Limitations on Wide Passbands in Short Wavelength Pass Edge Filters

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ABSTRACT

There are differences in the behavior of wide passband edge filters with short wavelength passbands and of those with long wavelength passbands. The bandwidth of the pass band is here defined by the longest wavelength in the band divided by the shortest wavelength. This is virtually unlimited in the case of a long wave pass filter. However, it is significantly limited in the case of the usual approach of using quarter wavelength layer thickness stacks for short wave pass filters. This limitation is encountered because the third and higher harmonics of the blocking band appear at the short wavelength position where the quarter wave optical thicknesses of the layers for the blocking band stack of layers become three (3) quarter waves, 5, 7, 9, etc., at the wavelength of that harmonic. It appears that bandwidths of over 2 start to have increasingly higher reflection losses, and bandwidths of 2.5 become virtually impractical for QWOT stacks.

When band-passes broader than about 2 are needed for edge filters with a short wave passband, recourse to rugate-like designs is needed. Such designs can be achieved with only two homogeneous materials by employing the concept of the Herpin approximation, although many layers may be required. The influence of the indices of refraction of the materials, number of layers, and design approach on the bandwidth, average reflectance in the passband, band edge steepness, blocking density, and "squareness" at the transition from the pass to blocking band are discussed.

INTRODUCTION

Edge filters have a certain slope at the edge which is usually specified, some degree of blocking which is also usually specified by wavelength band and optical density, and a transmission or passband (AR) which is specified. If the passband is on the short wavelength side of the edge, it is referred to as a short wavelength pass edge filter (SWP). If the passband is on the long wavelength side of the edge, it is a long wavelength pass (LWP) filter.

The passband of a LWP filter is essentially like an antireflection (AR) coating as shown in Fig. 1, except that further attention is paid to the filter edge which is normally outside the edge of the AR band (on the short wavelength side). In such a case, design targets would be added to the optimization process in addition to those already there for the AR band which would apply pressure for a steeply rising reflection edge at the desired wavelength. The steepness of the edge is a nearly linear function of the number of layers. The LWP bandwidth has no inherent limitation because there are no harmonic bands at longer wavelengths than the fundamental blocking band generated by a quarter wave optical thickness (QWOT) stack at the center wavelength of the blocking bands as illustrated in Fig. 2 (at the left end). In this figure, the frequency scale is used (1/wavelength in cm^{-1}) because of the more symmetric presentation.

When a SWP filter is designed with a basic QWOT stack, the passband width is limited to the region between the first and third harmonic (1000 and 3000 cm^{-1}) as seen in Fig. 2. Small adjustments in the thicknesses of what started as QWOT layers in order to improve the average transmittance in the passband cannot overcome the above limitation. We will discuss the effects of this limitation and an approach which can overcome this limitation.

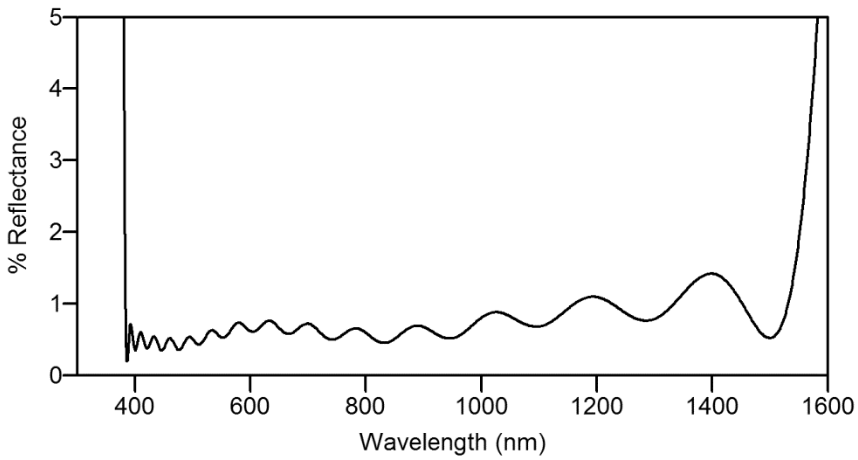

Fig. 1. A broadband AR coating started from a QWOT stack at about 310 nm. This could be extended to the right as much as needed with a tradeoff in the average reflectance percentage (Rave) in the band.

