Filters for Dual Band Infrared Imagers

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ABSTRACT

Dual band infrared imagers require a similar set of filters as are needed by single band infrared imagers but with the added requirement of high transmission in the mid and far infrared. The design of discrete layer filters with optimized dual band transmission is investigated for three types of filters. These are a visible-infrared beamsplitter, a long wavelength edge filter and a dual bandpass cold filter. These designs illustrate the role that harmonic reflection bands can play in the design of dual band filters. The visible reflection beamsplitter design does not have harmonics in the infrared but requires additional layers to reduce reflection at mid and long wavelengths. The long wavelength edge filter requires suppression of the second and third harmonics while the sensor band pass cold filter can use harmonics to advantage. Design techniques are discussed and the results of an initial set of fabrication runs are presented to assess the sensitivity of example designs to manufacturing errors.

Keywords: dual band, infrared, interference coating, dichroic, cold filter

1. INTRODUCTION

Dual band optical systems require a number of complex optical filters to achieve enhanced performance. These filters may be required to pick-off a spectral band, reduce the impact of stray light or improve the contrast of a scene. The filters must provide these spectral functions while maintaining high transmission in the mid and far infrared spectral region. This technical note takes a quick look at three types of designs which require high transmission in dual infrared passbands. The first design is a visible reflection infrared band pass filter designed to operate at 45^{o} angle of incidence. The second design is a dual bandpass long wavelength edge filter. The third design is a sensor band pass filter. A requirement of each design is high pass band transmission in the mid and far infrared bands. All three designs are approximately 50 layers and use the same material set and process conditions. The visible reflecting infrared beamsplitter is approximately 1/3 the thickness of the other two designs.

The visible reflecting dual bandpass beamsplitter reflects in the visible from 0.45 to 0.8μm and has high transmission from 3.5 to 5μm and from 7 to 11μm. The beamsplitter is designed to operate at 45^{o} angle of incidence (AOI). Its purpose is to pick off the visible channel ahead of the infrared channel. The dual band shortpass long wavelength edge filter operates at near normal incidence and must exhibit good edge slope, high out of band rejection and high dual band transmission. This is a long wavelength notch filter. The challenge of this design is the suppression of the second and third harmonics characteristic of a quarter wave discrete layer notch filter. Harmonic suppression is not an issue for the visible beamsplitter since the harmonics of the reflection band are at shorter wavelengths. The third design, the dual band pass filter, is similar to the long wavelength edge filter in that it is a notch filter at long wavelength, but instead of suppressing the second and third harmonic, the harmonics are modified and used to define the dual band pass spectral region. Each filter type requires a dual band antireflection (AR) coating on the opposing surface.

2. DESIGN APPROACH FOR DUAL BAND FILTERS

These three designs, along with the dual band pass anti-reflection coating, illustrate the basic elements of dual band filter design. The starting designs of each filter approximate the desired spectral performance and are refined and optimized using needle synthesis. These techniques are available in a number of commercial software packages. Optilayer®[1] was used to develop these designs.

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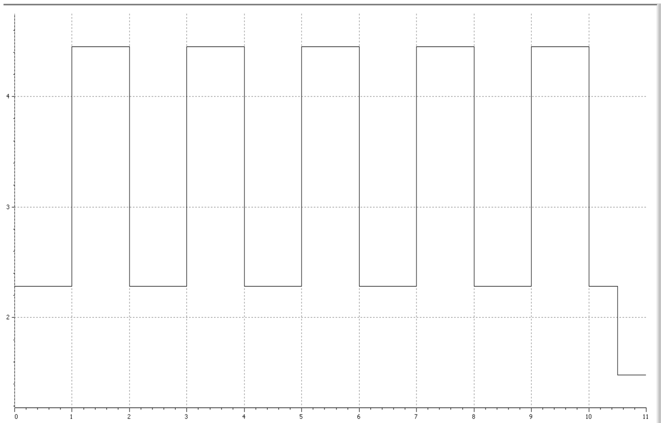

Figure 1:Refractive index profile for a discrete quarter wave notch filter[(MH)^5 0.5M 0.5L].

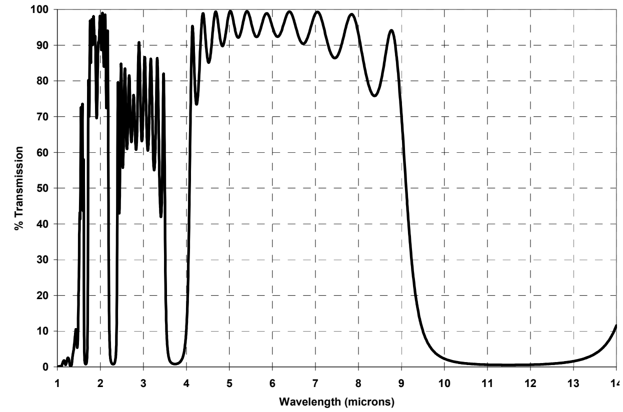

Figure 2: Modeled transmission for a quarter wave notch filter exhibits odd ordered harmonics. The third harmonic falls within the mid-IR pass band.

