

# Design of Multi-Band Square Band Pass Filters

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## ABSTRACT

All dielectric band pass filters typically consist of all dielectric mirrors made up of quarter-wave optical thick layers and half-wave thick cavity layers. The cavity layers can also be thicker as long as they have multiple half-wave optical thickness. Filters with a single cavity layer will have a triangular shape. Filters with multiple cavity layers can have a square shape. In this paper we will discuss what happens when the cavity layers are made very thick, resulting in multiple pass bands within the quarter-wave stack rejection region.

## INTRODUCTION

Band pass filters can be designed by several different methods. Those which cover very wide wavelength regions are typically constructed using an all-dielectric long wavelength pass filter (SWP) and a short wavelength pass filter (SWP) where the pass regions overlap [1]. In this type of filter it is important that no higher reflectance orders from the LWP fall within the pass region. However if a higher order rejection band were to fall within the pass region, it may be possible to suppress them using a technique defined by others [2, 3].

Another type of band-pass filter is to use a metal dielectric combination where the mirrors are thin metal layers and the spacer is an all-dielectric layer [4]. This type of filter suffers from lower transmission due to absorption losses in the metal mirrors and a nonsymmetrical pass region shape due to dispersion in the metal film optical properties.

The most common structure for narrower band-pass filters is an all-dielectric filter consisting of quarter wave optical thick (QWOT) layers for the mirrors and half-wave optical thick (HWOT) or multiple HWOT layers for the spacers [4]. Single cavity band pass filters have a triangular shape with high transmission at the center wavelength of the spacer. They consist of balanced mirror structures on either side of the spacer layer. The bandwidth of the filter is determined by the relative index of the materials, the material chosen for the spacer layer and the number of layers and/or periods in the mirror structures. In Figure 1 we show that as the index ratio is

decreased the bandwidth increases. The filter design has the structure  $[H L]^x [L H]^x$  which has a single HWOT spacer layer ( $n_L=1.45$ ),  $x=4$  and the central wavelength is 1000 nm.

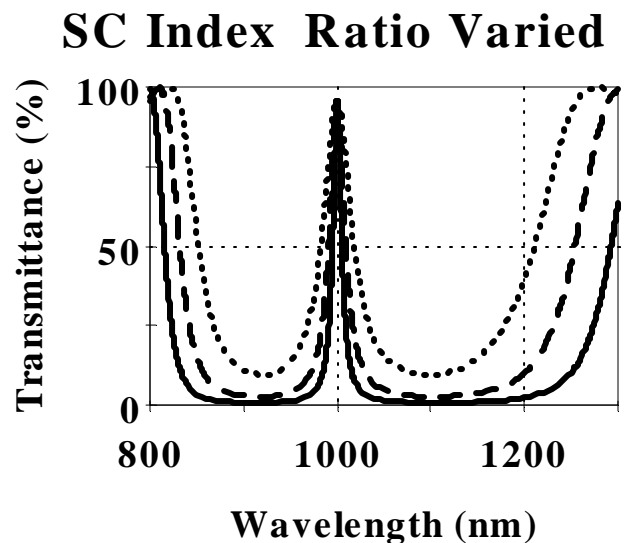


Figure 1. Single Cavity (SC) band-pass filter with  $n_L=1.45$  and  $n_H$  is varied. solid line  $n_H=2.3$ , dashed line  $n_H=2.1$  and dotted line  $n_H=1.9$ .

If the mirror period value is varied, a similar effect occurs. Consider Figure 2 where the  $x$  value is changed from 4 to 3 to 2 while the materials are  $\text{SiO}_2$  ( $n_L \sim 1.45$ ) and  $\text{TiO}_2$  ( $n_H \sim 2.3$ ) and the refractive indexes are dispersive rather than being fixed. These effects, relative to the refractive index of the materials and the number of mirror periods, will continue to be applicable as we consider multiple cavity band pass filters and multiple-pass band filters.

If the thickness of the spacer layer is increased from a single HWOT layer to multiple HWOT layers, then the central pass band becomes narrower and additional pass bands can form in the rejection regions of the mirrors.

This is shown in Figure 3. Consider the situation where the central spacer layer is 5 HWOT. One might intuitively

are shifted an additional amount towards the central pass wavelength.

