Low Ripple Notch Filter Designs Using Apodized Thickness Modulation

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Abstract: An apodized discrete layer thickness design method for notch filters is presented. The method produces error tolerant designs with low ripple in the pass band regions without any additional numerical optimization. Sample designs are presented.
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1. Introduction

Multiple approaches have been used in the past for producing notch filters (also called minus filters) [1, 2, 3]. The two main approaches can be grouped into rugate and discreet layer designs. Although narrow stop band designs can be generated both as rugate as well as using discrete layers, an advantage of rugate designs is that the ripple (sidelobes) in the transmission regions can be minimized by applying an apodization function to the index amplitude variation [4].

The method presented in this paper, combines the relative ease of manufacturing of discrete layer designs with the natural low ripple of an apodized graded index design.

2. Design methodology

We can achieve a narrow bandwidth of the reflection region of a regular quarterwave stack by shifting the ratio of high index material to low index material for a half wave pair in the stack:

$$[aH\ (2-a)L]^{(N-1)/2}\ aH \qquad (1)$$

Where *a* is the fractional quarterwave thickness of the high index layers and *N* is the total number of layers (odd integer) in the design. *H* and *L* are the usual quarterwave optical thickness of the high index and low index layers respectively. *a*=1 represent the usual quarterwave stack. Letting *a* go towards 0 or 2 results in a narrower and narrower reflection region. However, these designs have larger oscillations in the transmission outside the stop band resulting from poor matching between the optical admittance of the coating and the substrate and media.

Perrilioux [5] showed that a thickness modulated design (TMD) realized by applying a Gaussian thickness modulation to the ratio *a* in equation (1) through the coating, can be used to design a notch filter. However, the resulting design does not match the admittance of the substrate or media and has significant ripple in the pass band regions.

We can combine Perrilioux's approach [5] with an apodization similar to the one used in rugate designs [4] by applying an apodization function to the ratio *a* in equation (1). If we pick a Gaussian shape centered in the middle of the coating design, we can write:

$$T_H(n) = a \cdot e^{-\left[n-\frac{N}{2}\right]^2/(2\cdot C^2)} \qquad (2a)$$

$$T_L(n) = 2 - \left[a \cdot e^{-\left[n-\frac{N}{2}\right]^2/(2\cdot C^2)}\right] \qquad (2b)$$

Where T_H and T_L are the quarterwave optical thickness of the n^{th} layer. N is the total number of layers in the coating and *a* is the fractional quarterwave thickness of the high index layers at the middle of the coating. C is related to FWHM of the Gaussian function by:

$$FWHM = 2\sqrt{2\ln(2)} \cdot C \qquad (3)$$

Applying this apodization to the layer thicknesses results in the high index coating layers gradually getting thinner from the center of the coating stack towards both the top and bottom of the stack. It is useful to consider the case of an immersed coating with the substrate and media both having the index of the low index coating material. In this case, the design naturally matches the admittance of the surrounding media on both sides. In the case of SiO2 as the low index material and either Fused silica or BK7 as the surrounding media, we get quite a good admittance match. A separate anti-reflective (AR) coating can be applied for the desired transmission band region matching the top side of the coating to air. However, this can be a challenge by itself since the notch filter transmission region is very broad.

Since the admittance matching of the apodized designs is achieved by a gradual change in high index to low index thickness ratio, the optical performance is quite tolerant to layer errors. Relatively large errors in the thickness of the thin layers are tolerated without significant increase in ripple in the transmission regions.

It is worth noticing, that the design method also works if we interchange the high index and low index layers and let the low index material be the one forming the thin layers. In this case, the design matches the index of the high index layers at the top and bottom of the layer stack. This makes it necessary to both have an AR coating matching the transmission region to the substrate as well as to the air. However, the overall coating thickness is considerably thinner.

