Ultra-narrow Bandpass filters for infrared applications with improved angle of incidence performance

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Abstract

Narrow band-pass optical interference filters are used for a variety of applications to improve signal quality in laser based systems. Applications include LIDAR, sensor processing and free space communications. A narrow band width optical filter allows for passage of the laser signal while rejecting ambient light. The more narrow the bandwidth, the better the signal to noise. However, the bandwidth of a design for a particular application is typically limited by a number of factors including spectral shift over the operational angles of incidence, thermal shift over the range of operating temperature and, in the case of laser communication, rejection of adjacent laser channels. The trade-off of these parameters can significantly impact system design and performance. This paper presents design and material approaches to maximize the performance of narrow bandpass filters in the infrared.

1.0 Background

Narrow and ultra-narrow (less than 1 nm) bandpass filters can be readily produced on wavelength. Figure 1 presents a figure from a previous paper showing measured spectral transmission for filters fabricated with bandwidths of 1.0, 0.6 and 0.35 nm[1]. While the filter bandwidth can be very tight, the question of how it will perform in a specific optical system must be considered. The center wavelength of the filter will shift with angle of incidence (AOI) and operating temperature.

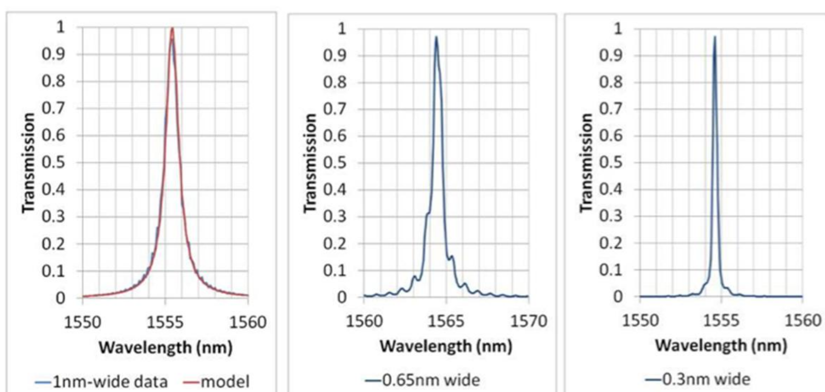

Figure 1: Laser wavelength scanning data for 1nm wide, 0.65nm wide, and 0.3nm wide bandpass filters. Ultra-narrow notch bandpass filters can be reliably fabricated, but spectral shift with angle and temperature need to be matched to system requirements. (*SPIE Paper 9612-21: Sub-nanometer band pass coatings for LIDAR and astronomy)*

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In order to prevent the bandpass from shifting off the laser line, bandwidth must be increased to accommodate these effects. This creates a design trade-off between filter bandwidth and maximum signal to noise and operational parameters such as field of view and temperature. Filter design and material choices can mitigate these issues and allow for minimum passband bandwidth.

Optical interference filters characteristically shift to shorter wavelength with increased angles of incidence[2]. This spectral shift establishes a trade-off between filter bandwidth and the system's field of view. To illustrate this point, consider the measured spectral performance for a filter set of two narrow bandpass filters presented in figures 2 and 3. These filters must pass a specified near-infrared C-band laser wavelength with high transmission while rejecting a laser with a 5 nm adjacent wavelength. The filter passband is approximately 2.5 nm full width half maximum (FWHM) and the off band rejection is OD 4 for the adjacent laser wavelength. The filters must operate between 0 and 5^o angle of incidence (AOI). The passband of the filters was designed to be no wider than the angular spectral shift angle of 0 to 5^o. The bandpass center wavelengths are offset to allow the laser wavelengths to pass on the left side of the filters at normal AOI and the right side of the passbands at 5 degrees AOI. A narrower band pass would limit the working angle of the system. A wider passband would compromise the signal to noise rejection.

