Design of blocking filters of any narrow bandwidth

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A design approach is described to achieve spectral blocking filters of any spectral width and optical density for narrow blocking bands. The ratio of the thickness of the high-index material to the low-index material in the layer pairs is adjusted to obtain the desired bandwidth in the first-harmonic reflection band. The number of layer pairs is adjusted to provide the required optical density. Equations are provided for estimating the ratios and number of layer pairs needed to achieve a given bandwidth and optical density. This approach can be useful for laser line blocking filters, night vision filters, and other general applications. © 2007 Optical Society of America

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1. Introduction

Thelen[1] introduced the concept of the minus optical interference filter to block or remove certain narrow wavelength regions of the spectrum. The motivation of the present work is to be able to produce a blocking band of any desired bandwidth (BW) and optical density (OD).

The spectral BW of these filters, when produced with stacks of layer pairs of high- and low-index materials of equal quarter-wave optical thickness (QWOT), is determined by the difference in the index of refraction between the high- and low-index layers, or by utilizing the relatively narrower higher-order harmonic peaks of interference in the usual equal QWOT periodic stack designs. The new technique described here uses normal high- and low-index material layers in designs that can achieve essentially any desired BW and OD. This approach can lead to more satisfactory implementation of the concept of minus filters and narrowband blocking filters that might be useful for laser line blocking, night vision filters, and more general applications.

The widest BW occurs where each layer is one QWOT and is determined by the greatest difference between the high and low indices in proportion to the relationship $(n_H - n_L)/(n_H + n_L)$. Figure 1 illustrates this for three combinations of index: 2.35/1.46, 1.65/1.46, and 1.38/1.46. The low index has been kept to a constant 1.46 in this study. The usable BWs are limited by the finite number of indices available from real materials. Figure 2 shows the same designs as Fig. 1 on a transmittance scale. The out-of-band ripples can be reduced by further design.

Narrower band results can similarly be obtained by utilizing the higher-harmonic blocking bands of the first-order bands as seen in Fig. 3. The third-, fifth-, seventh-, etc., harmonic bands will be 1/3, 1/5, 1/7, etc., as wide as the first-order band. These would produce spectral curves that look similar to Fig. 1 on a wavelength scale as shown in Fig. 4. The higher-order approach is limited to specific discrete values as in the index difference approach, and it has the added problem that orders other than the one intended may encroach upon the desired total passbands of interest as seen in Fig. 4, where the fifth- and ninth-order bands encroach on the seventh-order band. More layers are needed to produce a given OD as the index difference decreases, and therefore more total optical thickness is needed as the band is made narrower. For example, in Fig. 1, 78 layer pairs were needed with the high index of 1.65 and 162 layer pairs with an index of 1.38, as compared to 20 layer pairs for an index of 2.35.

The approach of this paper is to change the ratio of the thickness of the high- and low-index layers while maintaining the overall thickness of two QWOTs at the center blocking wavelength for each layer pair. As discussed in Ref. 2, changing the ratio from the 2:1 shown in Fig. 3 to some other ratio will change the relative OD of the bands as seen in the example of Fig. 5 for a ratio of 10:1 and indices of 2.35/1.46. It was noticed, as in Fig. 5, that the different harmonics in high-ratio designs have different BWs as well as different ODs. This allows the BW to be chosen by the use

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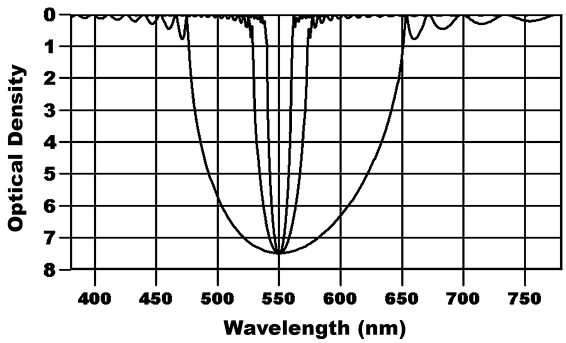

Fig. 1. Blocking bands with low-index layers of index 1.46 and high layers of 2.35, 1.65, and 1.38 to achieve progressively narrower bands.

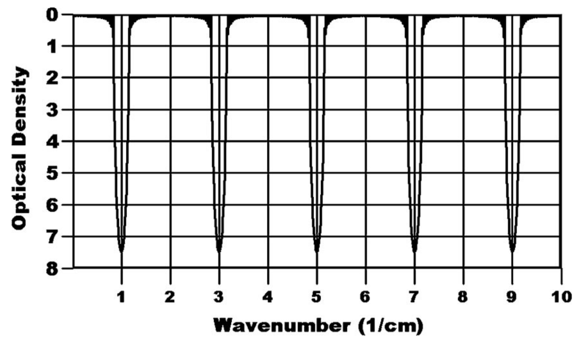

Fig. 3. Higher-order harmonic bands at three, five, seven, and nine times the basic ($1H$ $1L$)20 design at 1.000 wavenumbers on a frequency scale.

of an appropriate ratio. This reduces the BW of the blocker from that of the equal QWOT stack of the two given indices. There are two significant advantages of this new approach. The first is that the blocking band remains in the first order and therefore higher orders do not encroach as much on the passbands. The second is that the BW is not quantized by available materials as in the other two approaches. The BW can be of any desired value from the maximum determined by the equal QWOT thickness up to some practical limit at ~1/10 of that BW. The number of layers and the overall thickness of the stack required for a given OD increases in inverse proportion to the BW. It has further been observed that the overall optical thickness to obtain a given narrow BW is essentially the same with the approach of this as it is with the higher-harmonic approach.

