RESEARCH ARTICLE OPEN ACCESS

Graphically Selecting Optical Material for Color Correction and Passive Athermalization

Raghad Ismail Ibrahim *
**(Physics Department, Al-Mustansiryah University, and CollegeOf Education)*

ABSTRACT
This paper presents pair optical glass by using a graphical method for selecting achromatize and athermalize an imaging lens. An athermal glass map that plots thermal glass constant versus inverse Abbe number is derived through analysis of optical glasses in visible light. By introducing the equivalent Abbe number and equivalent thermal glass constant, although it is a multi-lens system, we have a simple way to visually identify possible optical materials. ZEMAX will be used to determine the change in focus through the expected temperature changes in Earth orbit. The thermal defocuses over -20°C to +60°C are reduced to be much less than the depth of focus of the system.
Keywords-Athermal glass, ZEMAX, graphical method for selecting, athermalize lens.

I. INTRODUCTION

Athermalization is the principle of stabilizing the optical performance with respect to temperature. Any temperature changes experienced by the optics may be with respect to time or space or both. Time refers to a uniform heat soak across all the optics, and space refers to a gradient across the optics resulting in each lens (and housing) being a different temperature, or there being a radial change in temperature across an optic. Athermal systems are highly desirable for a multitude of applications in the broad field of integrated optics such as mobile phone and black box cameras, so, it is important to develop an athermal optical system: an optical system that is insensitive to an environment's thermal change and the resulting system defocus. To reduce thermal and chromatic errors, many design methods have been reported. Perry studied the effect of temperature changes on optical performance in infrared optics. Rogers showed that the multi-lens system could be achromatized and athermalized with three materials by solving three equations, but it was difficult to find a proper combination of materials [1].As alternative approaches to overcome these problems, graphic methods have been developed. Rayces and Lebich proposed a γV-V diagram and showed that chromatic aberration corresponds to the area of a triangle [2]. Tamagawa, et al. suggested other graphical approaches by plotting the thermal dispersive power versus chromatic dispersive power and included a discussion of selecting the element powers in addition to the element materials [3, 4]. Schwertz studied how developing an optical system that is insensitive to an environment's thermal change and the resulting system defocus [5], this research has been performed mainly on infrared optics, and there are few studies on visible optics. In order to solve these difficulties, in this paper we introduce the equivalent Abbe number and equivalent thermal glass constant. Even though a lens system is composed of many elements, we can simply identify a pair of materials that satisfies the athermal and achromatic conditions, by selecting the corresponding materials for an equivalent lens from an athermal glass map and test them by application of Zemax software for a good solution.

II.THERMAL DEFOCUS

The variations of temperature change the radius of curvature, lens thickness and air spacing, and refractive index. These changes cause alignment errors and degrade the optical performance.An athermal system is meant to have stable optical performance, even during temperature changes in the optical system [6].

Table 1 lists the quantitative variations of design parameters due to temperature change [7], the parameters of n (T), R (T), t (T), and L (T) are measured values after temperature change. The coefficients of a linear thermal expansion (CTE) are designated as α_g for the lens material and αm for the housing material, respectively.

Table 1. Variations of design parameters due to Temperature change [8].

Index	$n(T) = n + dn = n + (dn/dT)\Delta T$
Radius	$R(T) = R + dR = R(1 + \alpha_g \Delta T)$
Thickness	$t(T) = t + dt = t(1 + \alpha_g \Delta T)$
Space	$L(T) = L + dL = L(1 + \alpha_m \Delta T)$
Air	$n_{air}(T) = n_{air} + dn_{air} = n_{air} + (dn_{air}/dT)\Delta T$

The parameter dn/dT denotes the variation of the refractive index with temperature.
The expansion and contraction of a material due to temperature changes is governed by a material's coefficient of thermal expansion, α, which has units of 10-6m/°C (or ppm/°C). The change in length (L) of a material due to a temperature change is given by Equation 1.

