

Design of Optical Thin Films Using the “Fencepost” Method

R.R. Willey, Willey Optical, Consultants, Charlevoix, MI

ABSTRACT

The technique described here is called the “Fencepost” Method because the resulting plots of index of refraction versus film thickness look like thin fence posts of high index material widely spaced and standing above a ground of low index material. This general structure has been shown to have scratch-resistance benefits in antireflection coatings. It is shown here to be generally capable of designing essentially all types of thin film coatings such as: antireflection, high reflection, edge filters, blocking filters, minus filters, narrow bandpass filters, polarizing filters, etc. All of the high index layers (for example) would be constrained to some fixed thickness of perhaps 1/5th of a quarter wave optical thickness and only the low index layer thicknesses would be varied in the design optimization. The low index layers could be the fixed thin layers (“Posthole” Method), but this might be less favored for scratch resistance in the visible and near infrared spectral regions. However, postholes might be advantageous in other spectral regions and also might reduce the angular sensitivity of some designs. The restraint of not varying the thicknesses of half of the layers (high index) makes some designs somewhat more difficult, but satisfactory results can still be achieved.

INTRODUCTION

Schulz et al. [1-5] have shown the hardness benefit of anti-reflection (AR) coatings composed mostly of thick SiO_2 low index layers interspersed with multiple thin layers of high index material. They showed that good broad band AR's can be achieved and also have the scratch resistance of a thick SiO_2 layer on polymer materials. The index versus thickness profile of such designs would be like that shown in Figure 1. This looks like thin fence posts of high index material widely spaced and standing above a ground of low index material; hence, we will refer to these as “Fencepost” designs (FP). Conversely, designs wherein the low index layers are thin might be called “Posthole” designs (PH). The latter will be shown to have some potential advantages in reducing angular sensitivity.

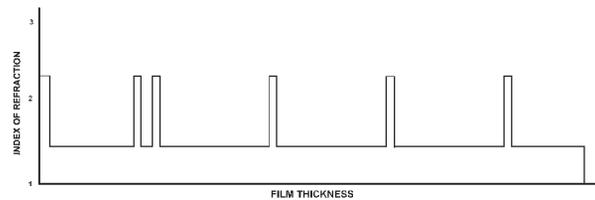


Figure 1: An index of refraction versus thickness plot of a typical “Fencepost” design.

This paper reports on the investigation of the possibility of using FP designs for most of the various types of thin film designs in addition to AR's and the possible design advantages and disadvantages. These designs included high reflection, edge filters, minus filters, single and multiple band blocking filters, narrow bandpass filters (NBP), polarizing filters, etc.

DESIGN METHOD

The design of any narrow bandwidth minus or blocking filter by changing the ratio of the thickness between the high and low index layers was recently reported [6]. The optical thickness of each pair of high and low index layers is the same as ordinary quarter wave optical thickness (QWOT) designs at two (2) QWOT's at the center of the blocking band. However, the width of the blocking band becomes less as the ratio of the overall thickness to the thinnest layer in the pair becomes greater than 2:1 (1 QWOT high plus 1 QWOT low index). As the ratio is made higher, more layer pairs are needed to achieve a given optical density (OD).

In an effort to achieve the benefits reported by Schulz et al. [1-5] in other than AR coatings, designs are started with thin layers of high index material at an arbitrary thickness of about 0.2 QWOT. A stack for a narrow blocker might then be represented by (.2H 1.8L)20 at the design blocking wavelength. The approach for more general spectral distributions would then be to hold the high index layer thicknesses fixed and vary all the low index thicknesses independently. This could be viewed as having all of the same sized fence posts and just varying the distance between them. This constrains the optimization to only half of the available variables, and that tends to make the designs somewhat more difficult for given requirements.

DESIGN EXAMPLES

For example, if two narrow bands were to be blocked where the second band was at 1.5 times the wavelength of the first such as 440 and 660 nm, the starting design might be:

.2H 1.8L .2H 1.8L .2H 1.8L (.2H 1.8L)40 .2H 1.8L .2H 1.8L .2H 2.8L .2H 2.8L (.2H 2.8L)40 .2H 2.8L .2H 2.8L .2H 2.8L.

