Stable and tunable performance of ultra-narrow bandpass and high edge slope dichroic optical filters

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Abstract

Laser based applications including optical communications, LIDAR and Raman spectroscopy benefit from ultra-narrow (< 1.0 nm) bandpass and high edge slope dichroic optical filters by rejecting off-band ambient and scattered light. However, applications for these filters are limited by shifts in wavelength due to temperature and angle of incidence, system f-number, doppler shift and pointing error of the gimbal as well as the stability of the source. Passive design techniques such as athermalization, use of high refractive index materials and widening the passband are compared with active tuning options. Adding thermal or tilt tuning can expand the operational range of the filter and mitigate the compromise to signal to noise which follows from widening the passband.

1.0 Introduction

Ultra-narrow bandpass and high edge slope dichroic filters are used extensively in laser-based systems to improve signal to noise[1]. While these filters perform well on wavelength, performance degrades rapidly with incident angle and f-number[2]. The trade-off of filter performance and angle of incidence is to open up the filter's bandwidth or accept a reduction in the filter's edge slope. Temperature shift is typically treated by using athermalization[3,4] techniques when designing the filter.

Active tuning of the filter wavelength provides an alternative to widening the filter's bandpass or accepting the wavelength shift with angle of incidence. The filter's wavelength can be tuned to compensate for a shift with angle of incidence or for a Doppler shift of the laser signal due to the relative velocity between the sensing and transmitting platforms. Methods of actively tuning the filter wavelength include temperature control of the filter, angular tilt of the filter and a compensation filter.

Figures 1 through 3 present examples of a narrow bandpass filter, a high edge slope long pass and a high edge slope short pass filter. These filters are niobium and silicon oxide films deposited using high energy magnetron deposition with plasma assist. The shift in spectral performance with angle of incidence is presented in figure 4. The filters are athermalized and shift less than 0.002 nm per degree[5]. The optical performance of these filters can be shifted by tilting the filter, but with the consequence of displacing the image.

An alternate approach to tilt tuning the filter is to design the filters to be temperature sensitive and use a transparent conductive oxide (TCO) heater layer to tune the center wavelength of the bandpass filter and the edge wavelength of the dichroic filters thermally. The rate of performance shift with temperature can be designed into the filter by appropriate selection of the thin film materials and substrate. The TCO layer we are using is indium tin oxide (ITO). The heater layer offers good transmission over the spectral range of 400 to 1600 nm. Power consumption is 1 to 2 watts for a temperature range of 20 to 40C over ambient.

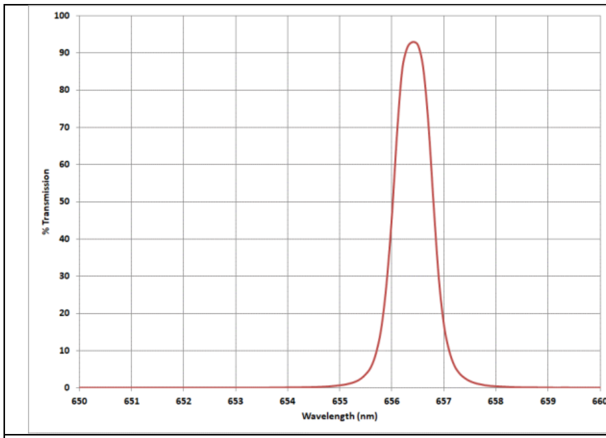


Figure 1: Spectral transmission of an ultra-narrow bandpass filter designed at the hydrogen-alpha emission line. The filter bandwidth is 0.75 nm and is typically used with a sub-angstrom etalon to block higher orders.