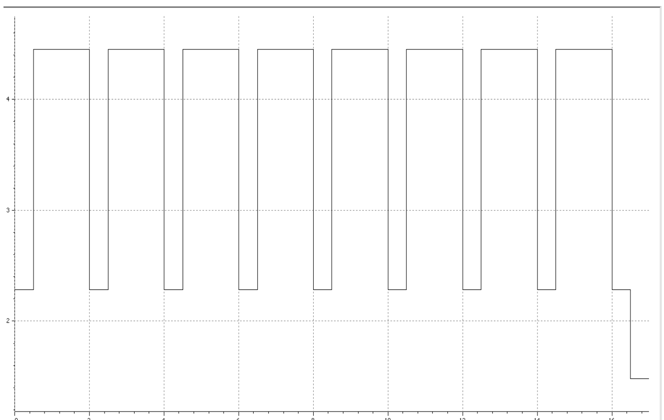

Figure 3: Refractive index profile for an asymmetric notch filter [(0.5M1.5H)^5 0.5M 0.5L].

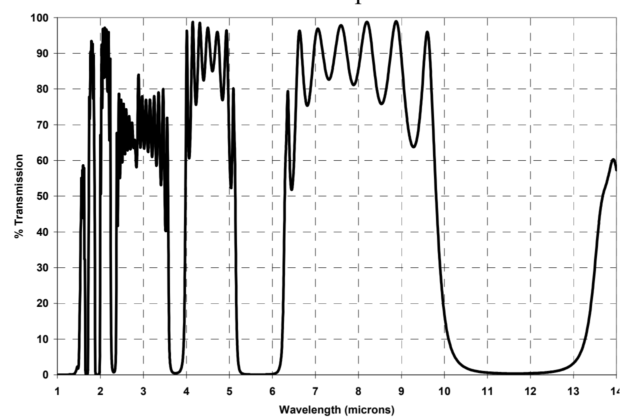

Figure 4: Modeled transmission for an asymmetric filter exhibits even and odd ordered harmonics. This design technique allows for better edge slope and potential blocking of the off band region from 5 to 7 microns.

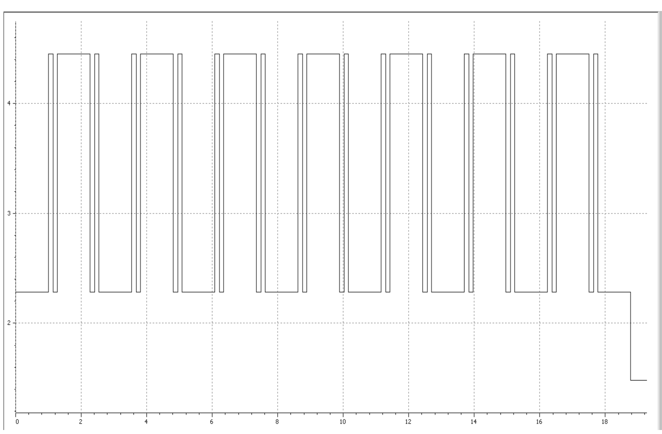

Figure 5: Refractive index profile for a discrete notch filter with suppressed 2nd and 3rd order harmonics. [0.9M(0.12H0.12M0.9H0.12M0.12H0.9M)^70.5M0.5L]

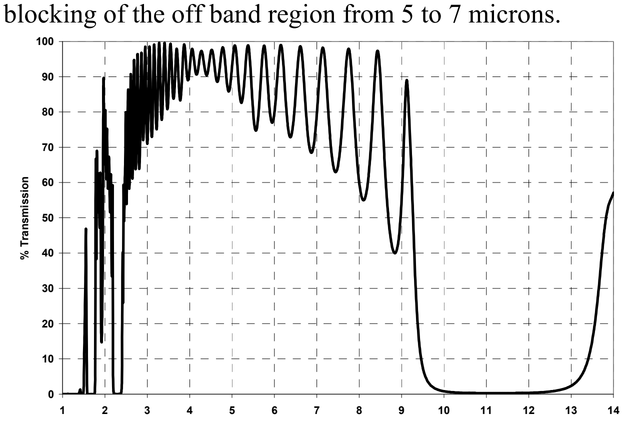

Figure 6: Modeled transmission for a discrete notch filter with suppressed 2nd and 3rd order harmonics. This is the starting design used for the long wavelength edge filter.

