The optical design of highly efficient cold shield in IR detector based on ASAP

Xianjing Zhang1, Jian Bai1,*, and Shuang Yin2
1 State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou, 310027, P.R.China
E-mail: bai@zju.edu.cn
2 Kunming Institute of Physics, Yunnan, 650223, P.R.China

Abstract. In order to obtain higher stray radiation suppression of a cold shield and enhance the cold shield efficiency of cooled infrared system, different configurations of the vanes inside cold shield are proposed. The effects of these configurations of vanes on stray radiation suppression are simulated and analysed by Advanced Systems Analysis Program (ASAP software), which not only trace ray by Monte Carlo method but also simulate the scattering of each surface. According to the analysis of results, vane plays an important role in the improvement of cold shield efficiency and the suppression of stray radiation. The cold shield with 6 vanes characterized by rounded-square hole, whose configuration is calculated based on the principle of laying out a set of vanes, suppresses 99.5% more stray radiation comparing to the original one without any vanes. However, considering that the cold shield with 6 vanes is complicated and difficult to fabricate, the cold shield with 3 vanes owing rounded-square hole is selected, since its stray radiation suppression level is acceptable.

1. Introduction
In infrared system, stray radiation is the radiation that is received by the detector [1,2], but does not originate from the conjugate object plane [3]. It will reduce signal to noise ratio(SNR) and may damage the optical components inside, especially in thermal imaging systems. Nowadays, since the resolution of detector reaching diffraction limit, higher level stray radiation suppression is imperative to enhance cold shield efficiency [4]. In cooled infrared system, cold shield is of great importance in decreasing the amount of stray radiation incident into the detector and increasing the SNR of system. 100% cold shield efficiency will be achieved when the cold shield is on the exit pupil, indicating no out-of-field thermal radiation is propagating to the detector. However, considering surface scattering and spontaneous radiation of internal objects, it is impossible to achieve 100% cold shield efficiency. Furthermore, with the goal of obtaining a compact structure, most of the infrared systems get far below 100% cold shield efficiency, and some are even less than 50% [5]. In this paper, different configurations of vanes are proposed to improve cold shield efficiency of the cooled infrared system.

2. Theory
According to radiation transfer formula [7], scattering radiation from an infinitesimal area propagates to an infinitesimal detector area. And the radiation flux $d\Phi_c$ received by this infinitesimal detector area can be calculated by the following formula:

$$d\Phi_c = d\Phi_s(\theta_s, \phi_s)BRDF(\theta_\epsilon, \phi_\epsilon;\theta_\epsilon, \phi_\epsilon)GCF_{\epsilon_c} \pi$$

(1)
Where \( d\Phi_s(\theta, \phi) \) is the radiation flux scattered from the infinitesimal source area as a function of scattering angle \( \theta \) and azimuth \( \phi \); \( BRDF(\theta_s, \phi_s; \theta_i, \phi_i) \) is the bidirectional reflectance distribution function of the scattering source surface, \( \theta_i, \phi_i \) are reflecting angle and reflecting azimuth respectively; \( GCF_{\omega, \pi} \) is called geometrical configuration factor, which represents the projected solid angle from scattering source area to the detector area.

Apparently, in equation (1), the radiation flux \( d\Phi_s \) received by infinitesimal detector area can be reduced by decreasing the three terms on the right hand of the equation.

- Decrease \( d\Phi_s(\theta, \phi) \): reduce the spontaneous radiation from internal objects by lowering the temperature of workspace \(^{[8]}\).
- Decrease \( BRDF(\theta_s, \phi_s; \theta_i, \phi_i) \): improve the absorption of surfaces by the process of nigrescence or choosing a special material with high absorption and low emittance.
- Decrease \( GCF_{\omega, \pi} \): block the transmission paths of stray radiation by adding an aperture or some vanes inside the system.

Once one of the above three factors reaching zero, the detector plane will not be illuminated by stray radiation. Actually, no material can achieve 100% absorption, and spontaneous radiation would always exist no matter how low the temperature of workspace is. Obviously, \( GCF_{\omega, \pi} \) is the only factor that could equal to zero so it is the key point in this study.

The energy of the radiation can be reduced when the radiation is scattered or absorbed. When the absorption of one surface reaches 90%, the attenuation coefficient would be \( 0.1^n \) (\( n \) is the times that radiation hits surfaces before it gets to detector). Obviously, the more times stray radiation is scattered or absorbed, the greater its energy would be attenuated.

3. Modeling

There are three different parts as shown in this section, presenting the modeling of the cold shield system.

3.1. Scattering model

The inside walls of cold shield and the surfaces of vanes are both considered as Lambertian diffusers after the process of nigrescence. When each stray radiation hits surface of internal walls or vanes, additional radiation with different directions is generated, based on the Lambertian scattering properties.

In ASAP software, these can be simulated precisely. In addition, children radiation that is split from parent radiation after hitting the surface, can also be traced in this software.