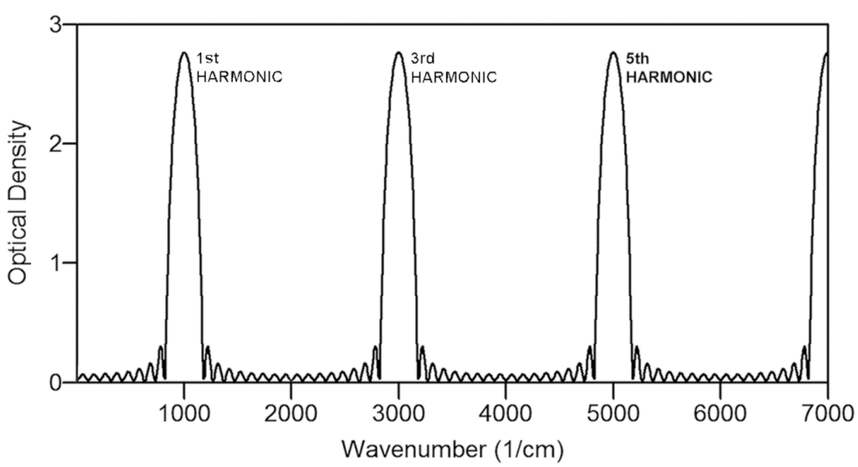

Fig. 2. A QWOT stack design with its fundamental blocking band at 1000 cm^{-1} and harmonics at 3, 5, 7, etc., of that frequency. There are no bands less than 1000 cm^{-1} (LWP side).

DESIGN LIMITATIONS of a SWP FILTER of QWOT STACK DESIGN

Many SWP edge filter designs of the basic QWOT stack nature were investigated to determine what could be achieved as the bandwidth was made wider to the point of approaching the third harmonic blocking band as seen in the 3000 cm^{-1} band of Fig. 2. It was found that Rave in the band was primarily a function of the bandwidth (B), and almost no function of the number of layers from the 18 to 36 layer studied. It was also found that reducing the index of the last layer from 1.46 to 1.38 had no significant effect as it would in a broad band AR coating as in Fig. 2.4 of Ref. 1. The slope of the edge as measured in the change in %T or %R per nm was almost a linear function of the number of layers. Therefore the designer can use whatever number of layers needed to obtain the required slope or steepness and the estimated Rave of an optimized design will be determined by the empirical Eqn. 1. The bandwidth (B) of the pass band is here defined by the longest wavelength in the band divided by the shortest wavelength.

$$\mathbf{Rave = -25.246 + 48.786*B - 30.584*B*B + 6.448*B*B*B} \qquad \mathbf{(1)}$$

It can be seen from Fig. 3, which is a plot of the Rave versus B per Eqn. 1, that the Rave rises rapidly beyond a bandwidth of 2, and a B as great as 2.5 becomes impractical.

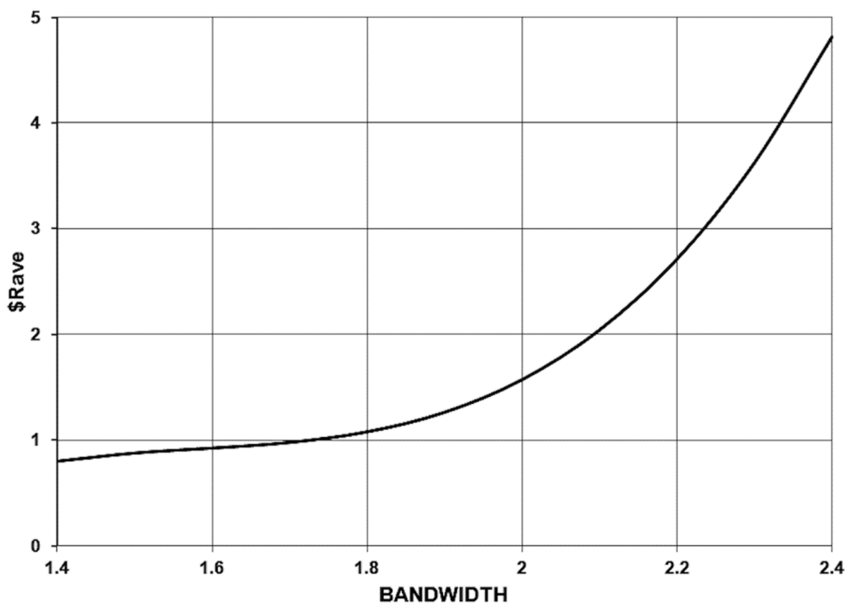

Fig. 3. Estimated potential Rave versus Bandwidth in a **QWOT** stack SWP edge filter.

