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IR Thermographic System Supplied with an Ordered Fiber Bundle for Investigation of Power Engineering Equipment and Units

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Abstract

In this article, the authors propose an IR imaging system, supplied with an IR bundle of ordered silver halide fibers, for the acquisition of 2D temperature field distribution in hard-to-reach places. We assessed crosstalk between neighboring individual fibers of the bundle, carried out calibration of the IR imaging system, and determined modelled defects using this system. The results showed the applicability of the system for the inspection and investigation of power engineering units.

Keywords: IR fiber bundles, IR thermography, internal defects detection

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1. Introduction

By now, infrared (IR) thermography has become widely accepted as a nondestructive technique of inspection and investigation for various applications in different fields, such as metrology, biomedical diagnosis, intraoperative monitoring, etc. [1–3]. One more possible application sphere of IR thermography is power engineering [4–6]. IR thermography is one of the most attractive and successful techniques, which allows detecting the object's surface and subsurface defects remotely without harmful radiation effects of other technologies (such as X-ray imaging). It also enables to study heat fluxes of heat transfer media. This technique may be used for the monitoring and research of heating networks, thermal power-generating equipment and other units, as well as for the optimization of working processes in different mechanisms and systems of this industry.

Commonly, the investigation by means of IR thermography is conducted outside, though there are many units where the external inspection is impossible. In recent years, the very few applications of IR thermography, concerning the investigation of

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heat field distribution of internal surfaces, have been reported. In particular, Tahiliani et al. used a stainless steel mirror placed inside the pipe in order to view the reflected IR radiations using an IR camera [4]. Mancaruso et al. also took IR images by means of a 45° IR-mirror located in the elongated piston (in order to analyze fuels combustion in engines) [5]. However, all the aforementioned approaches do not allow carrying out on-field experiments in hard-to-reach places, for example, in curved internal pipes of heat exchangers or in spaces near gas turbine blades.

To fill this gap, IR imaging systems provided with optical fiber bundles may be used. In this article, we discuss the applicability of ordered fiber bundles made of silver halides for *in situ* internal IR imaging of 2D temperature field distribution. Due to their flexibility, great lengths, and small diameters, these bundles allow conducting measurements in restricted spaces and in locations having no line of sight between objects and IR camera.

2. Methods

We developed and implemented the complete technological cycle of bundle fabrication. As seen from Figure 1, the fabrication process involves the following five steps: (1) producing raw materials by the thermal-zone crystallization-synthesis technique, which enables to carry out both synthesis and purification simultaneously [6]; (2) growing single crystals of silver halides using the Bridgman technique based on directional crystallization [7]; (3) obtaining cylindrical billets by means of mechanical treatment; (4) manufacturing polycrystalline fibers using extrusion technique [8]; (5) assembling ordered fiber bundles varying the following parameters: diameter of individual fiber, number of individual fibers, manner of fibers arrangement, and length.

We fabricated an IR ordered bundle of $AgCl_{0.25}Br_{0.75}$ multimode single-layer fibers, using a mechanical assembly of the fibers in a heat shrink tube. It consisted of 16 ordered fibers with the diameter of 0.525 mm and with the length of 300 mm. The outer diameter of the bundle was 2.5 mm; each end being equipped with a connector SMA-905.

This bundle is highly transparent in the spectral range of 2.5–20 μm without absorption windows, flexible, nontoxic, and nonhygroscopic. Its spatial resolution is 0.5 mm. The low loss region of the bundle covers most of the radiation wavelength range of blackbody at temperatures from −130 to +1100°C, thus being able to transmit radiation corresponding to these temperatures [9].