The needle synthesis method begins with a starting design which can be a legacy design or simply a single layer of one of the available thin film materials. A performance target is described and a thin needle of material is systematically inserted along the thickness of the starting design. A performance merit is calculated at each insertion point, and the thin layer is inserted at the point where the needle most reduces the performance merit function[1]. The performance merit is the root-mean-square of the deviations between predicted performance and the performance target. The new design, now two or three layers if a single layer starting design was used, is refined, allowing the layers to change in optical thickness so as to further reduce the merit function. The process is repeated inserting a new layer and refining the design until the insertion of any thin layer does not further reduce the merit function.

Needle synthesis is a powerful method for producing designs with complex performance. However, while the method can produce acceptable solutions, it can just as easily produce solutions which are not easy to manufacture, or which contain a large number of layers and fabrication time would prohibitively drive coating cost. Understanding the design trade-offs of film thickness, number of layers and the choice of coating materials can significantly impact coating complexity and cost.

The harmonics of a discrete interference filter can complicate or be used to advantage in designing dual band filters. Figures 1 to 6 present the index profile and modeled transmission of three potential starting designs to illustrate this point. Figures 1 and 2 present a quarter wave (QW) notch filter. Figures 3 and 4 present an asymmetric notch filter. Figure 5 and 6 present a design with suppressed the 2^{nd} and 3^{rd} harmonics. These designs place the notch filter at 10.5 microns and have the same final two layers acting as a short-pass, step-down, antireflection film. The QW filter exhibits odd ordered harmonics. The asymmetric notch filter exhibits harmonics at both odd and even orders. The advantage of the asymmetric design is that the bandwidth and edge slope of the notch can be reduced but at the cost of adding the even harmonics and the need for more layers to achieve a similar optical density as the balanced QW design[2]. The location of the second and third harmonics can be modified making it useful as a starting design for the band pass filter. The third filter design illustrates harmonic suppression. The second and third harmonics are suppressed and can be used as a starting design for the dual band edge filter.

The design examples presented all use a common infrared materials set and process. Germanium and zinc selenide were selected as filter substrates.

2.1 Dual Band Anti-reflection Coatings

The development of dual band infrared sensors with optics that share a common aperture creates the need for high performance optical coatings in multiple spectral bands[3]. This new generation of IR imagers can have 10 or more surfaces and use a selection of high to low refractive index lens materials. High performance, dual band anti-reflection coatings that reduce surface reflection to less than 1% per surface in each spectral band for these materials are required to maximize system sensitivity. Dual band IR coatings are typically thicker and more complicated than anti-reflection coatings which have been optimized for either the mid-IR (3.5 to 5µm) or far-IR (7.8 to 10.5µm) spectral bands.

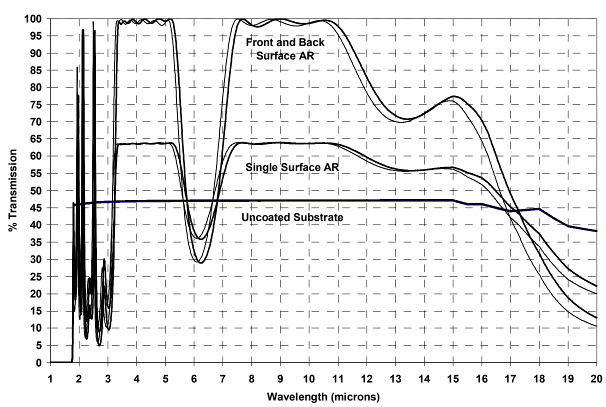

Figure 7: Ge AR transmission is modeled on a 1 mm thick germanium substrate. Uncoated, single surface and dual surface coated germanium are presented at normal and 30° AOI.

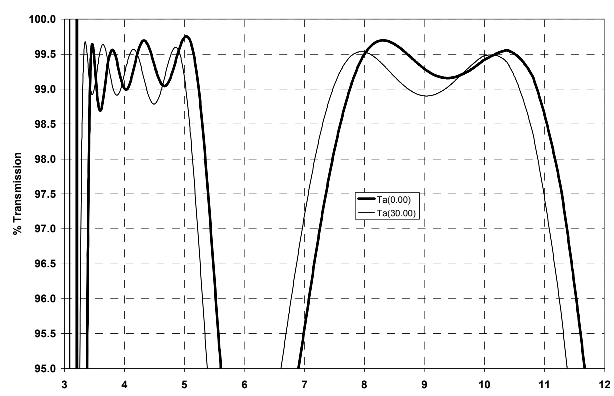

Figure 8: Dual Band 15 layer AR design for ZnSe. Transmission at 0 and 30° AOI is presented.

Figures 7 through 8 present the modeled spectral transmission for Germanium and Zinc Selenide dual band AR films used in development of the three filter designs. These designs are described in more detail in a previous paper[4].