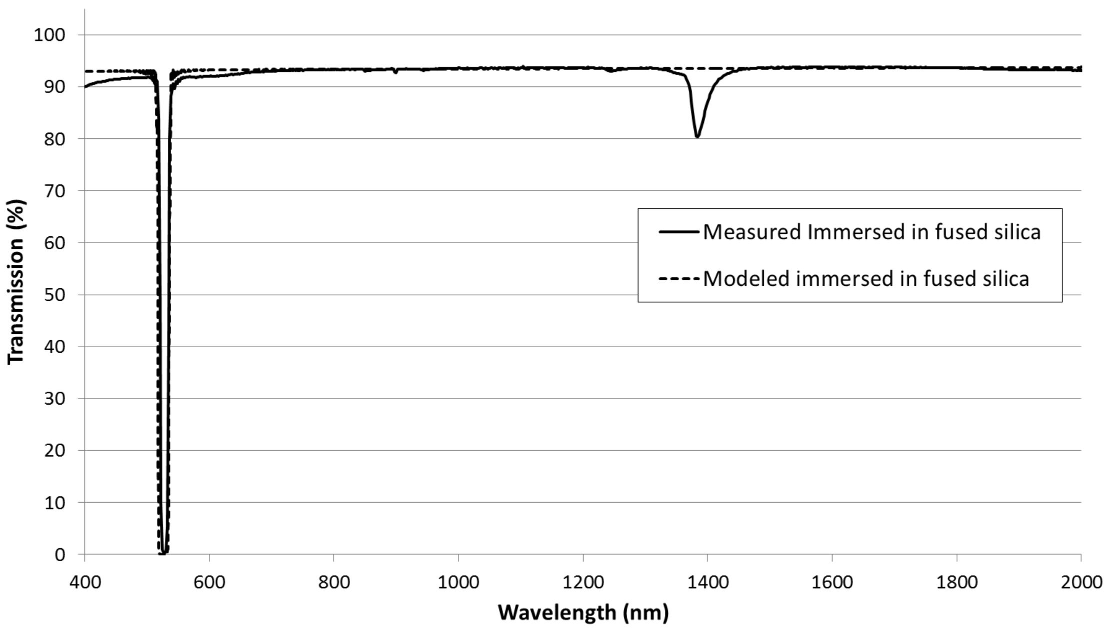

Fig. 1. Measured and modeled transmission of 301 layer design immersed in fused silica. Measurement and model includes losses from the uncoated front and backside.

3. Sample designs

Fig. 1 shows the modeled and measured transmission of a sample design using equation (2) and (3) with N = 301, a = 0.1, and FWHM = 215. The design is centered at 532nm withTa_2O_5 (n = 2.14) for the high index material and SiO_2 (n = 1.49) for the low index material.

The coating was coated by ion beam sputtering (IBS) using time-power control in a Veeco SPECTOR^{TM} coating chamber. The coated sample was optically contacted to an uncoated fused silica substrate and measured through the sample including the losses from the two uncoated outside surfaces. The modeled transmission also includes the losses from the uncoated surfaces. The transmission dip at ~1390nm is due to the usual absorption in the fused silica substrate.

The broadest stop band is achieved when a=1, corresponding to both high index and low index layers having a thickness of one quarterwave in the middle of the design. The measured and modeled transmission of a 100 layer design is shown in Fig. 2 with *a* =1 and *FWHM* = 53. The coating is centered at 690nm using Ta2O5 for the high index (n=2.10) and SiO2 for the low index (n=1.48). The design was coated on microscope slides (n ~1.5). An uncoated microscope slide was optically contacted to the coating before measurement. Both the model and the measurement include losses from the two external uncoated surfaces. The drop in transmission at the longest wavelengths is attributed to absorption in the microscope slides.

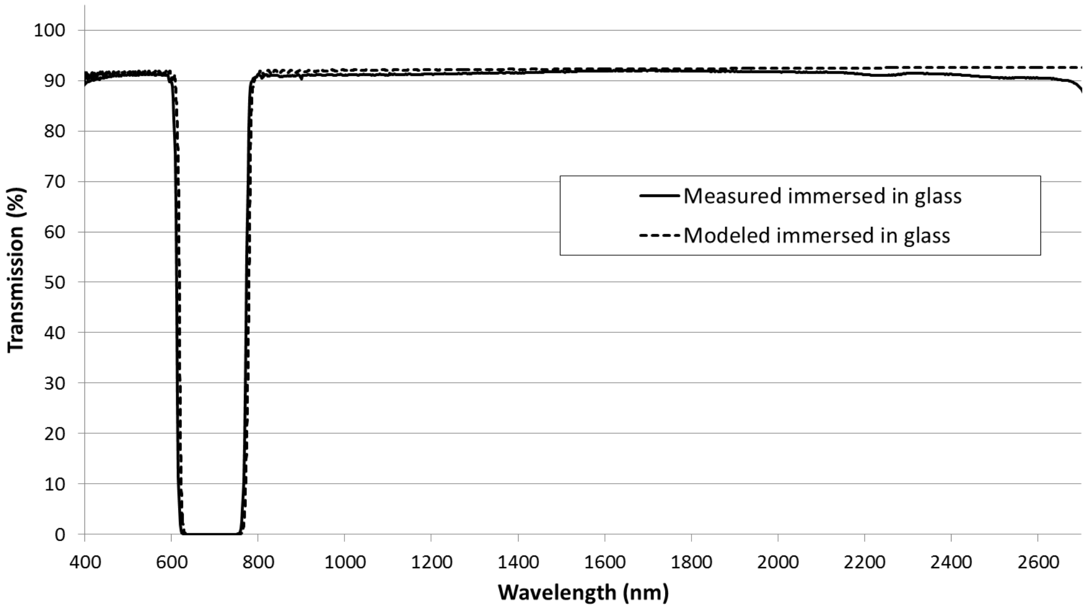

Fig. 2. Measured and modeled transmission of 100 layer design immersed in glass. Measurement and model includes losses from the uncoated front and backside.

4. Conclusion

The apodized thickness modulated design method presented in this work generates notch filer designs with very low ripple in the transmission regions without the need for numerical optimization. The designs are tolerant to layer errors and the sample designs coated on time- power control with IBS deposition, show performance close to the theoretical designs.

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5. References

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