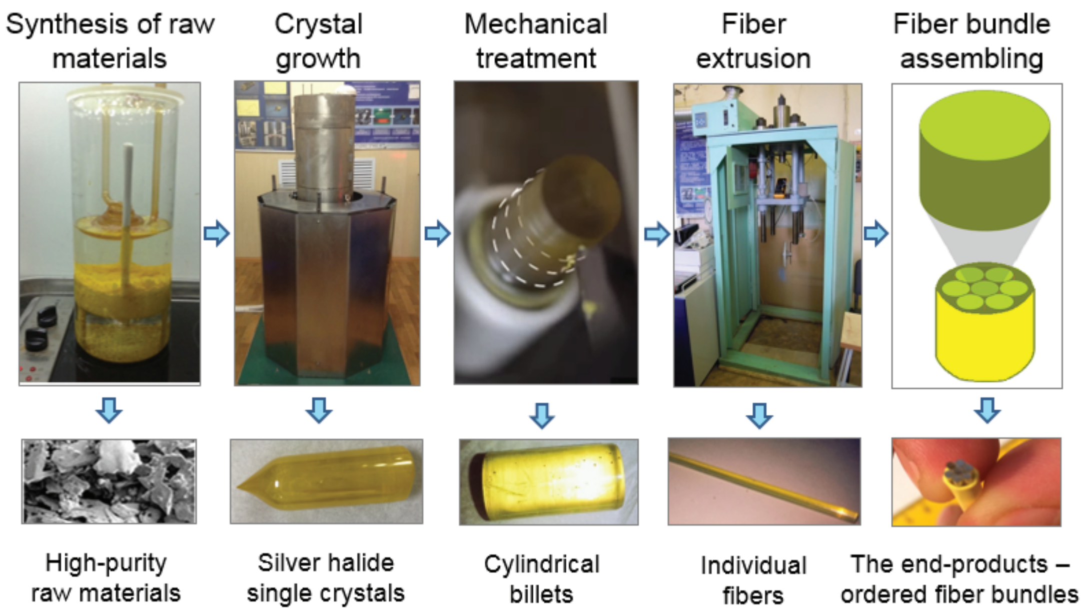

Figure 1: Steps of fabrication process of ordered fiber bundles.

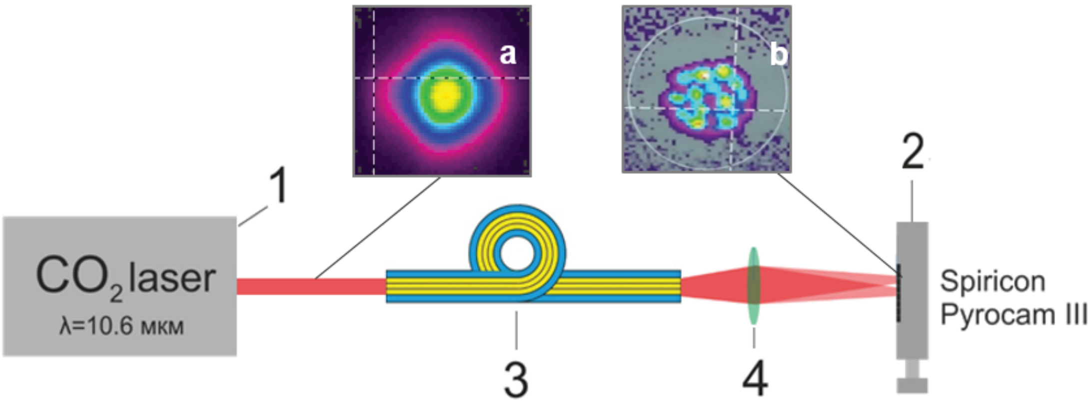

Figure 2: Schematic drawing of the first experimental setup for measuring crosstalk: 1 – CO_2 laser; 2 – CCD camera; 3 – 16-fiber bundle; 4 – AgClBr lens. Inserts: (a) radiation field distribution of CO_2 laser beam; (b) field distribution of radiation transmitted through the bundle.

3. Results

The first part of our research was measuring crosstalk between neighboring individual fibers of the bundle using a CO_2 laser (λ = 10.6 μm, CW mode, introduced power was 1 W, beam diameter was 3 mm). Firstly, we checked the uniformity of radiation distribution across the fiber bundle. For this, we used the laser beam without focusing (Figure 2). Radiation distribution was assessed by viewing images of CCD camera Spiricon Pyrocam III. All fibers showed the uniform distribution of transmitted radiation.