### SC-Mirror Period Varied

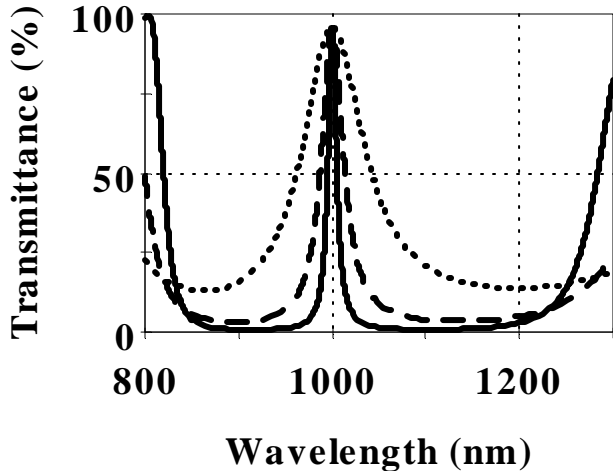


Figure 2. varying x as explained in text. Solid x=4, dash x=3 and dotted x=2.

### SQUARE BAND PASS FILTERS

The above examples all have triangular shaped pass regions. The shape of the pass region can be squared off or made rectangular by adding additional mirror sections and spacer layers. Consider a filter with the construction  $MM'CMM'$  or  $MM'CMM'CMM'$  where "M" is a mirror  $[H L]^3$ , M' is a mirror  $[L H]^3$  and C is a coupling layer [L]. In Figure 4 we plot the performance of a single cavity band pass filter, a double cavity band pass filter and a triple cavity band pass filter where the spacer or cavity layers are all a single HWOT thick.

### Multiple Cavity HWOT

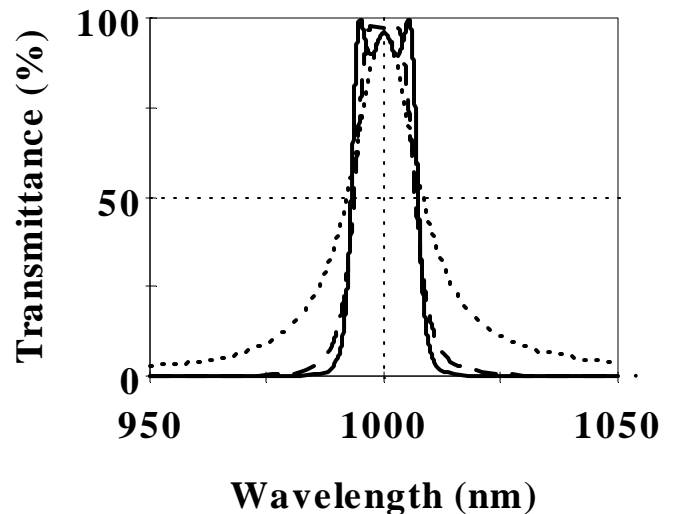


Figure 4. Single cavity (dotted), double cavity (dash) and triple cavity (solid) band pass filters as defined in the text.

### SC-Multiple HWOT

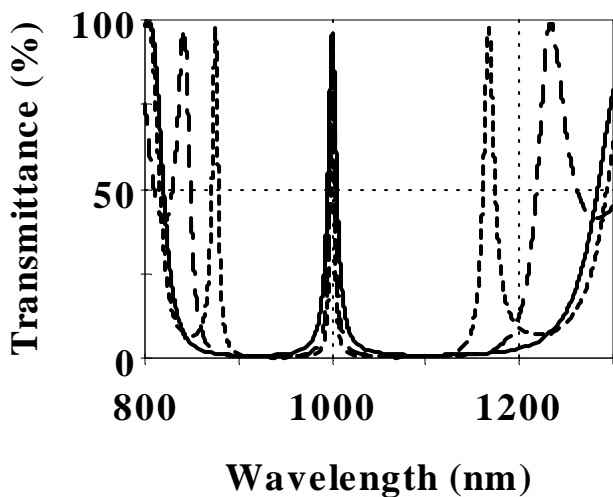


Figure 3. Varying the number of HWOT in spacer layer from 1 to 5 in increments of 2. solid x=1, dashed x=3 and dotted x=5.