WHEN WIDER PASSBANDS ARE NEEDED FOR SWP EDGE FILTERS

Macleod[2] discusses this problem and some solutions, and he refers to the earlier work of Epstein[3] and Thelen[4]. Thelen also has a chapter in his book that deals with the subject[5]. As will be seen below, the solutions are of a rugate nature with respect to the profile of the index of refraction with thickness. In the practical case, the inhomogeneous index versus thickness profile can be replaced by non-QWOT layer structures of just two indices along the lines introduced by Herpin[6] and Epstein[7]. These substitutions of Herpin equivalent layers or Epstein periods (homogeneous layers) as **surrogates** for **rugate** (inhomogeneous) structures will be here called **"surrugate"** designs.

The troublesome 3rd, 5th, etc., harmonic blocking bands seen in Fig. 2 can be eliminated by a surrugate design.

Figure 4 shows the index versus thickness profile of the first four periods (layer pairs) of the normal QWOT design which would produce a spectrum such a Fig. 2. Figure 5 shows the reflectance spectrum which is produced by a 40 layer or 20 cycle design with the index profile of Fig. 4.

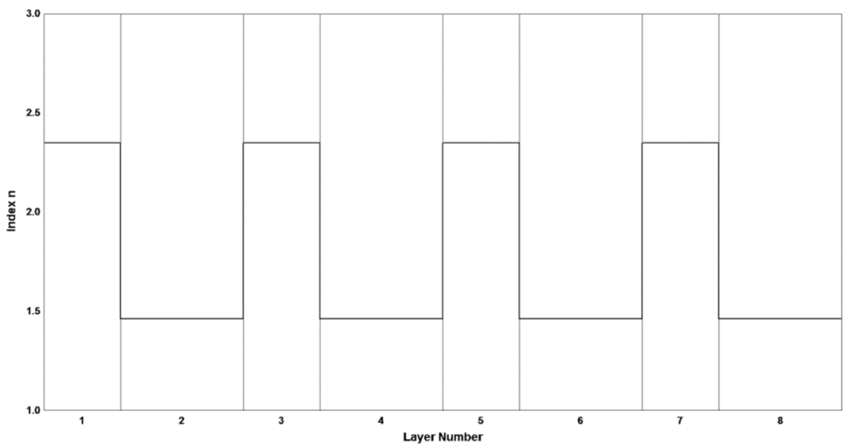

Fig. 4. Index versus thickness profile of QWOT stack with 2 layers per cycle. This gives blocking bands at all odd harmonics (1, 3, 5, 7, etc.), but NOT at the even harmonics, as seen in Figs. 2 and 5.

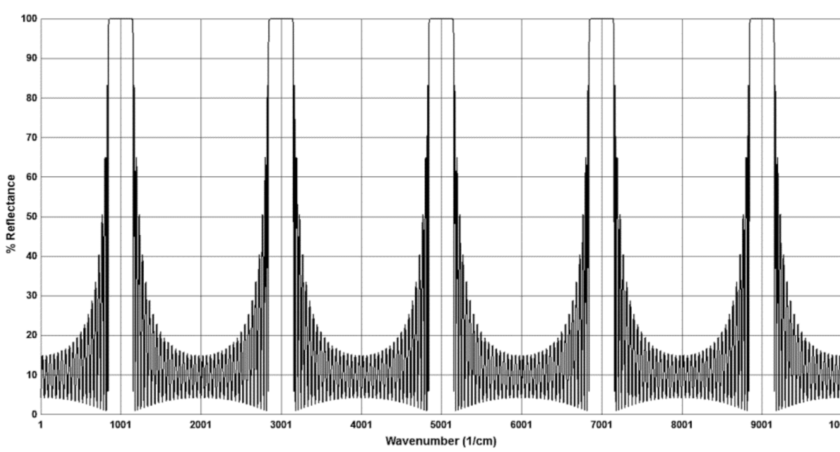

Fig. 5. Blocking- and pass-bands produced by the index versus thickness profile of Fig. 4.

Those familiar with the rugate concept will recognize that a sinusoidal index profile instead of the "square" profile in Fig. 4 could produce a spectrum with only the first harmonic and all of the other harmonics would be suppressed. The first step in this direction would be to replace the two (2) layers per cycle with six (6) layers per cycle as in Fig. 6. These have been optimized with some of the layers linked to others to maintain symmetry, while reducing the third harmonic band to zero as seen in Fig. 7.