Then we used an additional AgClBr lens (the focal spot of 220 μm and the focal length of 50 mm) to focus the laser beam on the particular individual fiber, which

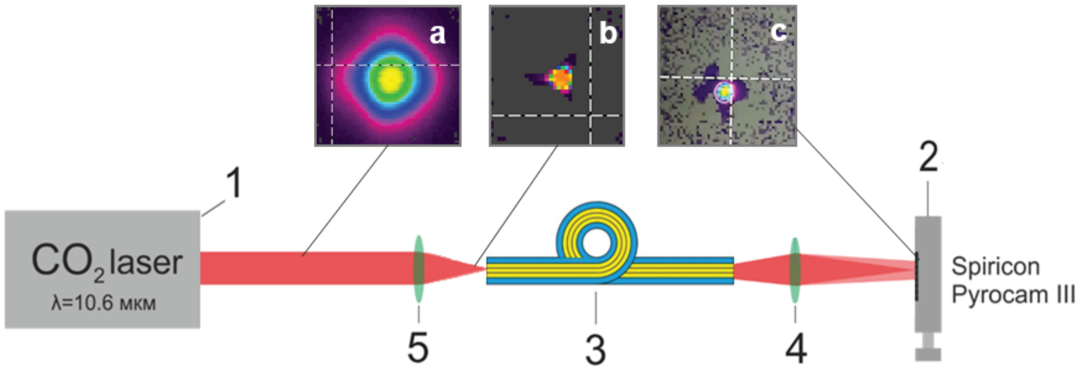

Figure 3: Schematic drawing of the second experimental setup for measuring crosstalk: 1 – CO_2 laser; 2 – CCD camera; 3 – 16-fiber bundle; 4, 5 – AgClBr lenses. Inserts: (a) radiation field distribution of CO_2 laser beam without focusing; (b) the same but with focusing on certain individual fiber; (c) field distribution of radiation transmitted through the bundle.

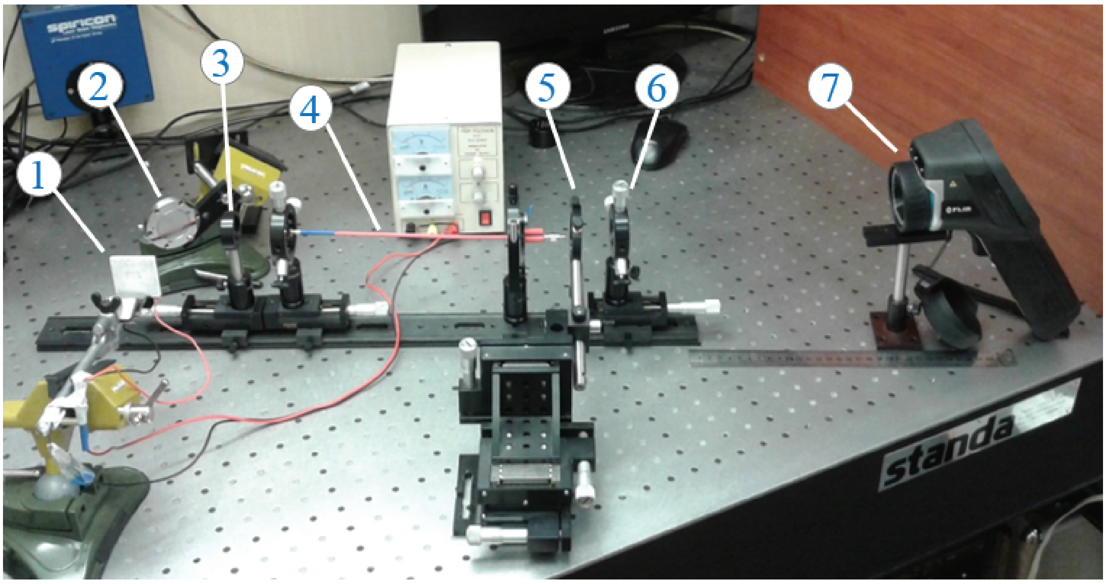

Figure 4: Thermal imaging setup: 1 – Peltier device, 2 – IR-mirror; 3, 5, 6 – AgClBr lenses; 4 – IR fiber bundle; 7 – thermal camera.

was surrounded by neighboring fibers from all the sides (Figure 3). 3D distribution of transmitted radiation was gained using the same CCD camera. Using it, we estimated the volume of Gaussian distribution of the radiation emerging from each individual fiber, that is, the radiation volume for the main testing fiber and for neighboring ones. The volume of small radiation peaks was summarized and divided by the total volume of radiation peaks. It was found that less than 5% of the total power of the output radiation leaked into neighboring fibers. This means that distortions of measured temperature due to crosstalk are low. The experiment was carried out for all fibers of the assembly. The results showed a good mutual agreement.