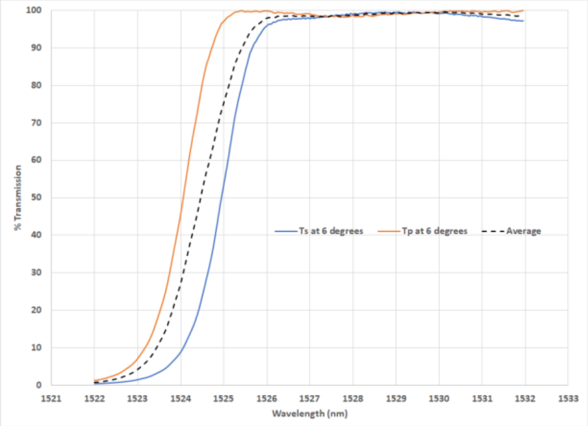


Figure 2: Spectral transmission of a high edge slope long pass filter operating in the C-band. Measurement is made by scanning a laser through wavelength. Measured average polarization slope is 2nm or 0.13% at 1524nm between 10 and 90% transmission

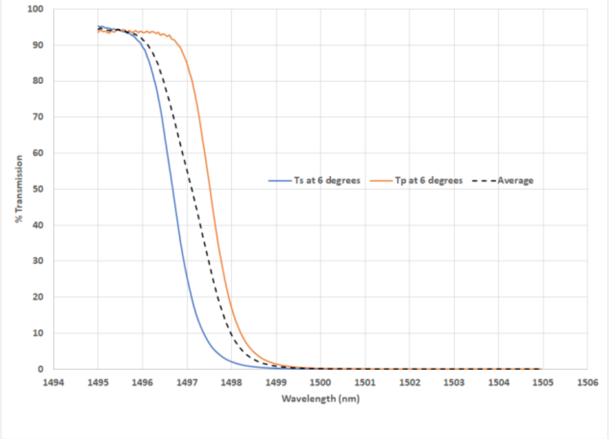


Figure 3: Spectral transmission of a high edge slope short pass filter operating in the C-band. Measured slope is 2nm. Measurements for S, P and average polarization are presented at 6° angle of incidence.

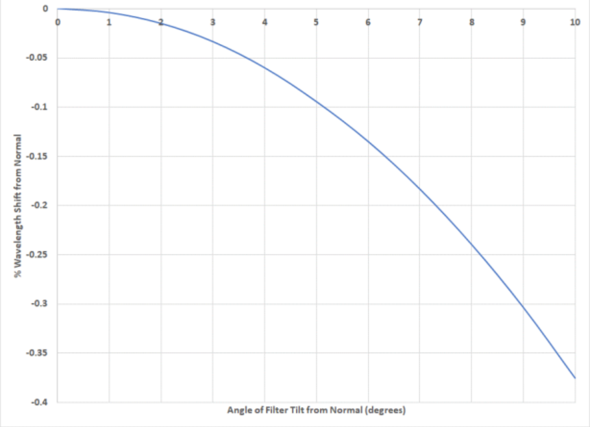


Figure 4: Spectral shift is plotted as a percent change from normal as a function of angle of incidence. For the oxide film system used in figures 1 through 3.

Applications can require that narrow bandpass filters operate over a range of incidence angles and temperatures as well as be able to tolerate variations in source performance due to either manufacturing variance or performance at different operating conditions.

Interference filters shift to shorter wavelengths with off normal angles of incidence (AOI)[7]. The magnitude of this shift can be mitigated by raising the effective refractive index of the film[8]. Figure 5 and 6 present measured performance for two film systems. Both filters were designed to a similar bandwidth. The refractive index of the materials used in the figure 5 example are 2.3 and 1.34. The refractive index of the materials used in the figure 6 example are 2.39 and 1.46. The figure 5 filter used thermal evaporation while the figure 6 filter was fabricated using magnetron sputtering with plasma assist. The higher energy, magnetron process produces a denser film with refractive index values approaching bulk. The result is that the operation angle for the filter in figure 5 is 2° and the operating angle for the filter in figure 6 is 5° AOI.