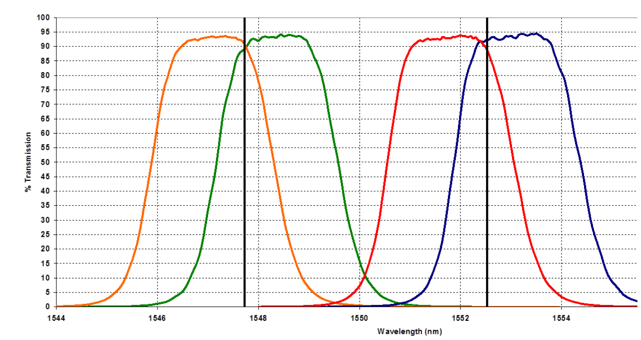

Figure 2: Measured transmission for two 2.5 nm, multi-cavity bandpass filters at 0 and 5^o AOI are overlaid with the target laser wavelengths. The application is for free space laser communication. The operational angle of incidence is 0 to 5^o. The laser wavelengths are 1552.3 and 1548.7.

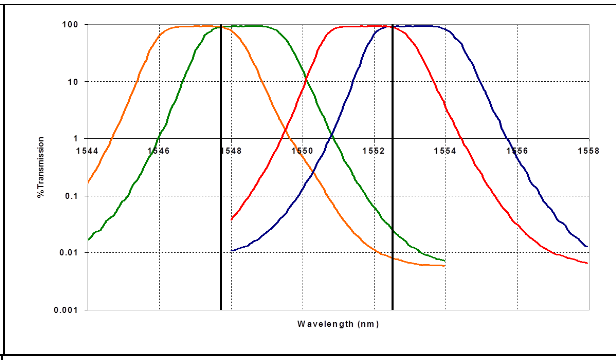

Figure 3: The same measured transmission data presented in figure 2 are plotted on a log scale to highlight filter slope and rejection of the corresponding adjacent laser line. The filters provide high in-band transmission at 0 to 5^o and OD 4 rejection of the adjacent laser bands.

The narrow passband filter can also shift in wavelength with changes in temperature. The thermal shift can be stabilized by proper selection of the substrate[4,5]. Figure 4 presents the measured spectral shift in wavelength for the center passband wavelength for the same design deposited on three different glass types. Figures 5 presents the measured thermal shift of this filter set over a temperature range of -50 to +50^o C. Measured spectral shift was 0.2nm over the 100 degree range. Figure 6 presents a comparison of measured transmission using a Cary 5E spectrometer and a scanning laser. The F# of the spectrometer causes a slight shift in passband position and bandwidth. Since we can effectively mitigate the influence of temperature, minimum filter bandwidth is driven primarily by angle of incidence in the system and angular shift of the filter.

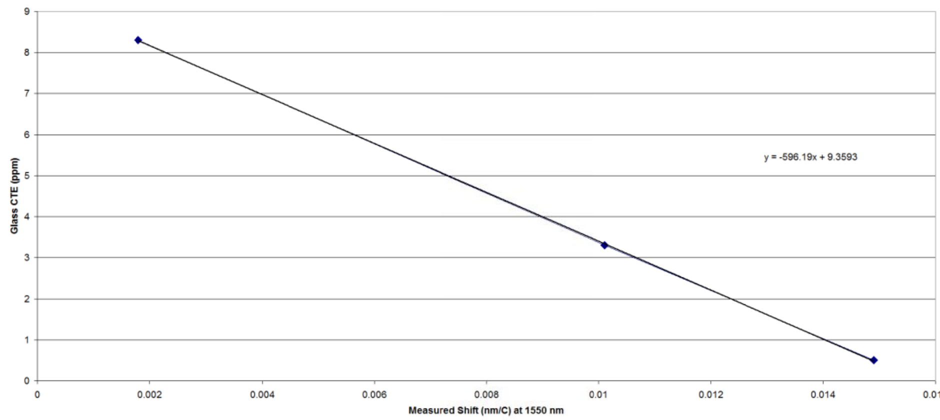

Figure 4: Measured spectral shift of the center wavelength of the narrow bandpass filters is plotted against the coefficient of thermal expansion (CTE) of three glasses. Matching the filter to the proper substrate reduces the spectral shift to 0.2 nm over a 100^{o} C range in temperature.

