SOLUTION FOR THE DESIGN OF THERMAL IR OBJECTIVES

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Abstract: The paper presents a complete design of an IR objective, working within the spectral range of (5…10)μm. Such IR components are appropriate to night vision apparatuses, thermographic cameras or other applications, which collect temperature distribution and turn it into visual signals. Large spectrum IR optical components design is difficult because of the limited offer regarding suited optical materials and lack of specific design algorithms. The paper provides a solution using a pair of materials AsGa-ZnSe and insuring a very good quality of the image. The air-spaced resulted doublet analyzed on the specialized software OSLO belongs to the diffraction limited systems class.

1. INTRODUCTION

Thermal vision is relatively recent, but it is very frequently used in now-days. There are a lot of applications based on transforming the temperature distribution captured by a special IR camera into a visual image. Military night visions, civil surveillance in public or private spaces, industrial or medical thermography are very common examples of IR imagery.

Environmental radiation, including human body, covers a large spectral range, comprising the domain of 5 to 10 μm, which belongs to the infrared electromagnetic radiation. IR cameras sense the difference of temperature between adjacent areas of an object and transfer the information to a converter of signal, which translates the IR information into a visible one. The objectives of such cameras are totally different from the one working with visible radiation. These objectives must be transparent for the IR radiation and must provide a high quality image regarding clarity, contrast and resolution.

There are three major difficulties in IR objectives design:

- ❑ IR transparent materials are available only in a limited number of sorts
- ❑ small number of materials can hardly provide compatible combinations to ensure correction of aberrations
- ❑ design algorithms created for optical components working in the visible range might not fit for IR applications because refractive and dispersive properties of the materials are very different.

2. DESIGN ALGORITHM FOR AN IR OBJECTIVE

Proper image quality imposes the use of a compound objective. The doublet is the first choice, as it assumes the correction of spherical aberration, coma and chromatic aberrations.

By short, the design algorithm of the doublet goes through the following steps [1], [2]:

- ❑ calculus of total curvatures (c_a and c_b) from the condition of chromatic correction:

$$f'_a = \frac{f'(\nu_a - \nu_b)}{\nu_a}, \tag{1}$$

$$f'_b = \frac{f'(\nu_b - \nu_a)}{\nu_b} = -f'_a \frac{\nu_a}{\nu_b}, \tag{2}$$

$$c_a = \frac{1}{f'_a(n_a - 1)}, \tag{3}$$

$$c_b = \frac{1}{f'_b\,(n_b - 1)}, \tag{4}$$

where a, b are the indexes for the first, respectively the second lens, f' – effective focal length, ν - Abbe number, n – refractive index of materials

- paraxial tracing of the marginal ray and principal ray
- calculus of G – sums for both materials using the formulae:

$$G_1 = \frac{1}{2}n^2(n-1),\ G_2 = \frac{1}{2}(2n+1)(n-1), \tag{5}$$

$$G_3 = \frac{1}{2}((3n+1)(n-1),\ G_4 = \frac{1}{2n}(n+2)(n-1), \tag{6}$$

$$G_5 = 2\frac{(n^2-1)}{n},\ G_6 = \frac{1}{2n}(3n+2)(n-1), \tag{7}$$

$$G_7 = \frac{G_2}{n},\quad G_8 = \frac{G_1}{n}. \tag{8}$$

- calculus of curvatures c_1 and c_3 from the conditions of correcting coma and spherical aberration:

$$\sum CC = CC_a + CC_b = 0, \tag{9}$$

where CC is the coma contribution of a lens.
Equation (9) gives a linear relationship between curvatures c_1 and c_3:

$$c_3 = k_1 c_1 + k_2, \tag{10}$$

where

$$k_1 = -\frac{G_{5a}c_a}{G_{5b}c_b}, \tag{11}$$

$$k_2 = \frac{1}{0.25G_{5b}c_b}\left(G_{7a}c_a p_a + G_{8a}c_a^2 + G_{7b}c_b p_b + G_{8b}c_b^2\right). \tag{12}$$