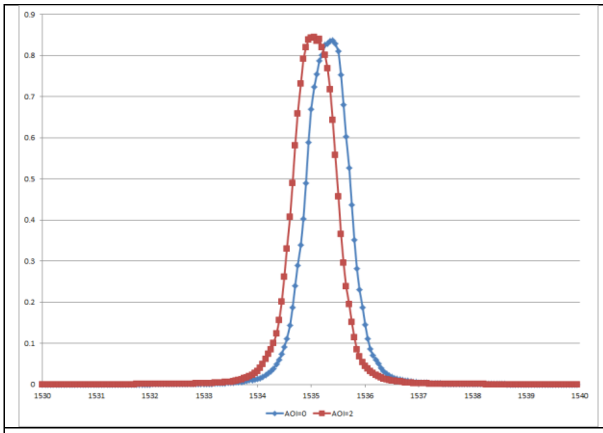


Figure 5: Transmission of a Cryolite/ZnS narrow bandpass NIR filter. Measurements were made using a scanning laser spectrometer at 0 and 2° AOI.

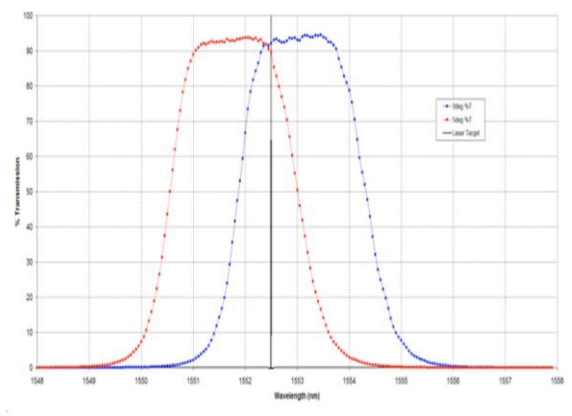
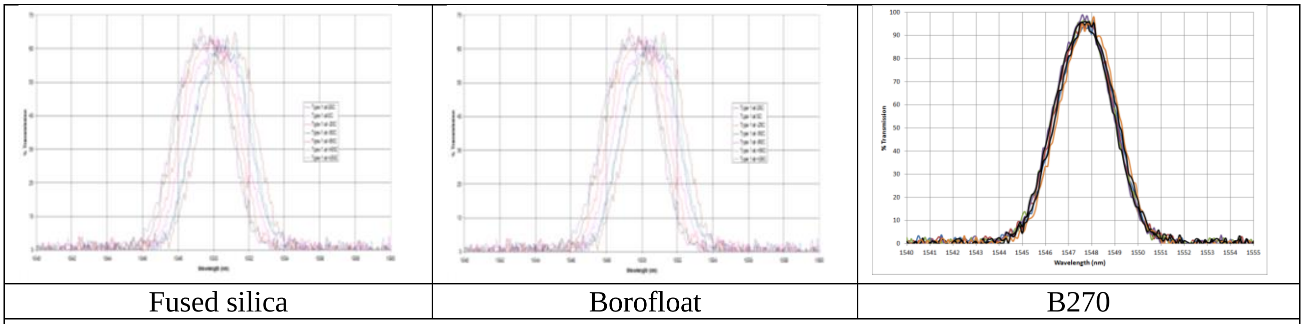


Figure 6: Transmission of an oxide narrow bandpass filter. Measurements were made using a scanning laser spectrometer at 0 and 5° AOI.

2.0 Thermal Tuning

The stability of optical interference filters with temperature is a function of the choice of the coating materials, the filter substrate, the process used to fabricate the filters and the filter design. Figure 7 presents spectral measurements of a narrow bandpass filters on different substrates coated in the same coating run. Measurement at increments of 25° C between -50 and +50C are overlaid in these figures. The coefficient of thermal expansion (CTE) of the three glasses are 0.5, 3.2 and 6.7 ppm respectively. The film system used to fabricate this filter set is SiO_2/Nb_2O_5. The process was magnetron sputtering with plasma assist.