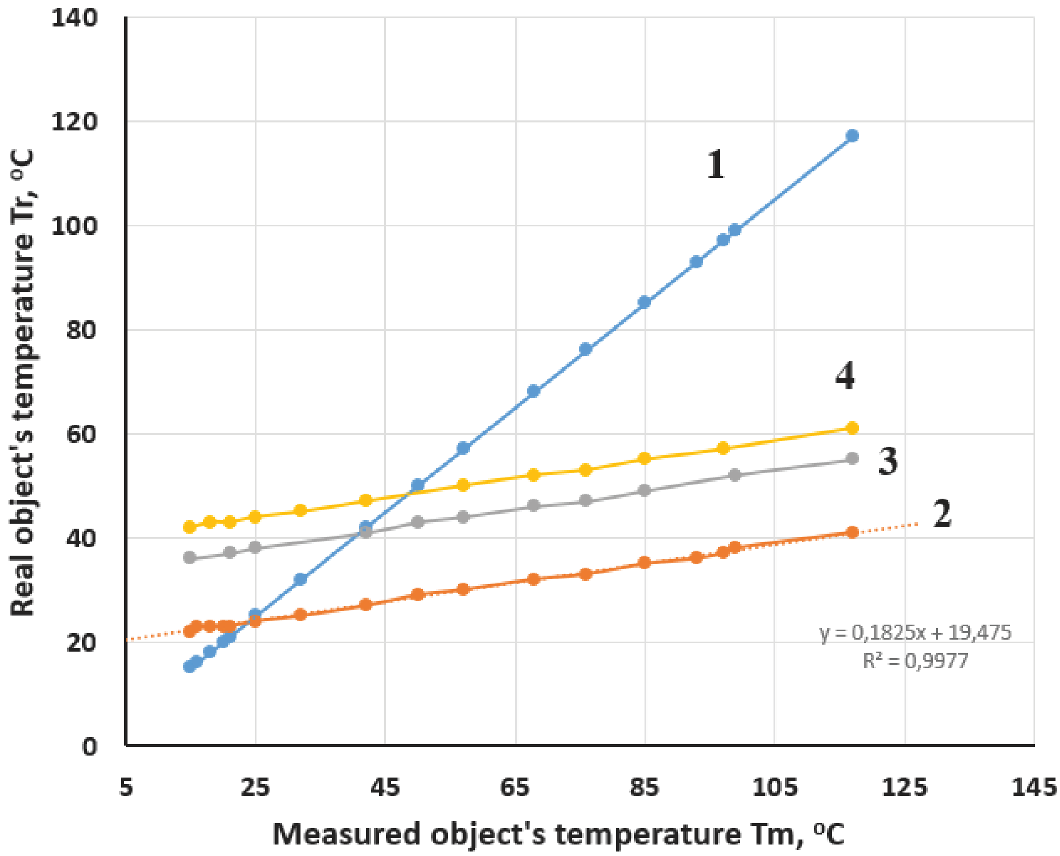

Figure 5: Calibration curves: 1 – line of equal temperature values; 2 – measured temperature values while the bundle temperature equal to room temperature; 3 – the same, but the bundle end temperature equal to 60°C; 4 – the same, but the bundle end temperature equal to 70°C.

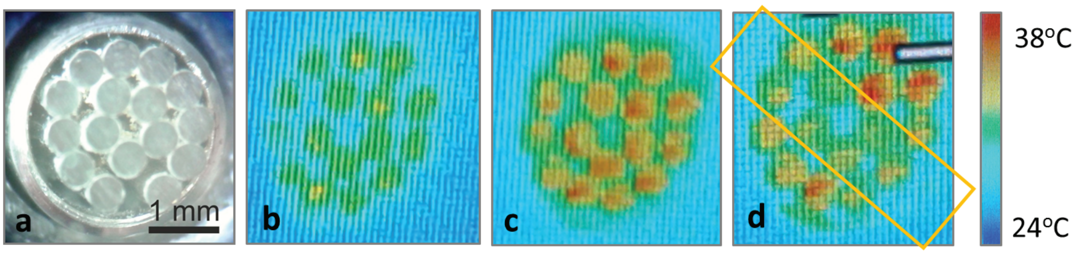

Figure 6: Photo of the IR fiber bundle end face (a) and thermal images transmitted through the IR imaging system supplied with the bundle: image of modelled extended defect (b), image of a Peltier device (c), image of a modelled linear defect (d).