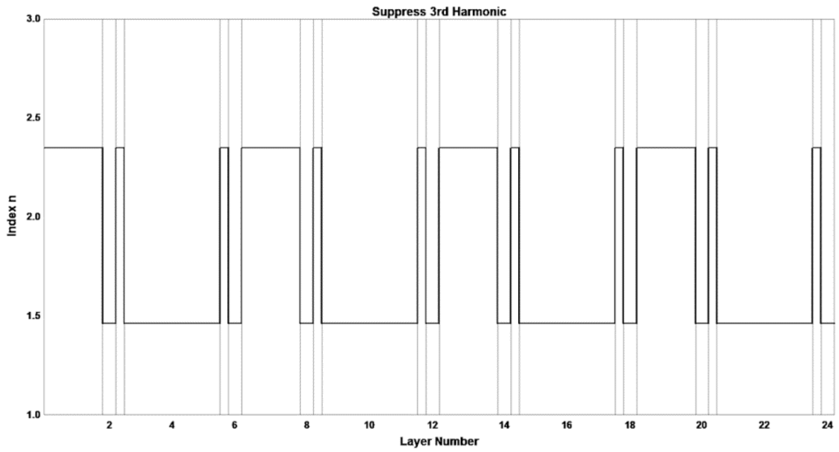

Fig. 6. Index versus thickness profile of symmetric layer stack with 6 layers per cycle. This gives blocking bands at harmonics 1, 5, 7, etc., but **NOT** at the 3rd harmonic, as seen in Fig. 7.

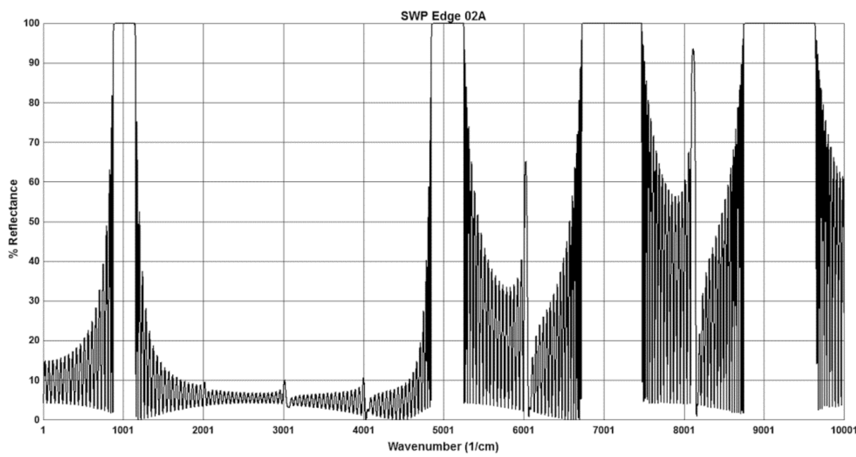

Fig. 7. Blocking- and pass-bands produced by the index versus thickness profile of Fig. 6.

When the above approach is extended to 10 layers per cycle as in Fig. 8, the third and fifth harmonics can be suppressed as in Fig. 9. When extended further to 14 layers per cycle as in Fig. 10, the third, fifth, and seventh harmonics can be suppressed as in Fig. 11. It seems that this process could be extended by increments or four layers to suppress higher and higher harmonics. As this is done, the Herpin equivalents would come closer and closer to approximating the sinusoidal rugate index profile that would have only the first harmonic band. This, in turn, would allow a pass-bandwidth which was as wide as desired. However, there are limitations to how much the reflection in the pass band can be reduced.

The points in Fig. 12 show the average reflectance (Rave) in the passband which was achieved for a given bandwidth by optimization of two cycles of layers on each side of a fixed set of 16 cycles of layers. Therefore, the total number of cycles was kept at a total of 20, which would be 20 layer pairs or 40 layers in the QWOT case of 2 layers per cycle. It can be seen that the Rave becomes progressively larger with increased bandwidth in a linear fashion until it approaches the next harmonic band. At that point, the Rave rises, indicating the need to suppress yet another harmonic.