expect the longer wavelength pass band to form at 1250 nm ( $=5 \times 1000/4$ ) and the shorter wavelength pass band to form at 833 nm ( $=5 \times 1000/6$ ). However this is not the case. The actual position of the non-central pass bands is influenced by the QWOT mirror layers and therefore each

The pass region becomes more rectangular with a bandwidth similar to the half power bandwidth of the single cavity filter as the number of cavity increases. The bandwidth of the multiple-cavity (MC) filter depends on the ratio of the refractive index of the materials chosen, the material chosen for the cavity layer and the number of periods in the mirror structures. It also depends on the number of half-wave optical thick layers in the spacers. In the above example, there is only one half-wave thick layer for the spacers. If the number of half-wave thick layers in each of the spacers increases, then the pass band will become narrower. That is shown in Figure 5 for the same 3-cavity filter from Figure 4 where the spacers are made 2 HWOT and 3 HWOT.

## MC - Multiple-HWOT

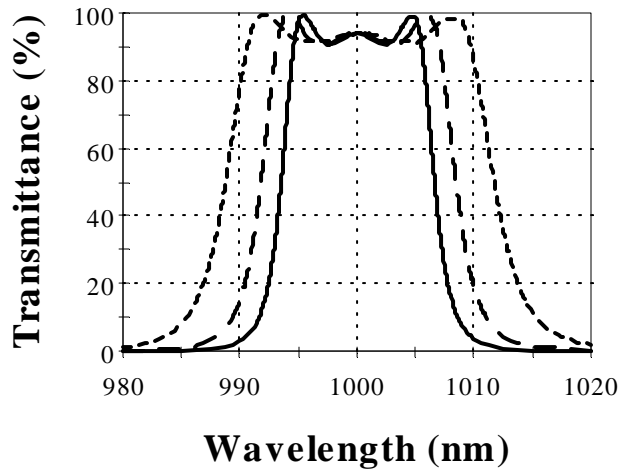


Figure 5. 3-cavity Band Pass with spacer thickness 1-HWOT dotted, 2-HWOT dash and 3-HWOT solid lines.

Also, it is not critical that all of the spacer layers need to be the same thickness. Mixing 1-HWOT, 2-HWOT, 3-HWOT etc spacer layers will produce other widths for the pass bands. However mixing spacer thicknesses does change the shape of the filter slightly (see Figure 6). The dashed line with mixed spacer thickness is less square.

## MC 1-H 3-H 1-H

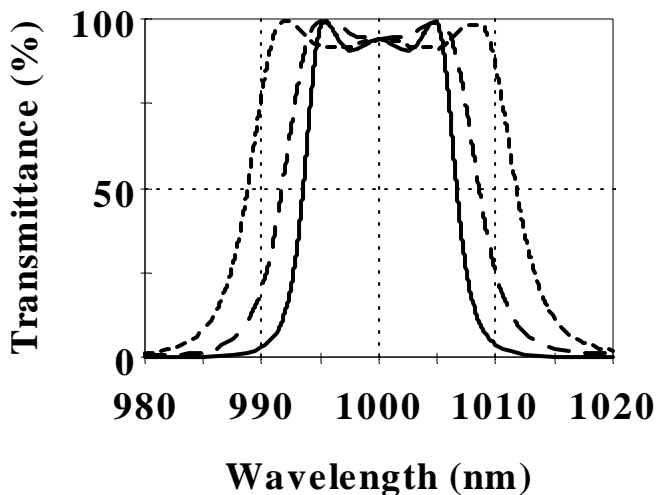


Figure 6. 3-cavity filter with all spacer thicknesses 3-HWOT solid line, 1-HWOT/3-HWOT/1-HWOT dashed line and all 1-HWOT dotted line.

## MULTIPLE SPACER SQUARE BAND-PASS FILTERS

We are now in position to make multiple square pass band filters which is the main topic of this paper. All that we need to do is to make the spacer layers even thicker and multiple pass bands will form. If we had shown a broad spectral range for the 3-HWOT spacer design from Figure 6, an additional band on either side of the central pass-band would be seen (as was shown in the thick spacer for the single cavity filters. To make this more apparent consider a similar structure where all of the spacer layers are 7-HWOT (see Figure 7).