2.2 Filter design: The Dual Band Dichroic

The function of the beamsplitter filter is separation of the visible and infrared bands. The visible band is reflected and the mid and far infrared bands are allowed to pass through with minimal insertion loss. The filter is designed to operate at 45^o AOI. Since the reflection band is at shorter wavelengths than the infrared pass bands, harmonic suppression is not required. The visible reflector is typical of other visible dielectric designs except that infrared transmitting materials are used. However, the design must include an anti-reflection component for the mid and far infrared region. This requirement adds to the film's thickness and the total number of layers. The starting point for the design is a set of quarter wave reflectors that cover the visible region from 0.8 to 0.45µm. The order of the notches is from long to short since the materials begin to absorb at the shorter wavelengths and placing the blue reflector near the top of the film stack minimized absorption. The design is then refined and optimized using needle synthesis.

Table 1: Summary of Visible/Dual Band IR Beamsplitter Design Performance AR 45^o AOI.

Thickness (microns)	Number of Layers	Vis Reflection (0.45-0.8)	MIR Reflection (3.5-5.0)	NIR Reflection (7-10.5)
4.72	31	94.8	2.34	2.60
6.11	38	96.7	1.84	1.30
8.73	59	98.1	1.43	1.35

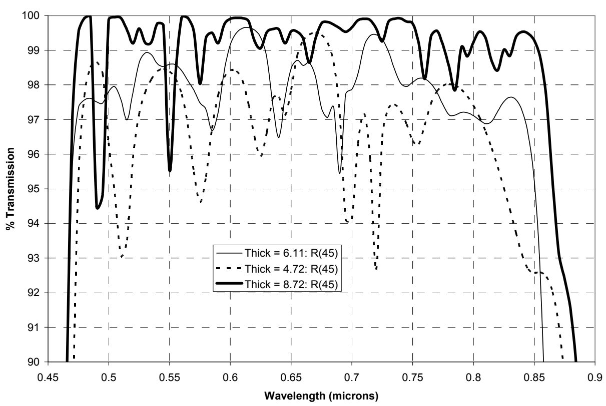

Figure 9: Visible reflection for three potential designs of different film thickness.

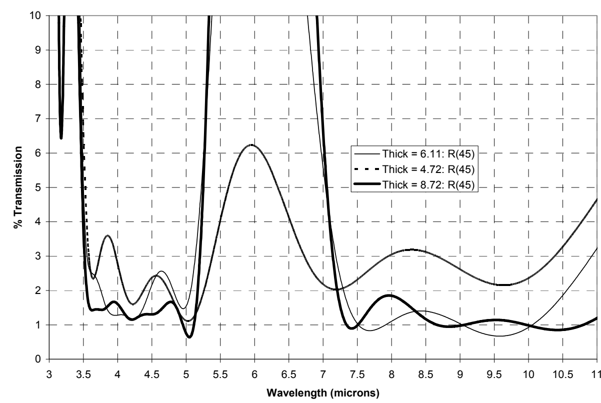

Figure 10: Infrared reflection for three potential designs of different film thickness.

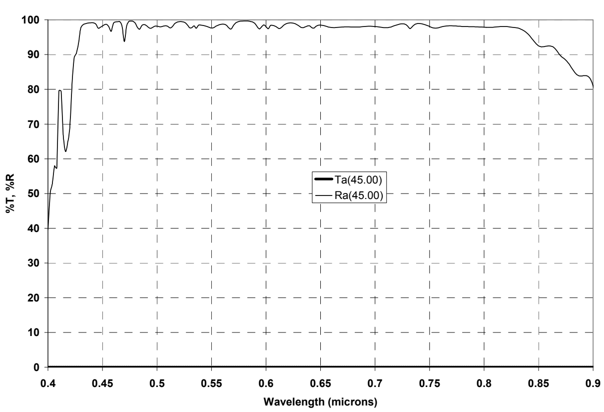

Figure 11: Predicted visible reflection of the beam splitter design selected for fabrication.

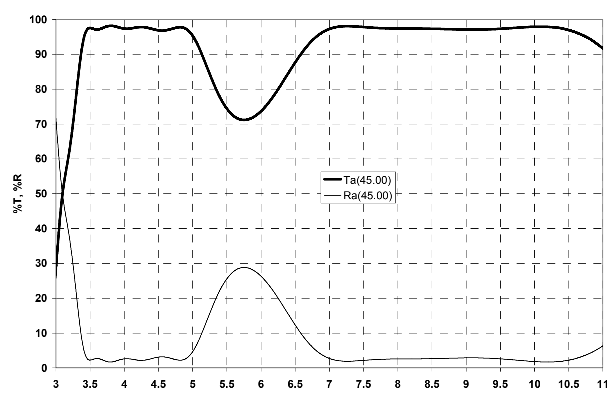

Figure 12: Predicted infrared transmission and reflection of the beam splitter design selected for fabrication.

