common point has the same reflectance amplitude, magnitude, and phases; which meet the requirements of the problem. Figure 15 shows the locus of the end points for wavelengths from 520 to 580 nm along with the 40% to 60% boundary lines.

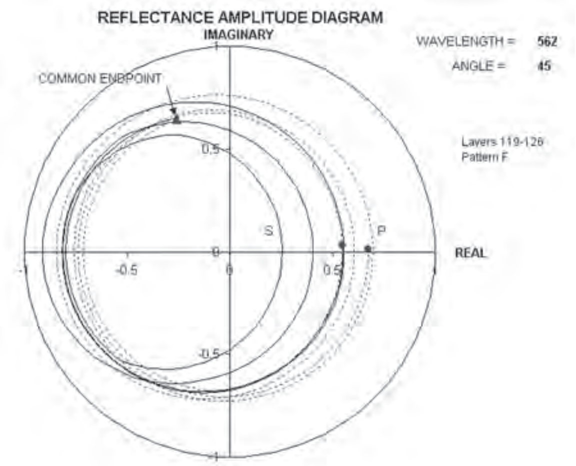

Figure 14: Locus in s- and p-pol of eight layers in the F Pattern of Figure 7.

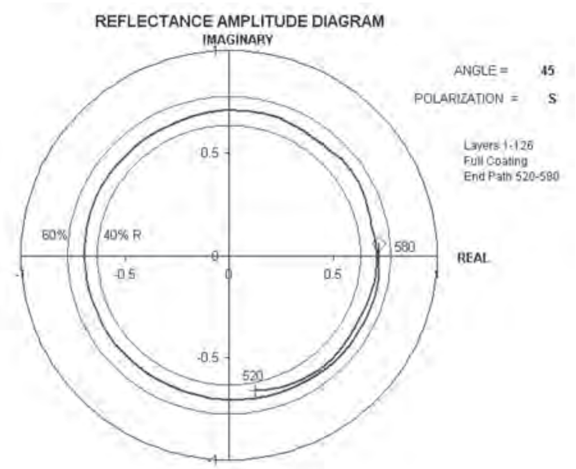

Figure 15: Locus of the non-polarizing end point from 520 to 580 nm for Figure 7.

CONCLUSIONS

Patterns have been observed in designs submitted to the OIC 2007 contest which are common to the best designs and seem to give some insight to the basic elements needed for broad-band non-polarizing beamsplitters. Since the designers had worked independently with various tools and approaches, it is thought that these patterns are inherent in the nature of the ideal design. The three most clear and significant patterns are referred to here as A, C, and F. Repetitions of pattern A move the reflections for p- and s- polarization to higher values while reducing the difference between them and then reversing the difference. Pattern C primarily has a function that is orthogonal to that of pattern A in that it changes the relative phase between the polarizations. Pattern C has an interesting play of the effects of Herpin layers on phase which is different from that of the single layers that they simulate. Pattern F makes the final transition from the preceding layers to bring the reflectances and phases of the polarizations to common values. Patterns B and D are more hybrid in nature and more difficult to understand, but they do seem to serve unique functions that are beneficial to the designs.

Some better understanding has been gleaned from the results of the contest, and it appears that non-polarizing beamsplitters of even broader bands may be possible.

REFERENCES

1. Markus Tilsch, Karen Hendrix, "Optical Interference Coatings Design Contest 2007: triple bandpass filter and nonpolarizing beam splitter," *App. Opt*. **47,** pp.C55-C69 (2008).

2. R. R. Willey, *Practical Design of Optical Thin Films*, Second Edition, 47-57, Willey Optical, Consultants, Charlevoix, MI, USA (2007).