## MC 7-HWOT Spacer

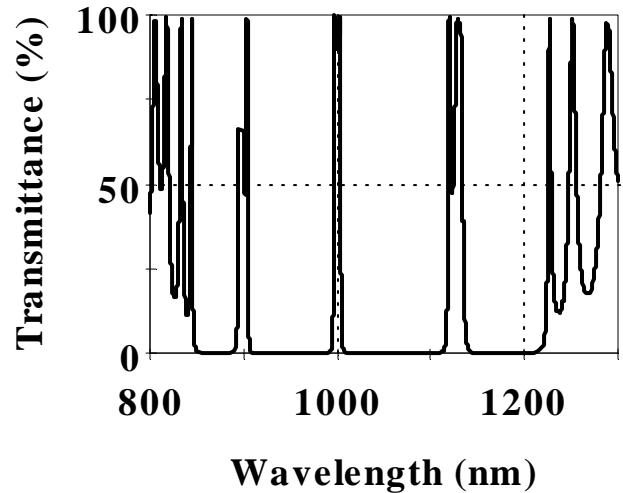


Figure 7.  $(HL)^3 12L (LH)^3 L (HL)^3 12L (LH)^3 L (HL)^3 12L (LH)^3$ .

There are basically three pass bands formed. The central pass-band is at 1000 nm, a shorter pass-band is at 8 nm and a longer pass-band is at 1125 nm. There are two problems with these pass bands. First they do not have the same bandwidth and second the short and long pass bands do not have good impedance matching so that there are strong rings. The central pass-band will normally have fairly good impedance matching. The equivalent optical admittance in each of the pass bands is shown in Figure 8. If the 3-spacer layers had been made even thicker, then the pass bands would have been narrower, the outer two pass bands would have been closer to the central band and they would have had better impedance matching. Also, additional pass bands would be formed at shorter and longer wavelengths. See figures 9 and 10 for the pass bands and admittances where the spacer layers are 10-HWOT

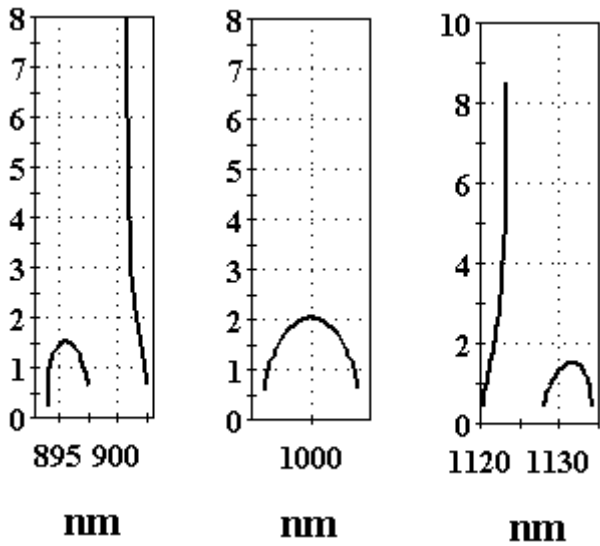


Figure 8. Optical admittance for three pass bands of MC-7-HWOT as defined.

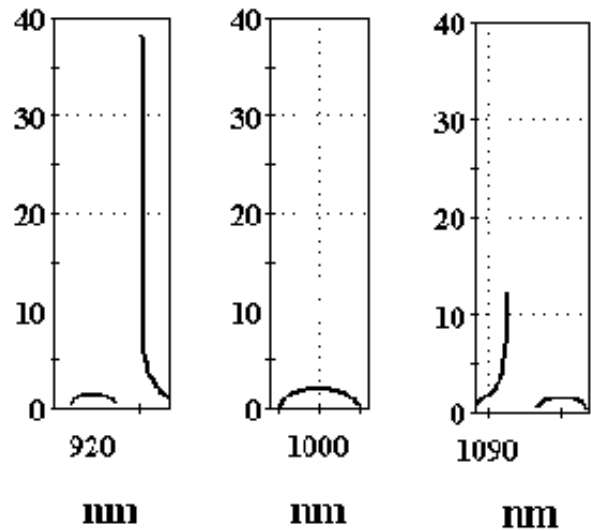


Figure 10. Optical admittance for three pass bands of MC-10-HWOT as defined.