The four low index layers between the bracketed “stacks” and the three each before and after the stacks could be optimized to get better index matching and improve the pass band transmittance. Figure 2 shows such a design where the optimized result was:

.2H 1.38419L .2H 1.86074L .2H 1.54147L (.2H 1.8L)40 .2H 1.54768L .2H 1.52246L .2H 2.14169L .2H .79498L (.2H 2.8L)40 .2H .37251L .2H 2.46193L .2H 1.36763L.

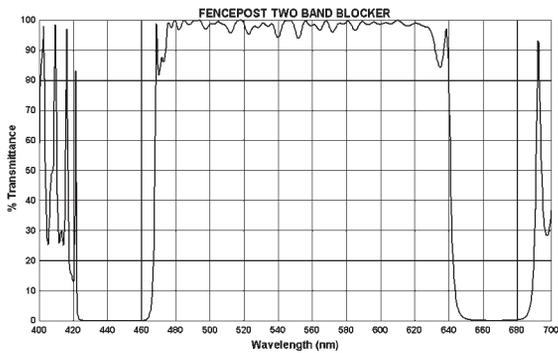


Figure 2: Design of two blocking bands with the second 1.5 times the wavelength of the first.

Figure 3 is another example of a dual-blocker design where greater than OD 5.0 was achieved in the blocking bands with 226 layers.

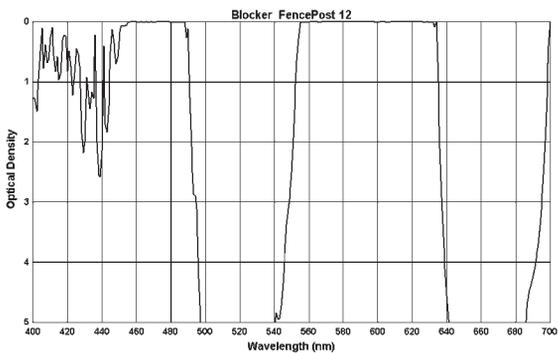


Figure 3: Another design like that of Fig. 2 with OD 5.0 using 226 layers.

Broad band high reflectors can be designed, although they do require more layers than 2:1 type designs. However, the overall optical thickness is about the same. Figure 4 shows

a 2:1 design of 20 layers and Figure 5 shows an equivalent FP design of 200 layers. Neutral density beam splitters can similarly be designed.

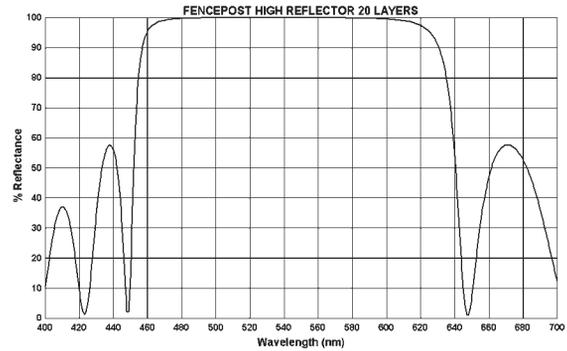


Figure 4: Typical broad band high reflector of 2:1 design with 20 layers.

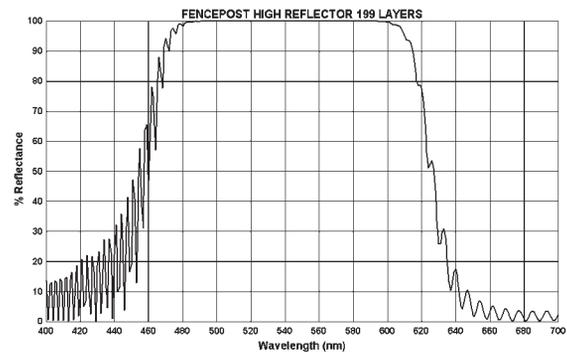


Figure 5: Fencepost broad band high reflector design like Fig. 4 with 200 layers.

General shapes such as the triangle spectrum of Figure 6 with 52 layers using conventional design practice can be approximated as the FP design of 60 layers in Figure 7.

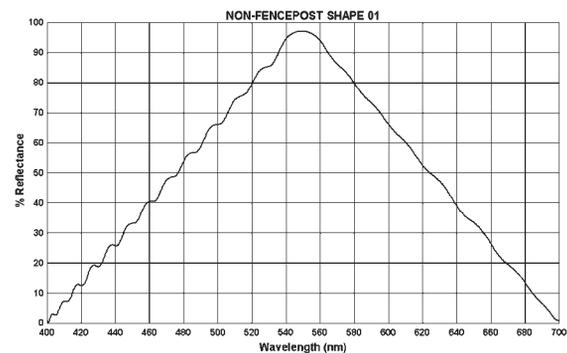


Figure 6: Conventional design of a triangle spectrum with 52 layers.