The cost driver for this design is the average reflection in the visible region. Figures 9 and 10 present an overlay of three designs for an average visible band reflection of 95, 97 and 98%. Table 1 summarizes these designs and modeled performance. Film quality is not a parameter listed in this table as it is not easily modeled. However, film quality is ultimately the limitation of the dichroic design as increased film thickness leads to stress induced distortion and cosmetic defects from problems with the manufacturing process. For comparison, the average reflection expected for a freshly coated aluminum film is 90.3% and for silver 98.4% over this spectral region[5]. Figures 11 and 12 present modeled performance for the design selected for fabrication.

2.3 Filter design: The Dual Band Edge Filter

The edge filter is a notch filter which defines the long wave cut-off for the optical system. The design challenge is that the second and third harmonics of the reflection notch used to define the edge need to be suppressed. The discrete starting design presented in figure 13 is similar to the method described by Baumeister for suppressing specific harmonics[6]. This technique uses thin trimmer layers to suppress a specific harmonic. This design approach significantly increases the number of layers in the design from 2 per group for a quarter wave filter to 6 layers per group in this example.

Table 2: Summary of Dual Band Edge Filter Coating Designs

Layers	Thickness (μ)	Slope	Max OD	OD @10μ	MIR %T	FIR %T
40	15.3	4.71 %	2.2	1.2	97.7 %	95.0 %
55	19.3	2.59 %	3.8	1.9	99.5 %	99.0 %
76	26.3	1.55 %	5.1	2.9	99.4 %	98.8 %

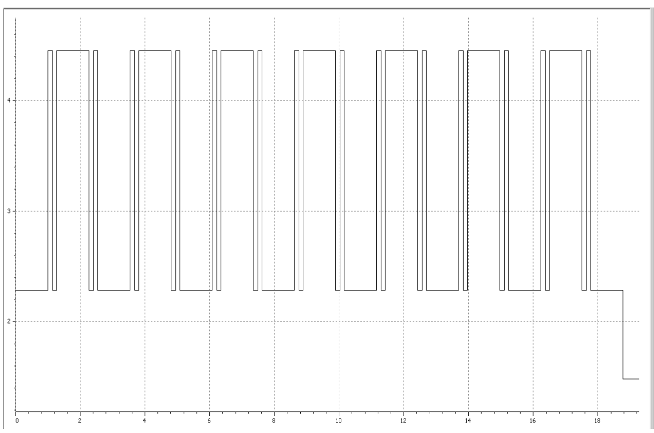
Figure 13: Starting design for the dual band edge filter

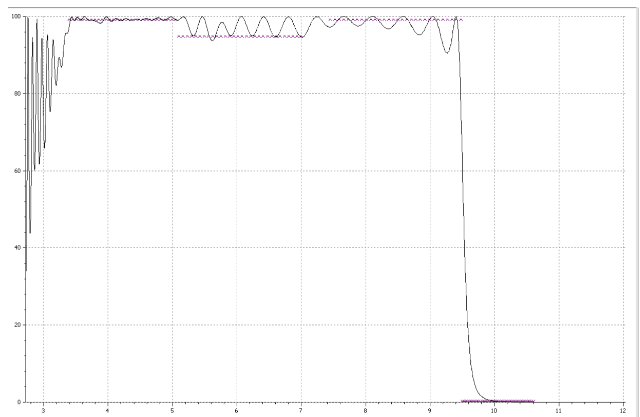
Figure 14: Predicted performance for the edge filter.

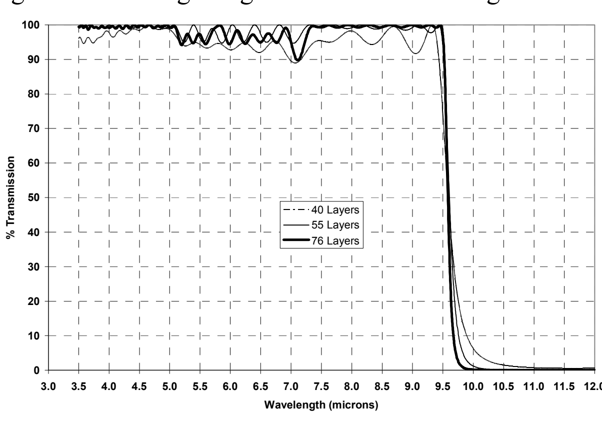

Figure 15: Predicted transmissions for three edge filter designs are overlaid.