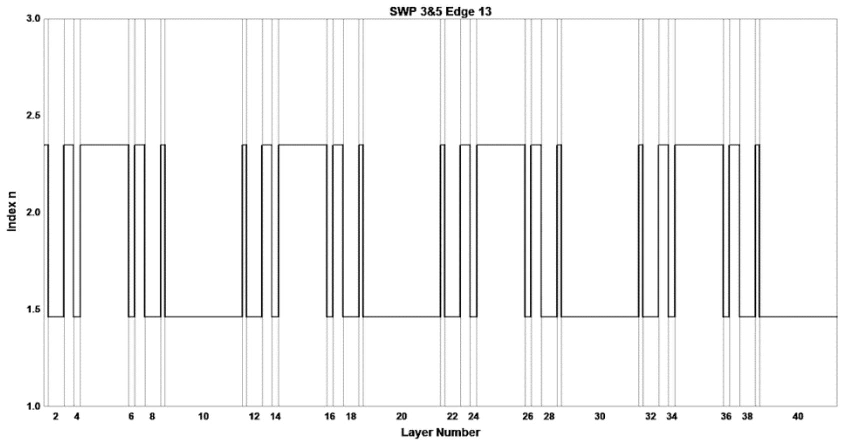

Fig. 8. Index versus thickness profile of symmetric layer stack with 10 layers per cycle. This gives blocking bands at harmonics 1, 7, etc., but **NOT** at the 3rd and 5th harmonics, as seen in Fig. 9.

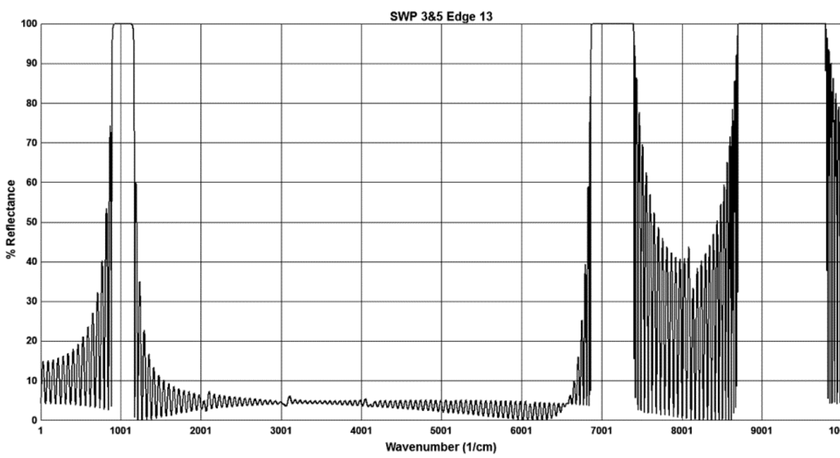

Fig. 9. Blocking- and pass-bands produced by the index versus thickness profile of Fig. 8.

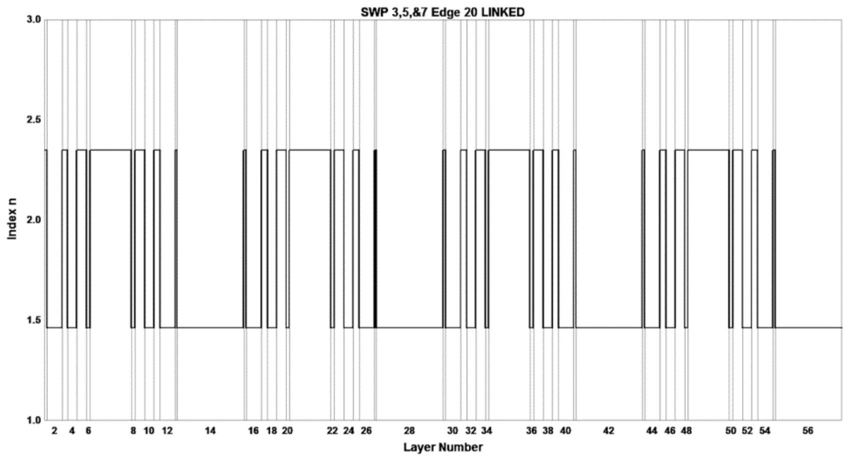

Fig. 10. Index versus thickness profile of symmetric layer stack with 14 layers per cycle. This gives blocking bands at harmonics 1, 9, etc., but **NOT** at the 3rd, 5th, and 7th harmonics, as seen in Fig. 11.