Figure 8 presents a plot of measured shift in spectral performance of narrow bandpass filters with temperature for two film systems as a function of the CTE of the substrate. The two film systems are thermally evaporated Cryolite/ZnS and sputtered SiO_2/Nb_2O_5. The proper matching of the film system and filter substrate will result in the spectral performance of the filter either being insensitive to temperature, athermalized, or quite sensitive and thermally tunable. The two material systems exhibit striking differences in their response to temperature allowing use to design to different application requirements.



Fused silica	Borofloat	B270

Figure 7: Transmission of a SiO_2/Nb_2O_5 oxide bandpass at +50C to -50 C in increments of 25C on different substrates. The substrates were included in the same coating run and were cleaned and processed identically. The difference in thermal shift is due to the CTE of the substrate.

Applications for ultra-narrowband filters with bandwidths less than 1 nm can be sensitive to variation in filter performance as well as variations in the source or optics. Actively optimizing the center wavelength of an ultra-narrow bandpass filter allows for adjustment of the filter to compensate for fluctuations in the source wavelength, doppler shift in wavelength due to the relative speed between the source and receiving platforms, or variations in the optics resulting in changes in f-number or variation in the optical path and angle of incidence. Wavelength tuning of the filter provides a means of re-optimizing the spectral performance of the filter to compensate for these changes.

Ultra-narrow bandpass filters using thermal tuning is not a new concept. Several commercial options are available for such applications as observing the sun at the Hydrogen-alpha line. These systems typically use a thermal cell to control temperature and thus the center wavelength of the filter passband[9]. We are using a similar but more compact and lighter-weight technique by applying a thin film heater layer directly onto the narrow bandpass filter. Figure 9 illustrates this filter design where a thin layer of indium tin oxide (ITO) is applied to heat the filter directly rather than heating the entire filter cell.

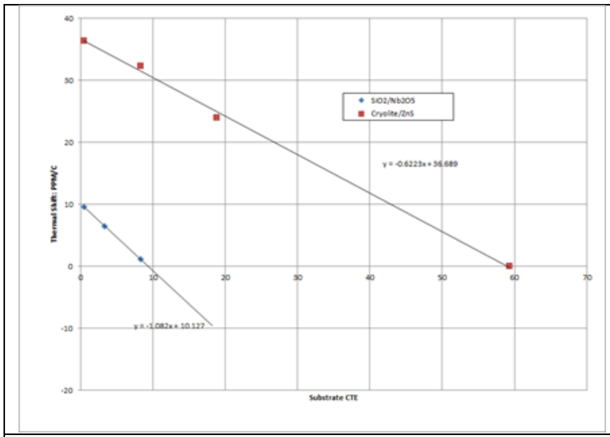
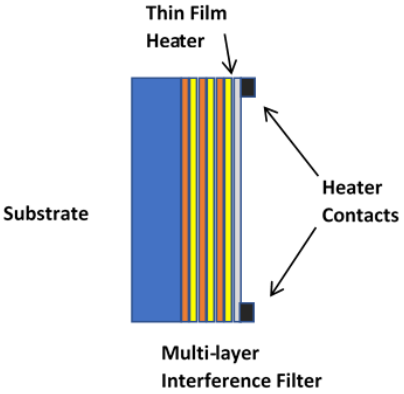
	

Figure 8: The measured shift in center wavelength for narrow bandpass filters is plotted as a function of substrate CTE. Two different film systems are presented: niobium oxide/silicon oxide and zinc sulfide/cryolite[6].	Figure 9: The center wavelength of a narrow bandpass filter can be modified using thermal tuning. In this example, a thin indium tin oxide (ITO) layer is used as a transparent surface heater on the filter.

Measurement of spectral shift with temperature were first made using an annular heater installed in the sample compartment of a Cary 500 without the ITO heater layer. This setup is presented in figure 10. Voltage was systematically ramped up and the filter was allowed to soak at each setpoint. Transmission measurements at each temperature setpoint are overlaid in figures 11 and 12 for the oxide and sulfide filter respectively. Figure 13 plots the measured percentage change in center wavelength location as a function of temperature for the two ultra-narrow bandpass filters each fabricated using different material sets: niobium oxide/silicon oxide and zinc sulfide/cryolite.