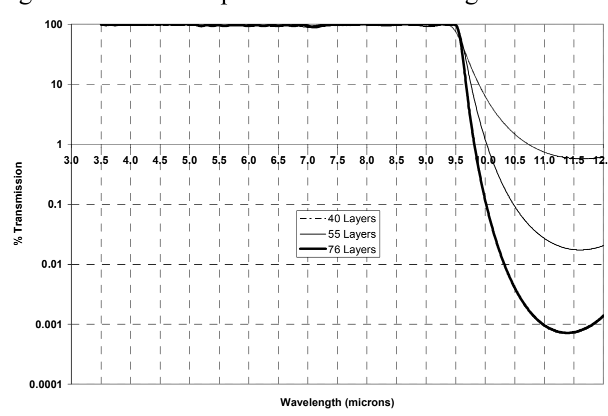

Figure 16: Predicted transmission for the edge filter designs on a logarithmic scale.

The technical drivers for this type of design include edge slope, bandwidth of the edge filter, optical density in the out of band region and performance over angle of incidence. Edge slope and bandwidth are indirectly proportional, with better edge slope resulting in the need for a narrower bandwidth and a higher number of groups to meet the same optical density.

Figures 15 and 16 present an overlay of transmission for three edge filter designs with 5, 8 and 11 groups used as the starting design. Table 2 presents a summary of each design and model performance. The optical density and edge slope improve with increased design thickness. Edge slope is calculated at the ratio of the difference between where the edge is 90% and 10% divided by the edge wavelength at 50%. Transmission in the band pass region can generally be optimized regardless of edge filter performance.

2.4 Filter design: The Dual Sensor Band Pass Filter

The bandpass filter defines the long and short edge of the dual band pass sensor as well as blocks the region from 5 to 7 μm where atmospheric absorption limits the sensor's range. The filter design is similar to the edge filter but rather than suppressing the harmonics, the harmonics are modified to provide blocking at the short edge of the band and the spectral region between the bands. Table 3 presents three examples of this design. The cost drivers are the out of band optical density and edge slope across the required angles of incidence.

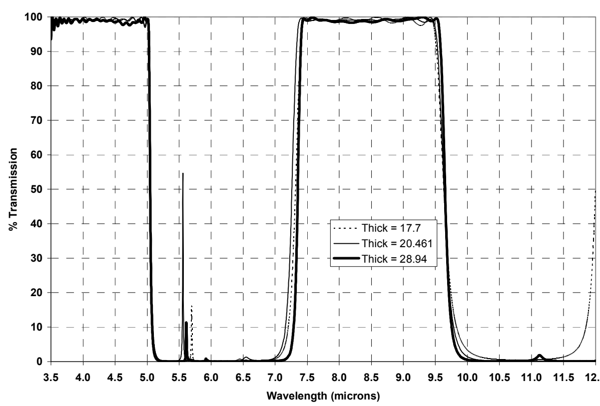

Figure 17: Alternate designs for the dual sensor band pass filter.

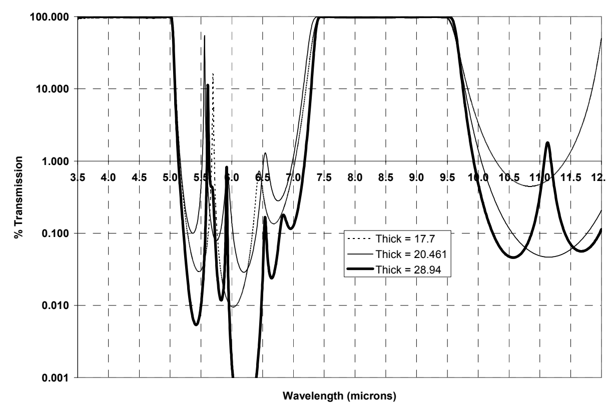

Figure 18: Predicted transmission for three potential dual sensor band pass filter designs.

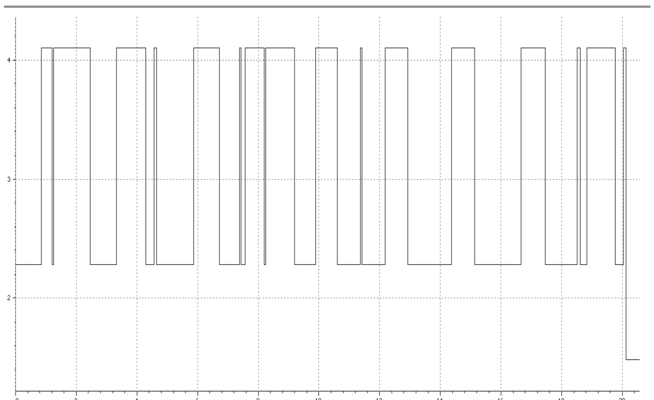

Figure 19: The refractive index profile for the dual sensor bandpass filter design.

