Optical system design of multispectral video camera for 8-14 microns range

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Abstract. To solve the actual problem of determining the composition of a gas mixture in an uncontrolled leak at industrial sites, it is proposed to use a multispectral camera that allows you to simultaneously form several spectral images on a bolometric matrix. This method will provide visualization of the gas cloud in the far infrared range from 8 to 14 micrometers with selection by chemical composition. The article proposes an optical scheme for simultaneous registration of images in eight narrow spectral ranges of wavelengths, as well as the design of its elements for a bolometric matrix with a resolution of 640x480 pixels: a lens, a raster, and light filters using the ZEMAX application software package. As a result of the design, a low F-number three-lens optical system for a necessary field of view and a raster with a block of light filters are obtained, forming sixteen images in different spectral ranges. Thus, we solved an issue of design an optical system with minimal aberrations for a multispectral camera.

1. Introduction
In our work, we focused on the multispectral range. The goal was to find and identify leaks of various gases in the LWIR spectral range. The current trend in creating multispectral cameras is to create optoelectronic devices with separate reception channels and photodetectors, while our solution is to simultaneously register an image with one optical system, which is then built on a matrix simultaneously in eight narrow-spectral wavelength ranges.

The advantage of a multispectral camera is that its infrared sensor is divided into a mosaic of tiny optical filters. Each filter passes through separate infrared regions of the spectrum, blocking the rest. In figure 1 below, you can see graphs with absorption lines from 8 μm to 14 μm – the spectral range that we choose to detect gases that are very relevant for indication in the oil and gas industry [1].

We selected 8 gases: propane C₃H₈, butane C₄H₁₀, methane CH₄, ethane C₂H₆, acetylene C₂H₂, carbon monoxide CO, carbon dioxide CO₂, ammonia NH₃, hydrogen sulfide H₂S. We have identified the strongest absorption lines (figure 1), which are at a distance from each other (this is an important fact to avoid overlap). The second critical point is that all these lines are located outside the water absorption zones. Water is the main factor interfering with gas spectroscopy, since it has absorption lines in almost all spectra.

To obtain 16 spectral images, we use 16 narrow-spectrum optical filters that characterize the absorption of a particular gas. At the same time, work was carried out to study the absorption spectra in the range of the maximum sensitivity of the bolometric matrix, i.e. in the range from 8 μm to 14 μm. The idea is that the receiving lens forms an image of the object in space, which is then collected by 16 separate raster lenses on its part of the matrix (figure 2). This approach allows you to increase the speed of collecting spatial-spectral data, optimize their analytical capabilities, and create methods for visualizing objects [2].
Figure 1. Absorption lines of different gases.

Our technology uses an electromagnetic spectrum in the range of 8 µm to 14 µm to search for hydrocarbon leaks, which ensures high measurement accuracy. In addition, this region corresponds to the "transparency windows" of the atmosphere, so it is characterized by low radiation absorption. The detector arrays currently contain at least 320×240 pixels, which makes it possible to obtain a high-resolution image with this device [3]. But this requires a low F-number lens with image quality close to the diffraction limit. Optical materials suitable for operation in this range of the spectrum, such as germanium monocrystalline, have a high cost, so it is extremely important to reduce the number of components of the optical system of a thermal imaging lens [4–5].

The technical result of this idea is the possibility of determining the spatial distribution of temperature and emissivity over the surface of objects without mechanical or spectral scanning by simultaneously registering several digital images in the narrow spectral ranges of ultraviolet, visible or infrared radiation. The uncooled 640×512 detector allows you to install up to 16 filters, the spectral characteristics of which was selected after analyzing the absorption spectra of several gases. The presence of these gases at an industrial facility is associated with the constant monitoring of the concentration of these gases in the working area of the enterprise. An array of data was processed to get the desired configuration. In the future, it will be possible to calculate the gas concentration and color the gas type in the image with the appropriate color in real time, based on data obtained using the software included in the system. Technically, we put a very narrow optical filter on each channel (16 channels), we use duplication, so one gas is 2 channels.

Figure 2. Example of building an image with 16 raster lenses.
We use a method for determining the spatial distribution of temperature and emissivity over the surface of an object, which consists in forming a light beam of broadband radiation $I(\lambda)$ emanating from the object; dividing this beam using a lens raster consisting of 16 lenses into 16 light rays carrying the image. Next, spectral filtering of these rays takes place using a raster installed after the lens, consisting of light filters, the number and position of which correspond to the number and position of the lenses in the lens raster, and the transmission curves correspond to the specified positions of the spectral channels. Simultaneous recording of 16 spectral images by a matrix radiation detector and joint digital processing of these images. This makes it possible to register simultaneously 16 spectrally separated (non-overlapping) images of an object. By digitally processing the totality of these images, the spatial distribution of temperature and emissivity at each point of the object is calculated [6].

The principle is explained in the figure 3 below. The diagram shows a block diagram explaining the described method, where: 1 – object, 2 – optical system, 3 – lens raster, 4 – light filter raster, 5 – spectral images, 6 – matrix radiation detector.

![Figure 3](image_url)

Figure 3. Explanation of a raster and filters functions.

The scheme can be implemented on the basis of a device consisting of optically connected and sequentially arranged elements: the optical system (2) forms a light beam of broadband radiation $I(\lambda)$ emanating from the object (1); a lens raster (3) consisting of 16 lenses and forming 16 broadband images of the object (1), a raster of 16 light filters (4) and a matrix radiation detector (6).