$$\Delta L = \alpha L \Delta T \qquad (1)$$

Thermal defocus is the change in the focus position on axis with temperature changes due to the variation of the index of refraction with temperature (dn/dT) and the expansion of the material. The analogous equation quantifying the change in focal length of a lens in air with temperature is given by Equation2:

$$\Delta f = \gamma f \Delta T \qquad (2)$$

Where γ is the therm-optic coefficient.
γ can be defined using Equation 3:

$$\gamma = \frac{1}{n-1}\frac{dn}{dT} - \alpha \qquad (3)$$

Whereα is Coefficient of linear thermal expansion

$$\alpha = \frac{1}{r_1}\frac{dr_1}{dT} = \frac{1}{r_2}\frac{dr_2}{dT}$$

III. ACHROMATIC & ATHERMAL DOUBLET EQUATIONS

A common optical element is the achromatic doublet, which uses a positive and negative element of different materials with equal and opposite amounts of chromatic aberration to correct for color. Assuming an element is in air, the ν-number (inverse dispersion) for an arbitrary waveband defined by the longest, shortest, and middle wavelength is given by Equation 4:

$$\nu = \frac{n_{mid} - 1}{n_{short} - n_{long}} \qquad (4)$$

If Equations 5 and 6 are satisfied, the result is an achromatic doublet, each element is required to have power:

$$\frac{\phi_1}{\phi} = \frac{\nu_1}{\nu_1 - \nu_2} \qquad (5)$$

$$\frac{\phi_2}{\phi} = -\frac{\nu_2}{\nu_1 - \nu_2} \qquad (6)$$

The optimal solution is one that has two elements with the largest ν-number difference: Δν.

A larger Δν results in longer focal lengths (lower power) and shallower radii (reduces aberrations and increases optical performance). By looking at the glass map, it is simple to visually select a crown and flint glass that have a large ν-number difference. Analogously, we can use the inverse of the therm-optic coefficient (equation), usually called the thermal ν number, in our achromatic equations to design an athermal double as follows in Equations 7 and 8:

$$\frac{\phi_1}{\phi} = \frac{\nu_{T1}}{\nu_{T1} - \nu_{T2}} \qquad (7)$$

$$\frac{\phi_2}{\phi} = -\frac{\nu_{T2}}{\nu_{T1} - \nu_{T2}} \qquad (8)$$

If we design a doublet where the achromatic doublet and athermal doublet equations are all satisfied (Equations 5-8), the result is an achrothermic system: a system that is both achromatic and athermal as shown in Equation 9:

$$\frac{\nu_1}{\nu_{T1}} = \frac{\nu_2}{\nu_{T2}} \qquad (9)$$

IV. GRAPHICAL METHOD FOR CHOOSING ACHROTHERM GLASS :

By plotting the therm-optic coefficient (γ) vs. the inverse color ν-number [9], we can visually identify two materials that can be used to develop an achrothermic system, this method not only helps identify two available optical materials, but also helps identify the CTE of the housing material required for a housed achrothermic solution. As shown in Figure 1, the y-intercept provides the required housing material via a line that extends through two materials and crosses the y-axis. In the case that a single housing material with the required CTE is unavailable, the required CTE can be achieved using a bimetallic housing or alternative mechanical mounting solution.

Figure 1 shows the athermal glass map for Schott glass [10]. Involves plotting the thermal glass constant versus the inverse Abbe number, we can visually identify two materials that satisfy the athermal and achromatic conditions [11] .

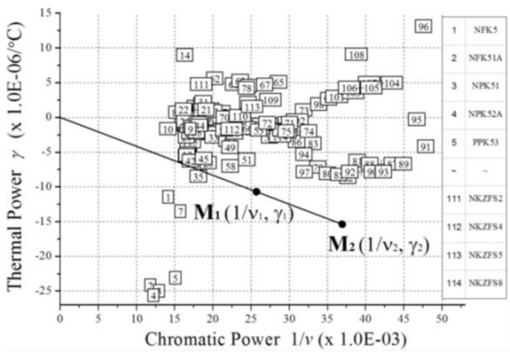


Fig. 1. Athermal glass map plotting □ v.s. 1/νfor visible Schott glasses.

In Fig. 1, any two materials (M1, M2) that can be connected by a line that passes through the origin will provide athermal and achromatic solutions. In other words, if one material is known on an athermal glass map, like M1(1/v1, γ1), then another material(M2) that serves color correction and passive athermalization can be found on a line connecting two materials. Even if a lens system is composed of many elements, the equivalent Abbe number and equivalent thermal glass constant reduce the problem to be that of a two-element system as a doublet. Unlike some of the previous methods using complex triangle geometry [3, 4].

V. RESULT AND DISCUSSION

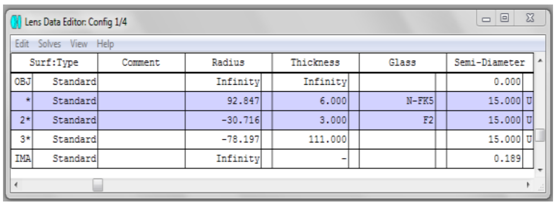
We will use the method as shown in Fig.1 to visually determine exactly what material is required to achromatize and athermalize the multi-lens system. We know we want the slope of two different materials to be equal in order to achieve color correction and athermalization; any two materials that can be connected by a line that passes through the origin will provide an achrothermic solution as shown in table 2.