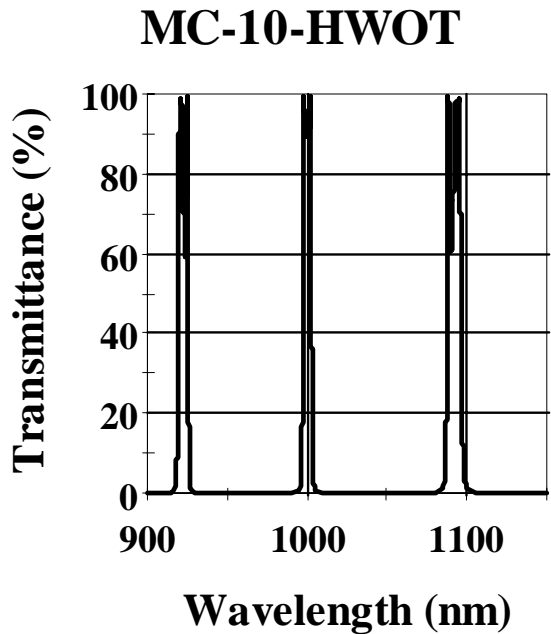


Figure 9.  $(HL)^3 18L (LH)^3 L (HL)^3 18L (LH)^3 L (HL)^3 18L (LH)^3$ .

Additional pass bands (not shown) formed below 900 nm (~860 nm) and above 1100 nm (1195 nm). The impedance matching of these bands is poorer.

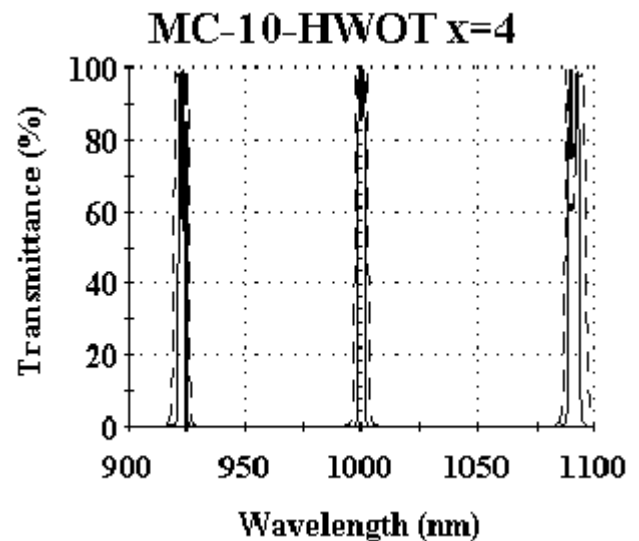


Figure 11. The effect of increasing the mirror period from 3 (dashed line) to 4 (solid line).

The ripple in the central pass band can easily be reduced [5,6,7] as shown by others. However these techniques will not work for improving the pass band of the non-central pass bands since we no longer have a symmetrical structure (relative to the center of the pass band and the mirror QWOT layers). In fact, these non-central pass bands have a highly dispersive optical admittance in the pass regions as seen in Figures 8 and 10.

Since I am not a theoretician, I have not found any sure way of designing the impedance matching. However, the traditional technique explained in reference 6 of finding a optical admittance structure intermediate between that of the filter and the substrate and the air seems a reasonable approach. As it turns out, adding a HLLH structure on either side of the design with 3-spacers of 10-HWOT thickness works fairly well (see performance in Figure 12 and optical admittance in Figure 13). This structure was arrived at by trial and error.

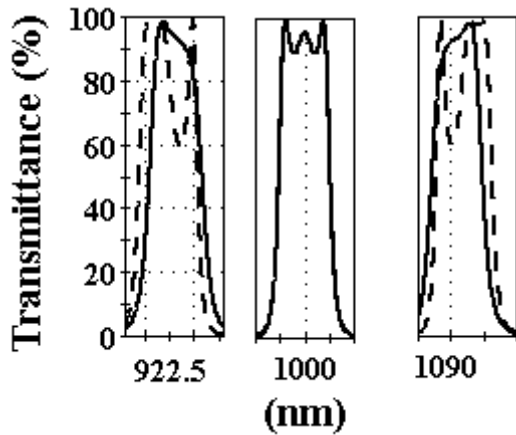


Figure 12. solid line HLLH (HL)<sup>3</sup> 12L (LH)<sup>3</sup> L (HL)<sup>3</sup> 12L (LH)<sup>3</sup> L (HL)<sup>3</sup> 12L (LH)<sup>3</sup> HLLH, dashed without HLLH layers.