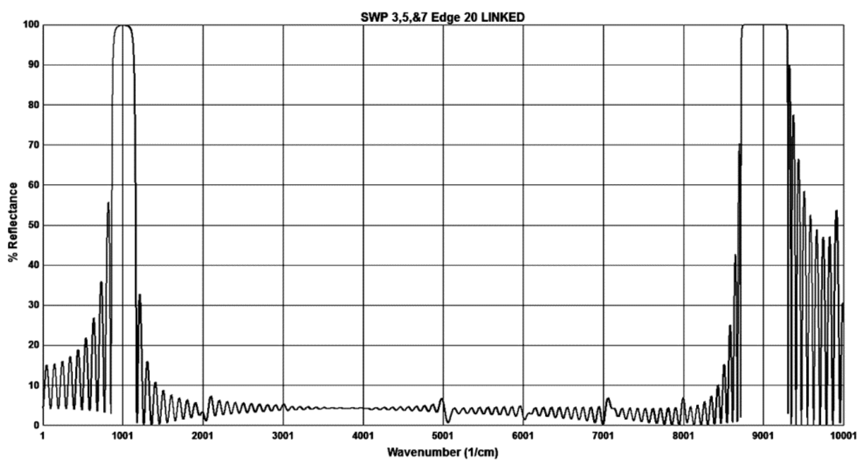

Fig. 11. Blocking- and pass-bands produced by the index versus thickness profile of Fig. 10.

For a semi-infinite bandwidth, it is conjectured that the Rave would approach that of an uncoated slab of materials of the index of the last layer (lowest index in the design) as described Sec. 1.5.2 of Ref. 1.

The present work also further clarifies and is consistent with the findings on the number of layers needed for a good AR shown in Fig. 2.18 of Ref. 1.

The broad band AR design process described in Appendix C of Ref. 1 was started as a SWP stack of QWOTs just outside the long wavelength end of the AR band. This was not consciously addressing the higher harmonic bands, but the results were layer structures similar to those described here. The only difference was that there were not repeated cycles of layers to produce a steep edge and a certain optical density in the blocking band as there would be in an edge filter design.

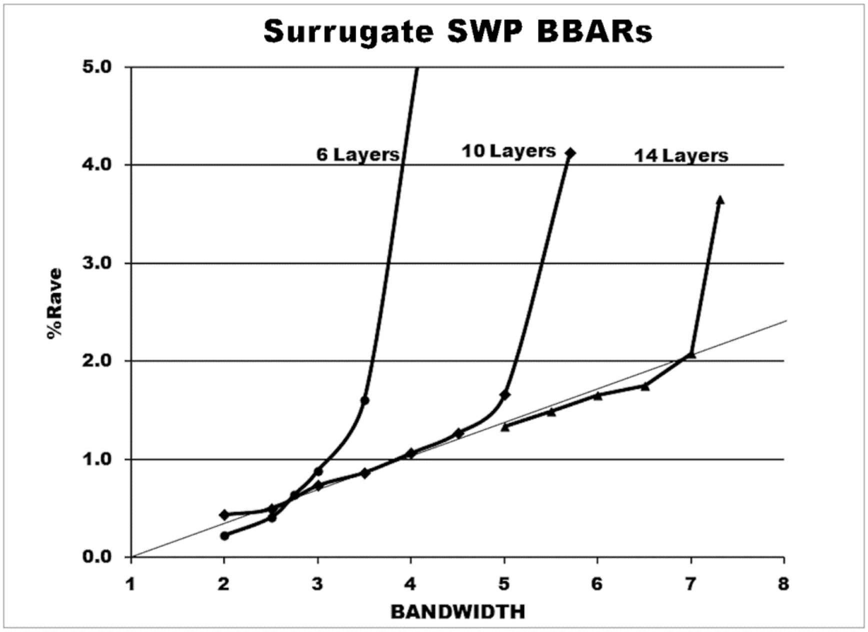

Fig. 12. Average reflectance in a passband versus bandwidth for designs of 6, 10, and 14 layers per cycle which suppress the 3^{rd}, 5^{th}, and 7^{th} harmonics respectively.

OPTICAL DENSITY AND BAND EDGE STEEPNESS

Figure 13 shows the blocking optical density (OD) of the first harmonic band for the designs of Figs. 4-5, 6-7, 8-9. and 10-11. The width and the OD is greatest for the QWOT design of 2 layers per cycle and they get progressively narrower with increasing numbers of layers per cycle. However, these reductions in OD and blocking bandwidth seem to approach a limit asymptotically as all of the harmonics of the square wave are removed to leave only the sinusoidal root.