The condition to annul the spherical aberration may be written as:

$$\sum TSC = TSC_a + TSC_b = 0, \tag{13}$$

where TSC is the transversal spherical contribution of a lens.
Relations (9) and (13) provide a second degree equation with the unknown variable c_1:

$$k_3 c_1^2 + k_4 c_1 + k_5 = 0, \tag{14}$$

where

$$k_3 = G_{4a}c_a + G_{4b}c_b k_1^2, \tag{15}$$

$$k_4 = -G_{5a}c_a p_a - G_{2b}c_b^2 k_1 + 2G_{4b}c_b k_1 k_2 - G_{5b}c_b k_1 p_b - G_{2a}c_a^2, \tag{16}$$

$$\begin{aligned} k_5 = {} & G_{1a}c_a^3 + G_{3a}c_a^2 p_a + G_{6a}c_a p_a^2 + G_{3b}c_b^2 p_b + G_{6b}c_b p_b^2 - \\ & - G_{2b}c_b^2 k_2 + G_{4b}c_b k_2^2 - G_{5b}c_b p_b k_2 + G_{1b}c_b^3 \end{aligned}. \tag{17}$$

- having the values of c_1, c_3, c_a, and c_b the other two curvatures result as:

$$c_2 = c_1 - c_a, \tag{18}$$

$$c_4 = c_3 - c_b. \tag{19}$$

The effective shape of the doublet depends on the given aperture and chosen pair of materials. There are three classical groups of shapes possible to obtain: Fraunhofer- type (edge contact, cemented and center contact), Gauss-type and Steinheill-type (fig.1).

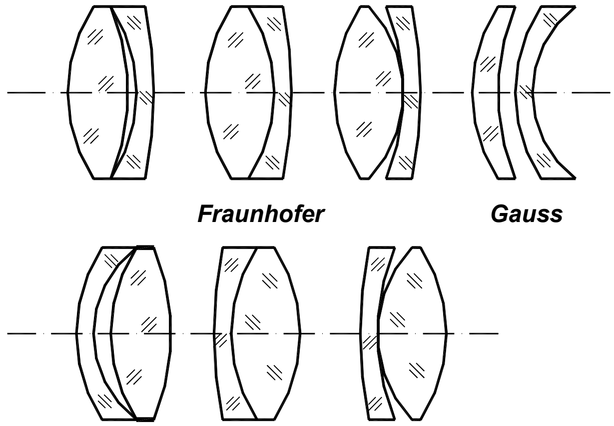


Fig. 1 Geometrical shapes of the doublet

- introduction of center thicknesses
- analysis of residual aberrations.

3. NUMERICAL APPLICATION

The primary input data for doublet are:

- EFL (f') = 100 mm
- D = 16 mm (corresponding to f/# = 1/6.25)
- object abscissa = - ∞
- half field angle = 5^o
- working spectral range: (5…10) μm.

The main problem consisted in finding a compatible pair of materials, so that equation (14) admits real roots. The final choice went to the pair GaAs – ZnSe, whose refractive properties are presented in table 1.

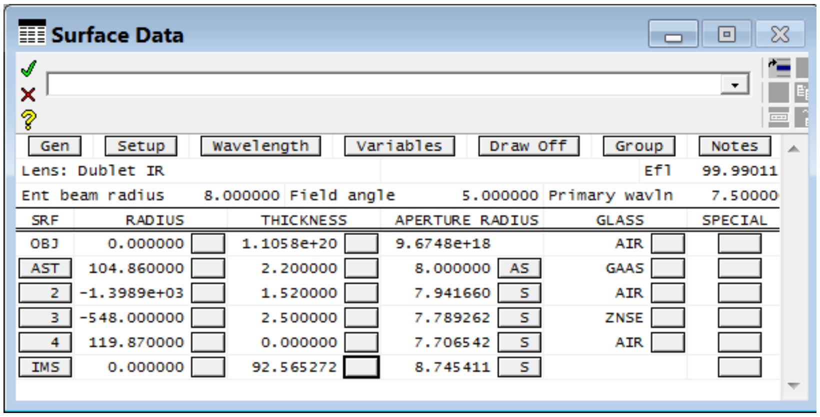
Table 1 Optical properties of GaAs and ZnSe [3]

Material	$n_{(\lambda = 5)\mu m}$	$n_{(\lambda = 7.4)\mu m}$	$n_{(\lambda = 10)\mu m}$	Transmission factor [%]/sample thickness [mm]
GaAs	3.3010	3.2905	3.2770	>0.5/7
ZnSe	2.4295	2.4201	2.4053	>0.7/6.3

Applying the algorithm described above, resulted the following solution:

- r_1 = 104.86
- $r_2 = \infty$
- r_3 = - 548
- r_4 = 119.87
- d_1 = 2.2
- d_2 = 1.52
- d_3 = 2.5
- f' =99.99.

Figure 1 shows data above introduced into the Surface Data window of the analysis software OSLO LT.