A feature of this scheme is that between the optical system (2) and the matrix detector (6), a raster (3) consisting of a number of lenses, the image (5) of the object (1) is focused on the matrix detector (6); and that in front of the matrix detector (6) there is a raster (4) consisting of filters, the number and position of which correspond to the number and position of lenses in the raster, and the transmission curve of these filters corresponds to the specified parameters of spectral channels.

It is necessary to calculate the small raster lenses that will need to be installed in the immediate vicinity of the infrared sensor, along with the filters. Typically, multispectral cameras use optical filter turrets to produce multiple spectral images on a single detector, but the huge disadvantage of this scheme is the time gap between the registrations of images in different spectra. For example, getting an image in the 10-spectral range for hyperspectral cameras takes about 10 seconds. This time is more than enough to lose the position of the gas cloud – as a result, each image is recorded in different environmental
conditions. In our innovative scheme, we get an image in a wide spectral range from 8 µm to 14 µm in less than one second.

This eliminates the need for a consistent spectrum realignment. As a result, the device based on the proposed method is characterized by a high registration speed, determined only by the exposure time of the radiation detector, compactness, high spectral resolution, the absence of moving elements and the ability to work in any spectral ranges. In this case, the spatial resolution of the device is determined by the resolution of the used matrix photodetector of radiation and the required number of spectral channels of the used mosaic raster [7].

![Figure 4. Optical scheme of the final lens.]

2. Optical scheme design
The current level of development of thermal imaging devices and systems involves improving the lenses of thermal imagers. Due to the trend of increasing the format of modern matrix photodetectors and reducing the pixel size, there is a need to develop new optical systems [8]. A conventional lens for large-format cooled photodetectors is based on the principle of using an intermediate image plane. Its disadvantages are a narrow field of view, large weight and large dimensions. We use a sensor that is a bolometric matrix with a resolution of 640×512 pixels, the pixel size is 17 µm.

![Figure 5. RMS wavefront error.]

| Unit | Same as µm | Airy Radius | Same as µm | Bull's Eye | Same as µm | 95% Confidence | Same as µm |bull' s Eye | Configuration 04_01_18 | same as µm |bull' s Eye | Configuration 04_01_18 | same as µm |bull' s Eye | Configuration 04_01_18 |
|------|-------------|-------------|-------------|------------|-------------|----------------|-------------|------------|-------------------------|-------------|------------|-------------------------|-------------|------------|-------------------------|
| 12.04 | 0.60       | 52.01       | 10.42       | 6.14       | 54.40       |
| 16.08 | 0.83       | 34.32       | 7.14        | 6.14       | 54.40       |
| 20.10 | 1.21       | 27.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 30.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 33.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 36.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 39.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 42.00       | 7.14        | 9.24       | 54.40       |
| 20.10 | 1.21       | 45.00       | 7.14        | 9.24       | 54.40       |
To calculate the optical system, we use a computer program that helps automate the process of calculating optical elements – ZEMAX. In the program, we set the input pupil diameter, the angular field of view of the optical system of $25 \times 25$ degrees and wavelengths from $8 \, \mu m$ to $16 \, \mu m$. We get three lenses for the lens and a paraxial lens that simulates the raster at the time of calculation. It is necessary to strictly limit the diameter of the exit pupil diameter, the overall focus of the system, and it is important that the selected distance of the paraxial lens is equal to the distance to the image (thus, a relative opening is provided). We introduce all these restrictions into the program, give weight to each of them, and run the RMS optimization. After optimization, we replace the paraxial lens with a raster and slightly optimize the system using the same constraints. The optical scheme of the final lens is shown in figure 4 below.

We received an optical scheme with the following characteristics: $f' = 4.49 \, mm$, $D/f' = 1:2.1$, total length $L = 46 \, mm$, diameter of the first surface $\varnothing 1 = 12.4 \, mm$, diameter of the last surface $\varnothing 6 = 8.6 \, mm$. The analysis of the root-mean-square deviation of the wavefront is shown in the figure 5 below. The result of the calculation is a diffraction-limited system.

3. Conclusion
Analysis of the design shows that this lens can be used as part of the optical system for a future multispectral camera. One of the applications of this camera is the analysis of the gas composition, when it is necessary not only to visualize the gas output, but also to identify the composition of the gas mixture by 8 main components due to the multispectral characteristics of the gas. The small size and weight of the lens allow it to be used on wearable devices, allowing the operator to perform the inspection using a portable device. The production of all lenses from a single material–germanium – minimizes production costs.

References
[1] Bryant K R 2004 Patent US 6999231 B2
[2] Bayya S S, Gibson D J, Nguyen V Q, Sanghera J S and Vizgaitis J 2014 Patent US 9658105 B2
[3] Treado P, Nelson M and Gardner C 2012 Patent US 0062697 A1
[4] Kester R T, Hagen N A 2012 Patent US 9625318 B2
[5] Holma H, Roos A, Hyvärinen T, Mattila A-J and Kormano I. 2012 Thermal hyperspectral imagers and their applications In Specim Spectral Imaging Ltd
[6] Machikhin A, Batshev V and Neverov S 2020 Patent RU 2 721 097 C1
[7] Neverov S 2019 J. Phys.: Conf. Ser. 1421 012046
[8] Zhang E Y W 2002 Patent US 0030163 A1