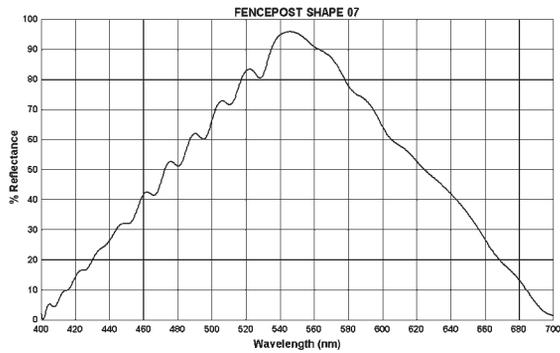


Figure 7: Fencepost design of a triangle spectrum with 60 layers.

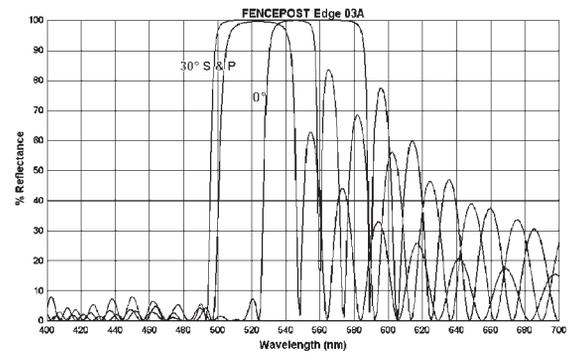


Figure 10: Posthole version of the SWP design in Figure 8.

EDGE FILTERS

Long and short wavelength pass (SWP) filters can be designed with the FP method, but the blocking bands are narrower and more layer pairs are required. Figure 8 shows the conventional 2:1 SWP filter at normal incidence and for the s- and p-polarizations at 30°. Figure 9 shows an FP design for the same edge. Note that the blocking band is narrower and the wavelength shift with angle is greater than the 2:1, but the wavelength separation of the s- and p-polarizations are less for the FP design. Figure 10 is the PH version of the design. Note here that the angular shift of wavelength is smaller than the 2:1 design. This might be helpful as a way to minimize edge shift with angle using the PH design method.

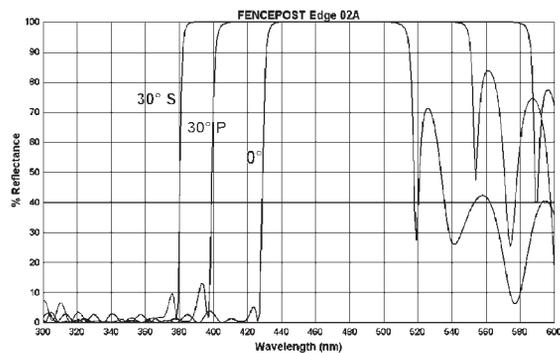


Figure 8: Conventional 2:1 SWP design at 0° and at 30° in s- and p-polarizations.

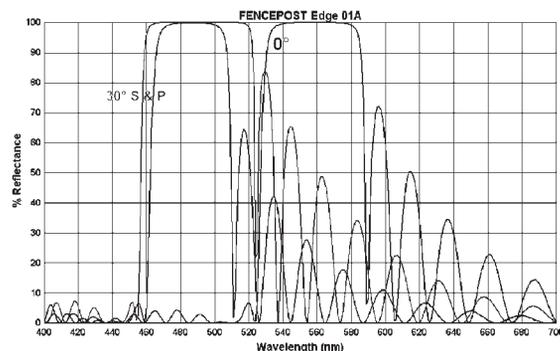


Figure 9: Fencepost version of the SWP design in Figure 8.

NARROW BANDPASS FILTERS

To illustrate the FP design of NBP filter, a conventional 3-cavity filter and an equivalent FP were designed where the maximum blocking density was about OD 5.0. Figures 11 and 12 compare the transmittance of these in the visible spectrum. Both the block bands and pass band are narrower in the FP design, but the shapes are generally the same. Figures 13 and 14 compare the pass band shape and width on an OD scale.