Surface Data

Gen | Setup | Wavelength | Variables | Draw Off | Group | Notes

Lens: Dublet IR — Efl 99.99011

Ent beam radius 8.000000 — Field angle 5.000000 — Primary wavln 7.50000

SRF	RADIUS	THICKNESS	APERTURE RADIUS		GLASS	SPECIAL
OBJ	0.000000	1.1058e+20	9.6748e+18		AIR	
AST	104.860000	2.200000	8.000000	AS	GAAS	
2	-1.3989e+03	1.520000	7.941660	S	AIR	
3	-548.000000	2.500000	7.789262	S	ZNSE	
4	119.870000	0.000000	7.706542	S	AIR	
IMS	0.000000	92.565272	8.745411	S		

Fig*. 1. *Geometrical and general properties of the doublet

The following figures illustrate the results of the optical quality evaluation, performed automatically by the software on the IR doublet. In figure 2, the right – down section provides a scaled scheme of the optical system.

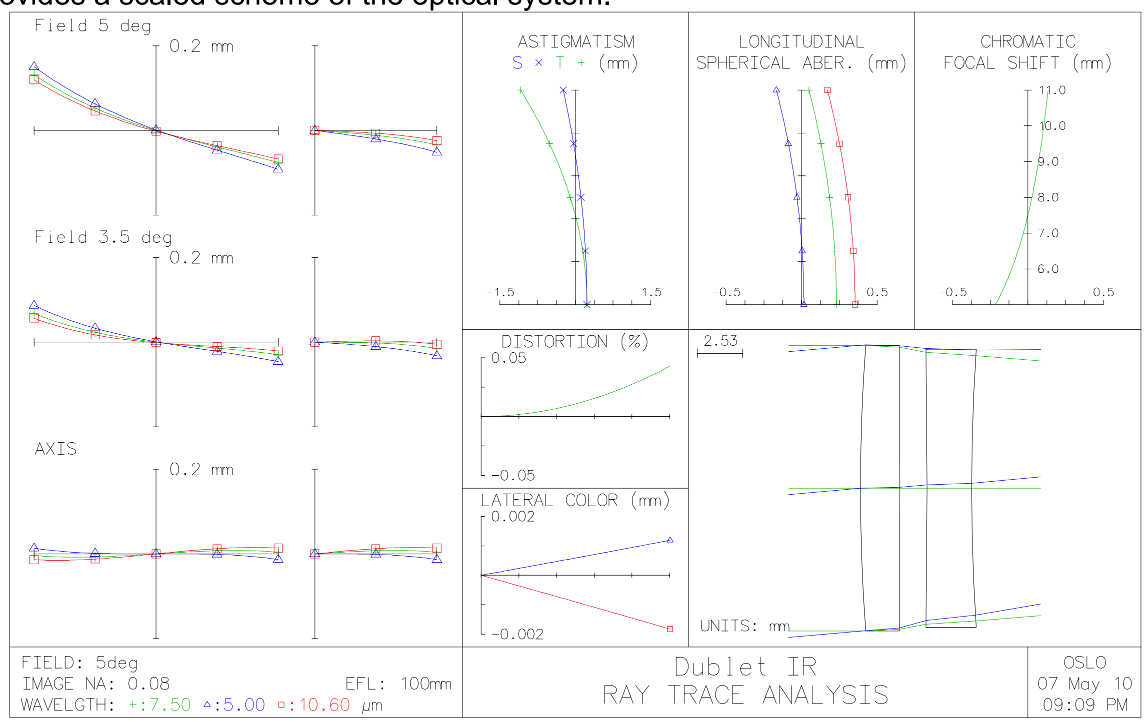


Fig. 2. Optical scheme, geometrical and chromatic aberrations of the IR doublet

The left – down section of figure 2 indicates that the reference spectral line is λ=7.5μm and that the spectral limits of the working domain are λ=5μm, respectively λ=10μm. Colours green, blue and red are assigned to these spectral lines in graphical representations of sphero-chromatism, distortion, lateral color and tangential ray intercept.

For the given aperture and considering the high refractive indexes, the spherical aberration is reasonably small. The chromatic aberrations are even negligible, taking into account the band-width. The chromatic focal shift is less than 0.1 mm all over the range.

Distortion and lateral colour are also far too small to alter the image quality.

Astigmatism is pretty small for a 10^o field.