3.2. Modeling of radiation source

A disk radiator placed at the entrance of cold shield is regarded as radiation source. Each point on the disk is considered as a point source emitting hemispherical radiation that can be catalogued as stray radiation and imaging radiation. Spherical coordinates are selected to describe the discrete radiation illuminated from each point source in the convenience of calculation. The whole system is axis-symmetrical, and so is the imaging information on the detector. Hence, only the point sources in first quadrant are necessary to simulate in consideration of efficiency. The imaging of other three quadrants could be calculated, thus the total flux distribution on the detector is obtained by making a superposition.

3.3. Modeling of vanes

Vanes can be used to reduce the amount of radiation that is reflected or scattered from the internal walls of an infrared system. As shown in the upper part in figure 1, out-of-field radiation would be reflected from the internal walls and split into several radiation, while in the lower part of figure 1, stray radiation is obscured by vanes and could not reach the detector directly.
Therefore, some configurations of vanes inside the system are proposed to minimize the stray radiation reaching the detector \cite{6}. The crucial point to making efficient utilization of vanes is to arrange them in positions so that no out-of-field radiation can illuminate to any part of the detector directly \cite{11}. The principle of laying out a set of vanes is illustrated in figure 2.

The principle of laying out a set of vanes is illustrated in figure 2. The necessary clearance space is indicated by the hidden lines \textit{CD} and \textit{AB} from the rim of the cold shield to the edge of the detector. Vanes cannot be intruded in the clearance space without blocking part of the radiation from the desired field of view. The dashed line \textit{MB} is the critical line where the extraneous radiation begins from the point on the internal wall to the rim of the detector. The first vane is placed at the intersection of the dashed line \textit{MB} and the hidden clearance line \textit{CD}. The solid line \textit{AM1} indicates the path of radiation from the rim of the cold shield to the internal wall. The area between first vane and the solid line \textit{AM1} is shadowed and cannot be seen by any part of the detector. The dashed line \textit{M2B} is another critical line, and the second vane is set up at the intersection of the dashed line \textit{M2B} and the hidden clearance line \textit{CD}. These procedures are repeated until no radiation from internal walls could illuminate to the detector directly.

However, if the effect of stray radiation suppression reaches the basic requirements, the number of vanes added inside the detector should be reduced and the complexity of cold shield should be reduced in consideration of cost and the influence of diffraction.

4. Simulation and Results

In this study, kinds of configurations are designed and simulated by ASAP software, including cold shields with several annular vanes (shorted as AN), with vanes which have rounded-square hole (shorted as RS) and the original one without vanes. The former two configurations are showed in figure 3, in which detector is marked as red, vanes are marked as green, and cold shield is marked as gray.

In this simulation, the internal walls of cold shield and the surfaces of vanes are regarded as Lambertian scattering bodies with the absorption of 93\%. The thickness of each vane, which is ought to be about 0.1 millimetres, is being ignored during this simulation since it would have little influence on the results. Moreover, the absorption of detector is supposed to be 100\% while it could not be achieved actually. The detector is partitioned into $251 \times 251$ multi-pixel squares for the convenience of analysis, by each the flux received can be obtained if it is necessary. And the flux of stray radiation is supposed to be 1000, while the total flux of whole radiation is 100000.
The result of stray radiation received by the detector is showed as Table 1 (A, B, C means the different arrangements of the vanes' positions; example: 3RS vanes(A) is shorted for 3 rounded-square vanes in Configuration A). According to the design principle mentioned in section 3.3, configuration C is obtained, including the number of vanes and the position each vane laid. In consideration of manufacturing cost and the influence of diffraction, configuration A and configuration B, both containing only 3 vanes, are proposed and simulated. And the cold shield without vanes is also considered for comparison.

**Table 1.** the stray radiation illuminate to the detector in each cold shield added with different configurations of vanes based on the simulation results in ASAP software

| Configuration      | Max Flux/square | Min Flux/square | RMS Flux/square | Total Flux |
|--------------------|-----------------|-----------------|-----------------|------------|
| 6 RS vanes(C)      | 0.0092          | 3.84E-07        | 0.0011          | 1.1716     |
| 6 AN vanes(C)      | 0.3392          | 1.67E-06        | 0.0070          | 1.6848     |
| 3 RS vanes(A)      | 0.7336          | 1.60E-06        | 0.0274          | 6.6723     |
| 3 RS vanes(B)      | 0.4927          | 1.57E-06        | 0.0161          | 4.2756     |
| 3 AN vanes(A)      | 0.7999          | 5.22E-06        | 0.0406          | 14.5104    |
| 3 AN vanes(B)      | 0.4930          | 1.02E-05        | 0.0228          | 9.8298     |
| No vanes           | 3.3422          | 1.58E-04        | 0.1716          | 234.1491   |

According to the results in table 1, detector in the cold shield added with vanes receive less illumination compared to the original cold shield and the more vanes are added into the cold shield, the less stray radiation illuminate into the detector. Moreover, vane with a rounded-square hole gets better effect on stray radiation suppression than the annular one. In the situation of using 3 vanes, configuration B does a better job than configuration A as a whole. Among these simulated flux distributions of different configurations, configuration of 6 RS vanes reduces 99.9% stray radiation to reach the detector, which suppresses 99.5% more compare to the original one without any vanes.