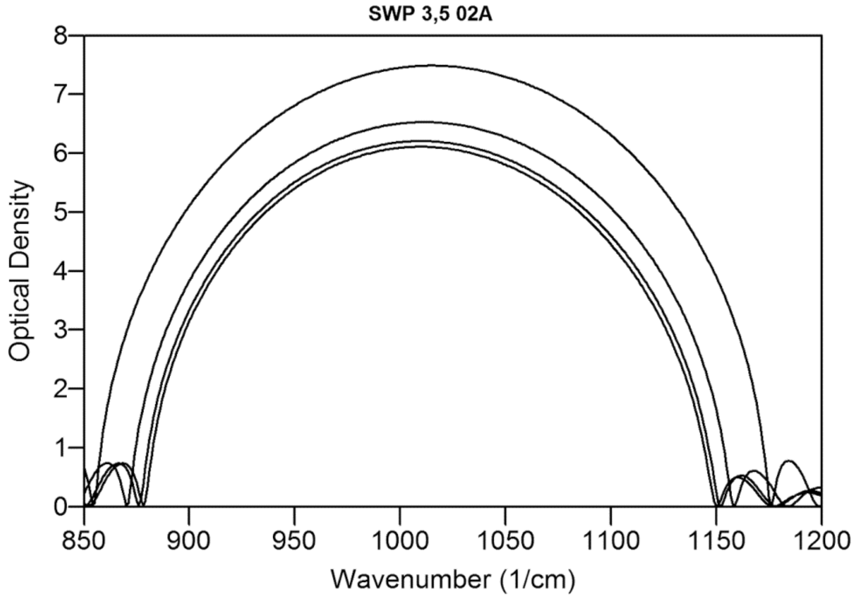

Fig. 13. Blocking optical density of the 1st harmonic band for the designs of Figs. 4-5, 6-7, 8-9. and 10-11. The width is greatest for the QWOT design of 2 layers per cycle and progressively narrower with increasing numbers of layers per cycle.

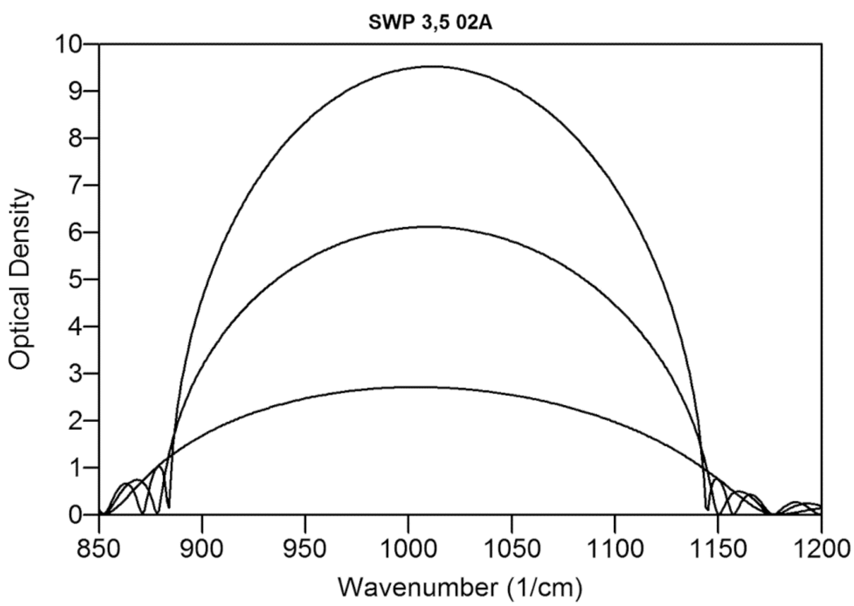

Fig. 14. Blocking optical density of the 1st harmonic for the designs of Figs. 10-11 (suppressed 3rd, 5th, and 7th harmonics) with 10, 20, and 30 layer cycles in the designs. The height is greatest for the design of 30 cycles and progressively lower 20 and 10 layer cycles.

The steepness of the edges can be seen in Fig. 14 to be approximately proportional to the number of layers. This shows the blocking optical density of the 1st harmonic for the designs of Figs. 10-11 (suppressed 3rd, 5th, and 7th harmonics) with 10, 20, and 30 layer cycles in the designs. The height is greatest for the design of 30 cycles and progressively lower 20 and 10 layer cycles.

SQUARENESS BETWEEN EDGE AND PASSBAND

If it is required to have high transmittance (low ripple) right up to the edge of the filter, more AR or matching layers are needed. Figure 15 shows the effects on this "squareness" of 3 to 13 AR layers on each side of the blocking stack. For six or more AR layers, the %R of the peak nearest the edge can be estimated as %R ≈ 10^(1.2 − 0.1285*N) , where N is the number of AR layers on each side.