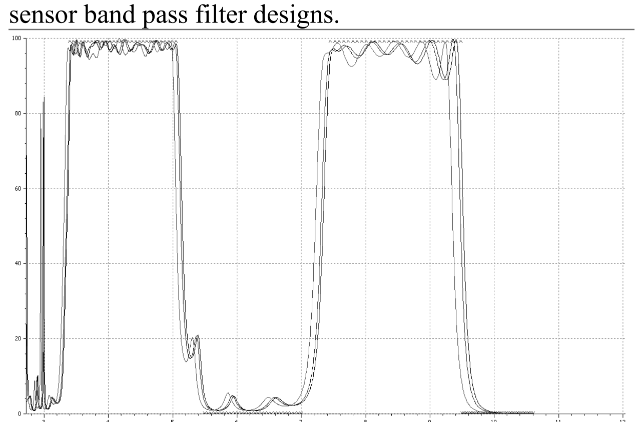

Figure 20: Predicted performance for the dual bandpass filter design selected for fabrication.

Table 3: Summary of Dual Sensor Pass Band Coating Designs

Layers	Thickness (μ)	Average OD 5.1-7μm	Average OD 10-12μm	Average %T 3.5-5μm	Average %T 7.4-9.5μm
42	17.7	3.0	1.9	99.3	99.1
41	20.5	2.6	3.0	99.0	99.2
55	28.9	3.8	2.9	98.7	99.0

3. FABRICATION RESULTS

A potential problem with using needle synthesis for filter design is that the resulting design may be too sensitive to layer thickness or material index to allow for practical manufacture. Addressing this concern, a prospective design of each filter type was selected for a single fabrication run. In practice, a candidate set of designs are fabricated repeatedly and run to run statistics are complied before moving the designs into production. The data presented here is just the beginning of that process.

The filter demonstration used the same material set and process for each filter type. The filters were fabricated using electron-beam evaporation. The visible/infrared beamsplitter was deposited on a germanium substrate and the other two filters were deposited on zinc selenide. Layer thicknesses were measured using quartz crystal monitoring.

Table 4 presents a summary of the selected designs and measured results. Figures 21 and 22 present measured results for the visible beamsplitter. The visible reflection is presented in figure 21 and the infrared reflection is presented in figure 22. Good infrared passband transmission was achieved.

Figures 23 and 24 present measured results for the edge filter. The filter is deposited on a ZnSe substrate. The second side of the substrate was coated with an anti-reflection coating. Good edge slope was demonstrated, but the passband transmission was not as smooth as modeled and will need to be addressed in future development.

Figures 25 and 26 present measured results for the dual band pass coating. The design was deposited on ZnSe. The back surface of the substrate is uncoated and therefore limits the pass band transmission. Location of the passbands is reasonable, but once again, the passband transmission is not as smooth as expected.

Table 4: Summary of Fabrication Results for the Three Filter Types at 45° AOI

Design	Layers	Thickness	MIR %R	FIR %R	Comment
Dual Band Dichroic	53	6.5μm	1.2	0.9	Visible Refl=94.5%
Dual Band Edge Filter	49	15.9μm	92.3	91.0	OD at 10μm=3.8
Dual Sensor Bandpass Filter	37	22.7μm	77.16	66.3	No coating on S2

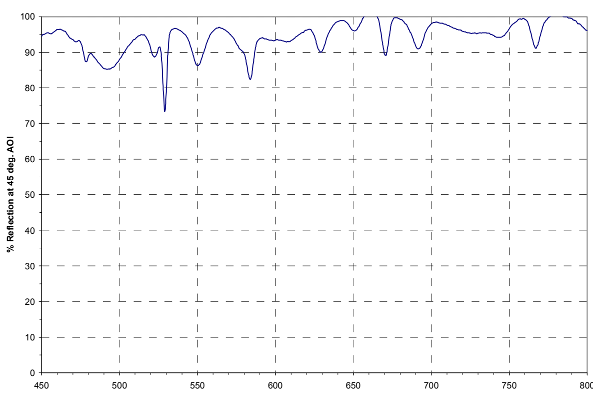

Figure 21: Measured visible reflection for the visible/infrared beamsplitter at 45° AOI. Measurement was made using an aluminum reference and scaled accordingly.

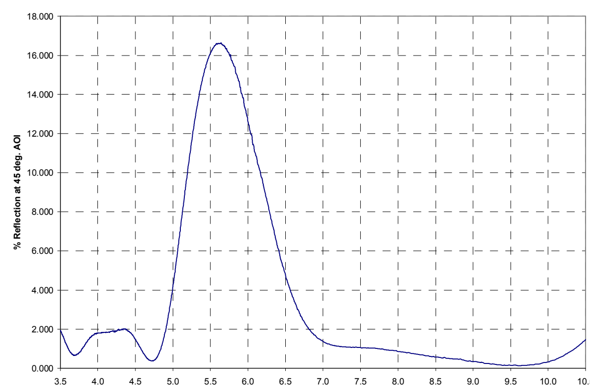

Figure 22: Measured infrared reflection for the visible/infrared beamsplitter at 45° AOI. Measurement was made using a gold reference.

