Improved narrow wavelength band blocking filters

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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. We give new criterions to find the necessary number of layers from the desired bandwidth and optical density, and give new estimate equations which describe the number of layers required for designing a blocking filter of given bandwidth, high index, and optical density. This approach can be useful for laser line blocking, night vision filters, and many other general applications.

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Edge filters which block one spectral region and pass an adjacent region are normally constructed with periodic stacks of high- and low-index layers of equal quarter-wave optical thickness (QWOT) at the center wavelength of the blocked band. A preliminary and a subsequent periodic structure of several layers which minimizes the reflectance in the passband is usually needed for the transition from the effective index of the substrate to the effective index of the periodic structure and from the structure to the final medium. Willey addressed the estimation of the possibilities and limitations of these antireflection or matching layers to reduce the reflections before the coating was actually designed[1]. Schmidt *et al.* gave the estimation of the average reflectance in the passband as a function of the number of layers and the width of the passband for both short- and long-wavelength pass filters and for passbands on both sides of a "minus filter"[2].

Thelen introduced the concept of the "minus" optical interference filters to block or remove certain narrow wavelength regions of the spectrum[3]. The motivation of the present work is to produce a blocking band of any desired bandwidth (BW) and optical density (OD).

The quarter-wave stack reflector is a basic building block of optical thin-film products. Composed of alternating layers of two or more dielectric materials[4] and each layer with an optical thickness corresponding to 1/4 of the principal wavelength, this coating has the highest reflection at the principal wavelength and transmission both higher and lower than the principal wavelength. At the principal wavelength, constructive interference of the multiple reflected rays maximizes the overall reflection of the coating; destructive interference among the transmitted rays minimizes the overall transmission. Reference [4] gives the spectral performance of a quarter-wave stack reflector. Designed for the maximum reflection of 550-nm light waves, each layer has an optical thickness corresponding to 1/4 of 550 nm. This coating is useful for three types of filters: cut-on filters, rejection filters, and blockers.

The spectral BW of these filters, when produced with equal QWOT stacks, is determined by the difference in the refraction index between the high- and low-index layers, or by utilizing the relatively narrower higher order harmonic peaks of interference in the normal equal QWOT periodic stack designs. The new technique described here uses normal high- and low-index material layers in designs which can achieve essentially any desired BW and OD. This approach can lead to more satisfactory implementation of the concept of minus filters and narrow band blocking filters, which might be useful for laser line blocking, night vision filters, and many other 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 (n_H and n_L) 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 a constant of 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.

Similar results can be obtained with one pair of indices by utilizing the higher harmonic blocking bands of the first order bands as shown in Fig. 3. The 3rd, 5th, 7th, etc., harmonic bands will be 1/3, 1/5, 1/7, etc., as wide as the 1st order band. These would produce spectral curves which look similar to Fig. 1 on a wavelength scale. The higher order approach is limited to specific discrete values as in the index difference approach, and it has the additional problem that other orders than the

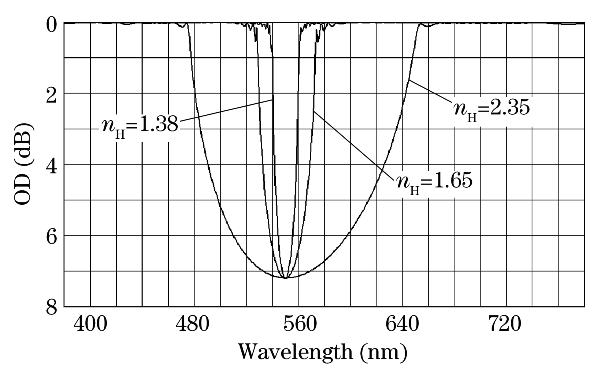

Fig. 1. Blocking bands with $n_L = 1.46$ and $n_H = 2.35$, 1.65, and 1.38 to achieve progressively narrower bands.