The second part of our research was designing and calibration of a setup for obtaining thermal images. We propose an IR thermographic system composed of our fiber bundle, three AgClBr lenses, a thermal camera FLIR E30bx, and a 45° IR-mirror made of polished titanium (Figure 4).

To estimate the influence of total optical losses of our thermal imaging system on the measured temperature, we carried out calibration (Figure 5). Curve 1 in Figure 5 represents a line of equal temperature values. Curve 2 depicts the first regarded case, when temperature of the bundle was constant and equal to room temperature. For the next two cases, the proximal end of the bundle was heated up to 60 and 70°C (curves 3 and 4, respectively). As seen from the graph, total optical losses of the system distort substantially measured temperature. Nevertheless, the calibration experiment confirmed that the dependence of detected temperature on the heating of the proximal end could be approximated linearly. Therefore, we will be able to readily exclude temperature distortions by means of appropriate software. To minimize distortions caused by heating, one can use thermal insulation or single-mode individual fibers. To minimize distortions caused by reflection of radiation, one can use anti-reflective coatings for lenses and bundle face ends.

As mentioned earlier, our bundle comprises multimode individual fibers. When the bundle's material is heated, it starts behaving like an array of point radiation sources, that is, it emits radiation in all directions. If this intrinsic radiation has the angle of incidence greater than or equal to the critical one (it is more than 20 degrees for multimode fibers), the radiation is summarized up with radiation from the research object, which causes additional distortion of the measured temperature. The great contribution of such additional intrinsic radiation to the measured temperature was reported previously [10]. To diminish the temperature distortion, it makes sense to consider the application of single-mode individual fibers.

Using single-mode fibers for the bundle, we will have the critical angle, which does not exceed 7 degrees. In this case, the extent of additional temperature distortions will be significantly reduced, because less part of the radiation from heated bundle particles will reach the thermal camera. Consequently, we will be able to determine temperature more accurately. It is important to maintain the distal end of the bundle (the length about 20–30 cm) at room temperature, because that additional intrinsic radiation has to overcome certain distance to be completely attenuated.

The last part of our research was testing the IR imaging system. For this, two experiments in quasi steady-state conditions were carried out. The setup was as shown in Figure 4. The thermal camera was positioned at an angle of 90° and a distance of 0.7 m from research objects. The appearance of an end face of the IR fiber bundle is shown in Figure 6(a). As a heated wall of power engineering unit, we used a Peltier device with the temperature of +100°C, emissivity of 0.95. From Figure 6(c) it can be seen that obtained thermal image of the device represents quite uniform distribution of temperature (about +38°C). According to the following equation, we can calculate the percentage of real object's temperature detected by the thermal camera n:

$$n = \frac{T_{meas} - T_{room}}{T_{real} - T_{room}} \cdot 100\%, \tag{1}$$

where T_{meas} – the measured temperature, T_{real} – the real temperature of object, T_{room} – room temperature. For the proposed IR imaging system n = 18%.

As an extended defect, we used a rubber plate (emissivity of 0.94) at room temperature on the background of the heated Peltier device (Figure 6(b)). Obtained thermal distribution was uniform and the detected temperature was approximately 31°C that is related to the heating effect of the background. To imitate a linear defect of the heated wall (a crack), we used a blackened stainless steel wire (emissivity of 0.95) of 1 mm in diameter and the same heated Peltier device as a unit's wall. Obtained thermal image of the modeled crack shows rather good detection ability of the system (Figure 6(d)).

4. Conclusion

In the present study, we proposed the scheme of an IR thermographic system provided with IR ordered fiber bundle of silver halides. It was revealed, that our system with proper calibration enables online temperature monitoring and detecting defects of power engineering units. We assessed crosstalk between neighboring individual fibers of the bundle. It was found, that they did not exceed 5%. We also carried out calibration of the IR imaging system in different operating conditions, taking into account the total optical losses of the system. The use of single-mode individual fibers for the bundle instead of multi-mode ones as well as thermal insulation can help to improve the system owing to reducing temperature distortions. Anti-reflective coatings would be also useful. Using the proposed system, we successfully determined modeled defects located at an angle of 90° with respect to the thermal camera. Our future task is to optimize the design of the system, for example, fabricate miniature IR mirror, which may be consolidated with the bundle forming a sealed connection, and develop the embedded system of lenses. It is also necessary to increase the spatial resolution of the bundle, its length, and maximum scan area.

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