2. Design Process

The ratio of the overall optical thickness of each layer pair (two QWOTs) to the optical thickness of the thinnest layer in the pair is 2:1 when equal high- and low-index layers are used[2] (which produces the largest BW for given indices). In the case of a design of 40 layers with an n_H of 2.1 and an n_L of 1.46 at 2:1, the BW at 50% of the peak OD (at 5.53) would be 0.2092. If the ratio were changed to 30:1, the BW would be 0.0455 and the peak OD would be reduced to 0.2776. Approximately 182 layers would be needed to achieve this narrower BW and have a peak OD near 5.53. Therefore, the design process is to increase the ratio in order to narrow the BW to the desired value and to increase the number of layers to maintain the required OD.

Many cases of various indices, ratios, and number of layers have been systematically evaluated for BW and OD. These data were statistically fit to produce equations for the estimation of the ratios and number of layers required for given BWs and ODs. It was interesting to find that the number of layers required for a given OD at a given BW is almost not a function of the indices of refraction (it is a very weak function). This appears to be because lower-index differences produce narrower BWs in almost the same proportion as they reduce the peak OD.

To design a blocking filter of a given BW, one finds the necessary number of layers from the desired BW and OD on Fig. 6 or from the equations given below. Then the approximate ratio needed can be found from Fig. 7 (or the equations) using the BW and the value of the high index used. The ratio is also a function of the number of layers and can only be used as a starting point for a design. The number of layers needed for a given OD and BW is, however, a more accurate estimate.

Given the estimated number of layers, the ratio, and the predetermined indices, the design can be

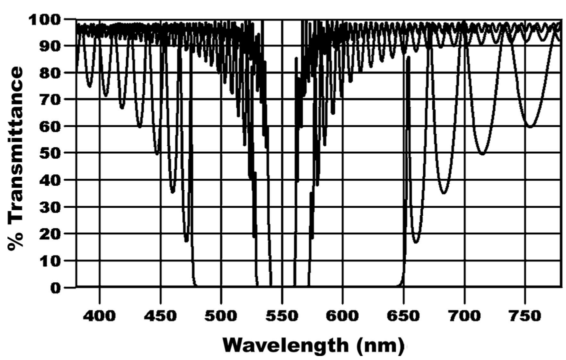

Fig. 2. Same designs seen in Fig. 1 on a transmittance scale. (The out-of-band ripples can be reduced by further design work.)

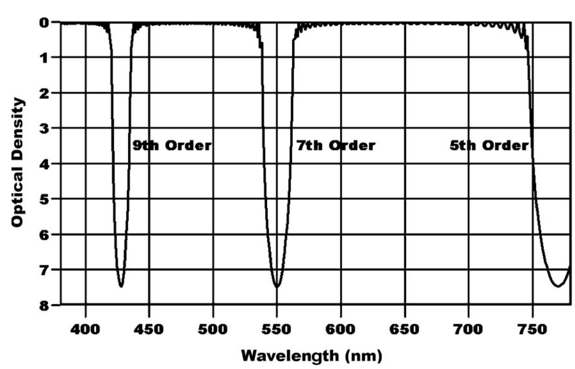

Fig. 4. Blocking filter at 550 nm using the seventh-harmonic-order band but showing the intrusion of the fifth- and ninth-order bands.

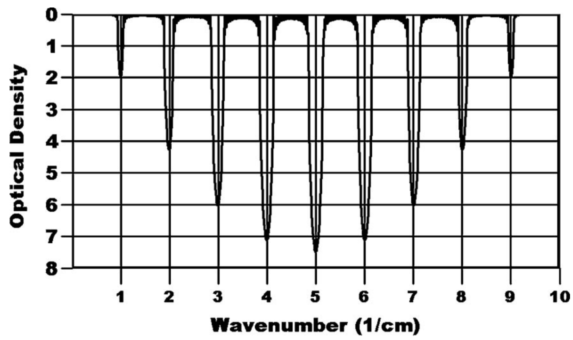

Fig. 5. Higher-order harmonic bands from two to nine times the basic (0.2H 1.8L)20 design (10:1) at 1.000 wavenumbers on a frequency scale.

verified and adjusted using a conventional thin-film evaluation and design computer program. The most satisfactory approach has been found to be to maintain the number of layers at the predicted value and then adjust the ratio of the design for the desired BW. A final adjustment can be made in the number of layers to obtain the exact desired peak OD.