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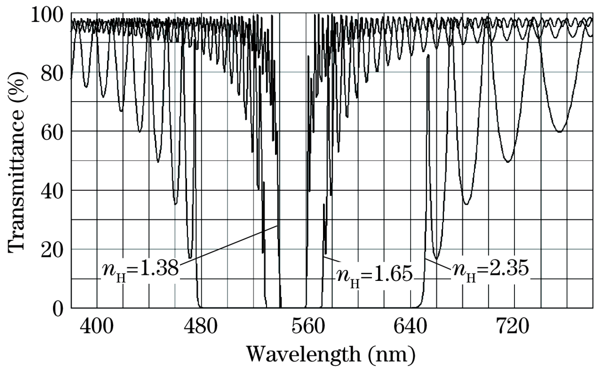

Fig. 2. Designs same to those in Fig. 1 on a transmittance scale.

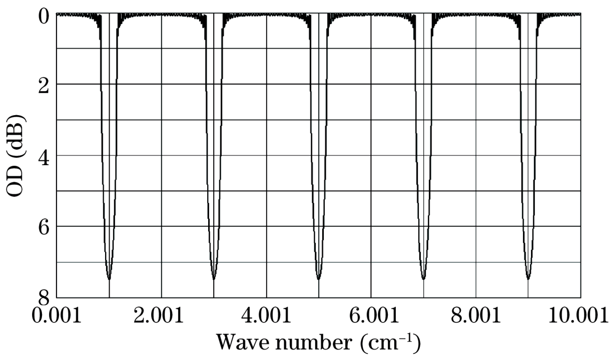

Fig. 3. Higher order harmonic bands at 3, 5, 7, and 9 times the basic (1H1L)20 design at 1.000 wave numbers on a frequency scale.

one intended may encroach upon the desired passbands as shown in Fig. 3, where the 5th and 9th order bands encroach on the 7th order band. More layers are needed to produce a given OD as the index difference decreases, therefore more total optical thickness is needed as the band is made narrower.

The approach of this letter is to change the thickness ratio of the layer pair to the high-index layer while maintaining the overall thickness of two QWOTs at the center blocking wavelength for each layer pair. Changing the ratio from 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. 4 for a ratio of 10:1 and indices of 2.35/1.46. It was noticed, as shown in Fig. 5, that the different harmonics in high ratio designs have different BWs as

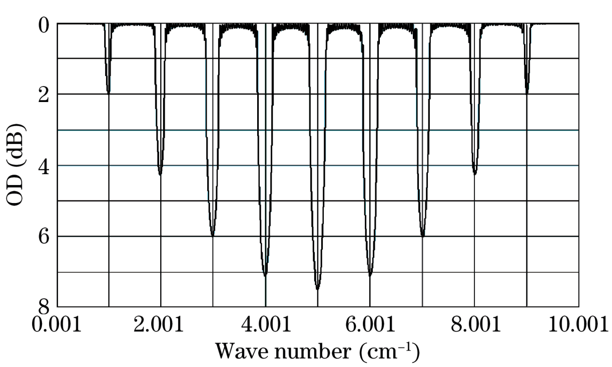

Fig. 4. Higher order harmonic bands from 2 to 9 times the basic (0.2H1.8L)20 design (10:1) at 1.000 wave numbers on a frequency scale.

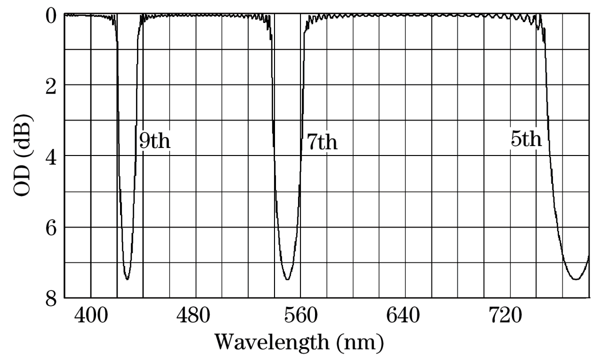

Fig. 5. Blocking filter at 550 nm using the 7th harmonic order band but showing the intrusion of the 5th and 9th order bands.

well as different ODs. This allows the BW to be chosen by the use 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. One is that the blocking band remains in the first order and therefore higher orders do not encroach as much on the passbands. The other is that the BW is not quantized by available materials as in the other approaches. The BW can be of any desired value from the maximum determined by the equal QWOT up to some practical limit at about 1/10 of that maximum. 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 this approach as it is with the higher harmonic approach.