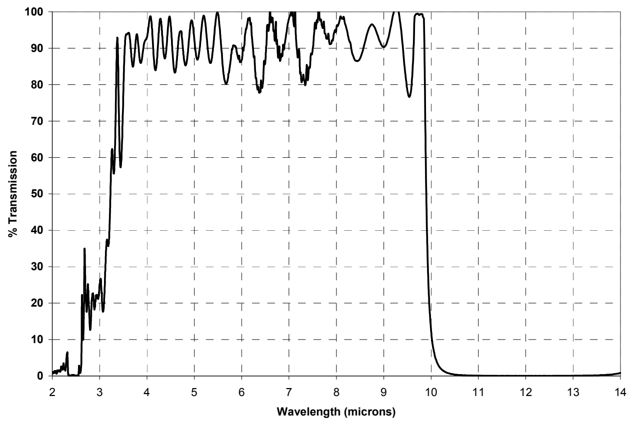

Figure 23: Measured transmission for the dual band pass long wave edge filter normal angle of incidence.

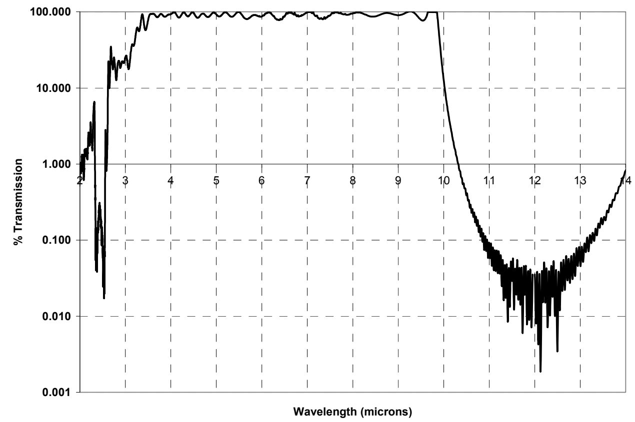

Figure 24: Measurements of the FIR edge filter plotted using a logarithmic scale.

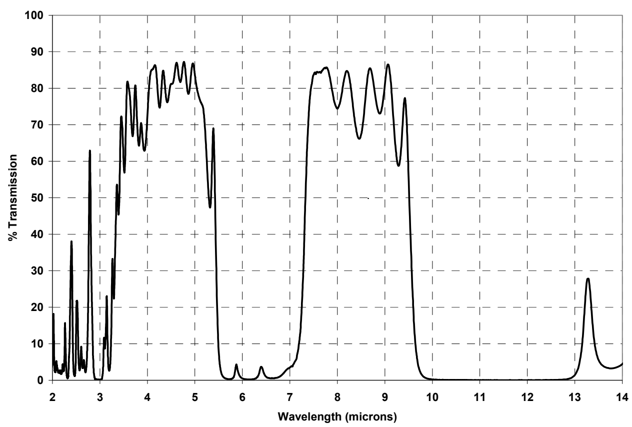

Figure 25: Measured transmission for a dual band pass filter. The back surface is uncoated.

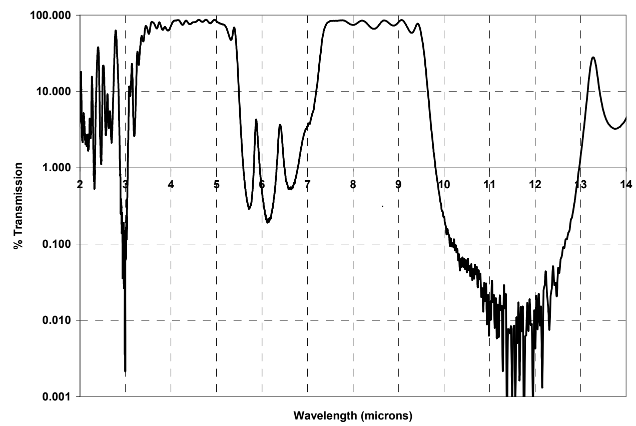

Figure 26: Measured transmission for the dual band pass filter. Transmission is plotted on a logarithmic scale.

4. CONCLUSIONS

Despite the added thickness and complexity of dual band filter designs, the films may be designed and fabricated to comparable performance levels as single band films, however, manufacturability requires a significantly higher level of control. To demonstrate this, an example of three filters types were designed and fabricated; a dual band visible dichroic, a dual band far-infrared edge filter and a dual sensor band pass filter. Three designs were developed for each filter type and complexity and manufacturability versus performance was evaluated. A common set of coating materials were used for all three designs and can be used for substrate materials of various refractive indices. The fabricated films exhibit good spectral performance and cosmetic quality. Environmental durability should be assessed further.

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