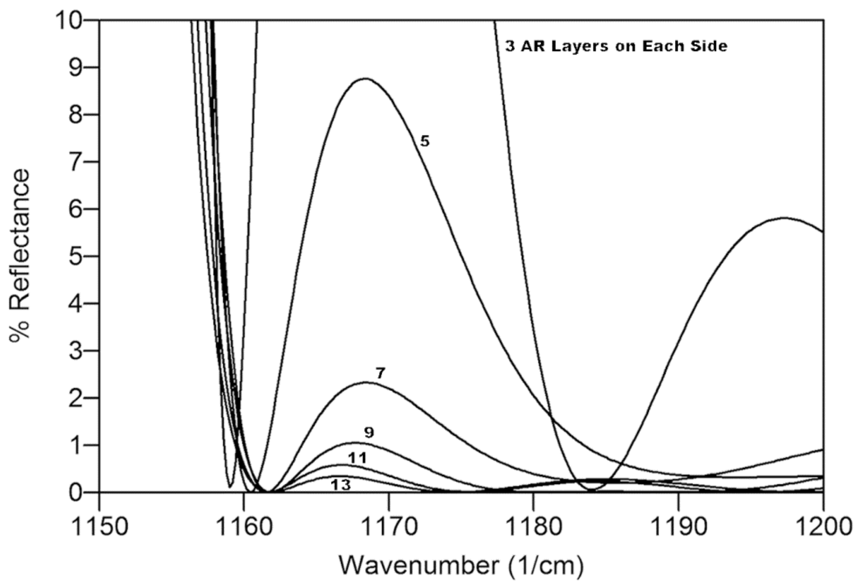

Fig. 15. Squareness between the band edge and passband as a function of the number of AR layers on each side of the blocking band stack.

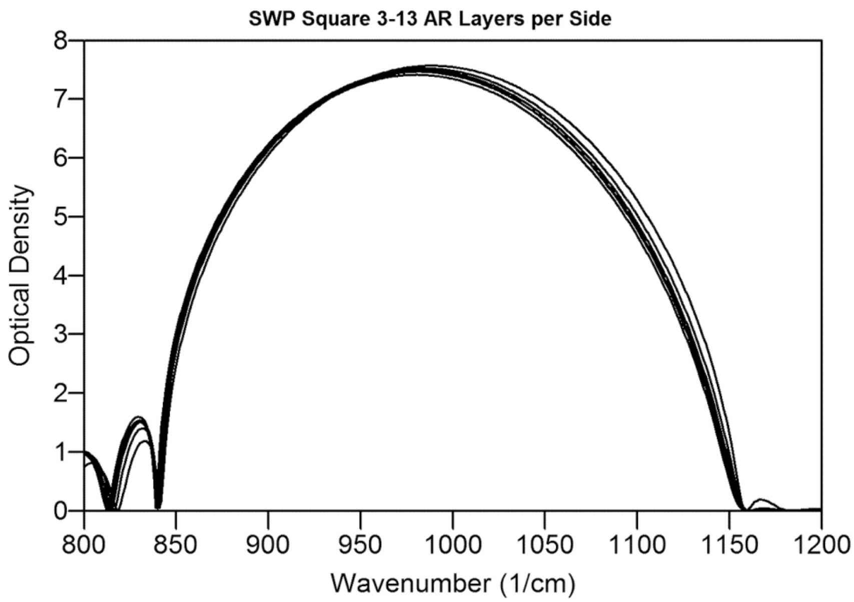

Fig. 16. Steepness of the band edge and passband as a function of the number of AR layers on each side of the blocking band stack.

Figure 16 shows that the edge steepness only varies a small amount with the number of AR layers. This could be compensated by the addition of a few more blocking layer cycles if needed.

CONCLUSIONS

When band-passes broader than about 2 are needed for edge filters with a short wave passband, recourse to rugate-like designs is needed. By employing the concept of the Herpin approximation, two materials can be used as a surrogate for the rugate principle, or a "surrugate" design. The number of layers per cycle required to eliminate the 3rd, 5th, 7th, etc., harmonic blocking bands is 6, 10, 14, etc. The design approach to broaden the pass bandwidth has been described, and the average reflectance as a function of bandwidth has been shown. The band edge steepness and density of blocking band have been discussed, and it has been shown how many AR matching layers are needed to make the transition from edge to passband more square.

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