The ratio of the overall optical thickness of each layer pair (2 QWOTs) to the optical thickness of the thinnest layer in the pair is 2:1 when equal high- and low-index layers are used[5,6], 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 dB) will be 0.2092. If the ratio is changed to 30:1, the BW will be 0.0455 and the peak OD will be reduced to 0.2776 dB. Approximately 182 layers would be needed to achieve this narrower BW and a peak OD near 5.53 dB. 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 numbers of layers have been systematically evaluated for BW and OD. These data were statistically fitted to produce equations for the estimation of the ratios and numbers of layers required for given BWs and ODs. It is 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

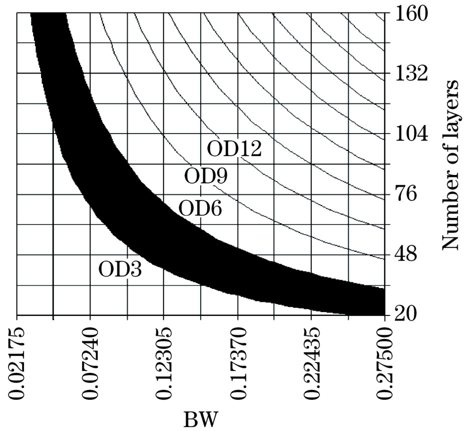

Fig. 6. Peak OD versus BW and number of layers for a high index of 2.1. The dark region represents the OD between 3.0 and 6.0 dB.

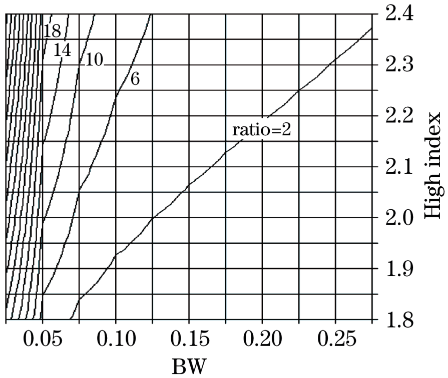

Fig. 7. Ratio required as a function of high index and BW for 80 layers. This will vary somewhat with the number of layers.

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

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

In the following, the estimation equations are given. The parameters used here are: 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, and BW = $(\lambda_{max} - \lambda_{min})/\lambda_p$; R=ratio of the thickness of the layer pair to the optical thickness of the thinnest layer in the pair; H=refraction index 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

$$L = \frac{\text{OD} + 1.75728 - 0.32558 \times H}{0.79501 \times \text{BW}}.$$

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

$$R = -0.49391 - \frac{2.8864}{\text{BW}} + \frac{0.01908}{(\text{BW})^2} + \frac{5.54919 \times (H - 1.46)}{(H + 1.46) \times \text{BW}} + \frac{6.5233}{L^{1/4} \times \text{BW}}.$$

The BW and OD can be estimated from H, R, and L by

$$\text{BW} = 0.0139 - \frac{1.0257}{R+1} + \frac{0.42241 \times H}{L} + \frac{0.75582 \times H}{R+1},$$

$$\text{OD} = -0.53589 - 0.3003 \times L + 0.1878 \times (H \times L) + \frac{0.3804 \times (H \times L)}{R} - \frac{0.5111 \times L}{R}.$$

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

In conclusion, a method has been introduced to design blocking filters of any desired BWs which are less than the maximum BW determined by the high and low refraction indices in a normal 2:1 QWOT stack (of equal optical thickness layers). This method is based upon designing in the first order band, but by changing the thicknesses ratio in the layer pairs from 2:1 to some higher value, we can narrow 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 required BW and OD when a given high index material is used with a low index material of index 1.46.

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