The ultra-narrow bandpass filters were overcoated with a thin film heater consisting of a thin layer of indium tin oxide (ITO). Surface resistance of the heater was measured as 220 Ω/sq. Figure 14 presents a photograph of a filter with the thin film heated mounted in the sample compartment of a Cary 500. Voltage to the heater was systematically ramped up and the filter was allowed to soak at each setpoint. Transmission measurements at each voltage setpoint are overlaid in figures 15 and 16 for the oxide and sulfide filter respectively. Figure 17 presents measured spectral shift as a function of heater voltage.

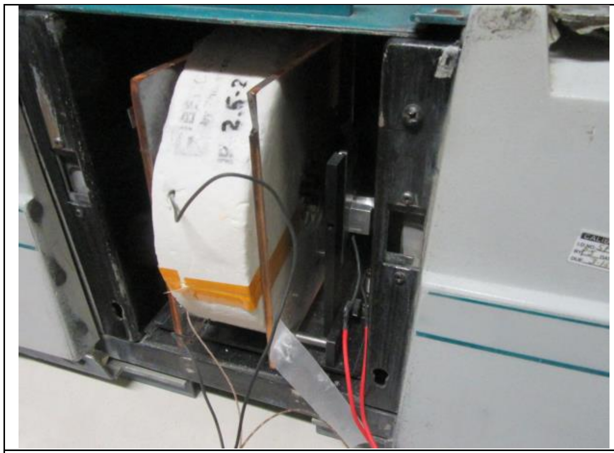


Figure 10: An annular heat was used to heat the filter. The heater fits into the Cary 500 sample compartment. Glass plates are used on both sides of the heater to stablize temperature within the cavity. The filter sits in the center of the heater. A thermocouple is used to measure cavity temperature.

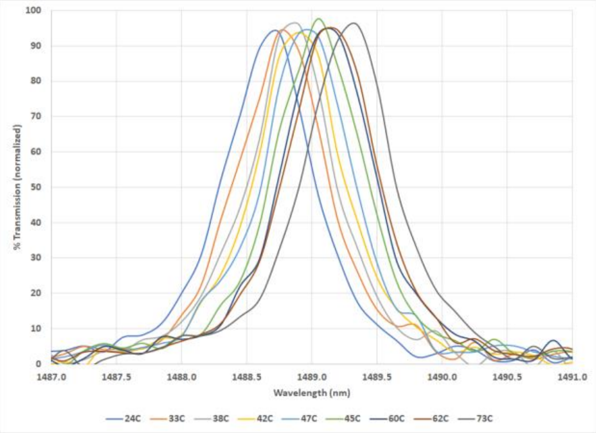


Figure 11: Measured transmissions (normalized to the maximum transmission in the set) for a Nb_2/SiO_2 filter at 25 through 73C are overlaid. The 0.5 nm wide filter maintains good shape across the temperature range. The filter is on a borofloat substrate.

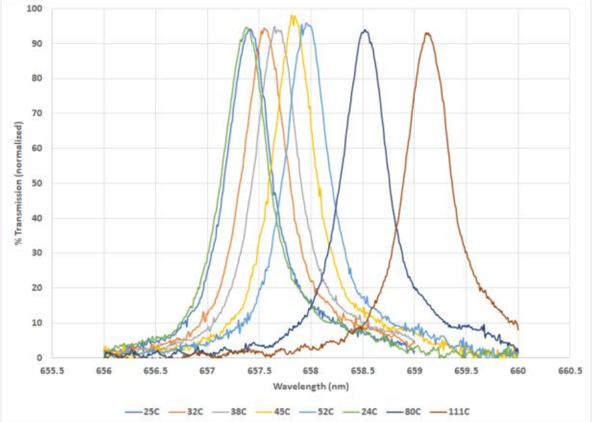


Figure 12: Measured transmissions (normalized to the maximum transmission in the set) for a ZnS/Cyolite filter at 25C through 111C are overlaid. The 0.5 nm wide bandpass filter maintains good shape across the temperature range. The filter is on a borofloat substrate. Off band blocking is maintained at greater than OD 4 from 200 to 1100 nm.