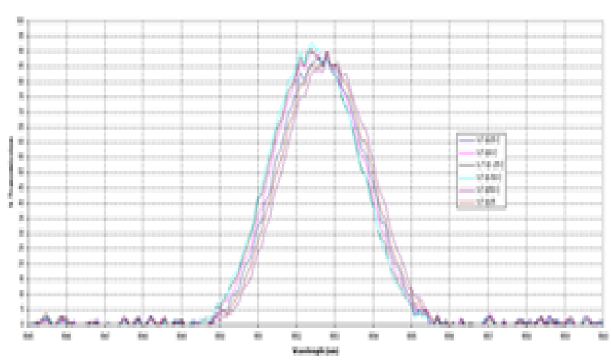

Figure 5: The filter is fabricated from hard oxide materials and matched to the substrate for high thermal stability. Measured transmission of the filter is presented for different temperatures: +50, +25, 0, -25, and -50. The measurements were made using a Cary 5E.

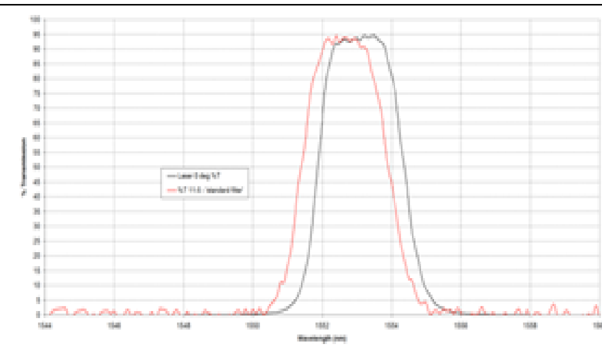

Figure 6: Overlay of laser and Cary measurement. The scanning laser measurement is taken as the more 'correct' result. The Cary has an offset due to the F# of spectrometer[3]. Cary measurements typically exhibit a wider bandwidth and less sharp edge slopes.

Spectral shift with angle of incidence is a function of the effective refractive index of the filter layers. The higher the refractive index, the lower the spectral shift. Figure 7 presents measured transmission for a germanium and zinc sulfide bandpass filter on a sapphire substrate. Modeled performance from 0 to 45 degrees AOI is presented in figure 8. Maximizing the effective index by selecting high index materials is an effective way of minimizing spectral shift but it may still not offer adequate insensitivity to field of view.

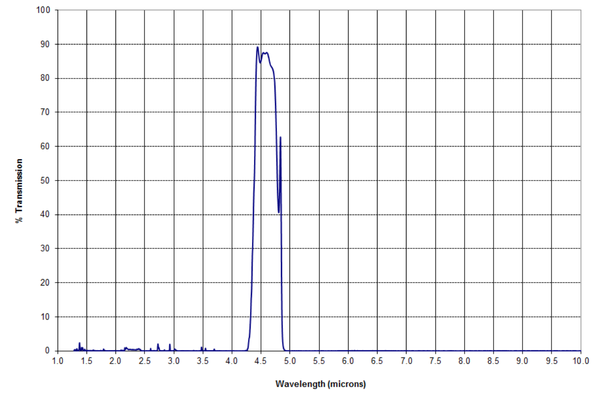

Figure 7: Measured transmission for a 380 nm FWHM filter at 4.5 microns on sapphire is presented. The filter uses high index materials (germanium and zinc sulfide).

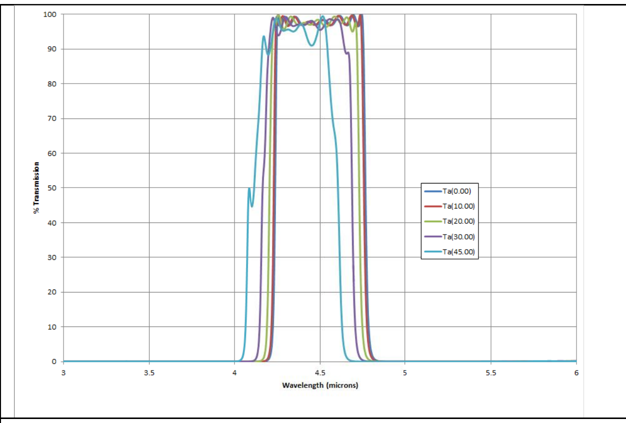

Figure 8: The spectral performances at angles of incidence from 0 to 45^{o} are overlaid. The use of high index materials is used to mitigate the spectral shift with angle.

2.0 Design

Using design techniques which minimize the ratio of low index to high index materials in the filter design have been shown to effectively minimize the shift of notch rejection filters[6]. Similar design techniques can be applied to bandpass filters. The classical design of a bandpass filter is the Fabry-Perot consisting of a pair of matched reflectors separated by a phase cavity. The optical thickness of the phase cavity offsets the phase of the reflected light from the second reflector from the first by half a wave so that the reflections interfere destructively. Stacking multiple cavities and reflectors allows for the development of sharper slopes and flatter band pass regions.