After a superposition and interpolating operation, the flux distributions of 6 AN vanes(C) and 6 RS vanes(C) are showed in figure 4 and figure 5 respectively. As is shown in figure 5, the flux of every multi-pixel square is lower than 0.008, which decreases two order of magnitude in comparison to the maximum one in figure 4. In figure 4, the flux received by the four corners of detector is much greater than which received by the other places of the detector. It illustrated that annular vane does not block...
out-of-field radiation completely and there is some stray radiation illuminate to the rim of the detector plane directly. Obviously, the configuration of 6 RS vanes is better at stray radiation suppression.

Figure 4. The flux distribution of 6 AN vanes(C)(colour online).

Considering that the cold shield with 6 vanes is complicated to fabricate and would have more influence on diffraction, though the cold shield with 6 RS vanes has a perfect effect on stray radiation suppression, it is wise to decrease the number of vanes as a widespread product. Based on the results in table 1, the configuration of 3 RS vanes(B), which suppress 98% more stray radiation comparing to the original one without any vanes, has an advantage on blocking stray radiation comparing to the other configurations of 3 vanes. The flux distribution of 3 RS vanes is showed in figure 6. Hence, a compare among 6 RS vanes, 6 AN vanes and 3 RS(B) vanes is made. The configuration of 6 RS vanes get far less stray radiation on detector while the the gap between 6 AN vanes and 3 RS(B) vanes on stray radiation suppression is not wide. Therefore, the cold shield added with 3 RS vanes(B) is choosen as a compromise proposal.

Figure 5. The flux distribution of 6 RS vanes(C)(colour online).
5. Conclusion
In this paper, several configurations of vanes inside cold shield are designed and simulated, and the results presented in this paper are summarized as follows:

- Vane plays an important part in minimizing background radiation and enhancing cold shield efficiency of cooled infrared systems.
- Vane with a rounded-square hole is more effective on stray radiation suppression than the annular vane.
- Cold shield added with 6 RS vanes(C) has the best effect on stray radiation suppression, but the one added with 3 RS vanes(B) is selected in consideration of cost and the influence of diffraction.

Acknowledgment
This study is supported by Kunming Institute of Physics.

Reference
[1] Pancrazzi M, Vives S, Landini F, Guillon C, Escolle C and Garcia J. 2013 Optimization of baffle configuration for stray light reduction Proc. SPIE Optical Engineering Applications, International Society for Optics and Photonics (California, US, 25 August 2013) pp 886205-886205
[2] Jinxing N, Shuheng S and Renkui Z 2011 Analysis to stray radiation of infrared detecting system Proc. International Symposium on Photoelectronic Detection and Imaging, International Society for Optics and Photonics (Beijing, China, 24 May 2011) pp 81931H-81931H
[3] Scholl M S, Pérez-Padilla G 1997 Using the y, y-bar diagram to control stray light noise in IR systems Infrared phys. & techn. 38 25-30
[4] Breault R P. 1977 Problems and techniques in stray radiation suppression Proc. SPIE/SPSE Technical Symposium East. International Society for Optics and Photonics (Reston, 18 April 1977) pp 2-23
[5] Kaiyu Y, Ning J, Ling C and Man X 2012 Calculation of energy distribution in image plane for all shapes of cold shields Infrared Laser Eng. 7 009
[6] Breault R P. 1995 Control of stray light Handbook of Optics 1 38-1
[7] Xia W, Sun W, Xiao kun W and Yanjin L 2012 Study on stray light suppression in IRFPA Dewar Conf. 6th International Symposium on Advanced Optical Manufacturing and Testing Technologies, International Society for Optics and Photonics (Xiamen, China, 26 April 2012) pp 84172I-84172I
[8] Xiao J, Xiuwen Y, Bin Z, Shuguang Z and Pan H 2010 The influence of the thermal environment on the stray light performances of infrared telescope systems Conf. 5th International Symposium on Advanced Optical Manufacturing and Testing Technologies, International Society for Optics and Photonics (Dalian, China, 26 April 2010) pp 76540V-76540V

[9] Yan Z. 2010 Study of Stray Light Suppression by Cold Shield in Dewar Infrared 7002

[10] Zhiqiang H, Tingwen X 2006 Principle and realization of baffle and vane’s programmable design Opto-Electronic Engineering 33 135-142

[11] Smith W J. 1966 Modern optical engineering (Tata McGraw-Hill Education) pp 148-150