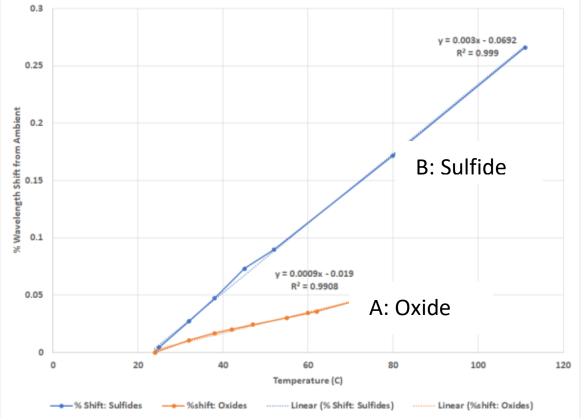


Figure 13: The change in center wavelength of the narrow bandpass filter is plotted as a function of temperature for two filter fabricated using different material sets. Filter A is a narrow bandpass filter at 1450 nm fabricated using niobium and silicon oxides. Filter B is a narrow bandpass H-alpha filter fabricated using zinc sulfide and cryolite.

Figure 14: Filters were mounted on a glass strip coated with an ITO film. Voltage was applied across the strip.

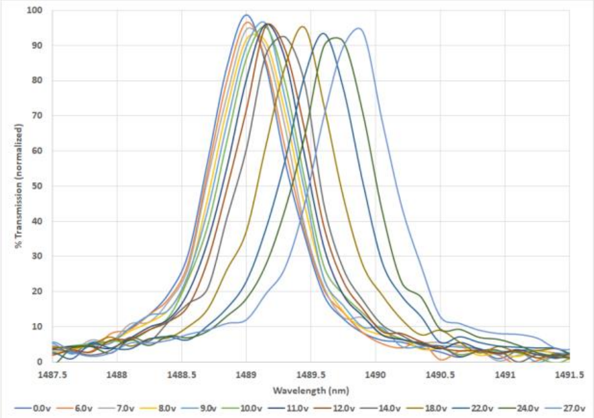


Figure 15: Measured transmissions (normalized to the maximum transmission in the set) for a Nb_2/SiO_2 filter at 0 through 27 volts are overlaid. The 0.5 nm wide filter maintains good shape acros the temperature range. The filter is on a borofloat substrate.

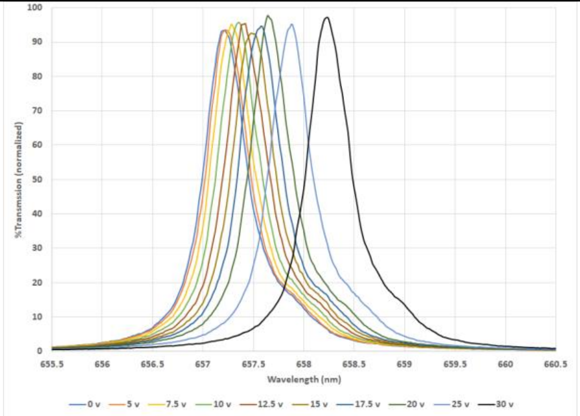


Figure 16: Measured transmissions (normalized to the maximum transmission in the set) for a ZnS/Cyolite filter at 0 through 30 volts are overlaid. The 0.5 nm wide bandpass filter maintains good shape across the temperature range. The filter is on a borofloat substrate. Off band blocking is maintained at greater than OD 4 from 200 to 1100 nm