It can be seen in Fig. 7 that, for a specific index, the ratio of thickness is in inverse proportion to the BW. The maximum BW has an upper limit at 2:1, which decreases with decreasing high index.

3. Estimation Equations

The following parameters are used in the estimation equations below:

OD, peak optical density of the design at some wavelength λ_p;

L, total number of layers in the design;

BW, full bandwidth at 50% of the peak OD where BW is $(\lambda_{max} - \lambda_{min})/\lambda_p$;

R, ratio of the thickness of the layer pair to the optical thickness of the thinnest layer in the pair;

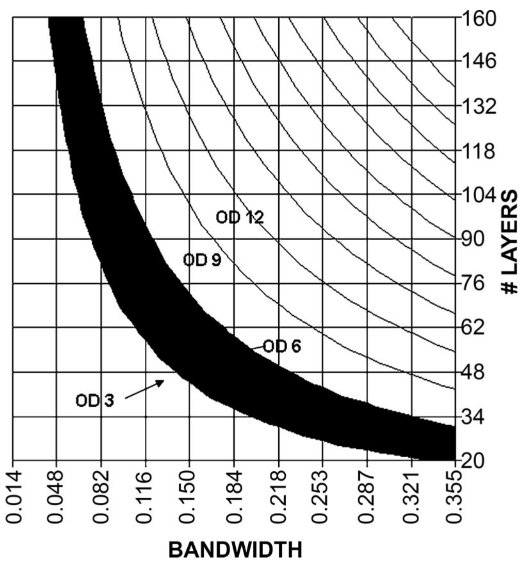

Fig. 6. Peak OD versus BW and number of layers for a high index of 2.1. Dark is between OD 3.0 and 6.0.

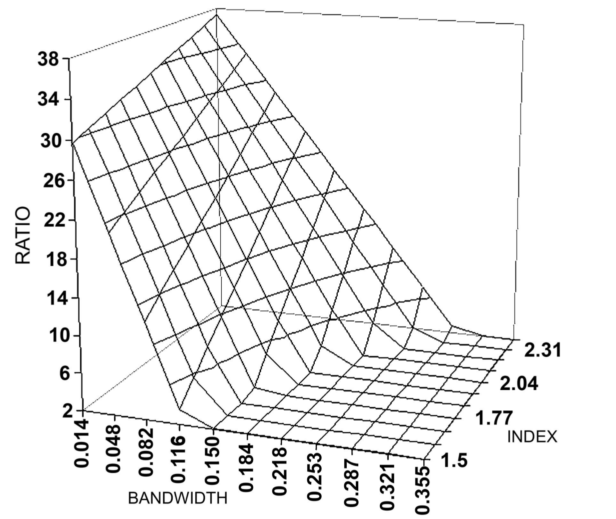

Fig. 7. Ratio required as a function of high index and BW for 90 layers. This will vary somewhat with the number of layers.

H, index of refraction of the chosen high-index material.

The number of layers required for designing a blocking filter of a given BW, high index, and OD is as follows:

$$L = (\mathrm{OD} + 1.75728 - 0.32558 * H)/(0.79501 * \mathrm{BW}). \tag{1}$$

The estimated ratio needed for the BW using this number of layers and the chosen high-index material is

$$R = -0.49391 - 2.8864/\mathrm{BW} + 0.01908/(\mathrm{BW} * \mathrm{BW}) + 5.54919 * (H - 1.46)/((H + 1.46) * \mathrm{BW}) + 6.5233/(L^{\wedge}0.25 * \mathrm{BW}). \tag{2}$$

The BW and OD can be estimated from the H, R, and L by the following equations:

$$\mathrm{BW} = 0.0139 - 1.0257/(R + 1) + 0.42241 * H/L + 0.75582 * H/(R + 1), \tag{3}$$

$$\mathrm{OD} = -0.53589 - 0.03003 * L + 0.01878 * H * L + 0.3804 * H * L/R - 0.5111 * L/R. \tag{4}$$

These estimation equations have been given in a format readily implemented in a spreadsheet computer program such as Excel, and they allow easy computation of the results using the input values.

4. Conclusions

A method has been introduced to design blocking filters of any desired BWs that are less than the maximum BW determined by the high and low indices of refraction in a normal 2:1 QWOT stack (of equal optical thickness layers). The method is based upon designing in the first-order band, but changing the ratio of the thicknesses in the layer pairs from 2:1 to some higher value that narrows the blocking BW. A simple design procedure with graphs and equations has been provided for the estimation of the necessary number of layers and ratio to achieve a required BW and OD when a given high-index material is to be used with a low-index material of index 1.46.

References

1. A. Thelen, *Design of Optical Interference Coatings* (McGraw-Hill, 1988), Chap. 7.
2. R. R. Willey, *Practical Design and Production of Optical Thin Films* (Dekker, 2002), pp. 106–111.