Figures 9 and 10 present modeled transmission for a 2.5 nm bandpass filter using silicon oxide (n = 1.46) and niobium oxide (n = 2.32) layers. These figures are designed to pass 1550 nm over an angle of incidence from 0 to 5^{o}. Figures 11 and 12 model transmission for a similar design using a higher index pair of materials: niobium oxide (n = 2.32) and silicon (n = 3.81). This 2.5 nm bandpass design operates over an angle range of 0 to 7.5^{o}. The third design is presented in figures 13 and 14. This design uses antimony selenide (n = 3.32) and silicon (n = 3.81) and the 2.5 nm design can operate over 0 to 10^{o} AOI.

3.0 Summary

Narrow bandpass filters are a key component for improving the signal quality of a laser based optical system. The more narrow the passband, the better the signal to noise. Unfortunately, interference filters shift towards shorter wavelengths with increased angle of incidence. This shift requires that the passband be opened up to meet the required field of view of the system, but by opening up the passband, signal to noise is compromised. Fortunately, several material and design options exist to mitigate this problem, and while it can't be completely eliminated, it can be controlled.

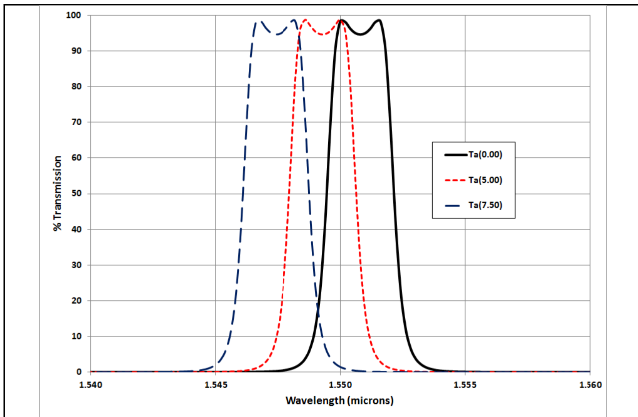

Figure 9: Modeled transmission for a 2.5 nm bandpass at 0, 5 and 7.5^o AOI using SiO_2/Nb_2O_5. The design is (AH)^^{5} 5A (AH)^^{5} (AH)^^{6} 5A (AH)^^{6} (AH)^^{5} 5A (AH)^^{5} H

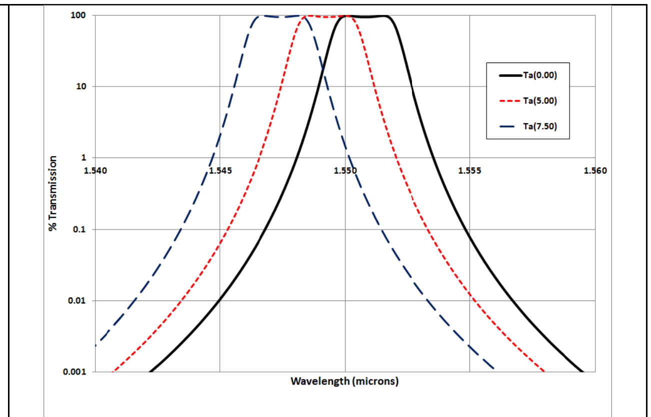

Figure 10: Modeled transmission for a 2.5 nm bandpass at 0, 5 and 7.5^o AOI using SiO_2/Nb_2O_5. The design is (AH)^^{5} 5A (AH)^^{5} (AH)^^{6} 5A (AH)^^{6} (AH)^^{5} 5A (AH)^^{5} H