There are possibly other techniques which might give further improvements in impedance matching. An interesting dual pass band filter structure was used by Sullivan [8] where the pass bands had very good impedance matching. The purpose of this paper was the technique used in monitoring and depositing the filter and not the design itself. Therefore no explicit information was given about the design. However it seemed obvious that most and possible all of the layers were not related to any specific quarter-wave optical thickness value. That is, the layers seemed to have been arrived at by some random optimization routine to achieve some target values for transmission. A plot of the 35-layer design performance is shown in Figure 14.

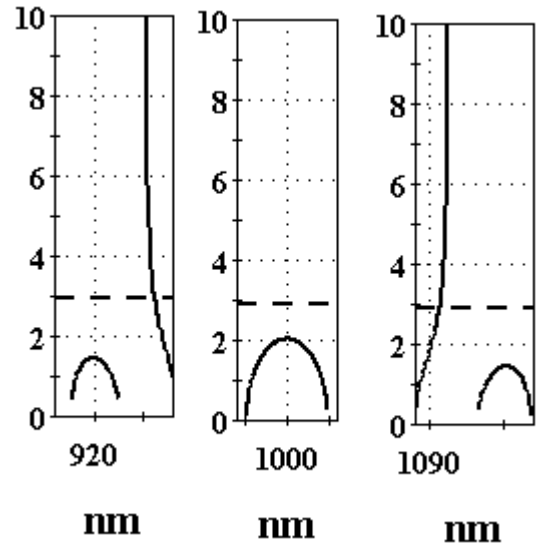


Figure 13. Optical admittance of design shown in Figure 9 (solid) and the HLLH structure (dashed).

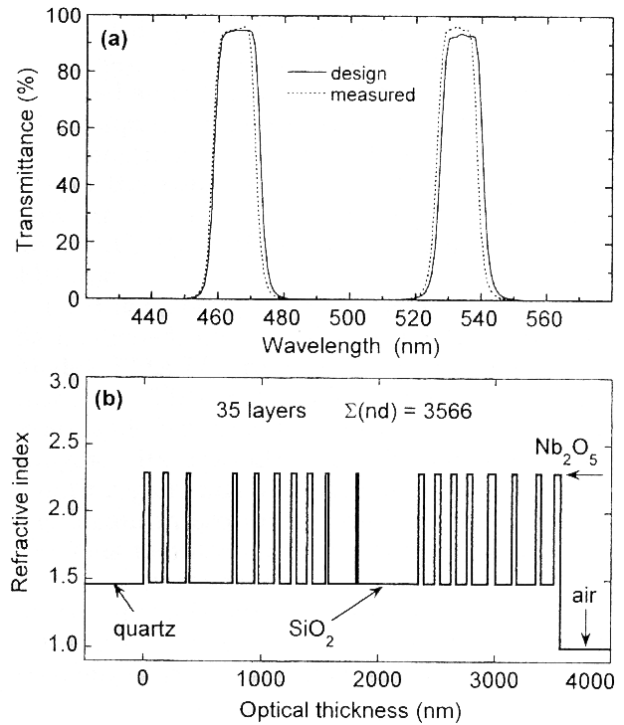


Figure 14. Performance and index profile from Sullivan's paper.

## CONCLUSION

We have developed here-in a technique that allows one to easily design a filter with multiple square pass bands. The band width of any one of the pass bands can be controlled by adjusting the materials used in the design, the thickness of the spacer layers and the number of periods in the mirror structures. These terms also determine the band widths of the other pass bands but they cannot be controlled independent of each other.

This technique is relatively good for designing two pass bands within the blocking region of an all-dielectric blocking stack. It has only limited application to designing three or more pass bands within the blocking region. A simple solution for improved impedance matching of the pass regions was shown. However, I suspect that there are alternative methods for improving the impedance matching that might be as good or better.

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