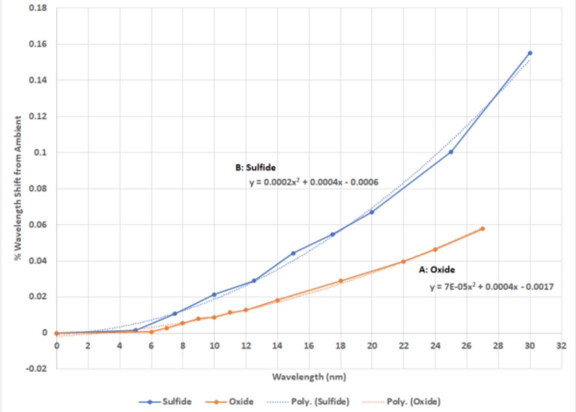


Figure 17: The shift in spectral performance is plotted as a function of applied voltage to the filter. The measured voltage curve are fit to a least squares second order polynomial. A linear fit to power is provided in figure 18.

3.0 Results

Table 1 summarizes measured performance for the two material sets tested using an ITO overcoat. Measured thermal shift and normalized thermal shift are calculated as the slope from a least square fit of the measured center wavelength versus temperature. The normalized % shift is the measured wavelength shift divided by the center wavelength at ambient. The power required to shift the center wavelength by ½ the filter bandwidth is presented in the final column of table 1.

Table 1: Summary of Spectral Shift with Heater Power

Material Set	Substrate	Measured thermal Shift (nm/C)	Ambient CW (nm)	Normalized % shift from ambient wavelength	Power for ½ Bandwidth
Nb_2O_5/SiO_2	Fused Silica	0.013	1488.6	0.0009	1.48 watts
ZnS/Na_3AlF_6	Borofloat	0.020	657.38	0.0030	0.83 watts

Figure 18 plots percent wavelength shift from ambient for the two filter as a function of power. The trend lines are a linear least square fit to the power curves.

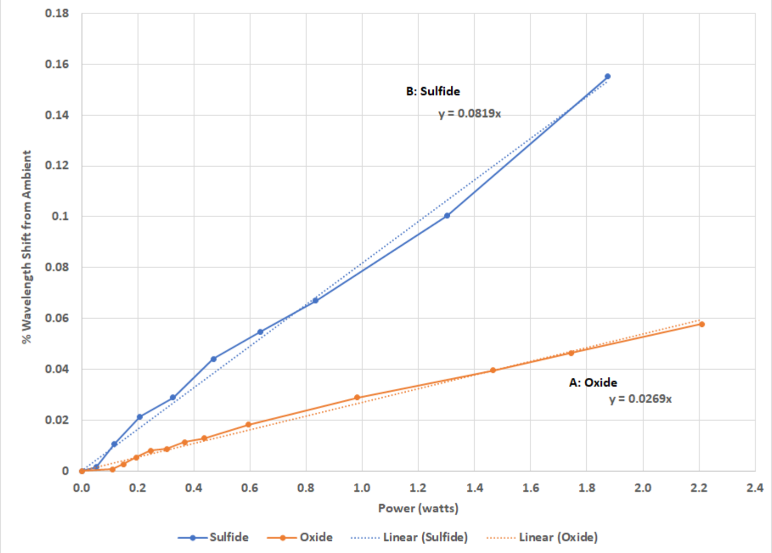


Figure 18: Percent wavelength shift of the center wavelength is plotted as a function of power to the thin film ITO heater. The resistivity of the ITO film was measured at 220 Ω/sq. The thin film heater allows for thermal tuning of the passband wavelength at low power.

4.0 Summary

The versatility of ultra-narrow bandpass filters and sharp transition edge filters can be extended by adding a degree of tunable control. The accepted trade-off of wider bandwidth to accommodate source instability or variability compromises signal to noise. Adding the ability to tune the passband wavelength allows for a tighter passband matched to the characteristics of each individual source laser or a change in system f-number. Using a thin film heater allows for a low power/low voltage solution which compensates for ambient temperature without undue heating other components with the system.

The magnitude of temperature shift is a primarily a function of the selected thin film materials and the substrate CTE. The filters can be athermalized, or designed to shift with temperature. Allowing the filter to shift with temperature allows for tuning the filter in the field to maximize signal strength.

5.0 References

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