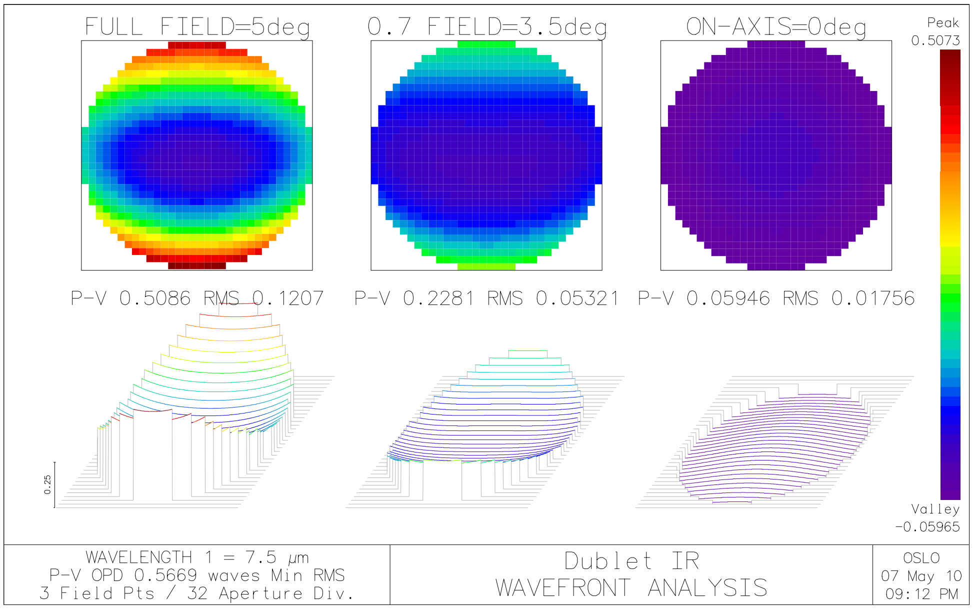


Fig. 3. Results of wavefront analysis of the IR doublet

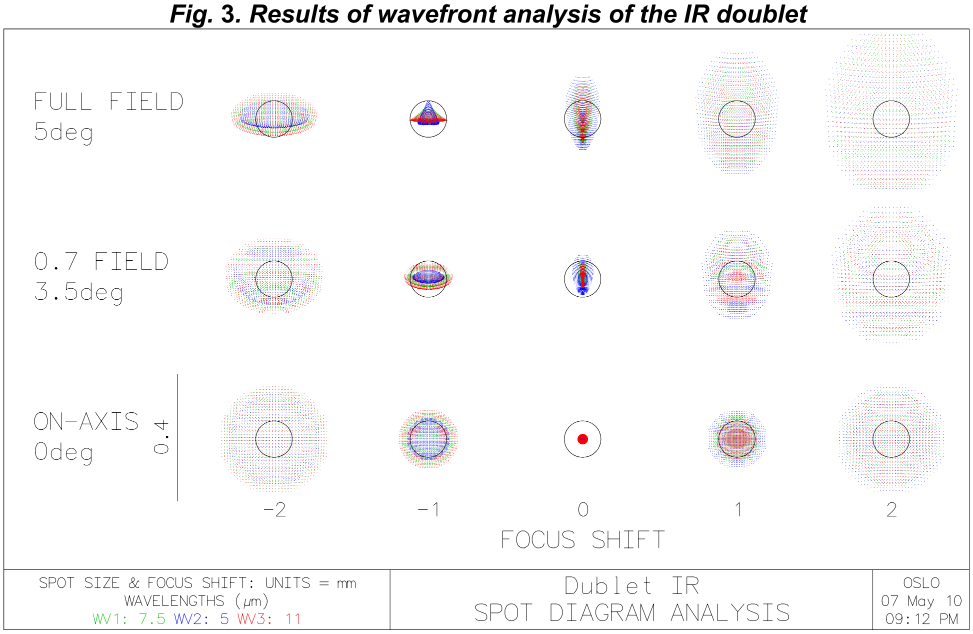


Fig. 4. Spot diagram for five focus abscissas and three field angles

Wave wise, the doublet is diffraction limited over two thirds of the aperture, where RMS OPD is less than 0.25λ (accordingly to Rayleigh criterion), as figure 3 renders.

The abscissa of the image plane was optimized on the criterion of minimum RMS OPD – on axis and the spot diagram analysis (fig. 4) confirms the correctness of the resulted position for the receiver of radiation. The black circles on the spot diagrams indicate the size of the theoretical Airy circle.

The Fourier analysis provides the PSF representation (fig. 5) and the course of MTF and PTF of the system (fig. 6). A value of 0.98 for PSF surely indicates a diffraction limited optical system. Figure 6 is very important as it is the only one to characterize the resolution and global illumination of the image. The cut-off spatial frequency happens to be 32 cycles/mm, which coincides with the limit resolution of the human eye. That means the thermal sensor must have at least the same resolution in order to preserve the objective's quality along the entire optical system.