Table 2. Achrothermic Glasses Used in a Double design.

Number of double achromatic lens	Glass 1	Glass 2
1	N-FK5	F2
2	N-PSK53	SF66
3	BK10	N-BASF2
4	N-KZFS11	N-SF66

Table 2 would provide athermal glasses solution in air for visible. A general expression for the thermal defocus of a system of separated lenses is very complex. In practice, optical design software may be used to aid the designer in developing such an athermal system, So, ZEMAX will used to test double glass shown in Table 2 . The thermal modelling capabilities in ZEMAX optical design software can model changes in refractive indices due to temperature changes and also the expansion/contraction of components. A common optical element is the achromatic doublet, which uses a positive and negative element of different materials with equal and opposite amounts of chromatic aberration to correct for color. Before doing any thermal modeling, We must make sure that all necessary operands affected by temperature change has been inserted in ZEMAX to make athermal design [12] .

The optical design of this system was performed in ZEMAX from Table 2. It is a double type objective designed to image over wavelengths (0.486- 0.656) microns .The lens prescription, optical layout, and performance data are given in Fig.2.


Lens Data Editor: Config 1/4
Edit Solves View Help

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard		Infinity	Infinity		0.000
*	Standard		92.847	6.000	N-FK5	15.000 U
2*	Standard		-30.716	3.000	F2	15.000 U
3*	Standard		-78.197	111.000		15.000 U
IMA	Standard		Infinity	-		0.189

Fig.2. Lens Prescription (units: inches) for double thermal design.

Thickness should be changed in the design above when a pair of glasses tested every time until the image shows clear. The lens layout for double design in Fig.3.

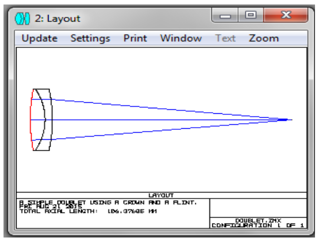
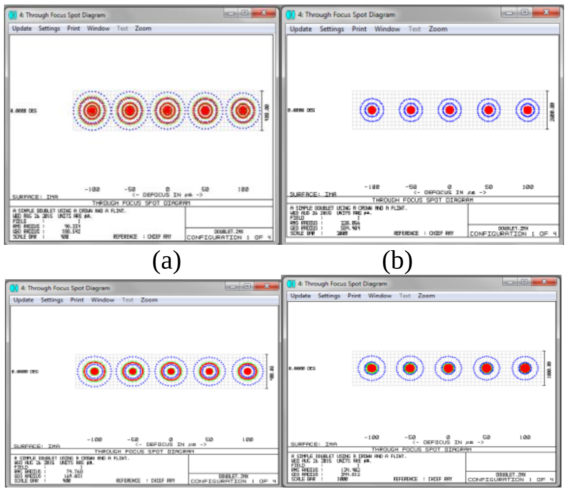


Fig.3. Optical Layout for athermal double design.

The important thing in athermal design is the RMS spot diagram, which shows that with refocusing, the optical performance holds up well over the field of view for extreme observing temperature. Blur sizes at -100^{0}C, 0^{0}C, and +100^{0}C (from left to right) shown in Fig .4.



(a) (b)

(c) (d)

(A) N-FK5-F2 :(B) N-PSK53-SF66: (C) BK10-N-BASF2: (D)N-KZFS11-N-SF66

Fig.4. the spot diagram of a thermal design.

The spot diagrams in Figure 4 show the improvement in lens performance over temperature when the lens is optimized over a temperature range, rather than just at one temperature, Zemax's estimated RMS spot radius is now essentially constant over temperature, All spots are at best focus, this spots are for the athermalized lens.

VI. CONCLUSION

The paper will culminate by demonstrating how a set of two materials can be used to both color correct and passively athermalize a single lens; these materials can be quickly chosen By plotting the thermal glass constant versus the inverse Abbe number, athermal glass maps were derived for Schott glasses in visible light. This graphical method of selecting materials is a simple and powerful way to find athermal design solution. By utilizing the graphs and ZEMAX software presented in this study, an athermal doublet, or lens that does not change focus under temperature changes for an optical instruments lens has been found.

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