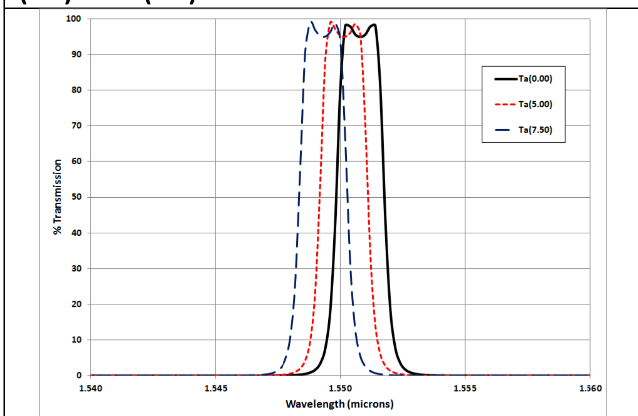

Figure 11: Modeled transmission for a 2.5 nm bandpass at 0, 5 and 7.5^o AOI using Nb_2O_5/Si: (AH)^^{5} 5A (AH)^^{5} (AH)^^{7} 5A (AH)^^{7} (AH)^^{5} 5A (AH)^^{5} H

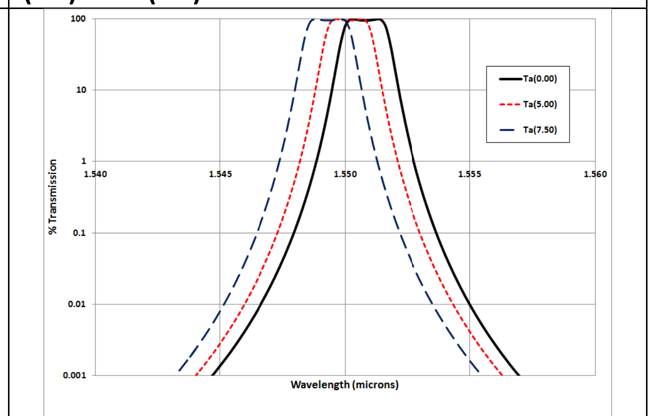

Figure 12: Modeled transmission for a 2.5 nm bandpass at 0, 5 and 7.5^o AOI using Nb_2O_5/Si: (AH)^^{5} 5A (AH)^^{5} (AH)^^{7} 5A (AH)^^{7} (AH)^^{5} 5A (AH)^^{5} H

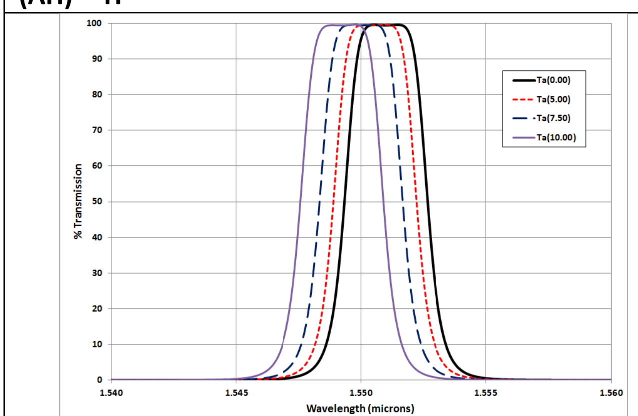

Figure 13: Modeled transmission for a 2.5 nm bandpass at 0, 5, 7.5 and 10^o AOI using Sb_2Se_3 and Si: (AH)^^{9} 5A (AH)^^{9} (AH)^^{18} 9A (AH)^^{18} (AH)^^{9} 5A (AH)^^{9} H

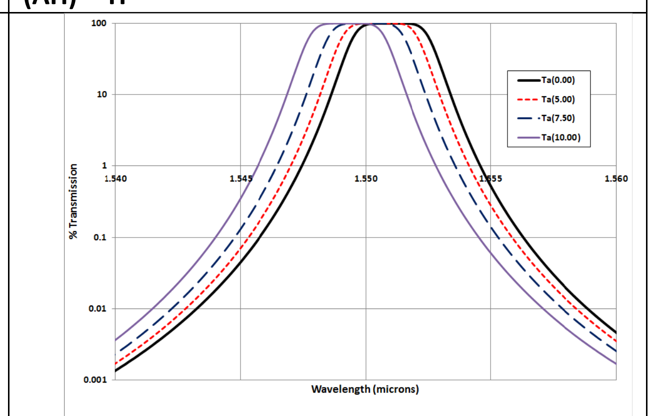

Figure 14: Modeled transmission for a 2.5 nm bandpass at 0, 5, 7.5 and 10^o AOI using Sb_2Se_3 and Si: (AH)^^{9} 5A (AH)^^{9} (AH)^^{18} 9A (AH)^^{18} (AH)^^{9} 5A (AH)^^{9} H

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