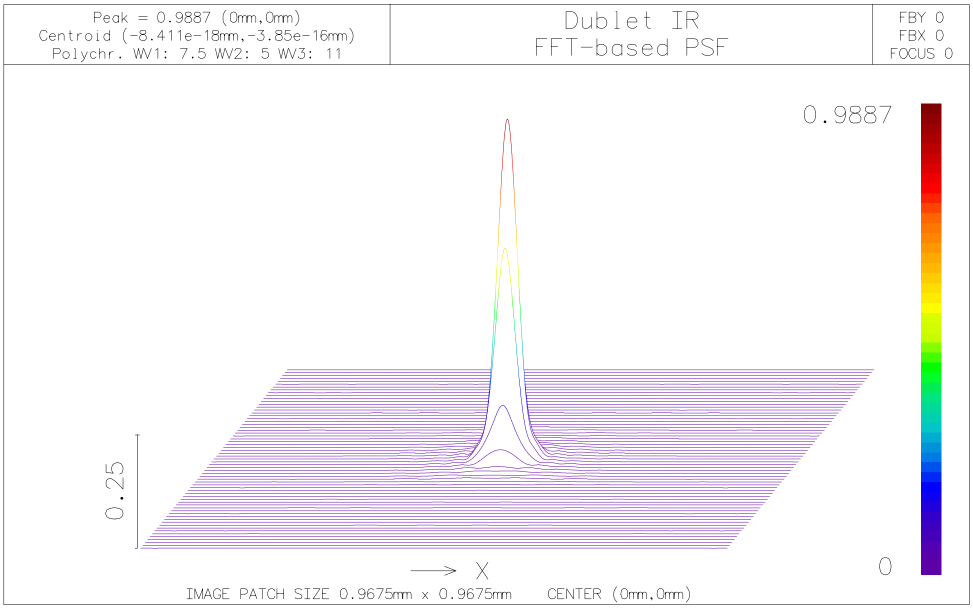


Fig. 5. PSF of the IR doublet

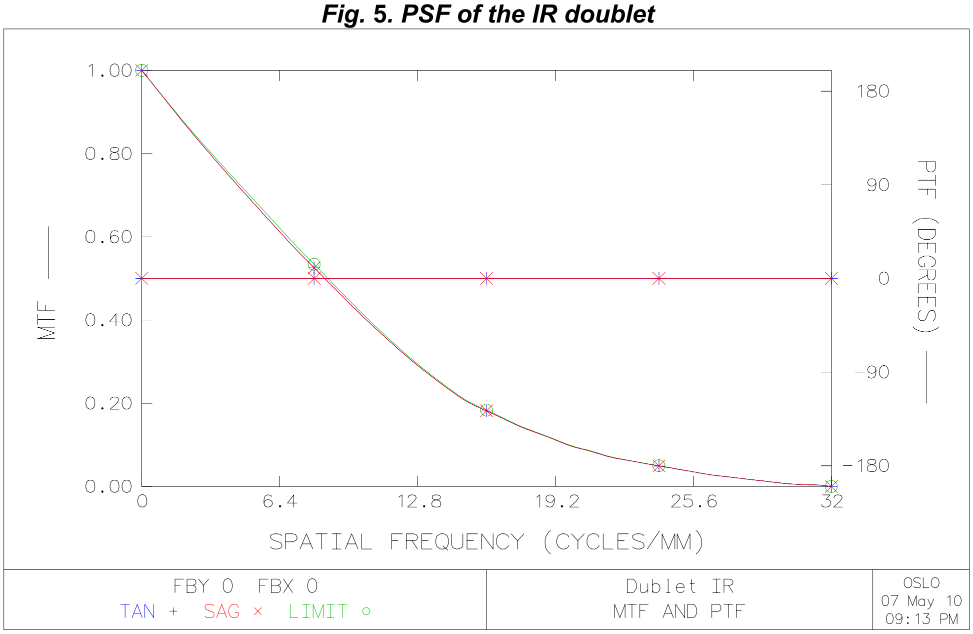


Fig. 6. MTF and PTF of the IR doublet

4. CONCLUSIONS

Traditional design algorithms created for components working in the visible range can be adjusted for high quality IR applications. Specific problems occur due to extended spectral band, high refractive indexes of IR materials and limited number of sorts available for such materials. Skills and expertise in optical design allow getting very good quality systems for infrared application, such as the solution presented above.

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