The conventional design is:

$$(1H \ 1L)3 \ 2H \ (1L \ 1H)3 \ 1L \ (1H \ 1L)3 \ 2H \ (1L \ 1H)3 \ 1L \\ (1H \ 1L)3 \ 2H \ (1L \ 1H)3 \ .26569H \ 1.30674L.$$

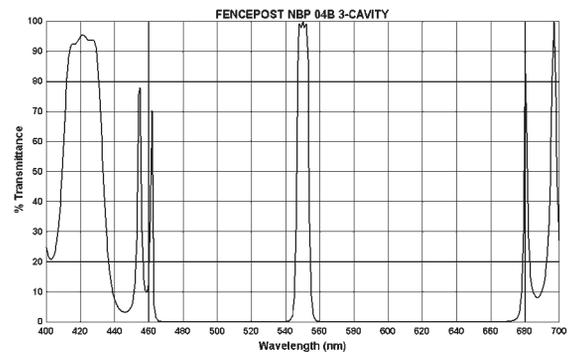


Figure 11: Conventional 3-cavity NBP filter with blocking of OD 5.0.

The FP design is:

$$(.2H \ 1.8L)9 \ .2H \ 2.75L \ .2H \ (1.8L \ .2H)9 \ 1.74L \ (.2H \\ 1.8L)9 \ .2H \ 2.75L \ .2H \ (1.8L \ .2H)9 \ 1.74L \ (.2H \ 1.8L)9 \\ .2H \ 2.75L \ .2H \ (1.8L \ .2H)9 \ 1.8L$$

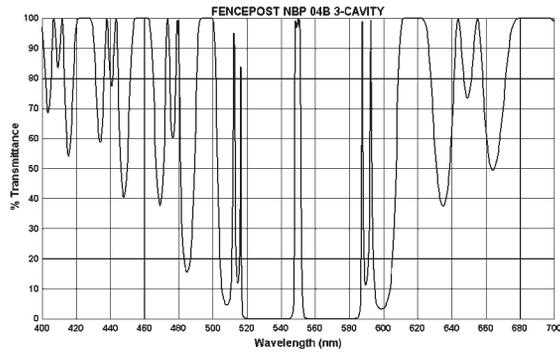


Figure 12: Fencepost 3-cavity NBP filter like that of Figure 11.

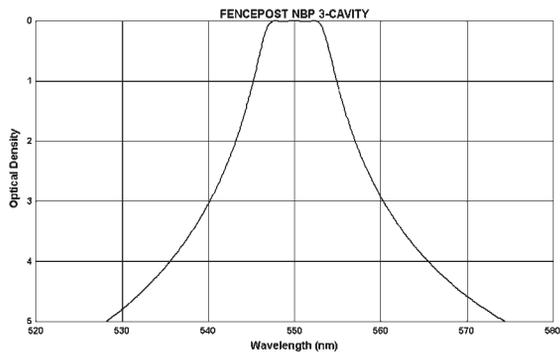


Figure 13: Conventional 3-cavity NBP filter as in Figure 11 on an OD scale.

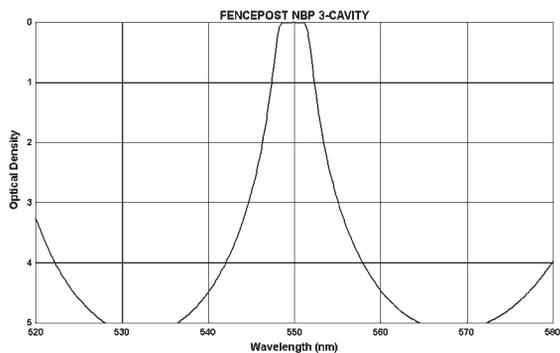


Figure 14: Fencepost 3-cavity NBP filter as in Figure 12 on an OD scale.

The number of layers in the conventional design is 42 and the physical thickness is 3.43 microns, whereas the FP design has 120 layers and an overall thickness of 11.06 microns.

The possible motivations to use an FP design for a NBP filter are probably only: 1) if a narrower blocking band was needed to have some adjacent pass band(s), or 2) to use the PH version of the method for reduced angular shift sensitivity.

CONCLUSIONS

The advantages of Fencepost and Posthole design methods have been introduced. The FP method shows that essentially all design types can be achieved with the benefit of the increased abrasion resistance (particularly on polymer surfaces) reported by Schulz et al. [1-5]. The PH method shows a potential to reduce angular shift sensitivity of a variety of design types. Some of the disadvantages of more layers and thicker overall coatings have been described.

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